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Co-simulation Framework for Blockchain Based Market Designs and Grid Simulations

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***Abstract*—The increased penetration of Distributed Energy Resources (DERs) on the distribution network creates local challenges in balancing consumption and generation. To coordinate the roll-out and the operation of DERs, distribution-level energy markets have been proposed, but there are currently few tools for simulating the operation of DERs in these proposed markets. We present a framework which utilizes a grid co-simulation platform (Mosaik) to simulation DER operation, while simulating market clearing operations with a blockchain network (Ethereum). The use of blockchains, an emerging technology for decentralized computing and data storage, allows us to model secure decentralized execution of market clearing functions and payment processes. By unifying simulation of market clearing rules and the physical grid, we are able to ensure that economic incentives are aligned with physical constraints, helping facilitate the development of more effective distributed energy markets. We demonstrate the use of this new simulation platform on a small feeder, for which a market mechanism to incentivize DER integration is explored.**

I. INTRODUCTION

The historical paradigm of centralized power generation flowing out to distant consumers has been challenged by the increasing development of local generation at the edge of the electricity grid[1]. For instance, in California more than 21% of the renewable energy capacity is now provided by distributed solar generation [2]. Several reasons justify this shift toward DERs: economic incentives, reduction of transmission losses, and the desire for greener energy sources and greater independence from the main grid.

As distribution grids host more DERs without any particular means of coordinating them, challenges are emerging [3]. Distribution grids are not ready for large amounts of local generation, creating high voltages, congestion, and risks for protection systems [3]. These events can create incentives for prosumers[1] and consumers to balance their consumption and generation at a local level.

Microgrid energy markets provide small-scale prosumers with a platform to trade locally generated energy [4], [5]. They promote local consumption by providing the opportunity to buy energy from local producers, incentivizing local generation and self-contained microgrid communities [5].

To provide a trusted operator for the microgrid without requiring a third-party aggregator or utility, we consider the use of a *smart contract* operating on a *blockchain* to provide secure, decentralized market clearing [6]. Blockchains are an emerging technology for decentralized computation and data storage, secured by a combination of cryptographic signatures and a distributed consensus mechanism, as described in [7]. They offer new opportunities for decentralized energy markets, providing a transparent interface for local consumers to participate in the decision of where and how their energy is produced [4].

While blockchains have been discussed for use in coordinating DERs in transactive energy markets [8], [9], these works have not considered the interaction of physical constraints, market structure, and DER operation – instead treating DERs as idealized financial assets [10], [11], [12]. As an example, the Brooklyn Microgrid pilot project[2] developed by LO3 energy[3] used a static tariff due to the complexity of modeling market operations [4], clearly demonstrating the need for a validation platform to test market mechanisms as more participants come on-line and more DERs are added on the grid.

This paper describes a co-simulation platform which unifies a grid simulation platform (Mosaik[4]) and a blockchain network (Ethereum[5]) to provide a powerful tool for modeling how distributed energy resources may act together in a transactive energy market. This work advances prior literature in the following important ways:

- Demonstrates an architecture for simulating and testing DER operation when market clearing is coordinated through a blockchain
- Makes available an open-source toolkit combining distribution network simulation and blockchain network testing.
- Demonstrates feasibility of market coordination through a blockchain with a sample market mechanism.

The first section describes the co-simulation platform, in-

[1]a prosumer is defined as a consumer producing energy

[2]https://www.brooklyn.energy/about
[3]http://lo3energy.com/
[4]https://mosaik.offis.de/
[5]http://www.ethereum.org/

cluding the grid co-simulation and the blockchain network. The second section presents a use-case for the platform, where PV and household simulators represent prosumers connected on a distribution feeder with a blockchain network to participate on a local energy market.

II. Technical Description

A. Co-simulation platform

We choose to develop a co-simulation approach in order to break down complex smart grid environment into subsystems [13]. This approach allows reliable simulators, specialized in their respective fields, to be merged on a common platform. Simulators are required to implement a common interface, the co-simulation platform is then responsible to exchange data between simulators and coordinate their execution [14]. In this study, we use the Mosaik co-simulation tool which is designed for steady state simulators with discrete time stepping. Mosaik is an open-source platform which enables simulation of large-scale smart grid systems while preserving simplicity, flexibility and scalability of the simulation.

In our study, we use multiple simulators to represent the distribution grid (Fig. 1). At the edge of the grid we use households[6] and PVs[7] simulators to represent production and consumption of electricity. Demand and generation are then apply to the distribution network simulator[8]. To model the interactions between participants and the energy market, we have created a simulator to interact with the blockchain, which implements the functions required to interface with mosaik.

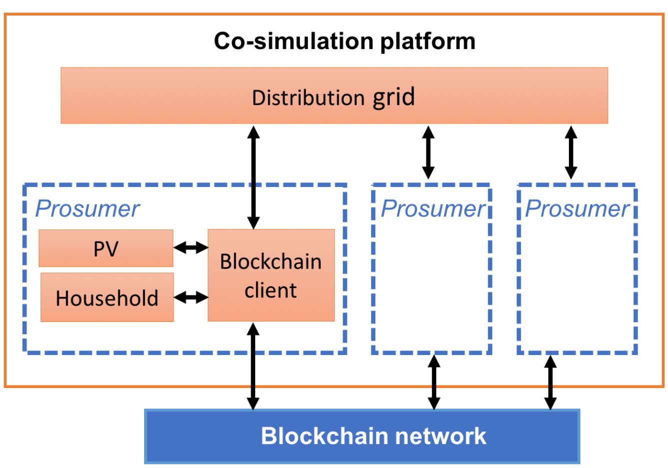

Fig. 1. Overview of the co-simulation framework, orange blocks represent mosaik simulators. The blue block at the bottom represents the live blockchain shared between all the participants.

B. Blockchain Platform

Blockchains are an emerging paradigm for distributed structure of data storage and computation in which a decentralized consensus mechanism is utilized to provide guarantees of consistency and immutability of the share data. By sharing verification amongst all peers on the network, blockchains are able to solve trust issues even in the presence of faulty nodes [15], making them resilient to cyberattacks, communication dropouts, and participants joining/departing the network. These characteristics have made blockchains an attractive platform for decentralized markets.

Smart contracts extend the functionality of blockchains by adding computation capabilities to the distributed data system, offering guarantees of execution and acting as decentralized computer applications. In this study, we use the Ethereum blockchain as the foundation of our energy market implementation. Ethereum provides a robust, open-source, and publicly tested infrastructure for smart contract development and testing in the *Solidity*[9] programming language.

While blockchains solve many challenges of coordinating trustless decentralized actors, they are not a panacea: the concensus protocol introduces additional computation and communication overheads, they require that shared information be publicly available, and they cannot address failures of hardware sensors such as smart meters.

C. Market design

One objective of the energy market simulation is to demonstrate the capabilities of the co-simulation platform to interact with the blockchain. The market rules designed for this study are based on several constraints:

- Consumers are incentivized to participate
- Local energy production and energy storage is incentivized
- Participants do not need to forecast their generation or consumption to participate
- Participants are not required to actively optimize their consumption or generation
- Electricity prices are the same for all consumers ($price_{buy}$) and all prosumers ($price_{sell}$), to avoid inequalities
- Energy back-feed at the feeder head is penalized

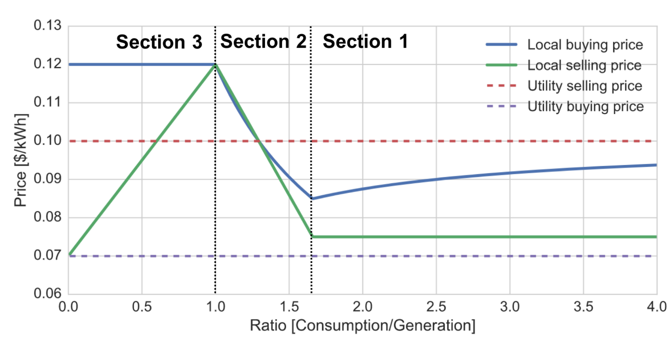

Fig. 2. Electricity market design

With these constraints, we propose a simple market design in which we define 3 domains of operation, characterized by

[6]https://bitbucket.org/mosaik/mosaik-householdsim
[7]https://bitbucket.org/mosaik/mosaik-csv
[8]https://bitbucket.org/mosaik/mosaik-pypower

[9]https://solidity.readthedocs.io/en/develop/

the ratio between consumption and generation as shown in Fig. 2. When consumption is larger than generation the market operates is section 1; conversely when generation is larger the market operate in section 3. In each of the sections electricity prices are represented by equations 1 to 7. The market assumes that utilities sell electricity at a higher price than they buy it from the prosumers. Table I defines the market variables.

TABLE I
MARKET NOMENCLATURE

Variables	Description
$price_{sell}$	local price for generating electricity
$price_{buy}$	local price for consuming electricity
$utility_{sell}$	utility price for generating electricity
$utility_{buy}$	utility price for consuming electricity
$minimumlocal_{sell}$	minimum price for local generators
$maximumlocal_{buy}$	maximum price for local consumers
$ratio$	local consumption divided by local generation
$ratio_{upper}$	ratio defining section 1 and 2
$ratio_{lower}$	ratio defining section 2 and 3

In the first domain, local consumption is larger than local generation. The price of selling local generation is set to a higher value than the retail price from the utility to create a financial incentive for producers. Energy consumers buy as much power as possible from the local producer and import the rest from the main grid. In the worst case, consumers pay the same price they would have paid the utility (large $ratio$).

$$price_{sell} = minimumlocal_{sell} \tag{1}$$

$$price_{buy} = \frac{price_{sell}}{ratio} + utility_{sell} \times (1 - \frac{1}{ratio}) \tag{2}$$

When local generation is close to local energy demand, the market operates in the second section. The price of buying electricity increases encouraging participants to consume more energy in order to lower the price. The price of buying electricity is calculated from equation 2, and the price of local generation linearly increases following equation 3.

$$price_{sell} = a \times ratio + b \tag{3}$$

$$a = \frac{minimumlocal_{sell} - maximumlocal_{buy}}{ratio_{upper} - ratio_{lower}} \tag{4}$$

$$b = maximumlocal_{buy} - a \times ratio_{lower} \tag{5}$$

Finally, in the last section, local generation is higher than consumption. The price of producing energy decreases as the production is no longer sold back to local consumers but instead to the utility. The price of buying electricity stay high to encourage participants to lower the price by consuming more energy.

$$price_{sell} = price_{buy} \times ratio + utility_{buy} \times (1 - ratio) \tag{6}$$

$$price_{buy} = maximumlocal_{buy} \tag{7}$$

D. Market implementation on the blockchain

The market mechanisms are implemented through a smart contract written in the *Solidity* language. The smart contract gives two options to the participants, one is to send their current energy consumption, the second is to trigger the market clearing process. Participants in the market can post their energy balance every 15 minutes, this information is broadcasted as a new block to every party on the network. Once a majority of participants approve this new block, it is appended to the chain of blocks shared by all participants (Fig. 3). In the same manner, every 15 minutes, any participant can clear the market and send the results as a block to the network. This process provides an indelible and transparent record of all the transactions. The decentralized aspect of the blockchain allows the system to work as long as there are participants, thus removing any single point of failure.

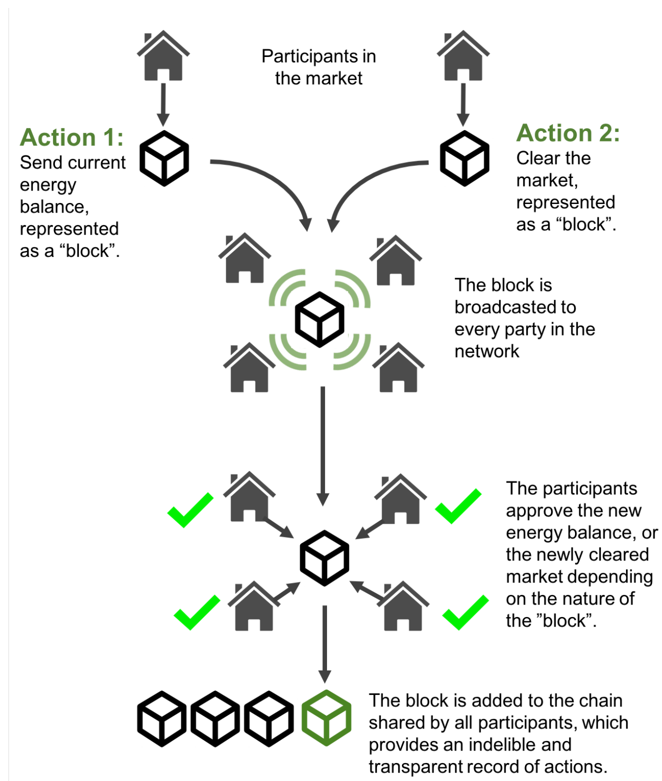

Fig. 3. Overview of the market implementation on the blockchain. Participants can post their current energy balance, or trigger the market clearing process if possible. Participants actions are represented as block broadcasted and validated by the entire network.

E. Participant modeling

Participants in the market are responsible for their consumption and production. It is likely that participants would use Energy Management Systems (EMS) to optimize their energy bill. Although, EMS are a necessary component of the energy market ecosystem, the implementation of an optimal scheduler is left out of the scope of this paper. For the purpose of this demonstration participants do not actively change their energy generation and demand.

III. RESULTS

A. Use case description

We model a low voltage network composed of 37 nodes (Fig. 4). Each node is assigned a household model, and 15 PV systems are randomly assigned across the network. The resulting peak load is below 40kW.

From this network 10 nodes are participating in the energy market (see red star on Fig. 4), 5 of those nodes have PV generation. Each of the market participants post their net energy consumption at 15 minute intervals. Once all the participants have updated their consumption, the market sets the local price for buying and selling electricity based on the ratio between load and generation. The participants are then billed using the prices set by the market.

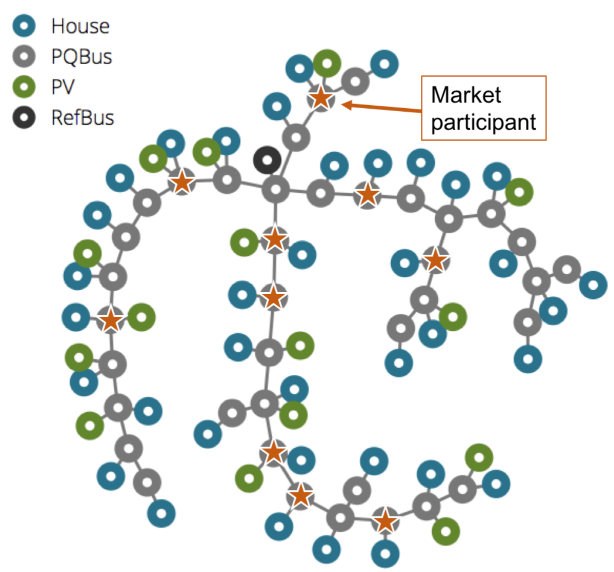

Fig. 4. Overview of the co-simulation with PVs in green, houses in blue and the distribution grid in gray.

B. Market results

The system load is dominated by the household consumption (Fig. 5), except around 3:00 pm when solar generation is briefly larger than the load demand.

The market prices remain the same until PVs start generating energy around 9:00 am (Fig. 6). As soon as PVs generate energy, they inject local and cheaper power which

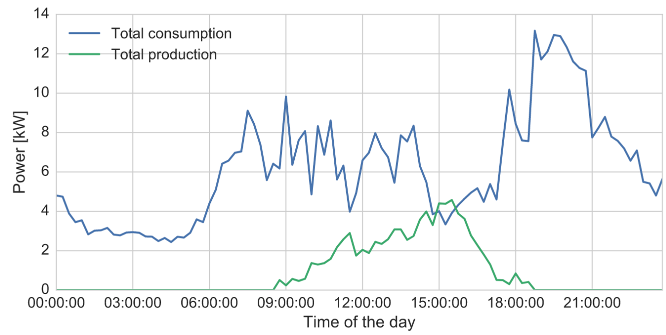

Fig. 5. Total production and generation within the market participants

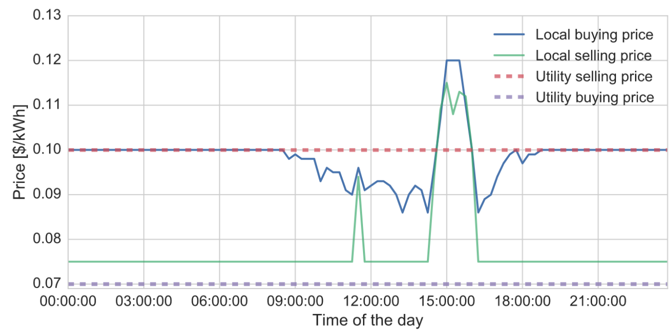

Fig. 6. Market prices cleared by the blockchain network

lowers the cost for the other consumers, while still providing PV owners with a better price than the utility price. Around 11:00 am, the system experiences a ratio between consumption and generation close to one, leading the market to operate in section 2 (Fig. 2). The resulting price for local generation increases, incentivizing local buyer to consume more to lower the price. Around 3:00 pm, the local generation exceed the participants power demand, pushing the market to operate in section 3. The price of local energy is at its highest which is undesirable for local consumers. Although local generators experience a higher price, generating more power only leads to a decrease in price, as the excess power is sold back at the utility price.

C. Blockchain performance

The blockchain application is deployed on a test network using testRPC [10]. The blockchain test network can not handle new transactions as fast as the co-simulation platform can solve the power-flow equations for the distribution grid. Therefore, in order to allow time for each block to be added to the chain, blockchain client simulators implement a 2 seconds delay after every transaction posted to the blockchain. This demo is publicly available on GitHub[11].

IV. DISCUSSION

The energy market incentivizes consumers to increase their power demand during over-generation periods to keep prices

[10] https://github.com/ethereumjs/testrpc

[11] https://github.com/Jonathan56/mosasik_ethereum_demo

low. Energy producers are also encouraged to stay below the back-feed threshold, to get a higher selling price. The community is financially incentivized to install more DERs, as the market creates a higher price for local generation that is no longer defined by the utility. Storage systems are greatly incentivized to avoid back-feed, especially with high levels of renewable energy penetration.

Simulating the market is a critical aspect for designing a robust system. It is likely that energy markets will progressively roll-out to more participants, thus they should be tested and designed for it. Local energy markets should adapt and calibrate to the community goals of introducing more DERs, coordinating consumers, and adding storage systems. This co-simulation tool enables to calibrate market rules to optimize market incentives, and forecast electricity cost for the participants.

A. Challenges and limitations

This paper focuses on the use of the proposed tool; users may explore many potential market structures and smart contract designs.

The market model could be improved by including additional time horizons, endogenously computing a fair energy price from the utility, and including network constraints (as discussed in [6]).

The system currently relies on each node to promptly post its energy balance; this relies both on the smart meter hardware and on timely communication from the node. For discussion of the security of smart meters see [16] and for discussion of blockchain security challenges see e.g [15], [17].

V. CONCLUSION

We have developed a grid co-simulation platform interacting with a blockchain network, and demonstrated the implementation of a local electricity market on the blockchain. By using a co-simulation framework that can handle complex device-specific constraints, and a high-level scripting language for blockchain smart contracts, the proposed platform is able to handle a variety of DERs and market designs.

Future work will address market designs with network constraints, to improve the balancing capabilities of local grids.

This tool has been made publicly available, and we invite other researchers to use it for developing improved distribution-level energy markets which take advantage of the strengths of both co-simulation tools and blockchain consensus networks.

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