A Survey and Evaluation of the Potentials of Distributed Ledger Technology for Peer-to-Peer Transactive Energy Exchanges in Local Energy Markets

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(Survey Tutorial)

***Abstract*—The unpredictability and intermittency introduced by Renewable Energy Sources (RESs) in power systems may lead to unforeseen peaks of energy production, which might differ from energy demand. To manage these mismatches, a proper communication between prosumers (i.e., users with RESs that can either inject or absorb energy) and active users (i.e., users that agree to have their loads changed according to the system needs) is required. To achieve this goal, the centralized approach used in traditional power systems is no longer possible because both prosumers and active users would like to take part in energy transactions, and a decentralized approach based on transactive energy systems (TESs) and Peer-to-Peer (P2P) energy transactions should be adopted. In this context, the Distributed Ledger Technology (DLT), based on the blockchain concept arises as the most promising solution to enable smart contracts between prosumers and active users, which are safely guarded in blocks with cryptographic hashes. The aim of this paper is to provide a review about the deployment of decentralized TESs and to propose and discuss a transactive management infrastructure. In this context, the concept of Proof of Energy is proposed as a novel consensus protocol for P2P energy exchanges managed by DLT. An application of the proposed infrastructure considering a Virtual Power Plant (VPP) aggregator and residential prosumers endowed with a new transactive controller to manage the electrical storage system is discussed.**

***Index Terms*—Aggregator, battery, blockchain, demand response, distributed ledger technology, local energy market, microgrid, peer-to-peer transactions, prosumer, smart contracts, smart grid, transactive energy.**

NOMENCLATURE

AnC	Analytics component.
BFT	Byzantine fault tolerant.
CHP	Combined heat and power.
CPF	Consumption-production function.
CSM	Certified smart meter.
DER	Distributed energy resource.
DLC	Direct load control.
DLT	Distributed ledger technology.
DR	Demand response.
DSM	Demand-side management.
DSO	Distribution system operator.
EMS	Energy management system.
EV	Electric vehicle
GWAC	GridWise architecture council.
HDG	Home device gateway.
HEM	Home energy manager.
HVAC	Heating, ventilation, and air conditioning.
IAS	Immutability, anonymity, and security.
IB	Information backbone.
ICT	Information and communication technology.
IoT	Internet of Things.
JSON	JavaScript object notation.
LEM	Local energy market.
MQTT	Message queue telemetry transport.
MV	Mid voltage.
P2P	Peer to peer.
PNWSGD	Pacific northwest smart grid demonstration.
PoE	Proof of energy.
PoS	Proof of stake.
PoW	Proof of work.
PV	Photovoltaic.
QoS	Quality of service.
REonly	Rewards only.
RES	Renewable energy source.
SOC	State of charge.
TC	Transactive control.
TCR	Transactive controller.
TE	Transactive energy.
TEonly	Transactive energy only.
TES	Transactive energy system.
TMI	Transactive management infrastructure.
TMP	Transactive management platform.

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VPP	Virtual power plant.
WT	Wind turbine.

I. INTRODUCTION

DURING the last decades, distributed generation units based on Renewable Energy Sources (RES) have been integrated into electrical grids, mainly at the distribution level. By the end of 2016, around 25% of the electricity production around the world originated from RES [1], with wind energy, bio-power energy, and solar photovoltaic (PV) being the energy pivotal sources. Studies reveal that in the next years there will be a major increase in the penetration of RES into the grid, which will reach a share around 30% by 2022 [2] and this share will even exceed 60% by 2050 [3]. Moreover, since the installation of Distributed Energy Resources (DERs), including PV panels, micro Wind Turbines (WTs), diesel, and bio-generators has become an affordable investment in many countries, from the point of view of both residential and business users, they have been deployed at the consumption side too [4]. At the same time, electric loads are not "dump" anymore. They can auto-regulate the power absorption, intelligently and/or by responding to external Demand Response (DR) signals from the grid. In recent years, the concepts of Demand-Side Management (DSM) and DR have arisen in order to balance energy generation with energy consumption [5] and help preventing the congestion problems [6]. By applying a DR approach, end users under incentive-based programs let suppliers to control all or some of their loads by means of Direct Load Control (DLC) [7]. For example, during peak hours, users may receive incentives to have their loads reduced, such as Heating, Ventilation, and Air Conditioning (HVAC) loads [8]. To do so, smart metering based on Internet of Things (IoT) is required in order to send real-time data among all users [9], [10]. Therefore, the overall network becomes a smart grid, as there is not only a flow of energy but also a flow of data, which managed properly, will determine an efficient distribution of energy through the entire system [11], [12]. Both DERs and DR have opened new opportunities for the power grid, and new challenges as well, because DERs are intermittent and nonuniformly deployed. Opportunities have arisen regarding the optimization of power flows, the improvement of the stability of the power grid, and the reduction of the economic impact of production and deployment of energy reserves. On the other hand, the energy market regulation and the management of energy trading also represent a concern.

In recent years, in order to exploit all the benefits of DERs and to meet policies and targets toward decarbonisation, a new kind of paradigm has been proposed. This paradigm is based on two key concepts, namely: Transactive Energy (TE) and peer-to-peer (P2P) management by means of Distributed Ledger Technology (DLT), based on blockchain. These concepts will be carefully addressed in the following sections.

As it will be better described and detailed in the next sections, the contributions of this paper are mainly related to, shown as follows.

1) The survey and assessment of the potentials of DLT for P2P Transactive Energy Exchanges in Local Energy Markets.
2) The detailed description of a new transactive management infrastructure, based on DLT, implementing a TE system leveraging P2P energy exchanges (defined here as P2P-TE) in Local Energy Markets (LEMs).
3) The proposal of an innovative Proof of Energy (PoE) function as a candidate of the consensus protocol for P2P energy exchanges managed by DLT. The proposed consensus protocol is not energy demanding as in other permissioned DLT and it is able to promote a social behavior based on sustainable and circular economy.
4) The proposal of an innovative transactive controller (TCR) to manage the operation of the battery of a residential prosumer.

The paper is structured as follows. Sections II and III give a survey on Local Energy Markets (LEM) and Transactive Energy Systems (TESs), respectively. Section IV reviews and discuss the concept of blockchain-based DLT applied to TESs. Finally, in Section VI, a novel transactive management infrastructure (TMI) to enable P2P energy exchanges among all the grid-connected users is proposed and described. An innovative Proof of Energy (PoE) function is also proposed in order to implement P2P energy exchanges based on DLT in a LEM context.

II. LOCAL ENERGY MARKETS AND THE ROLE OF PROSUMERS

The electricity market is defined by both entire market and sub market [13]. The former is based on end-product markets and intermediate-product markets, while the latter includes the wholesale market and those for ancillary services. A Local Energy Market (LEM) can be seen as a kind of sub-market, where participants can be aggregated for flexibility purposes [14] such as constraints management, portfolio optimization and system balancing in order to balance demand and supply. The current research activities on LEMs are related on market mechanisms [15], agent preferences and strategies [16] and transactional product of reserve energy [17]. The presented paper fits in the latter two topics.

In order to integrate a LEM into the entire market, different organizational models for flexibility management have been compared in [18] for both Germany and the Netherlands. This paper reveals that the dynamic pricing and local aggregator approaches work properly in the retail market. In [19] the use of a LEM is proposed to secure the integration of large renewable energy systems into the main energy system. The study developed in [20] proves that it is feasible to include Combined Heat and Power (CHP) plants to help balancing the fluctuation of wind power systems. Both [19], [20] focus their study on some examples in Denmark.

A current example of a LEM is furnished in the empower project [21], which does not focuses on price but on a value-oriented approach. It can be used to carry out different contracts among partners, such as cross-subsidized energy contracts or flexibility contracts. Some pilot tests combining the Empower concept and the real-time shared knowledge about energy needs among households and communities have been proved in Norway, Germany, and Malta with promising results. Another example is the design of a LEM which has been developed by the Chalmers University of Technology in Sweden for the campus itself [22]. The computational model in this project was validated by experimental results and it was concluded that the LEM was not able to provide itself the required energy, thus requiring external energy resources.

Let us consider, for example, a community or a set of communities of users who can arbitrarily belong to one of the following categories: 1) prosumers, i.e., users who provide the grid with locally generated electrical energy, such as PV, WT or diesel generators, that can either inject or absorb electrical energy; 2) active users with flexible and shiftable loads, electric vehicles (EVs) and HVAC systems that may be controlled by DR signals managed by TCRs; and 3) passive users, not participating in any DR program. These communities are usually organized geographically and, from the grid's viewpoint, they are attached to a common node in a distribution bus and can participate in a LEM [23].

In a LEM, whenever the net consumed energy is positive, prosumers can decide to sell part of the produced energy. In this way, a surplus of energy in the grid may exist. On the other hand, active users can "buy" this surplus by regulating their loads. Active users can also virtually sell energy, by responding to DR signals and reducing or time-shifting their electrical loads [24]. It should be noted that this trading must be done in a secure and privacy-preserving way, as the transactions in a LEM are carried out in a decentralized way. This can be achieved by a proper bidding algorithm with privacy-preserving protocols [25].

III. TRANSACTIVE ENERGY SYSTEMS

A. *Transactive Energy Concept*

As previously stated, in the new grid scenario the consumers with the ability to inject energy into the grid (prosumers) would also like to take part in the electricity market by maximizing their profits while delivering energy and minimizing their costs when absorbing it [26]. In other words, a two-way grid management is required in order to enable energy transactions among all the participants [27]. In this context, the GridWise Architecture Council (GWAC) [28] has proposed the following definition for Transactive Energy (TE): "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." The concept of "value" is related to the definition of price and incentives in order to guarantee that all DER owned by prosumers generate and consume electricity in a win-win approach [29], i.e., by looking for the benefits of all the users and not for the benefit of one or a few ones.

B. *Transactive Controllers*

A classification of control strategies in smart grids identifies passive, active, interactive, and TCRs [30]. While passive controllers operate without exchanging information with the utility, active controllers enable customers to adjust their energy consumption depending on price changes. TCRs represent the most promising evolution for energy users aiming at participating in LEMs since they allow both prosumers and active users to make bids considering the real time price of electrical energy and their energy requirements.

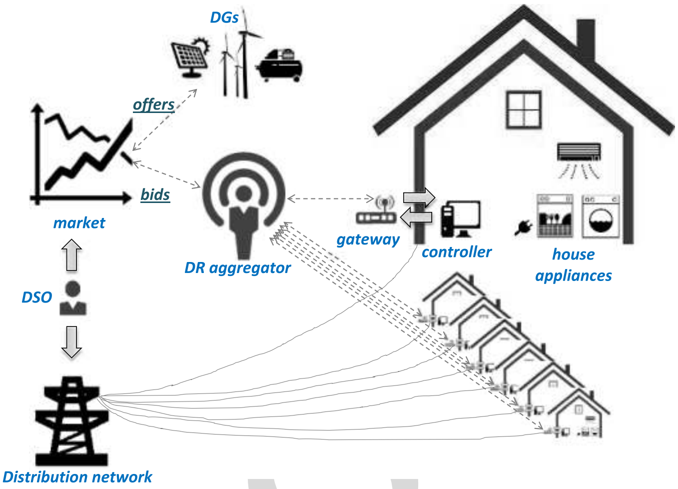

Fig. 1. System architecture adopted for TCRs' operation [33].

A TCR is basically implemented on an energy gateway which communicates over the Information Backbone (IB), e.g., the Internet, to exchange all the information needed to trade and manage energy transactions [31]. In other words, the TCR acts as a negotiator of energy prices on the energy market in order to modify the user's settings according to price signals, which perfectly fits with the concept of LEM, explained in Section III. The TCR is used also to grant access to the information platform used to coordinate the signing of smart contracts and the recording of energy transaction. Finally, the TCR communicates also to smart devices used by active users, which can be sensors or actuators, such as smart meters, smart lamps and HVACs.

A transactive scheme is proposed in [32], where a distributed iterative algorithm for optimal demand in residential applications is developed. Another example is given in [33], where a TCR and some smart plugs-in for some electrical loads are adopted. In this approach, a residential energy gateway exchanges information with a DR aggregator, which is in charge of different houses. Each DR aggregator sets the bids for electrical energy according to the signals received from the TCRs of each house and gives feedback signals (acceptance or rejection of a bid) to the corresponding TCRs. The described architecture is depicted in Fig. 1.

Among the three levels of control in electrical grids, i.e., primary control for dynamic response (milliseconds), secondary control for frequency control (seconds) and tertiary control (minutes) over the whole system, this last control acts in order to balance energy generation and energy consumption combined with economic signals, thus also contributing to frequency control in a social-welfare maximization approach [34]. In order to implement a proper Transactive Control (TC), distributed intelligent devices based on Information and Communication Technology (ICT), such as smart meters, must be used [35], [36]. Smart meters enable exchanging energy data in near-real-time fashion among all the agents (prosumers and active users).

When a prosumer wishes to make either a demand (buy) or an offer (sell) of energy from/to the grid (which is recorded by a smart metering), it sends its request to a parent node, where other prosumers are connected. Then, a TC-based platform evaluates all bids from all the energy-demand prosumers, assesses the offers from energy-production prosumers and finally sends the corresponding prices to all the prosumers, which can either accept or reject the transactions [37].

For the last few years, some pilot projects have been carried out on the topic of managing small communities under a TES perspective, showing promising results. For example, in the USA, the Pacific Northwest Smart Grid Demonstration Project (PNWSGD) [38] has coped with the grid congestion problem by acting on smart thermostats for HVACs control, while in the Netherlands the PowerMatching City Project [39] has dealt with supply and demand management issues in the first smart grid village in Europe. More examples of TE-based pilot projects and their comparison can be found in [31] and [36].

IV. DISTRIBUTED LEDGER TECHNOLOGY FOR TRANSACTIVE ENERGY SYSTEMS

A. Advantages of a Peer-to-Peer Decentralized Architecture for Energy Exchanges

In traditional power systems, every transaction is centrally managed for actions like tracking of consumed and produced energy, computation of energy prices, immutable, and secure recording of all the information related to the energy transactions [40], [41]. In a Peer-to-peer (P2P) context, this management is decentralized and regulated among the "peers" participating to the energy network, which becomes a virtual energy power grid [42]–[44].

In a centralized architecture, communication between prosumers should be authorized by centralized servers and the set requirements for them increase with the number of prosumers [45]. Centralized architectures are, therefore, not easily scalable to account for an exponential increase of prosumers, which in turn produce high volumes of data at high frequency (i.e., every 60 s). As a result, the integration costs to account for the magnitude of that increase would make a TMI not economically feasible [44]–[53].

The evaluation of the performances of a TMI is a complex task and different features can be considered, the most important being:

1) data security, because financial data is being exchanged;
2) data privacy, because energy data exchange can profile the user;
3) speed of financial transactions or transactions insertion rate, ideally a constant value or at least sublinear e.g., $O(\log N)$, with N being the number of transactions;
4) resiliency to failures and data integrity;
5) small energy footprint: the system must not consume more energy.

Given a certain level of performance, p, related to the previously listed features, the costs which must be sustained to guarantee this level can represent a metric for the scalability, $S = \mathrm{f}(N, p)$, which can be reasonably be assumed as a monotone function of the number of prosumers N. By using S as a metric for comparing the centralized and P2P approaches, the centralization of all the operations required to assure the level of performance p can become infeasible for a huge number of prosumers. P2P transactions are, instead, an order of magnitude cheaper than those in traditional systems based on a centralized information center [43].

To recall a parallel to computer networks where the exchanged value is a file (or a database), P2P reduces the costs of the scaled system and avoids to install more centralized hardware. The centralized servers represent single points of failure and may represent easy targets for attacks from hackers. The server loads and delay can be reduced by leveraging the capabilities of P2P networks which inherently scale "well" with the number of connected devices. In computer networks and data center management, a similar problem of performance arises whenever an increased service demand takes place. Usually, the owner of the data center has two options: vertical scaling versus horizontal scaling. In the vertical scaling, the owner installs more bare metal, i.e., by buying more hardware with increased performance and maintenance costs. In the horizontal scaling, the owner replicates its service on different (physical or logical) locations, thus reducing the maintenance costs (like redundancy, failover, etc.).

To summarize, the main advantages of a P2P decentralized architecture over a centralized one are in terms of scalability, resiliency, adaptability, fault tolerance, security, and trust. Investment and maintenance costs are also reduced due to the adoption of hierarchical storage capacity and a sublinear cost of ownership which grows as $O(\log M)$, where M is the number of nodes [46].

B. Blockchain Technology Applied to Transactive Energy Systems

Since envisioning totally disconnected micro-grids from the main Distribution System Operator (DSO) is still premature, a more realistic deployment of transactive energy systems will be a hybrid solution, where the regulation and the access to the information required for the implementation of P2P energy exchanges based on the TE only is managed by the DSO. For example, the DSO could manage the access to the smart power grid and grant access to the information system, but it would not manage the energy transactions centrally. It means that: 1) energy data transactions must be confirmed by peers by using a sort of consensus protocol embedded in a shared execution routine usually know as smart contract; and 2) transactions must be stored securely within peers participating to the program. A comprehensive review on P2P and community-based markets can be found in [47].

This is a call for the very popular technology named Distributed Ledger Technology (DLT), representing an abstraction of the so popular blockchain technology.

By abusing of the terminology, P2P may refer to both the way according to which energy transactions take place and to the information architecture supporting them. Accordingly, from the point of view of the information architecture, DLT is also a P2P based architecture and so it seems a natural candidate to implement a TE system based on P2P energy exchanges (P2P-TE). In general, the term P2P network is used when referring to the information infrastructure (e.g., Internet) and P2P-TE when discussing about the logical interaction among the peers which trade and/or exchange energy resources. Concerning the type of access to the P2P network, the terms "permissionless" and "permissioned" are used. A permissionless architecture is a public network where everyone can participate without any special authentication/authorization mechanism. All peers are anonymous and untrusted. In a permissioned architecture, the access to the network must be granted (for example by registering one's identity to a central data center), although no central action interferes during the information exchange among peers (e.g., Skype could be thought as a permissioned P2P network). In a permissioned architecture, peers share some kind of trust and the identity is not completely anonymous. In the following subsection, a permissioned P2P for the proposed P2P-TE system will be considered.

As stated before, to enable P2P energy transactions between prosumers and active users within a LEM context, DLT appears to be a promising solution [48], [49], as it avoids the need of an intermediator and can guarantee near real-time transactions. Currently, there are many type of DLT. The most popular has been that based on blocks-chain, where groups of transactions are stored in blocks of data chained one after another in order to make nearly impossible data forgery [50]. The storage of the transactions data into the blocks is secured by cryptographic functions and industry level security methodologies (e.g., signature based on the public-key paradigm) [51], [52]. The blockchain is stored globally within the network of participating peers and it is a virtuous application of decentralization algorithms. In the Internet universe, popular applications based on decentralized communication of information are Bittorrent for sharing files, and Skype, for sharing contacts. In the blockchain universe, the shared item is essentially some kind of "value." This value can be virtual coin or crypto currencies, smart contracts, virtual goods, agreements between untrusted parties. While in the centralized approach, the participating parties give trust one another to the central authority (e.g., in the case of a bank institution), in P2P untrusted parties use a mechanism to reach some kind of trust. This trust must at least guarantee:

1) anonymity;
2) impossibility to repudiate a transaction once it has been saved;
3) very low probability of forgery of saved data;
4) resiliency to possible attacks, like the byzantine attack where a transaction is authorized to be saved even if it should not.

It should be noted that points 2) and 3) are generally guaranteed by using cryptographic hashes which define each block and chaining of all blocks. In this way, transaction forgery would mean being able to modify all the chain. This is not a new concept, as it was popularized in 2009 when blockchain technology was used by the Bitcoin platform for cryptocurrency to enable secure virtual transactions [52].

That said, blockchain enables P2P transactions in a decentralized way, which perfectly fits with the idea of making energy transactions among the prosumers in a LEM context [53], [54], without the need of a central authority, such as the DSO in traditional distributed energy networks. Under these circumstances, a blockchain-based DLT might manage hundreds or even thousands of smart contracts [55] in near-real time and with no obstacle due to data center design and maintenance. However, the original algorithm found in DLT like Bitcoin is able to cope with a maximum of seven transactions per second [56]. For this purpose, other alternatives have arisen, such as Ethereum [57], which can handle tens of energy transactions per second, or Hyperledger [58], [59], which can cope with hundreds of transactions per second and has the additional advantage of being a scalable solution, which makes it very suitable for smart contracts [60]. A comparison between Bitcoin and Ethereum can be found in [61], a comparison between Ethereum and Hyperledger is given in [62], while a comparison between all current DLT-based platforms used for TE in microgrids is carried out in [63].

An example of an on-going project aimed at experimenting blockchain-based P2P energy trading is transactive Grid [64], [65], where prosumers in a small community in Brooklyn (USA) can buy and sell energy from each other using Ethereum platform for smart contracts. Another example is the UK company Electron [66], which has used blockchain technology to create an open-source platform for providing truthful metering. A comparison between current projects on P2P energy trading can be found in [67].

C. Consensus Protocols

In a LEM with blockchain-based DLT, since there is no central authority which manages the energy transactions, all prosumers (or nodes from a system viewpoint) must agree upon a financial energy transaction before storing it into the blockchain. The validity of a new transaction (or block, i.e., group of transactions) holds if and only if a consensus is reached among all nodes [68]. Consensus protocols are a set of algorithms and structured data well known in many engineering fields, such as Computer Science and Signal Processing. The key properties or requirements of a consensus protocol are [69] as follows.

1) Safety: nodes that take part in a consensus produce the same outputs according the protocol rules.
2) Liveness: all healthy nodes take part in consensus will produce a value.
3) Fault tolerance: if a node that takes part in the consensus fails, the consensus protocol can continue working.

The most common consensus protocols in blockchain-based DLTs are: Proof of work (PoW), Proof of stake (PoS) and Byzantine Fault Tolerant (BFT). The PoW protocol [52] is used by permissionless platforms (such as the aforementioned Bitcoin or Ethereum platforms) in which a large number of untrusted nodes seek for consensus to approve an energy transaction. PoW algorithm appears to be the best option as far as private data safety is concerned, because all nodes must solve a hard cryptographic puzzle before adding a block into the chain, thus, making the system impermeable to malicious trading [70]. The validity of the "work" done is represented by the difficulty (in terms of complexity and memory/CPU requirements) of the cryptographic puzzle. The process to find a solution to this puzzle is called mining [71]. To gain the right to approve the new block (and therefore to gain also an economic profit), one has to invest in hardware: The more powerful hardware, the higher is the probability to quickly solve the cryptographic puzzle. Once a solution is reached, the other peers can confirm the solution (confirmation of the solution is much simpler than finding it).

Although, it has been emphasized that blockchain-based DLT could enable TE exchanging among multiple DER parties, care should be taken to the energy footprint of (any) DLT technology. Indeed, a recent study reveals that Bitcoin's blockchain energy footprint is similar to Ireland's average electrical energy consumption [72], because of the energy hunger of PoW algorithms. Moreover, the Bitcoin requires over 3 GBs of compressed data to hold the entire blockchain, obviously outstripping the capabilities of smart inverters or transactive controllers [73]. Other aspects of DLT concern the type of access to the IB (permissioned or permissionless access, or a combination of both), real-time requirements for the energy transaction, Immutability, Anonymity, and Security (IAS) requirements of transactions [74].

In order to reduce the energy footprint in the Bitcoin-based PoW protocol, the PoS protocol [75] substitutes the mining process by the election of a node that acts as the evaluator. In other words, the right to validate and insert a new block is granted to that peer which can prove the ownership of some amount of a variable called *stake* (in the cryptocurrency, the stake can be also the currency itself). The selection based on stakes only suffers from some problems. For example, in a pure PoS the peer with the highest amount of stakes will gain a permanent advantage. To overcome these and other shortcomings of PoS, other variants have been proposed in the scientific literature. For example, in the cryptocurrency world PeerCoin [76] and Nxt [77] use a selection algorithm based on the concept of coin age and a transformation of the stake size, respectively. However, as it will be detailed in the next section, PoS is a good candidate to be used in the energy context. This manuscript will sketch (see Section V) an architecture based on PoS by showing that the basic problems of PoS can easily be avoided by using a permissioned architecture and a hard-to-forge stake values.

A very interesting modified version of PoS is used in SolarCoin [78], a promising platform for selling solar energy through certified production plants. In SolarCoin, every PV plant's owner registers their PV installations thus becoming a prosumer. Then, after verification of the identity and the details of the components of the installation, the owner grants access to the platform and receives a digital wallet. In SolarCoin, the software installed into the user-side smart inverter communicates the energy production only, and, subsequently, a block of "solar" transactions is inserted into the DLT. For every MWh produced, the platform pays back some "solar coins" and the transactions are stored into the digital wallet by means of the blockchain. There is no centralized ledger for transactions. The BFT protocol [79] is used to detect mismatches between the information shared among all the nodes, thus avoiding the malfunction of the whole system. A comprehensive explanation of PoW, PoS, and BFT protocols can be found in [68]. A variant of PoS and BFT protocols is the Tendermint protocol [80], which is a private one. Apart from the aforementioned blockchain consensus protocols, in the literature there are more examples. A comparison among all the consensus protocols based on blockchain is detailed in [81]. Recently, with the vision for a highly scalable DLT for the IoTs, other concepts have emerged. For example, in the Tangle algorithm, validation and insertion of transactions are based on acyclic graphs and not chain of blocks. Tangle is the core algorithm of the popular IOTA cryptographic token [82].

V. PROPOSED TRANSACTIVE MANAGEMENT INFRASTRUCTURE

A. *Architecture*

The proposed system is a permissioned blockchain based architecture where the consensus protocol is a modified version of PoS which, in comparison, uses less than 0.001% of the power of Bitcoin [78]. Therefore, it promotes energy efficiency and a sustainable behavior.

The envisioned architecture, called Transactive Management Infrastructure (TMI), represents the main novel contribution of the paper and is depicted in Fig. 2.

One of the innovative contributions of the present work with respect to the present literature is the attempt to establish the baseline for a reference framework for blockchain-based TMI that can be used by medium sized aggregators to manage LEMs. Without any claim of superiority, from an extensive analysis of the literature results that previous works do not provide technical details of their solutions. It is, therefore, not possible to understand the implementation details of the blockchain-based TMIs due to the lack of a detailed explanation of the software implementation. Instead, in this paper details related to the implementation of both the proposed TMI (based on MQTT + JSON) and of the proposed DLT technology are specified. The adopted DLT technology makes use of a PoS scheme, within a permissioned system where participants grant access to the TMI. While the proposed scheme overcomes the energy footprints many blockchains schemes suffer from, the consensus protocol is based on a novel CPF that promotes the rational use of energy resource also contributing to reduce power losses in the distribution and transmission systems.

The TMI is a layered architecture which consists of three layers: 1) the aggregator owned data center, where the virtual exchange of energy is accomplished; 2) the communication layer, consisting of all the components needed to let the TCRs communicate one other (this will contain also the Internet Cloud part which rules the access of the TCRs to the DR-TE program); and 3) the user layer, where the TCRs execute the DR algorithms and perform all the communication to the IT infrastructure. The first layer regards a digital communication infrastructure. Basically, it can be thought as a virtualized set of servers which are centrally managed by some central actor. The central actor can be an aggregator, or some other authority like the DSO.

The only purpose of the central actor is to provide participants of the LEM with the basic software and telecommunication networking components for the exchange of energy related data (energy measurements, smart contract info and/or market trading information). It does not implement any other functions, like energy transactions storage, validation of virtual "coins," etc., because all these information are exchanged by means of the DLT, i.e., by means of blockchain based smart contracts.

Therefore, the role of the central actor is to manage the Transactive Management Platform (TMP), only. The core components

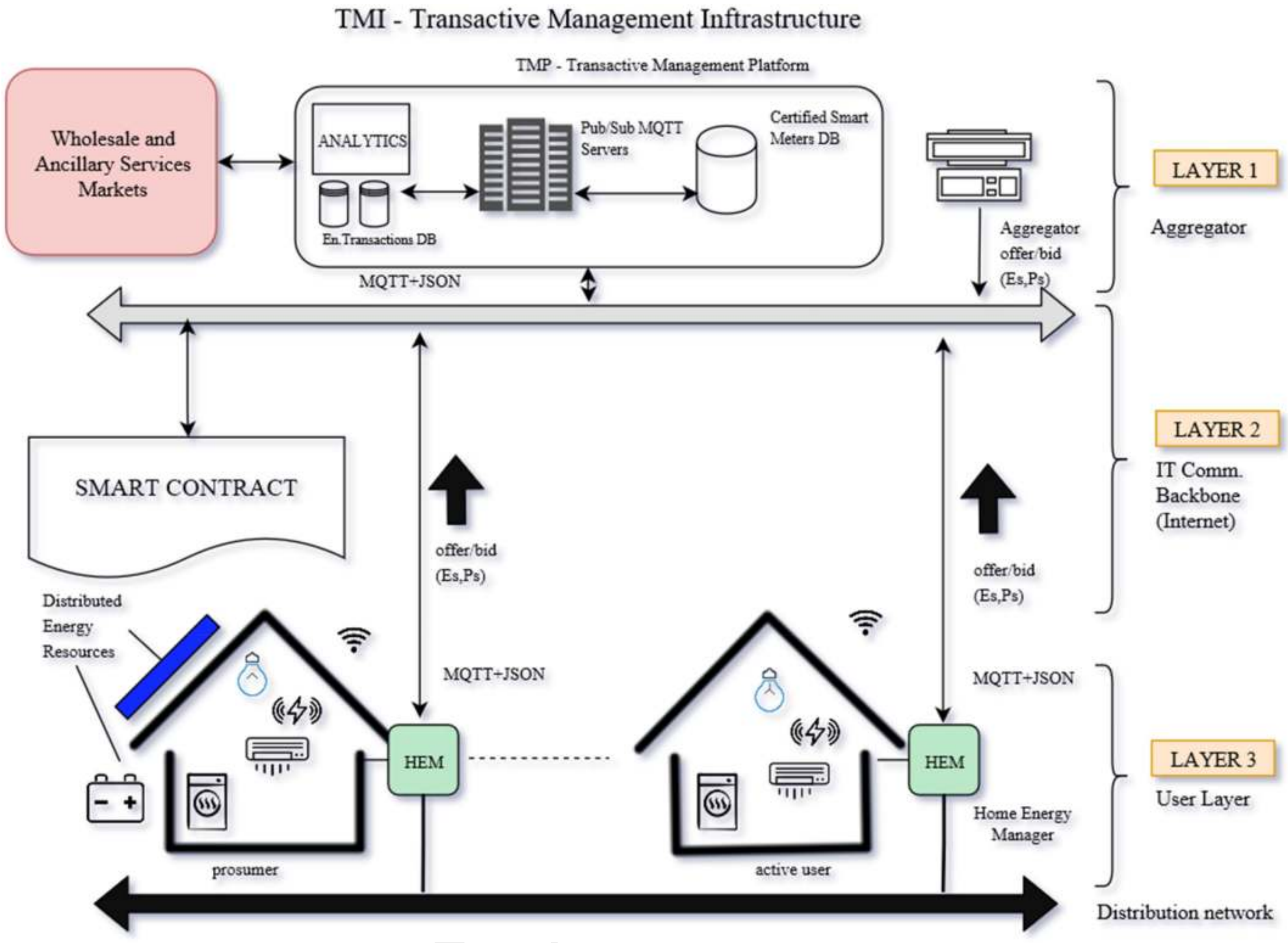

Fig. 2. Transactive Management Infrastructure (TMI): Proposed architecture to enable P2P transactive energy exchanges.

of the TMP are: 1) the Pub/Sub servers, 2) the Certified Smart Meters DB (CSM-DB), and 3) the Analytics Component (AnC).

The Pub/Sub servers are needed for asynchronous and ubiquitous communication among parties. They use a well-known computer network design pattern based on the concept of Publisher-Subscriber. Without entering into the details, it can be explained by saying that participants subscribe to virtual information channels, usually called rooms or topic rooms, and publish data on the subscribed channels. The role of the Pub/Sub servers or brokers is to receive the publishers' data and broadcast them to other participants on the same channel. In this context, the participants are the prosumers and active users that gain access to the platform through the HEM in a ubiquitous fashion, i.e., without any sort of operation on the user appliances (e.g., routers). The energy data is exchanged through the brokers by using dedicated channels the HEM are subscribed to.

The network protocol used to handle the data publishing is the Message Queue Telemetry Transport (MQTT), which is a lightweight application protocol very popular among the IoT community. It was conceived for embedded devices with constrained energy and computational resources. It also supports Quality of Service (QoS) concepts. For example, in MQTT three QoS levels are conceived. QoS 0 refers to the case of transmission without retransmission in case of packet loss. QoS 1 and 2 refer to guaranteed delivery of packets (e.g., this level can be used to send critical commands to devices). The data format transported by the MQTT is the JavaScript Object Notation (JSON), which is a ubiquitous data exchange format easily to extend and to implement. It is based on a key-value structure. For example, the following JSON snippet could represent the measured temperature of a sensor:

```
{
``clientId’’: ``01394u09’’,
``reqId’’: ``slkfjoiru20svkm038’’,
``date’’: ``2018-01-01 00:00:00’’,
``operation’’: ``state’’,
``parameters’’: {
``item’’: ``device’’,
``name’’: ``Smart Temperature Sensor’’,
``value’’: ``28’’
   }
}
```

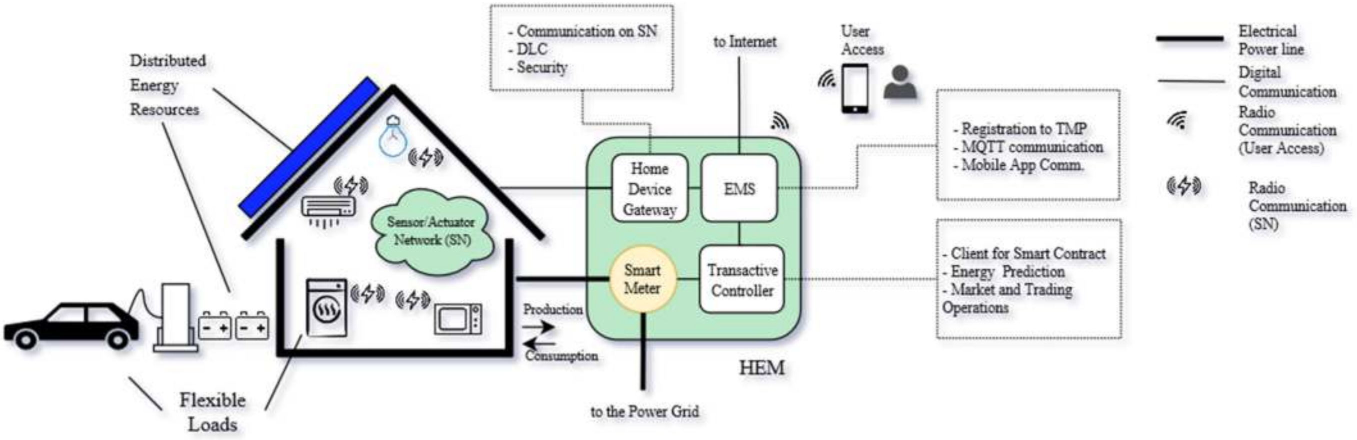

Fig. 3. Structure of the proposed home energy manager (HEM).

The CSM-DB contains users' information about verified smart meters and other data necessary for the transactive operations. For example, a record of the CSM-DB shall contain the type of smart meter, its serial number, and public key cryptographic key of the user which are used to validate blocks and/or other exchanged information during the smart contract execution.

The AnC is a component envisioned to store transacted energy related data. It could be used by the central owner or other parties in order to make statistics or energy trends offline analysis.

The second layer is the communication infrastructure, for example the public Internet or any other communication technology alternative, e.g., power line communication where digital information flows by leveraging the same power grid lines.

The third layer is composed by all the equipment installed at the user side, e.g., the house or the building, that is needed to let the active users and prosumers to access the TMP.

B. *Implemented Home Energy Manager*

Every participant to the LEM uses an HEM, which is a hardware component (a microcomputer such as a Raspberry Platform) installed inside buildings or houses. As assumption, every participant, both prosumer and active user, has a smart meter, i.e., an energy meter which can communicate outside and in near-real time the energy data flow, for instance the energy production and energy costs of the building. This information is vital for the operation of the overall architecture and must be shared with the components of the HEM.

The purpose of the HEM is to let the user (prosumer or active user) access the TMP in order to act as a transactive agent within the LEM. In other words, the HEM is the interface between the prosumer/active user and the smart grid. The HEM is composed of three main parts, as shown in Fig. 3: a Home Device Gateway (HDG), a TCR and an Energy Management System (EMS).

The HDG is an interface for communication to the smart devices deployed within the house or the building. For example, a set of smart switches and temperature sensors which communicate by means of a wireless mesh networking protocol like Z-Wave or Zigbee or a combination of other ad-hoc sensor network protocols [83]. The HDG provides the HEM with access to user's smart devices. After the access is granted, sensors and actuators (switches, valves, dimmers, etc.) can transmit measurements and receive control commands from the EMS. The HDG is responsible for the very important aspect related to information security and safety.

The TCR is the software engine needed to make decisions about the energy trading operations. For instance, the TCR makes energy bids and offers in order to buy or sell energy, respectively, and receives information related to their acceptance/rejection in the LEM inside the VPP aggregator, as it will be described more in details in the following sub-section. The TCR is interfaced to the EMS, the HDG and the smart meter. The EMS coordinates all the communication between the TCR and the HDG toward the TMP. The main functions of the EMS concern the registration of the HEM to the TMP and the communication of energy and trading data to the shared channels used by all participants.

C. *Smart Contract Deployment for Managing the Interactions Between the VPP Aggregator and Its Aggregated Prosumers*

Even though the proposed transactive management infrastructure is general and can be used in different contexts and with different players, in order to demonstrate a possible application, a realistic scenario is presented.

It is assumed that a Virtual Power Plant (VPP) aggregator can deliver services to the Transmission System Operator (TSO) by participating to the ancillary services market.

The proposed architecture can be used to provide reliable and speedy two-way communication, allowing the aggregator to interface with its internal prosumers and with external parties such as the DSO, the TSO or the market operator.

During the day-ahead or hour-ahead the aggregator provides a generation/load schedule for the aggregated prosumers also considering transmission network technical constraints under the TSO approval.

Day-ahead schedule is carried out in order to allow the aggregator to effectively participate to the ancillary services market. The schedule is based on historical data and on the forecasting of the baseline electrical load for each prosumer also considering RES and electrical load forecasts. Moreover, the schedule should depend on which strategy the aggregator adopts for participating in the ancillary services market. This choice depends on the price and load forecasts within the electricity market and on the optimal time slots for selling/buying energy in the ancillary services market.

Prosumers associated to the VPP are supposed to be connected to the same electrical distribution network or feeder, so that the physical energy exchange determined by the aggregator schedule may take place while complying with distribution network technical constraints. The technical feasibility of the energy exchange is previously approved by the DSO, which, if technical problems are expected in the distribution networks, can ask the aggregator to modify its schedule.

If the aggregator cannot follow the scheduled day-ahead program in real-time, due to an energy deviation caused by errors in the forecast of electrical energy generated by RES or absorbed by loads, it makes an offer or a bid to all its aggregated prosumers in order to sell or to buy, respectively, the required electrical energy quantity at a determined price. The prosumers can react to the offer/bid of the aggregator by making their own bids/offers, respectively.

Indeed, when an offer/bid is made by the aggregator, a smart contract is deployed to the blockchain and an auction is started allowing prosumers to make offers/bids by means of their TCRs.

The smart contract program, which is a set of rules encoded into the blockchain, enables the execution of an auction to determine the accepted offers/bids that will give rise to trusted energy transactions in the LEM of the aggregator. The selection of the auction type encoded inside the smart contract is agreed between the aggregator and the prosumers [27].

For example, when the aggregator makes a bid, the offers of the prosumers having prices lower than the aggregator's bid price are selected in increasing order of price until the quantity of energy required from the bid is reached. After that the transactions are completed and verified by the smart meters of the prosumers the cryptocurrencies exchanges are authorized.

D. Transactive Controller Operation to Manage the Battery of a Residential Prosumer

Even though different controllable electrical loads can be managed by the TCR as flexibility resources, such as HVAC, hot water heater, dish washer, washing machine, dryer, etc. [33], the use of the battery as flexibility energy source instead of controllable electrical loads makes the provision of the energy flexibility service more acceptable by the prosumers since it does not interfere with the normal activities and habits of the prosumer. Batteries group ensures a higher degree of reliability, indeed, because bidirectional power converters can charge the battery both from the main electrical grid and from the local PV source as well. On these bases, and in order to detail the bidding/offering process, it has been supposed that the battery is the only flexibility resource for a prosumer. As previously stated, the TCR can alternatively make an offer (to discharge the battery) or a bid (to charge the battery).

Different parameters, including the battery energy capacity, the degradation cost of the battery, the charging/discharging rate limits and the State of Charge (SOC) are considered by the proposed TCR to determine the bid/offer quantity and price. The quantity is determined considering the admissible range of the SOC, the charging and discharging rates and the capacity of the battery according to equations from (1) to (6).

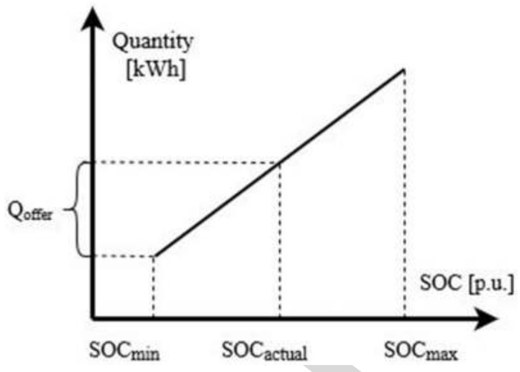

Fig. 4. Quantity offering curve.

Inequality (1) limits the SOC in its admissible range

$$\mathrm{SOC}_{\min} \leq \mathrm{SOC}_t \leq \mathrm{SOC}_{\max} \quad \forall t. \tag{1}$$

The charging and discharging rates of the battery at time t, r_t^{charge} and $r_t^{\text{discharge}}$ should respect their maximum rate limits as presented in the following:

$$r_t^{\text{charge}} = \left(\mathrm{SOC}_t - \mathrm{SOC}_{t-1}\right) / \eta^{\text{charge}} \quad \forall t \tag{2}$$

$$r_t^{\text{discharge}} = \left(\mathrm{SOC}_{t-1} - \mathrm{SOC}_t\right) \eta^{\text{discharge}} \quad \forall t \tag{3}$$

$$0 \leq r_t^{\text{charge}} \leq r^{\text{charge,max}} \quad \forall t \tag{4}$$

$$0 \leq r_t^{\text{discharge}} \leq r^{\text{discharge,max}} \quad \forall t \tag{5}$$

where η^{charge} and $\eta^{\text{discharge}}$ denote the charging and discharging efficiencies of the battery, respectively.

The following equation describes the model considered for assessing the SOC variations:

$$\mathrm{SOC}_t = \mathrm{SOC}_{t-1} + \gamma_t^B \eta^{\text{charge}} \frac{E_t^{\text{ch}}}{\mathrm{Cap}^B} - \chi_t^B \frac{E_t^{\text{disch}}}{\eta^{\text{discharge}} \mathrm{Cap}^B} \;\forall t \tag{6}$$

where Cap^B is the battery capacity.

The quantity offering and bidding curves are shown in Figs. 4 and 5, respectively. It is worth noting that the quantity is proportional or inversely proportional to the SOC, in the case of an offer or a bid, respectively.

Although the price offering and bidding curves exhibit a behavior similar to the quantity curves, some additional limitations should be considered. They have to take into account the degradation cost of the battery when the TCR makes an offer and in order to make the bid acceptable by the aggregator. In other words, the bid price should be higher than the offer price decided by the aggregator and the offer price should be always higher than the degradation cost of the battery, calculated as described in the following equations.

The degradation cost of the battery due to the operation in discharge mode is calculated by

$$\mathrm{Cost}_t^{\mathrm{Degr}} = E_t^{\mathrm{disch}} Cd \tag{7}$$

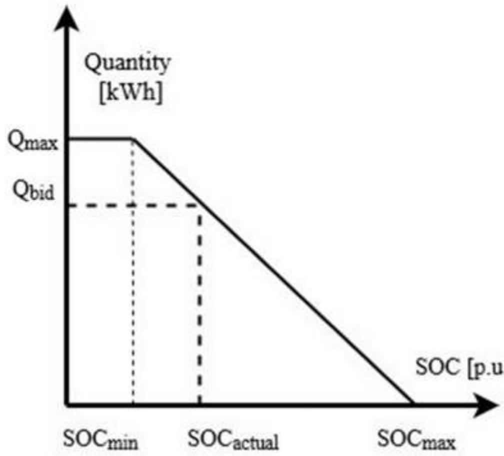

Fig. 5. Quantity bidding curve.

where E_t^{disch} is the discharged energy of the battery. C_d is the cost of the battery in euros/kWh dependent on the discharging and is evaluated by the following:

$$C_d = C_{\mathrm{battery}}/L_{ET} \tag{8}$$

where C_{battery} is the capital cost of the battery and L_{ET} is the battery life time for the specific cycling regime.

E. How the TMP works

In the presented TMP architecture, the software which runs inside the HEM, and specifically the TCR and the EMS, is capable of doing following functions.

1) Making and receiving bids and offers when these are advertised on the common MQTT channel.
2) Communicating anonymously the Consumption-Production Function (CPF) value in order to preserve the user's privacy.
3) The consensus protocol is based on the value of stakes, where stakes are distributed according to the CPF values.
4) Implementing the blockchain to store energy transactions.
5) Digital wallets can be queried anytime.

The requirement about anonymity takes into account security needs. A user could be profiled by inspecting his/her energy transactions on public channels of the TMP, and this information could be used to track habits or daily behaviors. To protect the identity of users on public channels, e.g., the offer channel, every user is given a random address.

The software installed on the user-side smart inverter communicates the energy production, while a smart meter communicates the energy consumption. Using a function that combines the consumed and produced energy from RES is an omni-comprehensive incentive to a green economy as explained in Section V-F.

In the proposed TMP, prosumers can also decide to take part in an incentive program for improving the self-consumption of locally produced energy.

Different options are thus allowed for the prosumers, i.e., 1) Transactive Energy (TE); 2) Rewards (RE); or 3) RE + TE.

In the TE option the prosumers and active users can start an auction process by making an offer or a bid in the LEM [84].

In the TE option the participants take part in energy exchanges. The key-value-based JSON structure for energy transactions can be as follows:

```
{
    ``clientId’’: ``01394u09’’,
    ``reqId’’: ``slkfjoiru20svkm038’’,
    ``date’’: ``2018-01-01 00:00:00’’,
    ``operation’’: ``bid-offer’’,
    ``signature’’
:’’asf09rjsd0vj09234u0wgj0234utpoj0g243j
tiwgj09823jht029gn0390’’,
    ``parameters’’: {
         ``address’’:
``asda6249ty2c3o9h99dadadqwq’’,
         ``cpf’’: 0.72,
          ``bid’’: {
            ``type’’: ’’sell’’
              ``energy’’:{
               ``unit’’: ’’kWh’’,
                 ``value’’: ’’10’’
         },
         ``price’’:{
          ``unit’’: ’’cents’’,
         ``value’’: ’’82’’
         }
       }
    }
}
```

The signature is a cryptographic value generated by the EMS and based on standard asymmetric encryption (public-private keys). The public key of the EMS uniquely identifies the user and it is stored in the CSM-DB. The EMS will sign every message with the private key. The validity of the message can be checked by verifying the signature embedded in the message. In the RE mode, the TMP can verify the authenticity of the message. Other forms of antiforgery of the value of the produced energy can be applied by exploiting additional cryptographic tools. But the system is supposed to be strictly coupled with the hardware of the inverter, which is assumed to be hard to hack.

F. Proof of Energy (PoE) Proposed Function

In the TE mode, the bids and offers are managed by the smart contracts registered into the blockchains and handled by a TCR, as in [81]. Once the smart contract is validated, for example whenever the bid or offer is going to be accepted by some participant, the generator of the next block in the blockchain must be chosen. The election of the next block generator is based on a simplified PoS, which is named Proof of Energy (PoE) and it is based on the following Consumption-Production

Function:

$$\mathrm{CPF} = \frac{1}{e^{|P-C|}}; \quad 0 < \mathrm{CPF} \leq 1 \tag{9}$$

where, for each prosumer, P is the energy production from local RES generators connected to the prosumer, such as a PV system, and C is its energy consumption, i.e., the energy absorbed by all the electrical loads including the energy storage. It should be noted that if either $P >> C$ or $C >> P$, then the CPF tends to 0; otherwise, if P and C are similar, then CPF tends to 1. The validator node will be the one which has the CPF closer to 1. In other words, the validator is chosen to be the prosumer with the best self-consumption ratio (ideally, the one having the produced energy from RES equal to the energy it consumes).

As in the PoS, the stakes are represented by the CPF values, these values are embedded in the transaction messages and, therefore, are publicly visible to all participants. In this way, every participants can predict which one has the chance to get the right to generate the next block. By taking part in the incentive program (RE or RE+TE), the prosumer achieving the right to become a block generator receives an incentive. The higher the CPF is, the higher the chance to become a block generator is and the higher the total incentive. The adoption of the proposed innovative CPF makes prosumers more empowered and incentivizes them to achieve energy efficiency. In this way, prosumers can contribute to improve the transmission and distribution systems operation in a twofold way:

1) by participating in the ancillary service market according to a smart contract and incentivized by the adoption of the CPF;
2) by maximizing their self-consumption ratio, thus promoting a sustainable behavior and, as an indirect consequence, it also contributes to reduce power losses in the distribution and transmission systems.

In the PoS, the nothing-at-stake-problem refers to the fact that a user could approve different branching of the blockchain, thus emphasizing the risk of the double-spending problem. Simply, it consists in a not unique and coherent transaction records stored in the ledger. In this case, for example, a user could be paid twice for the same transaction. In the proposed TMP, this problem does not happen, first because the blockchain is private and second, by assuming that user hardware is trusted, the multiple branching of blockchain is quite impossible to happen because it would require hacking the hardware.

VI. CONCLUSIONS AND FUTURE RESEARCH CHALLENGES

This paper highlights and discusses different concepts and technologies such as Distributed Ledger Technology, Peer-to-Peer transactive energy exchanges and Local Energy Markets for achieving energy efficiency in modern transmission and distribution systems.

Considering that the traditional centralized energy systems are no longer viable, peer-to-peer energy transactions based on DLT and transactive controllers in LEMs represent the most likely evolution for future smart grids, as confirmed by recent pilot projects. A crucial point for the use of DLT is the selection of a proper consensus protocol: as PoW consensus protocol is very energy demanding, new approaches such as PoS are needed.

On these basis, a permissioned blockchain based architecture, using an adapted version of PoS as consensus protocol is proposed to achieve energy efficiency and sustainability. The concept of proof of energy has been proposed as a modification of the proof of stake protocol in order to increase the self-consumption ratio of prosumers, thus contributing to power losses reduction.

A new designed and implemented TMI is proposed and described that can represent a baseline for a reference framework for blockchain-based TMI based on smart contracts that can be used to manage LEMs. The proposed infrastructure consists of three layers, namely: aggregator layer, communication layer, and user layer. The aim of the first layer is to manage the TMP, which is based on the Pub/Sub servers, the Certified Smart Meters and the Analytics Component. The second layer uses Internet Cloud to communicate among the different agents. The third layer consists of an HEM, which lets active users and prosumers to access the TMP.

It should be pointed out that different challenges should be addressed by future research activities in order to make P2P transactive energy exchanges and LEMs a reality. First of all, the preservation of privacy in blockchain-based architectures represents a research challenge and solutions to ensure the prosumer privacy by design should be researched. Even if P2P based solutions can exhibit better scalability than centralized ones, studies and real tests should be carried out to evaluate the scalability of blockchain based architectures when the number of prosumers significantly increases. Even though some solutions have been recently proposed to improve the scalability of blockchain based architectures, further researches are required to identify new methods for improving scalability. Also, standardization and interoperability issues need to be investigated when designing blockchain based architectures.

Concerning LEMs, future research activities should be carried out to evaluate the impact of different markets and auction mechanisms on the power losses and technical constraints of distribution and transmission systems. In addition, different options for managing the interactions and mutual effects between LEMs and the wholesale market should be investigated, while new rules are necessary to regulate the interactions between DSOs and the TSO. Further researcher activities are also required to investigate the effects of transactive controllers on consumers' behavior and their willingness to take part in LEMs.

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Authors' photographs and biographies not available at the time of publication.