Distributed solar self-consumption and blockchain

Solar energy exchanges on the public grid within an energy community

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***Abstract*— Self-consumption and local energy communities have a significant role to play for the energy transition and the development of renewable energies. This paper introduces a blockchain-based solution designed to serve energy communities sharing solar energy. This solution has been defined and developed to manage the energy exchanges according to the rules set by the energy community. It harnesses the available smart metering infrastructure installed by the DSO, as the trusted party for energy data to the energy stakeholders, to stay focused on the governance of the energy community. This paper summarizes the characteristics and field-proven benefits of the implementation.**

Keywords*— solar energy, photovoltaics, self-consumption, prosumer, distributed energy, energy communities, energy sharing, blockchain, distributed ledger technology, consortium blockchain, permissioned blockchain, consensus, smart contract, IoT, oracle, energy sobriety.

I. Introduction

Photovoltaic (PV) cell costs have substantially fallen since 2010, bringing residential PV plant costs down with them. As demonstrated by the International Renewable Energy Agency in its Cost and Competitiveness Indicators report, grid parity can now be achieved and rooftop PV Levelized Cost Of Energy can compete with the residential electricity rates in different metropolitan locations [1]. Self-consumption is the natural trend and represents a major one for solar energy development. Market forces, rather than subsidies, will drive a much more diverse mix of PV prosumers. Moreover, the new European directive "Promotion of the use of energy from renewable sources", still under negotiation at the time of this paper, proposes a legal framework to enable and accelerate the development of self-consumption and renewable energy communities [2].

Centralized energy systems, where power is transmitted and distributed from large production plants to the consumers is shifting towards more decentralized energy systems, through the integration of distributed intermittent power generation and flexible loads. This decentralization implies new roles, for citizens, communities, distribution and transmission system operators, and electricity suppliers. This pattern will bring new relationships between the energy stakeholders. Citizens and organizations who were not traditional actors in the energy sector will have a significant role and impact on the models.

New efficient digital solutions are needed. Energy exchanges sometimes only mean small amounts of energy in very short time periods, thus potentially inducing large quantities of data. The emergence of energy communities will also bring governance issues that need to be addressed. The co-existence of centralized and decentralized energy systems is also a challenge to take on, without compromising supply security. Digital technologies represent a stepping stone to providing solutions to an ever more distributed generation and the data management it implies. Smart meters are the primary enablers of this system evolution and their mass deployment will be the basis for the development of new services around renewable energy management. [3]

At the heart of numerous activities and discussions worldwide, blockchain technologies have shown that their applications are no longer restricted to cryptocurrencies. Blockchain technologies are being tested and even implemented in various economic fields. The energy sector is no exception and has seen many diverse experimentations. As of January 2018, more than 90 companies and projects using blockchain for energy have been interviewed by Thomas Boersma and Tom van Dorp [4]. Most of them have been created after 2016 and want to address peer-to-peer energy trading. The technology is under continuous development as shown by the substantial activity of developers' communities. Ethereum is supported by hundreds of engineers [5] and its community is strong and very active all around the world. Ethereum can count on AMD, Microsoft, BP Energy, Cisco, Intel and ING, among others, for financial and technical support [6]. Hyperledger is another strongly active blockchain project incubator. Hosted by The Linux Foundation, the

Supported by the GreenTech Verte program from the French Ministry for an Ecological and Solidary Transition.

Supported by the Investment For the Future Program (PIA) operated by ADEME.

Hyperledger community has developed several blockchain frameworks like Fabric, Sawtooth or Iroha [7] with the contribution of IBM, Airbus, Cisco, Intel, Bosch, Oracle, Samsung, Thales and more [8]. Fabric, Hyperledger's foremost and most advanced consortium blockchain, had its version 1.0 released in July 2017 after 16 months of open source development [9] which, in particular, leveraged 40 000 dedicated lines of code given away by IBM. Like Ethereum, weekly meet-ups are organized by the Hyperledger community all around the world.

II. DISTRIBUTED SELF-CONSUMPTION

The specific use case studied and addressed by the present blockchain-based solution is an energy community sharing local solar production. Sharing the energy produced by one or several common PV plants or mutualizing the surplus from PV prosumers copes with several obstacles raised by individual self-consumption:

- temporary absence of consumption (e.g., holiday),
- multi dwelling buildings,
- technical difficulties with the solar installation (e.g., inadequate sun exposure, building structure resistance, urbanism rules),

and provides benefits at different levels:

- combining of energy needs, by adding up consumers and increasing the rate of production effectively locally self-consumed,
- fostering of PV projects by pooling several PV plants or by selecting the best sites for a maximal economical result,
- gathering people around local collective projects that enable them to reconnect to their energy.

The main technical and economic argument for distributed or collective self-consumption is the aggregation of several consumer needs. Two scenarios are being compared hereafter, one with seven individual PV prosumers and the other with a collective installation feeding the same seven consumers. Energy consumptions and productions come from real measured data. The energy performance of such operations is assessed via self-consumption and self-sufficiency rates. The self-consumption rate is the part of PV-produced electricity that is directly consumed locally while the self-sufficiency rate describes the ratio of the electrical needs covered by the PV production:

Self-consumption rate = SCR = Quantity of PV electricity consumed / Quantity of PV electricity produced

Self-sufficiency rate = SSR = Quantity of PV electricity consumed / Quantity of total (grid+PV) electricity consumed

The seven individual residential consumptions are displayed for three days in September 2017, as well as the production of a 7 kWc PV plant in the South of France.

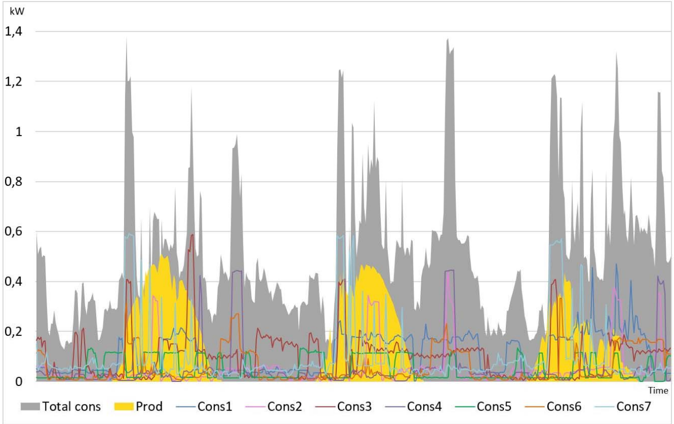

FIGURE 1. PV PRODUCTION AND RESIDENTIAL CONSUMPTIONS

The following table confronts the calculation results for the seven individual 1 kWc PV plants with those for the collective 7 kWc PV plant, over the first week of September:

TABLE I. INDIVIDUAL VERSUS COLLECTIVE SOLAR CONSUMPTION

Rates	***7*1kWc individual prosumers***	***7kWc Collective PV***
SCR	79,7 %	99,1 %
SSR	16,5 %	22,1 %

The benefits of distributing the energy among all consumers are significant. While individual self-consumption enables the prosumer to expect using 80% of his solar energy and covering 16% of his electrical needs, the collective operation enables the use of 99% of the solar energy to cover 22% of the participants' needs.

Such results give energetical and economical incentives to develop a model and solution aiming at implementing solar distributed self-consumption projects. Different entities can set up these energy communities: local authorities, multiple public or private building owners, collective housing companies, utilities, solar project developers.

Physically, solar power is fed into the electrical grid. For every designated energy community, energy consumption and production are measured through the smart meters on the distribution grid. A virtual network tracking the transaction between parties within the community is implemented. At each time period (e.g., 10, 15, 30 minutes), the energy generated by all participating producers is aggregated then virtually divided between participants according to rules previously agreed upon by the community. These rules notably take into account each participant's current consumption. Allocated production never exceeds consumption, and the delta between the two is purchased from the participant's own usual electricity retailer.

Date	Id	Consumption	Allocated Production	Grid Supplement
01/09/2017T11:10:00Z	Consumer01541	932	716	216
01/09/2017T11:10:00Z	Consumer02144	1561	1199	362
01/09/2017T11:10:00Z	Consumer01519	1210	929	281
01/09/2017T11:10:00Z	Consumer01632	754	579	175
01/09/2017T11:20:00Z	Consumer01541	871	687	184
01/09/2017T11:20:00Z	Consumer02144	1674	1321	353
01/09/2017T11:20:00Z	Consumer01519	1232	972	260
01/09/2017T11:20:00Z	Consumer01632	698	551	147
01/09/2017T11:30:00Z	Consumer01541	842	683	159
01/09/2017T11:30:00Z	Consumer02144	1589	1288	301
01/09/2017T11:30:00Z	Consumer01519	1301	1055	246
01/09/2017T11:30:00Z	Consumer01632	695	563	132

Consumption = Allocated production + Grid supplement

FIGURE 2. LEDGER DISPLAYING ENERGY QUANTITIES (KWH)

Looking at the community as a whole, the sum of the consumptions equals the sum of solar productions plus the sum of electricity quantities supplied by the different electricity retailers via the public grid. If, at any time period, the total production is superior to the total consumption, then the community can play the role of a producer of energy and sell this energy on the market, or split it and affect it to the different producers within the energy community, who can sell it on a marketplace out of the community.

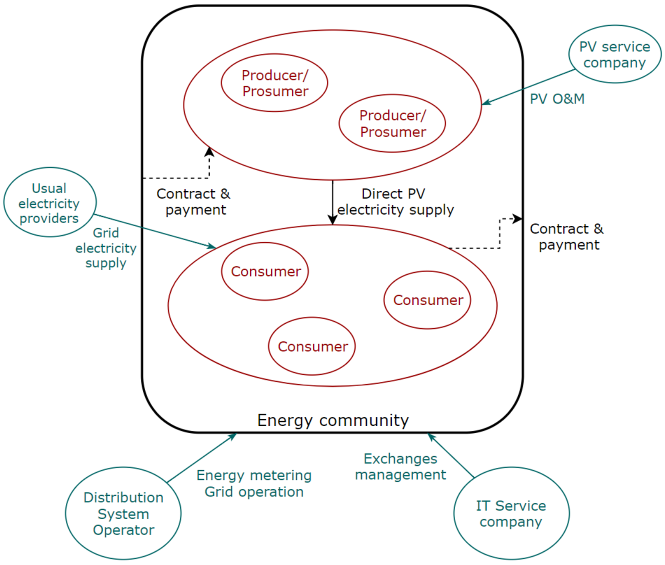

FIGURE 3. ORGANIZATION OF AN ENERGY COMMUNITY

These projects raise strong concerns with the energy data management and security. The different electrical measurements have to be collected at each time period for each party of the community. These data need to be reliable and not be corrupted. Transmission, processing and storage demands confidentiality and security. The IT system handling these data and operations must be trusted by the parties and auditable.

III. BLOCKCHAIN-BASED SERVICE

The service proposed by the experiment provides to energy communities the management of these energy flows into the blockchain.

Energy measurements done by the smart meter are integrated on a specific blockchain via IOT modules at defined time intervals. The processing of these data requires the use of specific technologies in order to transmit the information to the cloud with a high level of security and trust. These data are cryptographically signed and secured.

Autonomous and trusted programs running on the blockchain compute the proper allocation of the produced energy among participants according to rules previously enshrined in the blockchain. By doing so, the sharing is secured, certified by the blockchain consensus, and is auditable. This sharing reflects the relations and agreements between participants.

The solution needs to comply with the following requirements:

- Security and trust: consumption and production data of each participant must be tamper-proof;

- Confidentiality: energy measurements are personal data which storage needs to be secure and compliant with regulations;

- Reliability and Data integrity: participants are by default presumed not to trust each other;

- Robustness and resilience to provide quality of service;

- Auditability: every participant can verify and attest that energy allocation was done properly;

- Execution performance within the IOT device;

- System flexibility to adapt to different use cases involving, in particular, different hardware (smart meters…) to connect to;

- Scalability: the IT system architecture needs to adapt to different sizes of energy communities, but also to different time steps for the sending of consumption/production data from all types of meters; within the scope of the initial experimentations, the system will have to perform well with hundreds of participants;

- Energy sobriety: the system handles renewable energy transactions and needs to be energy-efficient.

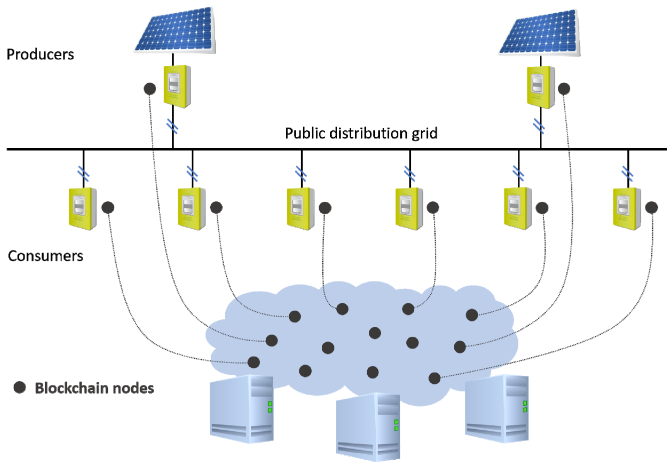

FIGURE 4. BLOCKCHAIN FOR THE DISTRIBUTED SELF-CONSUMPTION

IV. TECHNICAL SOLUTION PROTOTYPE

The term blockchain includes a family of technologies that vary significantly regarding three main characteristics:

- Blockchains can be public, consortium or private, depending on the sought governance and level of accessibility.
- The distributed ledger technology can be enhanced or not by autonomous programs, called smart contracts, to fit specific applications.
- Blockchains rely on a consensus. Very different ones exist, each with its own technical characteristics and its governance model.

A specific solution was designed to enable the distributed self-consumption experiment. It leverages the blockchain framework HyperLedger Fabric from the Linux Foundation. Energy allocation to the participants is performed by a smart contract, an unalterable program which code shall implement the rules and processes followed by the energy community.

Most often, the chosen consensus is the main cause for a blockchain's energy consumption. This is especially the case with the Proof of Work consensus [10], which requires a vast amount of energy to run the resource-intensive mining process over a great number of computers. The token-less blockchain architecture chosen for the experiment involves no mining - and no cryptocurrency. The permissioned blockchain requires negligible compute power for its consensus, while certifying on the blockchain the energy allocation coefficients which are dynamically and trustworthily calculated.

Under the use case of the experiment, data access is restricted to the corresponding energy community. Governance is ensured by actors that have been individually designated, as per the functioning of a consortium blockchain. A multi-ordering architecture has been deployed to ensure this distributed governance.

A specific client has been developed and implemented onto the IOT device. The collected data is cryptographically signed and secured thanks to embedded secure elements keeping the cryptographic keys protected. IOT integration is a major challenge, and memory and CPU usage have had to be limited to a minimum.

The choices exposed above lead to an architecture that is able to meet the requirements presented in the previous section. The basic characteristics of a blockchain (distributed consensus, distributed ledger, asymmetric cryptography) grant trust and transparency within each energy community, in addition to making the system secured, resistant and resilient.

Traceability of the energy origin is inherently allowed and could be used for green certification.

V. ONGOING PROOF OF CONCEPT

The solution has been recently deployed on a prototype that creates a small energy community gathering 2 producers and 3 consumers in France. At each measuring time step, power production is mutualized and shared between the 3 consumers through the public network. Beyond this experiment, several pilot projects are currently under the PV construction phase: in a few months, real energy exchanges will be performed between prosumers and consumers. An experimentation agreement was signed with Enedis, the main DSO in France, to carry out these projects.

The prototype has been used to test the interface with Enedis and its smart metering system. The prototype architecture connects IoT devices to smart meter's ports. These ports transmit energy data at an appropriate frequency to the device connected to the blockchain network. The blockchain network then calculates – at each time step – allocation coefficients representing the ratios of electricity self-consumed one on hand and provided by the respective retailer on the other hand, for each consumer registered in the community.

Afterwards, the DSO uses its smart metering infrastructure to upload the respective load curves and production curves, communicates with the blockchain network to recover the allocation coefficients and combines the data to calculate each consumers' energy quantities to be accounted as self-consumed and as provided by the respective retailers.

According to blockchain semantics, the DSO's metering infrastructure plays the role of the "oracle" in this architecture. The meters and the blockchain network implement trust and security on the entire information chain, dedicated to the energy stakeholders and the community. This architecture and data interface can be replicated for any other similar project, provided that a smart metering infrastructure able to measure production and load curves has been installed and that the data exchange protocol with the DSO has been properly defined.

Several distributed self-consumption projects hosting this solution are emerging in France, run by local authorities or private actors on the public grid, in accordance with the current regulation. Beyond self-consumption, this solution is a stepping stone towards other use cases, such as the integration of roaming scenarios (including EV-charging), energy storage, and other demand-side loads in a distributed energy management system serving the overall energy community.

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