https://doi.org/10.3311/PPee.20277

Periodica Polytechnica Electrical Engineering and Computer Science, 67(2), pp. 160–171, 2023

Application of a Blockchain Model in the Energy Market for Social Goodness: A Simulator to Generate Transactions

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Received: 05 April 2022, Accepted: 09 November 2022, Published online: 23 January 2023

Abstract

An application of blockchain technology to manage electricity flows in a Microgrid (MG) is studied. The grid is considered for civil use, equipped with generation and storage systems, and interfaced with the national grid. It is composed of energy nodes such as user, generator, accumulator, and customs officer node, each characterized by its own time profile, in a limited time interval, of energy flow (consumption, generation, charge/discharge, purchase/sold). The proposed management strategy is based on the principle of free trade managed through blockchain. A simulation tool is developed to evaluate the electricity flows for different scenarios. The blockchain of energy transactions is generated by means of a dedicated software and having as reference a set of ethical/economical rules. It is demonstrated that it is possible to design energy management and exchange systems that allow in an economic way, within the delicate balance between energy availability, technology, market, safety, freedom and needs of individual users, to optimize the exchange of resources and to decrease waste. This blockchain exchange strategy can be implemented without building new plants and avoiding expensive and complex systems, by installing only bidirectional meters equipped with telecommunication, in addition to a common computer management system. The aim of this work is to demonstrate importance and technical feasibility of enforcing rules on the correct use of energy. The peer-to-peer operating mode is different from the technique currently in force in conventional energy systems, in which always a control body (energy, economic, financial) supervises and manages any transaction between users.

Keywords

energy management, energy production systems, energy saving, applied ethic, microgrid, blockchain

1 Introduction

The European Union's goal is to reduce greenhouse gas emissions by 80–95% from 1990 levels by 2050. Among the various scenarios hypothesized by the European Parliament [1], the necessary interaction has been highlighted between large-scale centralized systems (e.g. nuclear and gas power plants) and decentralized systems, which will depend on each other, if for example local resources are not sufficient or vary over time. It is also specified the importance of the deployment of renewable energy technologies, and how this will affect energy markets, reaching 30% of gross final energy consumption by 2030 [2].

In this context, purchases and sales of energy, and in particular electric energy, take place and are aggregated in centralized platforms similar to those that govern financial markets. Common experience reveals that interest in a peer-to-peer transactional mode is growing, and that strong social pressures towards peer-to-peer transactions are present in all fields. The development of online commerce, the use of online methods for the conduct of financial transactions and for the management of utilities, the use of Internet for the control of the functionality of equipment and devices, reveal that the community exerts a strong push towards a type of transactions in which the two actors are on the same level, with an authority that is no longer part of the trading system, but only ensures the regularity of transactions and the impossibility of irregularities or misappropriations [3, 4].

In the transition from centralized energy management to a series of peer-to-peer transactions, one of the most impactful issues is updating the method of operation and participation of the bodies that currently regulate the market.

Blockchain technology has the potential to be used in sectors where the generic transaction is not associated with a physical exchange. In these sectors, it allows a way of

Cite this article as: D'Orazio, A., Elia, S., Santini, E. "Application of a Blockchain Model in the Energy Market for Social Goodness: A Simulator to Generate Transactions", Periodica Polytechnica Electrical Engineering and Computer Science, 67(2), pp. 160–171, 2023. https://doi.org/10.3311/PPee.20277

recording transactions that does not require verification of the physical exchange. The energy sector is characterized by the presence of both physical and intangible exchanges, and this boundary character makes it the ideal terrain for extending blockchain technology to physical transactions [5].

In recent years (2015 to 2018) 120 organizations have activated projects associated with blockchain technology in the energy field, with at least 40 pilot projects, targeting wholesale and retail electricity trading in peer-to-peer markets. The most frequent research topics concern system flexibility, balancing services, coordination between trading actions, the use of electric vehicles as accumulators enslaved to the grid, and the exchange of emission trading certificates [6]. Potentially, blockchain technology is applicable to energy exchanges in an immediate way, but beyond the theoretical potential, its application to the energy sector, particularly electricity, has an uncertain future, currently involving high costs, low transaction speeds, risks (associated with the difficult verifiability of the occurrence of energy exchange) and other limitations.

On the other hand, blockchain technology could give a strong impetus to micro- and mini-generation, effectively allowing the individual producer to place himself on the market at the same level and with the same potential and possibilities as traditional producers. A possible obstacle to this mode of generation and to the establishment of a regime of peer-to-peer transactions is constituted by network operators. In fact, the latter have a natural monopoly of certain essential functions, such as the constant balancing of electricity supply and demand. All electricity trading, including local or remote peer-to-peer exchanges, must be compatible with the operator who is responsible for maintaining network safety. At present, it seems impossible for an energy community, operating on a distributed model, to function independently of the grid operator – at least as long as it is connected to the central infrastructure [7, 8].

The above leads to deduce how more innovation and adequate experimentation are highly desirable. The present work fits into this context, intending to study the application of blockchain technology to an electricity microgrid (MG), evaluating the difficulties and proposing the use of the best strengths of this technology. It is important to remember that the "ethical development of technologies" is one of the main objectives of the European Union. In this framework, the proposed application provides, as a paradigm of trade, the power supply of loads with the lowest possible energy cost, without the need to generate financial profits [9].

A blockchain allows data to be exchanged according to a peer-to-peer network, completing transactions that are recorded in indelible, immutable repositories, shared by all users who join the system [10]. Its operation is based on the addition of several blocks, each of which consists of a set of transitions. Typically, the amount of data exchanged is huge. A block can be added to the chain only after the network participants have given approval of the stipulated transactions. Each transaction contains the data of the contracting parties, the goods being exchanged and the cryptographic signatures that ensure the uniqueness and authenticity of the transaction. The security mechanism, which acts in order to foil fraud, is carried out by the network nodes, which are asked to check the legitimacy and veracity of the stipulated transactions. Ultimately, the blockchain is configured as a series of blocks that store validated transactions, accompanied by a time stamp. Each block is characterized by a hash, i.e., a mathematical code that allows to identify and connect blocks in succession uniquely and securely.

Each block must be validated and encrypted: this task, which requires an effort especially in terms of computational power, is carried out by solving a complex mathematical problem. The ultimate goal of this is to foil possible frauds on the part of a node, by conceiving a cryptographic puzzle that puts all participants in the network in competition. The fastest of these to solve the problem, will be able to validate the block and obtain a remuneration. This operation is called mining and is carried out by miners, whose task is fundamental for the management of the blockchain and whose remuneration is equal to a fraction of the value of the validated transactions. Any user of the blockchain can become a miner. Of course, the more the number of these operators increases, the more the computational difficulties and remuneration of them increase; the more secure the system becomes.

For a correct assessment of energy use it is not sufficient to visualize the data in quantitative form. It is necessary to use a qualitative visualization with overlapping of the statistical data obtained by the blockchain system, this in order to evaluate the user's behavior [11].

The aim of this work is to provide scenarios of simulation, prediction and regulation for new energy management methodologies, based on the development and application of blockchain technology to energy operation within Smart Grids (SGs) [12, 13].

In particular, the application of blockchain technology to the management of electricity flows and relative rules in a Microgrid (MG) is studied. Such MG is composed of energy nodes such as user node, generator node (from conventional and renewable sources), accumulator node, customs officer node (transfer node with the external electricity grid), each characterized by its own time profile, in a limited time interval, of energy flow (consumption, generation, charge/discharge, supply/feeding) [14–16]. The energy transaction blockchain is generated by having as reference a set of rules of behavior within the MG based first on the ethicality of the individual transaction, the energy convenience of the transaction, and the economic convenience [17].

The rules assumed for the operation of the MG make impossible multiple transactions within the MG itself for the supply of energy, and thus prevent the creation of positional or contingency advantages among the components of the MG. The existence of such rules, and transparency about them, makes the system reliable as a whole but also has a reassuring effect on possible investors (e.g., possible owners of PV, wind, or cogeneration plants within the MG) [18–22]. These investors would have the certainty of a return on their investment and the impossibility of competition within the MG itself, since it is governed by consortium rules decided by users and not imposed from above. The management of energy production from photovoltaic generators is strongly facilitated by the presence of a blockchain system [23–25]. A system for supervising energy consumption gives the possibility to design correctly all investments even on large and complex buildings [26–29].

Even the necessary diesel emergency power supply systems can also automatically switch between different users and different power supply networks in the microgrid; it is therefore necessary to have different machines, networks and users collaborate with a direct exchange system [30].

The innovative characteristic of the proposed blockchain solution consists of using the Blockchain technology to join the grid to buy/sell energy between the involved nodes (energy providers and private citizens).

Simulation software has been developed and tuned to perform all possible simulations on free energy trading. The proposed trading strategy can be supported as much on Proof of Work (PoW) systems as on the faster Proof of Stake (PoS) systems as on others, it doesn't matter. Many works have treated the subject matter but generally to support profitable trades from the point of view of optimization and profits. The purpose of this paper is to emphasize how important the policy choices and rules that are imposed on a blockchain-type market are and how important these are socially and environmentally [5, 14, 17].

The open energy trading system encourages local energy production, sharing, and use, all of which are good things. At the same time, the blockchain system runs the risk of allowing only profit-maximizing rules to prevail, which run against basic social and environmental rules [3, 4, 29]. Using the proposed system correctly could greatly incentivize the use of renewable sources and also the process of decarbonization, this without damage to public service. For example, it is considered appropriate to give priority to some items with respect to others [30]. For example, the rules can establish the following order of precedence: in precedence to vital and strategic electrical systems (Hospitals, Fire Departments, Civil Defense, Police, etc.):

- precedence to the use of renewable resources;
- priority to the use of locally produced energy.

For all other decisions, the market could also be left free [31, 32].

2 Literature review

In buildings it is now possible, and required [1], to implement any automated management system [8, 32] and such management is currently implementable without any particular external constraints. Some articles help to define the impact that automated management can have on the economics [2, 3, 11, 18, 21, 22, 24, 33] and reliability [30] of the systems and to suggest a planning methodology based on the qualitative and quantitative evaluation of the reciprocal impacts among smart strategies [34–39] or to propose intelligent approaches to forecast electricity consumptions [40]. Aspects related to the reliability of management models and data security [4, 5], a relevant topic for the development of new electric transport management technologies [6], are explored in the literature. Even in the field of emergency management, no rules are defined other than those of reliability or economy [7]. Blockchain technologies are also being studied today to encourage the diffusion of small renewable sources, making it easier to manage the feeding of the energy produced into the grid [10, 12, 17]; again, there are no studies on how to use them and what rules producers/users must follow to ensure mutual respect [15]. Many articles suggest that island systems should be managed by blockchain, leaving any future rules to free self-regulation [13, 20, 25]; this makes the use of energy in island systems very dangerous, as the absence of help from the public grid would mean that, in the event of management problems, events would immediately evolve into blackouts [34, 35]. The problem is all the more stringent, and the stricter the rules should be, for island systems requiring maximum reliability, such as hospitals and prisons [16, 18, 29]. Some preliminary management rules, which aim to limit pollution, can be found in some articles that consider environmental aspects [14, 31]. Logics of technical energy sharing are also studied in the storage sector but, again, no rules are designed on who can use this energy and under what conditions [19, 36]. The authors note that there is a tendency in the literature to propose the use of blockchain without posing the problem of analyzing and proposing ethical rules at the design stage, and that this risks favoring purely economic systems that ultimately completely neglect the social aspects. An important part of this work is also to demonstrate the possibility of designing open systems that integrate ground rules in favor of people and the environment from the outset.

3 Materials and methods

The system used to base on a blockchain management the energy exchange [33] in a Microgrid is here described. Such MG is composed of energy nodes such as user node, generator node (from conventional and renewable sources), accumulator node, customs officer node (transfer node with the external electricity grid), each characterized by its own time profile, in a limited time interval, of energy flow (consumption, generation, charge/discharge, supply/feeding) [14, 15, 16]. The energy transaction blockchain is generated by having as reference a set of rules of behavior within the MG based first on the ethicality of the individual transaction, the energy convenience of the transaction, and the economic convenience [17].

Electricity flows are assumed to be at constant voltage, with zero losses in the usage, generation, storage, and transmission components: reactive power flows will not be considered at this stage of the research.

For each period of time (e.g. a day of the year), the time span from midnight (initial time equal to 0 minutes) to that of the following day (final time equal to 1440 minutes) is divided into intervals of 15 minutes (the interval can also be 5, 10 minutes or even longer), in turn divided into a large number of sub-intervals (or sub-steps). The above model is a static time-varying model, based on the load diagram. Such assumption is made since in many countries of the world the used or yielded energy is counted from the meters every quarter of hour; in every case such formulation can be easily changed in the simulation software. It is not taken into account a temporal analysis in transient regime.

The operators, as already said, realized according to a static time-varying model, have been identified as:

- Users (U), whose behavior is schematized by means of load diagrams;
- Producers (P), for which four different energy production technologies are considered (photovoltaic panels, micro-wind, co-generators, micro Organic Rankine Cycle, micro-ORC in the following) and whose behavior is schematized by means of generation diagrams [34];
- Accumulators (A), which can act as reserves, that draw energy, or as generators. They must operate under strict technological limitations. For this type of components, the following will be taken into consideration: minimum and maximum capacity, minimum and maximum speed of charge and discharge, guaranteed voltage value;
- Customs officers (T): they are located at the border between the MG and the external grid. They must know the exchange rules in order to maximize production or storage, i.e. savings (local production); they are naturally oriented to service continuity;
- Carriers: they intervene in the system by determining the efficiency of energy transport. To all intents and purposes they constitute the last technological limit to which the Smart Grid must be subjected. At this stage of the research they will not be taken into consideration.

In each time interval, the energy transactions constituting the blockchain are generated, according to the exchange rules accepted by all components of the MG, from consumption profiles (loads), generation profiles (energy availability), charge and discharge profiles (any accumulation and withdrawal from the reserve), and external network availability profiles, which are considered known.

According to the ethical exchange rules governing energy transactions within the MG and giving rise to the blockchain:

- The needs of user nodes are privileged, with particular reference to any hospital or civil protection demand [18];
- There cannot be multiple transactions within the MG (none of the components of the MG can buy energy to resell it at the same time to other users of the same MG);
- Speculative approaches are prevented;
- Energy selfishness is penalized, by demonstrating that the transfer of part of one's own accumulated energy does not compromise the expected operation of one's own system;

- Production from renewable sources is preferred, for environmental reasons, even if not economically convenient compared to external purchase.

Before each considered time interval, each component of the MG has to convey to the other users of the blockchain which transactions can be executed and to what extent. Regarding the evaluation of the exchange capacity of the storage nodes, meaning the charging and discharging capacity, the technological limit on the charging/discharging rate of the batteries determines the amount of energy that can be withdrawn or stored in a given time interval [35].

Based on the exchange rules previously established by the MG users, transactions are actually performed. The actual blockchain is then updated, so all nodes in the system can know the economic-energy transaction. The transactions are recorded on the network ledger, which is public and visible to all.

At each instant of time, the scenario of transactions is managed by the preliminary verification of the comparison between the energy that can be generated by the MG in a time interval (E_g) and that required by the users in the same interval (E_c).

If E_g is greater than E_c, a decision is made as to whether or not to use accumulators, based on contractual, economic and legal conditions, production impositions, dispatching priorities, etc.

If it is possible to use accumulators, it may not be convenient to sell the energy surplus to the external grid (or there may not be the conditions to do so) and therefore the accumulation is preferred. If it is impossible to accumulate all the surplus, it is chosen to sell to the external network if it allows it, otherwise it is necessary to disconnect from the MG of the production nodes.

If the accumulation is not preferred, it is decided to sell all the surplus energy to the external network; if the network establishes a limit of acceptance of energy, the surplus part could be accumulated, if this is possible, otherwise it becomes necessary to disconnect the production nodes from the MG.

If it is not possible to use the accumulators, it becomes mandatory to try to sell the surplus energy to the external network, as far as this allows it, and, in order to zero the surplus part, to disconnect the generators, since in no case now it is possible to use the accumulation nodes.

Even in the case where the energy required by the system is greater than that produced on site (E_g less than E_c), a decision can be made whether or not to use the stored energy.

If it is possible to use the accumulators, it may not be convenient to cover the energy deficit by purchasing from the external network (or there may not be the conditions to do so) and therefore the use of accumulated reserves is preferred. If it is impossible to cover all the deficit, it is necessary to buy energy from the external network, if it allows it, otherwise it is necessary to disconnect from the MG the consumption nodes. If the use of accumulated reserves is not preferred, it is necessary to buy energy from the external network; if the network establishes a limit of energy sale, it is necessary to use the storage nodes for the part still missing, if this is possible, otherwise it becomes necessary to disconnect the consumption nodes from the MG, through rules and programmed detachments [36].

If it is not possible to use the accumulators, it becomes mandatory to try to buy the energy deficit from the external network, as far as this allows it, and, in order to zero the residual deficit, to disconnect the loads, since in no case it is now possible to use the storage nodes.

At each time interval, particularly the initial one, the various energy flows, expressed in kWh, verify Eq. (1):

$$-C_0 + G1_0 + G2_0 + G3_0 + G4_0 \pm A_0 \pm S_0 = 0, \tag{1}$$

where:

- $-C_0$ = load;
- $G1_0$ = thermoelectric production;
- $G2_0$ = photovoltaic production;
- $G3_0$ = wind production;
- $G4_0$ = ORC production;
- A_0 = storage capacity;
- S_0 = exchanged energy.

A_0 and S_0 are taken with the sign, indicating the energy that is accumulated or transferred, sold or bought respectively.

4 The ethical rules

In generating transactions, the first ethical rule, that no speculative transactions are possible within the MG, translates into prohibiting nodes that feed energy into the grid (generators, accumulators in discharge, and customs officers in import) from generating transactions for energy amounts greater than those actually available. Furthermore, since the MG was not created with the objective of carrying out energy trading services, the energy supply to the outside world, by means of discharging accumulators, must be limited as far as possible to the actual needs of the external network and not be devoted to speculative intentions. Multiple transactions are therefore prohibited.

The second ethical rule, for which the MG is conceived with the objective of providing consumers with the energy they need, translates into a hierarchy of priorities, according to which the first nodes to be satisfied are the users. Among the user nodes, the primary user is the node that uses the largest amount of energy (always with reference to the generic time interval). This node may or may not decide (a priori) its own supply priority. In this way it is established a priority among user nodes and, for each user node, a priority among supply nodes. The third ethical rule is to always favor the use of energy from renewable sources [19, 20].

The fourth ethical rule, which concerns the safeguarding of energy, takes into account the fact that the charge and discharge of accumulators are extremely expensive from the energy point of view (with a charge/discharge cycle efficiency never higher than 0.8 p.u). The rule translates into preferring as supply nodes those of generation and transfer, with respect to those of accumulation, given also that the energy lost, in the charge and discharge cycle, is in any case accounted for at the accumulation node [21, 22]. In the selection of supply nodes to nodes of use, the order of preference will therefore be:

1. Generation nodes;
2. Customs officers nodes;
3. Accumulation nodes.

The operational sequence for generating the blockchain, with reference to the single time interval, is as follows:

1. The user nodes are provisioned by the generation nodes inside the MG;
2. If the generation nodes have exhausted their capacity and the user nodes are not yet fully supplied, the user nodes are further provisioned by the customs officers nodes;
3. If the customs officers nodes have exhausted their capacity and the user nodes are not yet fully supplied, the user nodes are provisioned by the accumulation nodes;
4. If, unlike in step 2, the user nodes have been fully supplied and there is still energy available from generation nodes, the latter supply energy to the storage (if possible);
5. If the storage is saturated, the generating nodes pour energy back into the customs officers nodes.

In each phase are always involved only two groups of operators. Each group of operators must be ordered on the basis of the energy that it will process in the transaction; therefore to the operator with the highest amount of energy will be assigned the first transaction, the second operator the second transaction and so on, always and in any case according to the priority order assigned by the single operator to all the other nodes in the network (obviously not to nodes of the same type, since it has been established above that an energy exchange between nodes of the same type must not be possible). According to this perspective (transactions according to dispatch priority) it is the node that exchanges more energy, both incoming and outgoing, that has exchange priority. Therefore, a preferential choice of nodes with which to initiate the first transactions is established, according to an energy hierarchy that rewards the greater demand or the greater availability of energy, as appropriate.

5 The nodes and the transaction scenarios

Regarding the characteristics of the nodes, with particular reference to the terms of the balance Eq. (1), their behavior depends on the available technology (accumulators and generators), the demands of the users (users) and the exchange rules.

Generator nodes (photovoltaic panels, micro-wind, co-generators, micro-ORCs) have been chosen from the perspective of energy diversification. As far as co-generators are concerned [37], cogeneration groups of variable size, from 6 kWel and 15 kWt up to 530 kWel and 660 kWt, have been considered. With regard to photovoltaic panels, their behavior is influenced by the global insolation on the oriented surfaces of the panels and by cloudiness [28]; the sizes considered are domestic (6–15 kW). Micro-wind systems have smaller sizes than the other systems, due to spacing and size issues, equal to about 2–4 kW; however, they demonstrate sufficient production as they present, compared to the photovoltaic system, a double amount of equivalent hours of production. Microturbines based on ORC system are used in sizes smaller than 30 kW for space and safety reasons.

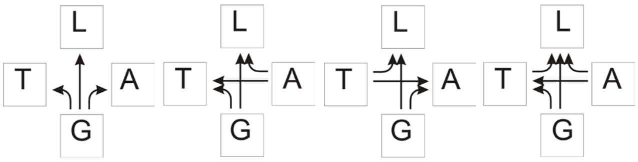
The behavior of battery nodes in the charging and discharging phases depends on technological limitations. During the charging phase it is necessary to keep the power supply voltage of the accumulators constant, at a fixed value and specific for each type of battery adopted. An excessive overvoltage would cause serious permanent damage, while a voltage lower than the nominal value is not sufficient to carry on the charging process. In the case of lead-acid batteries, for example, there are 3 consecutive charging phases: in the bulk charge phase, the battery is charged, thanks to an intense and constant current, up to a capacity value between 80 and 90%; in the taper charge phase the current intensity is progressively reduced until 100% of the capacity is reached; in the trickle charge phase, in order to compensate the self-discharge, the voltage is maintained at a constant level, generally slightly higher than the nominal battery voltage, set by the manufacturer. Discharge processes can be very different. Normally the voltage should be kept constant, however it tends to decrease over time. The manufacturers therefore indicate the end of discharge voltage (cut off voltage), beyond which it is necessary to interrupt the energy supply. An excessive depth of discharge, in fact, leads to a premature aging of the device. As regards the intensity of the current that can be delivered, it depends on how much energy the load requires and especially on the maximum discharge rate. Lead-acid batteries can supply a very high current intensity, 6 C, i.e. six times the capacity (Ah) of the battery, against 3 C of Li-Ion batteries. Conventionally is indicated as maximum discharge current in Ampere (6 times) the capacity of the battery for faston or screw/bolt terminal. For cable terminals a maximum discharge current of 3 C is considered. However, for batteries with a capacity of more than 10 Ah, it is necessary to limit the initial current to 1 C, to avoid excessive temperature rise during the charging phase.

In this work, four different batteries (Li-Ion and lead-acid), commercially available for renewable energy storage applications, have been considered.

As far as user nodes are concerned, it is necessary to take into account the difficulty of finding information about load diagrams related to existing mini and micro networks, or at least to small users or agglomerations of them. This difficulty increases if it is necessary to have daily and hourly data and preferably on the minute scale.

As regards the behavior of the exchange nodes, it is possible to trace the time profile of the power that can transit through them (transfer capacity of the MG exchange nodes) on the basis of the contractual forms that bind the MG to the whole electrical system, but also starting from the actual traffic limits of the network. Obviously, this quantity is not necessarily univocal since there may be an input limit and an output limit. If you want to prevent the energy input or output from a generic exchange node, you can simply set equal to zero the allowed input/output quantity. The evaluating of the energy input/output from the individual node is simply equal to the product between the input/output power and the length of the time interval.

Regarding the possible energy flows, four possible energy exchange configurations, summarized in Fig. 1, have been analyzed among the MG operators (generators (G), loads (L), accumulators (A) and customs officers (T)). The energy transactions are developed according to an exchange priority criterion, whereby each node acquires a certain dispatch priority based on the amount of energy requested or given up, and according to the role held.



(a) (b) (c) (d)

Fig. 1 Possible interactions between the categories of operators in the MG: generator nodes (G), load nodes (L), accumulators (A) and customs officers or traffic nodes (T); (a) User and accumulator nodes have the same priority of energy request; (b) User and transfer nodes have the same priority of energy request; (c) Generators satisfy user and storage nodes, then they sell energy to transfer nodes; (d) Transfer nodes satisfy user nodes, then internal resources are used; the arrows indicate the power flows of the four main conditions analyzed in this work

Fig. 1(a) shows the case where the generators can fully satisfy the demand of the utilization nodes. They still have enough energy to saturate the capacity of the storage nodes and to sell the remaining portion to the transfer nodes.

Fig. 1(b) shows the case in which generators and accumulators give up part of their energy to both user and transfer nodes. This is an unfavorable situation, because the discharge of accumulators involves energy losses and because the scenario is more difficult to manage: the available internal energy is used to cover the demand of user nodes and of transfer nodes that have acquired the same priority of energy demand. This situation is to be limited as much as possible for environmental reasons [31].

Also Fig. 1(c) shows a scenario more difficult to manage. In this case, the user nodes and the storage nodes have the same priority of energy request; the energy supplied by the generators is distributed to cover a part of the request of Load and Accumulator nodes, the remaining part is satisfied by purchasing energy from the external network.

Fig. 1(d) shows the diametrically opposite situation to case a. The internal power generation is not sufficient to cover the demand of the user nodes. In order to avoid energy losses due to the discharge of the accumulators, the energy demand is covered in the order by purchasing from the external network, and finally by drawing from the internal reserves.

6 Economic aspects

The economic aspect of the transactions has to do with the generation of the market price, that is, with the mechanism of price generation within a local energy market, for which the similarities and differences with the national electricity market can be preliminarily determined. As in other international experiences, the creation of a market corresponds to two very precise needs: to promote, according to criteria of neutrality, transparency and objectivity, competition in the activities of production and sale of electricity through the creation of a "market square" and to ensure the economic management of an adequate availability of dispatching services.

Currently, the energy market in Italy is a free market, where operators submit bids for the quantity of energy object of transaction, along with the maximum and minimum price proposed for purchase and sale. Some authors [33] believe that a "neighborhood market" should be based on an exchange model, with the trading periods corresponding to discretely fixed time frames throughout the day. In order to foster a decentralized approach, the order book and price of the last transaction are made public. In the generic time frame in which the trade is allowed, traders must be able to predict their energy supply or demand. Operationally, consumers propose the maximum price they are willing to pay to purchase energy, producers propose the minimum price for selling. The actual price of buying and selling energy, then, lies in the middle of this range of values generated by the consumers' maximum offer and the producers' minimum offer. Obviously, the transaction will be concluded if and only if the purchase price is greater than or equal to the sale price ($p_{\text{purchase}} \geq p_{\text{sale}}$).

A market based on auction sale, of course, assumes that participants behave rationally, and that the availability of energy is certain. This can be considered verified in the case in which the production of energy is obtained through an elastic and adjustable technology, such as, for example, the ignition of a thermal engine, but not in the case of production from renewable sources, which is affected by discontinuity and/or randomness of supply; in this case the technical and economic problems related to the more delicate management and maintenance of the production plant are left out. In a more refined model of generation of the prices and of forecast of the demand and supply, it could turn out uncorrect to assume that the behavior of the participants to the MG is always of rational type, and it would be necessary to take in account the human factor, conceiving the system like a not cooperative game, in which everyone can adopt one own strategy of game. The demand would therefore become flexible, and the result of the game would depend not only on the action of the single player, but also on the choices of the others. The prediction of demand and supply would then be given by the best set of strategies that each player decides to adopt simultaneously and independently from the choices of the other players. This would result in calculating the Nash equilibrium for each player.

In the cases considered in this work, the financial value of the transactions generated was attributed a priori on the basis of certain considerations. For transactions between operators of the MG, the indicative price for the purchase or sale of energy was set equal to 10 €/MWh, except for the purchase of energy from accumulators. In fact, it has been established that this purchase is to be considered more expensive (12 €/MWh), given the worse performance for the supply from this source. Think, for example, to the energy losses attributable to electric vehicles, not only due to the performance of the batteries, but to the need to speed up the charging and discharging processes, to the detriment of the efficiency of the process itself. As far as transactions with the external network are concerned, the purchase price of energy to supply the loads was set at 11 €/MWh, higher than the price of sale to the external network by the generators (9 €/MWh). The price of selling energy to the external grid by discharging the accumulators was set at an even higher value (15 €/MWh).

7 The software

The simulation of the entire system, with all the transactions evaluated in real time, is computationally heavy. A calculation software based on Fortran 90 has been constructed and a powerful PC with an Intel Core I9 and 64 Gb RAM has been used in order to obtain one good speed of calculation. The more complex part of the software has not been the quantity of operations to carry out, but the management of the rules and the relationships between users.

8 Results

In order to validate the analysis strategy, several plant configurations have been analyzed, considering various load and generation configurations reported in the literature. Here is reported for simplicity an illustrative case. The management of electricity flows in a Microgrid (MG) is described in the case of a microgrid named 11 BUS for which the load diagram required by the users is reported in [7] and shown in Fig. 2.

The MG consists of 2 load nodes, 2 generation nodes, 2 storage nodes and 2 exchange nodes. In this case it was decided to give priority to the use of accumulators in order to compensate for both any surplus and deficit of energy.

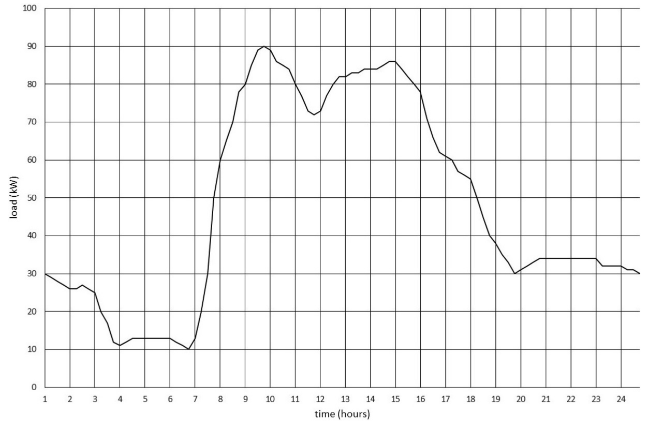


Fig. 2 Hourly load of a node of the 11-bus microgrid, adapted from [7]

Considering for each hour the average values of the powers (requested, generated and exchanged), the peak power requested by the 2 load nodes is 169.5 kW. Since the cogenerators are sized assuming that they cover 70.8% of the peak power, the two cogeneration units EM-50/81, with 50 electrical kW and 81 thermal kW, and EM-70/115, with 70 electrical kW and 115 thermal kW, have been chosen for a total of 120 electrical kW. The selected accumulators have the characteristics summarized in Table 1.

The customs nodes are characterized by a nominal power of 1000 kW, with an activity percentage equal to 100%. The availability diagrams of the single generators are shown in Fig. 3, together with the overall generated power; those of the availability of the customs nodes (external network) are shown in Fig. 4.

The results of the transactions generated within the MG are summarized in Fig. 5, where are reported, over 24 hours of a typical day, the trends of the powers supplied by the generators, those of the powers accumulated or provided by the accumulators and those exchanged to and from the external network, against the powers required by the user, already represented in Fig. 2.

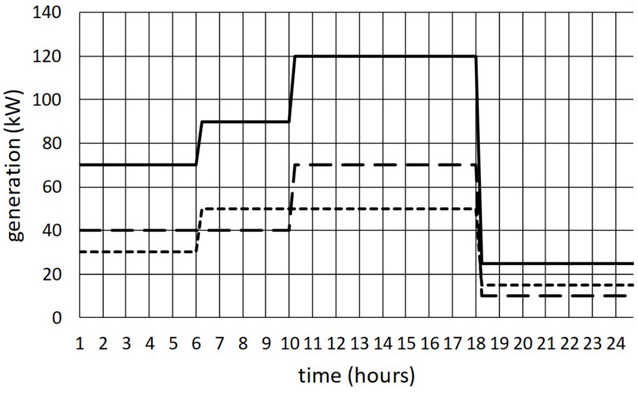


Fig. 3 Available power from generators: generator 1 and generator 2 (dashed lines) and cumulative generation (solid line)

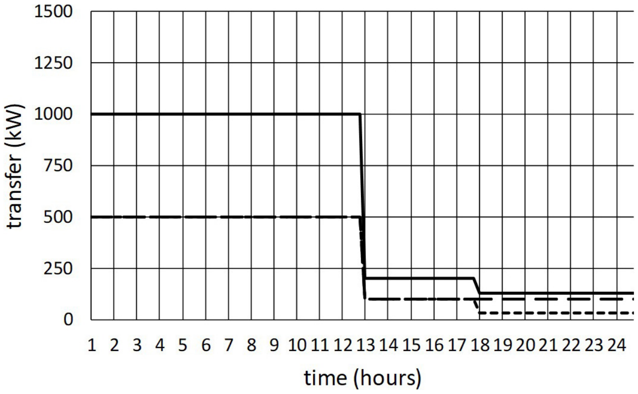


Fig. 4 Available power for the transfer (external network): sales and purchase operator 1 and sales and purchase operator 2 (dashed lines) and cumulative availability of interchanges (solid line)

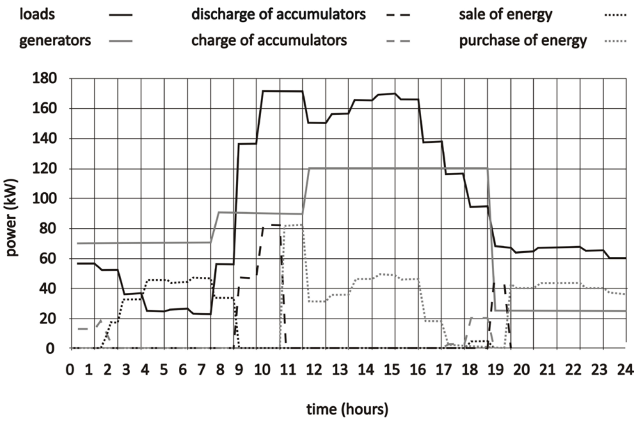


Fig. 5 Results of transactions generated within the MG

In the described case, the generation inside the MG is not able to cope with the maximum demand of the loads by itself. In the initial phase, in which the accumulators have 90% of their capacity, the charging phase, implemented thanks to the supply of excess power from the generators, holds less than two hours; therefore, it is the exchange nodes that are responsible for transferring to the external network the power not used by the loads. In the central part of the period of interest, a rapid increase in demand from the user nodes occurs. In this phase the accumulators supply all the energy possible, together with what is supplied by the generators, but it is only through the purchase of energy from the external network that the demand of the loads is satisfied.

Table 1 Accumulator specifications

Rated voltage (kV)	Rated capacity (Ah)	Minimum working capacity (Ah)	Maximum working capacity (Ah)	Working capacity at simulation start (Ah)	Maximum discharge speed (Ah/h)	Maximum charge speed (Ah/h)
1	100	10	90	80	100	10

The detailed list of all the transactions (not reported here) confirms that from the starting moment until 7:00 the series of transactions belongs to the case of Fig. 1(a): in particular, until 1:15 the surplus energy is used only to recharge the accumulators, from 1:15 the excess energy is sold to the external grid. The temporal arc from 7:00 to 9:00 is characterized by transactions belonging to the case of Fig. 1(b): the loads are fed by generators and accumulators and the energy of the accumulators is sold to the external network. From 9:00 to 15:45, there are transactions related to the case of Fig. 1(c): loads are fed by generators and customs nodes and the latter also supply energy to recharge the batteries. From 16:00, the transactions are again related to case Fig. 1(a), until 17:45, when they resume transactions of case Fig. 1(b). Finally, from the hours 18:45 they return to the case Fig. 1(c). Transactions belonging to the case Fig. 1(d) do not occur in this simulation.

9 Conclusions

In this paper, the application of blockchain technology to the management of electricity flows in a Microgrid has been proposed. A microgrid simulation tool has been developed to evaluate the possible flows of electricity for different scenarios of energy generation, exchange, storage and use in the presence of established constraints (ethical rules) for transactions. The proposed management strategy is based on the principle of free trade managed through blockchain, with a peer-to-peer operating mode intrinsically different from the one currently in force, in which there is always a control body (energy, economic, financial) that supervises and manages any transaction between two users. It has been demonstrated the possibility to design energy management and exchange systems that allow in an economic way, within the delicate balance between energy availability, technology, market, safety, freedom and needs of individual users/prosumers, to optimize the exchange of resources and to decrease waste. The need to impose behavioral rules, through blockchain management, in order to safeguard the rights, duties and limits of all actors involved, has been highlighted.

The study concerned a network for civil use, equipped with generation and storage systems and simultaneously interfaced with the national grid and therefore composed of user nodes, generator nodes (from conventional and renewable sources), storage nodes and customs nodes (transfer nodes with the external network), each characterized by its own time profile of energy flow (consumption, generation, charge/discharge, purchase/sold) [38].

The proposed strategy can be implemented without building new plants, avoiding expensive and complex systems. By installing only bidirectional meters, equipped with telecommunications, in addition to a common management information system, it is immediately possible to implement a blockchain system for the exchange of electricity. It would then have the possibility to monitor and control the single component and at the same time the whole system, making the MicroGrid a SmartMicrogrid (SMG).

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