# Blockchain for peer-to-peer energy exchanges: design and recommendations

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## *ABSTRACT*

Energy communities and peer-to-peer energy exchanges are expected to play an important role in the energy transition. In this context, the blockchain approach can be employed to foster this decentralized energy market. Our goal is to determine the design that should allow a Distribution System Operator (DSO) to accept peer-to-peer energy exchanges based on a distributed ledger supported by the blockchain technology. To this end, we evaluate several designs based on criteria such as the acceptance of the wholesale/retail market, the resilience of the consensus to approve a block, the accuracy, traceability, privacy and security of the proposed schemes.

## 1 INTRODUCTION

Since the arrival of Bitcoin [1] and its subsequent success as a cryptocurrency, the blockchain has emerged as a disruptive factor in many areas. With blockchain 2.0 and the future version 3.0 allowing the use of automated transactions, the energy sector is probably one of the next sectors to be impacted by this new way of performing verification and authentication of transactions between parties. Blockchains can be regarded as decentralized and distributed ledgers that keep track of any type of transaction. This move towards the blockchain is likely to accelerate with the emergence of energy communities where prosumers (customers having their own generation asset) will want to exchange their surplus generated energy with their neighbours and / or with nearby companies / institutions.

To guarantee the rights and duties of each party and to make the necessary link to the wholesale market, these exchanges must be supervised by a neutral metering party such as the distribution system operators (DSOs) as provided for in French law [2] on collective self-consumption or in the E-Cloud project [3]. Establishing the set of requirements necessary to perform this supervision is the goal of this paper, which is structured as follows: Section 2 clarifies the energy community concept. Section 3 then states the problem of interest in this paper and our proposed adaptation of the blockchain for energy communities. Section 4 presents the result of a simulation of the proposed miner selection algorithm. Section 5 concludes and provides directions of further work.

## 2 ENERGY COMMUNITIES

There are many possible configurations of energy communities. In this document, we focus on the European context and more precisely the Belgian (Walloon) and the French cases. In this section, we describe the use cases chosen for the purpose of this paper.

### 2.1 Collective self-consumption in France

In France, a series of decrees published in 2016 and 2017 specify the notion of collective self-consumption and the role of the DSO. According to Article L315-2 of the French Energy Code, self-consumption can be considered as collective if the supply of electricity (mainly generated by photovoltaic panels) of one or more producers to one or more final consumers is organized through a single legal entity, and the corresponding consumption and injection points are located downstream of the same medium voltage (MV) / low voltage (LV) substation. We can summarize this as a local LV energy community. The electricity supplied by the market (supplier or retailer) of a consumer participating in a collective self-consumption operation is the difference between the load curve of its total consumption and the reconstructed load curve of its production quantities allocated in the framework of self-consumption.

### 2.2 E-Cloud

The E-Cloud project [3] is an integrated power distribution network feeding an existing area of economic activity, which distributes electrical energy to industrial or commercial sites that have agreed to be part of the E-Cloud community. It is a MV energy community.

Regarding the data flow, generators and consumers are metered independently with a market period resolution. As they are connected to the MV network, this market period is 15 minutes. These metered quantities for generators are important for subsidies related to renewable generation (e.g. in Wallonia, the green certificates), and also for cross-checking the energy generated at the settlement stage. As customers have an interest in maximizing their self-consumption, a maximization based on real time data and not on metered data, we recommend to integrate the real-time data into a market step in order to compute the market period share of generation allocated to one participant by creating a virtual generation meter device.

### 2.3 Selected use case

The cases presented only records the electricity generation in the blockchain and the share of it amongst the different parties (the DSO deals with the consumption separately). The pricing of this generated energy is beyond the scope of this paper. We use a generalised energy community definition that covers these two concepts and serves as a basis for the remainder of this paper. It is defined by:

- a limited geographical area (e.g. same street, or same residential block, same business zone);
- at least one connection point between the community and the public grid (in an extreme case, each participant is connected to the public grid);
- the share of generated electricity allocated to one participant is recorded in its own virtual generation meter
- the market face meter gives each measurement step (i.e. 15 minutes). Obviously, this must also be the case for the consumption and (virtual) generation meters.
- generations units that are installed in the same geographical area as the community are considered as common asset(s) to the community (virtual power plant)

The link with the retail/wholesale energy market for a particular participant is created by a computed market face meter. This computed market face meter logs the difference between its consumption meter and its virtual generation meter. Regarding the exchange rules, in most energy communities (e.g. [4]), a local market is created in order to meet the demand with the generation and to define prices. This is not the focus of this paper and we consider that the repartition of the energy between participants and the energy prices are defined and fixed by contractual agreement. We focus our analysis on issues associated with the volume of energy recorded on the virtual meters.

# 3 PROPOSED BLOCKCHAIN ADAPTATION

As summarized in [5], the blockchain is "an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way." The first running blockchain was theorized by Satoshi Nakamoto in 2008 [1]. The verification of the correctness of each transaction could be done by every participant (node) of the chain. However, there is a specific role for creating a block (and thus guarantee that the transactions within it are correct), the so-called *miners*, who provide computational power to check the transactions and to put them together to form blocks, in exchange for a fee.

In [6] we argued that an energy community can reach social and market acceptance only if there is a strong and fair link between the community and the retail and wholesale energy markets, and as a consequence that every grid operator has to ensure four properties regarding the metered data: accuracy, traceability, security and privacy. We show how the blockchain concept has been adapted in order to fulfill the first two requirements.

## 3.1 Accuracy

This requirement is about satisfying the legally prescribed metering accuracy, such as described in [7]. From our definition of the energy community (cf. Section 2), the virtual generation meter must be synchronized with market steps. In the conception of the blockchain, this thus requires that a block is created exactly at every market step. This requirement has an important consequence on accuracy. Indeed, to avoid multiple investment in metering and measurement devices, many energy communities use Electric Meter Pulse Output as an effective way to have finer information than energy consumed over a market step. These meters, already MID[1] compliant, integrate the energy for each market step and are equipped with a serial port that communicates by e.g. RS485 wired link. Hence the basic information is MID compliant but to remain at this level of accuracy, the value of energy put into a blockchain transaction is an important parameter. For each pulse output by the MID meter, a transaction is created and broadcast. Obviously, blockchain transactions cannot be broadcast synchronously at every market step. Hence, it can happen that a transaction is sent just after a market step. In this case, it is added in the block corresponding to the next market step, creating an inaccuracy between the block and the MID meter. In order to be accepted by the wholesale/retail market, the error due to the broadcasting process cannot exceed the maximum permissible error (MPE) as defined in [7].

Furthermore, to be accepted by all parties, is has to ensure that each energy put in a transaction is really coming from the corresponding MID meter. In the blockchain, the solution to this requirement is a crypto or digital signature. We call the device that creates and signs each transaction a *cryptometer*.

## 3.2 Traceability

Traceability is about ensuring the origin of the generated energy and the correct flow of transactions between the generators (virtual power plant, or VPP) and each individual virtual generation meter. It is covered by design in the blockchain through three means, the transaction model, the consensus model and the Merkel tree. For the purpose of this article, we focus on the first-two items. More detail about the concept of Merkel tree is available in [6].

**Transactional model** The transactional model is illustrated in Table 1. Consider two generation units A and B and two participants (consumers) for which we build the virtual generation meters X and Y, respectively. For this example, only A and B are equipped with a cryptometer. The repartition of the energy between X and Y has to be correct as well, i.e. it must comply with the predefined arrangement (c.f. Section 2.3). The proposed design of the transactional model combined with the concept of cryptometer ensures that, at least at their creation, kilowatt-hours are actually produced by generators within the community. Considering that all these transactions are broadcast to every node and afterward put into a block also broadcast to every node, each participant of the commu-

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[1] MID stands for the Measuring Instruments Directive 2014/32/EU.

Table 1: Illustration of the transactional model.

1. Create 15 kilowatt-hours and credit it to device A
2. Transfer from A to VPP (digitally sign it by using a private/public key cryptographic signature protocol)
3. Create 10 kilowatt-hours and credit it to device B
4. Transfer from B to VPP (digitally sign it by using a private/public key cryptographic signature protocol)
5. Transfer to participants (digitally sign it by using a private/public key cryptographic signature protocol)
    - 8 kilowatt-hours from VPP to X (signed by VPP)
    - 17 kilowatt-hours from VPP to Y (signed by VPP)

The detail of transaction 5 is as follows:

- Inputs
    - Reference (hash) of transaction 2
    - Reference (hash) of transaction 4
    - Digital signature VPP
- Outputs
    - Value: 8 kilowatt-hours to Output public key X
    - Value: 17 kilowatt-hours to Output public key Y

nity is able to verify the correctness of the repartition. We now analyze how to prove that transactions are not modified afterward by a malicious node or a cyber-attack, nor ransomed.

**Consensus model** To avoid any influence of a malicious node, the simple consensus algorithm illustrated in Table 2 is widely adopted in the blockchain world. To select a node at step 3, as explained in [6], we recommend to use the proof-of-stake (PoS) method: the miner is chosen according to a measure of its wealth. The greater the wealth of a node, the larger its chances of being selected. The PoS method could be a good way to ensure that a block is created exactly at each market time step $T_i$, and thus will meet the accuracy requirement with a high probability. In addition, it requires less computational power than the other method called Proof of Work. The PoS algorithm for our use case is described in Table 3. This method relies on three important aspects:

1. how a node declares itself as a candidate,
2. the generation of $U_k$, and
3. how the maximum $W_k/U_k$ is known by all nodes.

Table 2: Blockchain consensus algorithm.

1. New transactions are broadcast to all nodes;
2. Each node creates a block with all the valid new transactions;
3. At each market period $T_i$ a node is randomly selected and broadcasts its block;
4. Other nodes check the validity of the block and, if they agree, increment their chain;
5. If the majority of nodes agree, the block is definitively approved.

Table 3: Proposed miner selection algorithm.

Let $\mathscr{K}$ be the set of nodes willing to support the chain at a specific time.

1. **Determine the wealth of each candidate miner.** The simplest definition of stake or wealth is the relative value of a node compared to the other nodes. This value can be derived from different criteria. In our use case, we choose the following wealth criteria to define the wealth of a node $k$, for a given $\mathscr{K}$ and for a time step $T_i$, as

$$W^k_{T_i} = \alpha E^k_{T_i-1} + \beta A^k_{T_i-1} + \gamma R^k_{T_i-1} i \tag{1}$$

   where we define

    - $E$ as the voting token corresponding to a subset of the volume of kilowatt-hours in the previous transactions (more kilowatt-hours increase the probability to generate the next block)
    - $A$ is an age measure of the previous block: how old is the last block created by a miner, how big is the probability to create the next one.
    - $R$ is a reputation measure: miners that have already created blocks than the other nodes will have a highest probability to be selected for the next block creation.

   The weights $\alpha$, $\beta$ and $\gamma$ are weights contractually agreed on within the community.

2. **Randomize.** Generate of a random number $U_k$ for every candidate $k$ with a uniform distribution in $]0,1]$.
3. **Output.** The selected node is

$$k^s_{T_i} = \arg\max_{k\in\mathscr{K}} \frac{W_k}{U_k} \tag{2}$$

To realize this method, we create a special set of transactions using a voting token and a selection algorithm described in [6]. This algorithm operates as an auction marketplace: candidate miners place their offer in the form of a part of their voting tokens and send these to the current miner. They may do this for a period between two moments called ”candidates gate opening” for the launch of the selection and ”candidates gate closure” for the end. After the calculation of (2), the selected node is communicated to all the nodes by a transaction that sends all the voting tokens offered to the winner. As the flow of the voting token follows the same path as the energy, only consumption nodes and virtual generation meter owners could act as miners. In order to circumvent any manipulation of the selection of the miner, one of the most important recommendation in [6] regarding the weights in the formula (1) of $W_k$ is

$$\gamma < \alpha < \beta.$$

## 4 SIMULATIONS

We have developed two sets of simulations in order to demonstrate the correctness of the miner selection algorithm. The simulations have in common that:

- At the start of the simulation, there are four candidates (named: Anne, Bob, Carla and George)

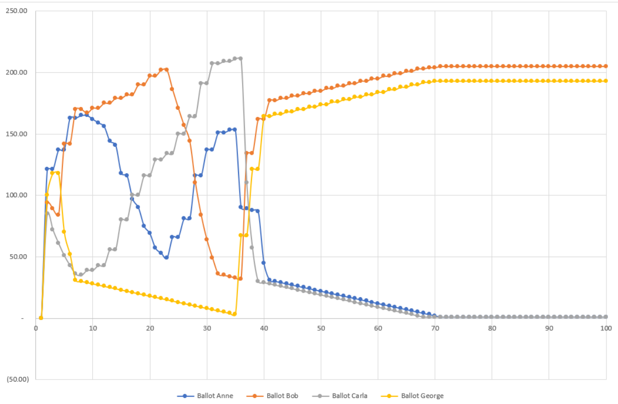

Figure 1: simulation without Age and Reputation (only E).

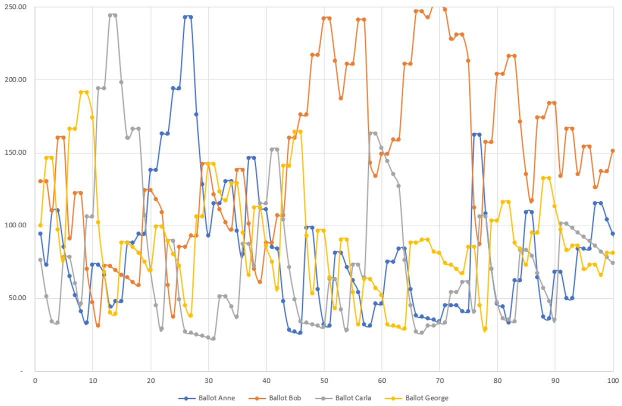

Figure 2: simulation with Age and Reputation.

- Each candidate $k$ begins with the same amount of $E_{0,k}$ (i.e. 100 $E$). Let's call $E_{n,k}$ the volume of voting token for $k$ before a turn $n+1$.
- At each turn, the candidate sends $E_{n,k} \times h_{n,k}$ to the actual miner, with $h_{n,k}$ a random percentage.

In the first set of simulations, $W_k$ is only a function of $E_k$. In the second set, we have introduced properly the age and the reputation in $W_k$. Figure 1 gives the evolution of the voting token owned by each candidate. The results of the second simulation is shown in Figure 2.

It can be seen that without Age and Reputation, only two candidates remain active after a while (here 70 turns). It is clearly due to the concentration of wealth. This situation is to be avoided in the context of blockchain because the main added value of this technology is the decentralization of the ledger's management.

## 5 CONCLUSION AND FURTHER WORK

We propose an adaptation of the blockchain technology for energy communities, based on a particular *Proof of Stake* consensus algorithm, in order to offer an efficient and resilient way to support transactions within an energy community, but also to get it accepted by the wholesale market. The topics discussed hereafter have only been touched upon in this article and deserve further development and validation. Upon several aspects (e.g. the feasibility of a time stamp, the integration of energy losses, the impact of the transaction rate, etc.), the analysis of different voting strategies for candidate miner is certainly worth. Finally, we considered that the virtual generation meter is a dead end for transactions but consumers may want to agree to exchange between each other a part of the energy recorded in their virtual generation meter, and, by doing so, create a local market. This can open up additional security issues since more parties can have an interest in defrauding the system (and not only the VPP).

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