Development of a Blockchain-Based Energy Trading Scheme for Prosumers

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***Abstract*—The combination of consumer owned Distributed Energy Resources, new Information and Communication Technologies (ICT), as well as changes to the national electricity regulations have created new opportunities for consumer engagement in the electricity sector. In this paper, this combination of technologies and regulations is examined in the Portuguese context. The new regulations dealing with self-consumption from prosumers are combined with smart contracts and distributed ledger technology to formulate an automated energy trading system for residential end-users in local energy markets. Results show that including prosumers in the local energy market brings significant benefits to all market participants. Additionally, results show that the newly created regulatory role of a Market Facilitator is beneficial to these type of local energy exchanges.**

Keywords—Blockchain, Local Energy Markets, Ethereum, Microgrids, Smart Contracts, Solidity, Market Facilitator.

I. Introduction

A. *Motivation*

It is well known that the rapid uptake and widespread use of Distributed Energy Resources (DERs) owned and operated by active consumers is a major goal if the energy sector is to be decarbonized [1]. This has been recognized by the governments of many countries and steps to achieve this uptake of DERs have been included in numerous national decarbonization strategies. This can be seen in legislation such as the European Union's European Green deal, which targets net-zero greenhouse gas emissions by 2050 [2]. These changes are being driven by decarbonization, digitalization and decentralization (the so called 3Ds of the energy transition). These three factors work together to deliver a clean, modern electrical grid which works for all end-users. These factors are shown in Fig. 1.

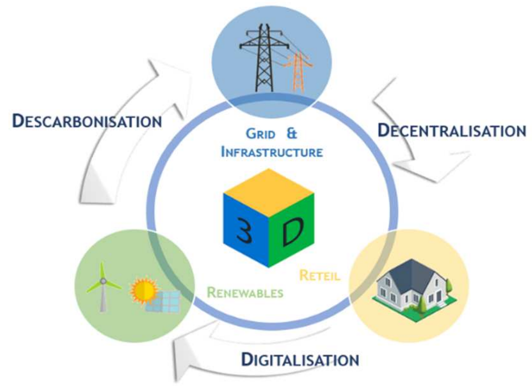

Fig. 1: The three dimensions of the energy transition.

This regional goal is being transcribed into national policies and legislation by the various member states of the EU, including Portugal. The Portuguese government has introduced a host of new legislation to help achieve the necessary carbon reduction goals, and specifically in the case of DERs, the government has introduced new legislation dealing with self-consumption and energy communities (Decree law 162/2019) [3]. This change in the legal and regulatory regime opens new opportunities for consumers to participate in the energy market and reap the benefits of owning DERs [4]. There are several avenues available for consumers to increase the utilization of locally produced energy, including demand response programs, energy storage systems or Peer-to-Peer (P2P) energy trading.

This paper focuses on how a novel ICT, smart contracts, can enable P2P trading. Thus, this paper presents a novel contractual agreement, which introduces new actors in the energy market and assists the consumers in their participation in Local Energy Markets (LEMs). This market construct uses smart contracts, an emerging ICT, to automate the energy trading amongst consumers while providing a safe and secure platform. This market construct is then applied to the Portuguese regulatory regime to examine how P2P energy trading may take place in the country and what changes may be needed to fully realize the potential of P2P energy trading.

Using blockchain to develop energy trading platforms has been carried out by various authors in the recent years [5-12]. In [6], a smart contract-based energy trading system is proposed. The authors use Ethereum and utilize ERC20 tokens as the medium of exchange in the platform. However, no significant benefits of the energy trading platform were discussed and no discussion was done concerning the possible roles of the various agents within the system.

The economic and technical benefits of using smart contracts for energy trading within distribution grids is studied in [7]. The authors use smart contracts to store the information of the energy trades rather than utilize their automated nature to execute energy trades within the test system. Furthermore, the various agents were not differentiated in any manner so that the different types of agents all had the same access rights in the system.

A P2P energy trading market considering both forward and real-time markets is proposed by [8] and the authors consider different types of agents, including so called suppliers or aggregators to act as intermediaries between consumers and generators. The paper does not consider smart contracts in order to record or execute the trading schedule.

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The authors of [9] develop a hybrid energy trading platform which considers both P2P transactions and transactions between the consumers and the existing electricity utility. Notably, the paper considers a matching strategy based on the distance between the two agents so to reduce any losses. The authors also seek to reduce the peak to average ratio and maximize the energy exchanged.

In [10], the authors proposed an integrated blockchain-based energy management platform with bilateral trading for residential buildings in energy communities. A combined analysis of optimal power flow and smart contracts-based energy trading was performed using Ethereum. The smart contract is used as a virtual aggregator of the local market. However, the different types of agents and their access rights according to a regulatory regime were not detailed.

A blockchain based energy trading platform using a novel demurrage mechanism is presented in [11] using a type of energy trading token which the consumers may purchase from generators or from a 'last-resort' energy trader. Within this model, P2P energy trades are not considered and neither are smart contracts.

From the literature reviewed, several blockchain-based trading platforms have been developed but very few platforms are designed with the regulatory and legal regime in mind. If these platforms are to move from computer-based simulations or small pilot projects, to large scale projects, they need to fit seamlessly within legislation. This paper achieves this by incorporating the legalization into the trading platform.

The contributions of this paper are twofold:

- Development of a smart-contract based energy trading platform considering different types of agents, including a system administrator agent and market facilitator (purchaser of last resort defined in the new Portuguese self-consumption regulations) to allow for P2P energy trading to take place.
- An application of this trading platform to the recent amendments in the Portuguese energy regulations concerning consumer self-generation through distributed energy resources.

The rest of this paper is structured as follows. The next section provides background information both to the use of smart contracts and blockchain in general as well as the recent changes to the Portuguese self-consumption regulations. In Section III the design of the model is shown. Following this, results from a case study are presented and discussed in Section IV. Section V contains the relevant conclusions and ideas for future expansion of this system.

II. Context

Key to the successful energy transition is the adoption of various new regulatory and legal frameworks as well as new ICT technologies in order to harness the potential of the increasingly digitized energy system.

A. *Portuguese regulations on self-consumption and energy communities*

In October 2019, the Portuguese government released novel legislation relating to so called self-consumption and energy communities. This was done to align the country's legislative framework with the relevant European Directives as well as the Portuguese National Plan for Energy and Climate (PNEC) [12].

This was enacted through the Decree Law 162/2019 of the 25th of October [3]. This law is concerned with the legal framework for the installation and use of small-scale distributed energy resources (DERs) with or without connection to the public electricity distribution system.

The aim of the law is to remove unnecessary burdens from consumers who would like to produce, consume, store, share and sell electricity. It encompasses P2P energy trading and renewable energy communities but crucially the law introduces the so-called Market Facilitator (MF). This agent is a supplier who is under obligation to purchase energy produced by DERs under market conditions [3].

The concept of MF was included in this energy trading model and its effects on the market outcomes will be studied. In order to make full use of energy trading platforms, new applications of ICT technologies are needed.

B. *Smart contracts*

An intriguing ICT for the energy system is smart contracts which have recently gained popularity with the rise of blockchain or distributed ledger technologies. In short, these smart contracts are pieces of code which are executed if certain criteria are met and are triggered by the users.

Smart contracts have the potential to replace traditional contracts between parties in certain circumstances and have gained significant attention within the energy sector potentially automating P2P trading systems.

The smart contract-based trading system was developed in Ethereum. Within Ethereum, for every transaction or smart contract carried out there needs to be a fee paid. This fee is called gas and is paid to the nodes of the system who validate (called miners) and process the transaction as a way to incentivize the miners to participate in the system. The more complex an operation or transaction, the more gas is required to ensure that the transaction is processed. More details regarding gas can be found in [13].

III. System Development

In this section the smart contract-based trading system is presented and discussed. This system requires numerous contracts between various agents to ensure the successful operation of the system. These agents and the layout of the system are shown in Fig. 2.

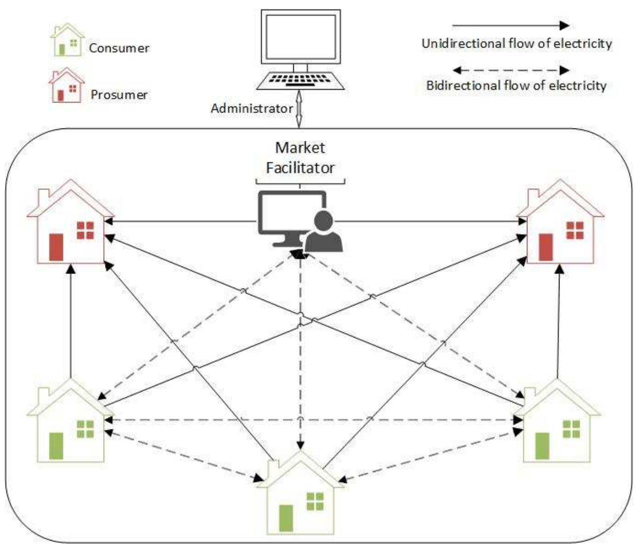

Fig. 2: Layout of proposed energy traing model.

This system relies on four different participating agents, which are the Administrator, Consumer, Prosumer, and Market Facilitator. In addition to describing each of the agents and the various contracts, issues relating to the security of the system as well as transaction costs (including Ethereum gas fees) are also discussed. Each of these agents have different roles and responsibilities within the system and are mainly differentiated by their different levels of permissions granted to them by the system.

Remix provides many options for the development of smart contracts and for this case study the JavaScript Virtual Machine was chosen. This is a sandbox blockchain implemented in JavaScript to emulate a real blockchain. Further information regarding Remix can be found in [14].

A. Agents

1) Administrator

The administrator agent is responsible for the overall functioning of the system. In some regulatory regimes this role could be played by an aggregator or Virtual Power Plant (VPP) operator. This agent is responsible for allowing consumers to enter and leave the LEM well as granting the consumers rights to sell their excess electricity thus allowing them to become prosumers.

While the presence of the administrator agent negates the true decentralized nature of the P2P energy trading system, the authors argue that it is a necessary agent as it provides security and reliability to the system and the inclusion of this market agent is required by the legal and regulatory regime. The administrator ensures that the consumers adhere to certain requirements and agree to certain behaviors. The use of the administrator agent is also a stepping stone to future full decentralization. The administrator does not participate in the market but rather acts as a market regulator.

2) Consumer

The consumer agent is a representation of the traditional consumer who solely purchases electricity from the system. When the consumer agent is authorized by the Administrator, they can request electricity from the market. Currently each consumer will be responsible for manually requesting their electricity but with the rise in the use of Home Energy Management Systems (HEMSs), the bidding for electricity may be done by a HEMS in the future in order to meet the energy needs and comfort preferences of the end-users.

3) Prosumer

The prosumer agent represents a consumer who can generate electricity through various DERs and can store or choose to sell their excess to the LEM. These agents can submit offers to both sell and buy electricity from the market.

4) Market Facilitator

The Market Facilitator (MF) is authorized to sell electricity to and buy excess electricity from the various consumers and prosumers within an area. This agent's responsibilities are most suited to the distribution system operator and is described in the recent changes to the Portuguese regulations dealing with self-consumption [3]. According to these regulations, the MF acts as both supplier and purchaser of last resort for any shortfalls in energy among the consumers in the LEM [3]. Currently, the market mechanism prioritizes the purchase and sale of excess electricity amongst the consumers and this is done by having the price of electricity from the MF at a higher level than that electricity from the individual prosumers.

There is a discrete flow of information passed between the market participants. The flow of information between a seller and purchaser of energy is shown in Fig. 3.

B. Contracts

This section provides the details of the various contracts used within the market. According to the permissions granted to them by the Administrator, each agent can execute different types of smart contracts within the system. When an agent requires energy, they submit a bid for the energy and when an agent has a surplus of energy, they submit sell offers.

Each user has access to 24 different bids and asks, if a prosumer, for a single day and is only able to process one kind of order for each period i.e. a prosumer is not allowed to offer energy at a high price and then request energy at a lower price during the same time block. The complete overview of the various contracts and interactions between the agents are shown in Fig. 4.

The contracts were designed to ensure that only the permissioned agents have access to the necessary contracts. This helps to maintain the security of the system. There were three main types of contract: Administrator, User, and Market contract and each contract had distinct functionalities only available to the authorized agents.

1) Administrator Contract

The administrator contract is the first contract to be called and executed when the system begins operating. The function of this contract is to store the addresses of the Administrator agent in a private variable for later use in other contracts.

2) User Contract

The User contract is called from the Administrator contract and thus can only be edited by the Administrator. In this contract the Administrator registers a user in the system and can authorize them to be prosumers or remain as consumers. This is equivalent to a register of active consumers and prosumers within the system and helps to keep track of who is performing the transactions.

3) Market Contract

The third type of contract is the Market contract and this contract records the information of the various asks and bids from the various agents as well as if those bids have been accepted and then delivered. This will allow the transfer of energy and money between the various agents within the system. This contract is available to all registered agents.

This contract provides additional information such as the electricity price charged by the MF for both buying and selling electricity to the agents within the system. While the agents are free to set the price of their bids and asks, this information of the prices from the MF is provided so that the agents can make informed decisions and ensure that they receive the best possible deal.

It contains links to the agent's wallet for monetary transfers and each transaction needs to be signed by the agent and this ability to sign the transaction is kept as a private function for that specific agent so that no other entities can access this and make transactions on behalf of the agent. An excerpt of the code describing the market contract is shown in Fig. 5.

C. Market Design

The market is designed in such a manner that it operates as a day ahead market with a time granularity of 1 hour using a Time of Use tariff.

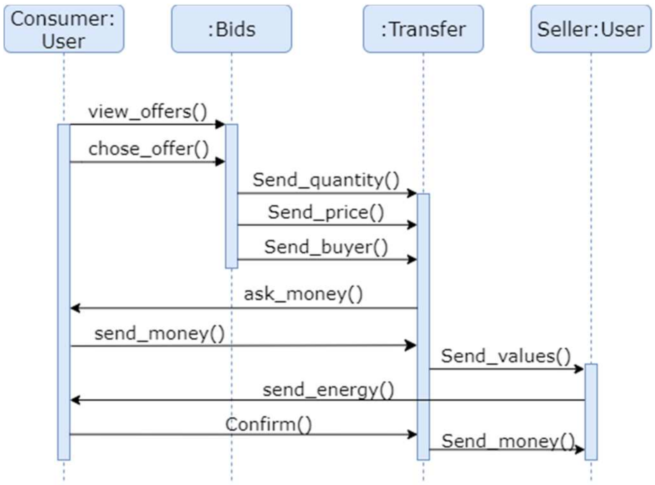

Fig. 3: Flow of information between seller and buyer of energy within the LEM.

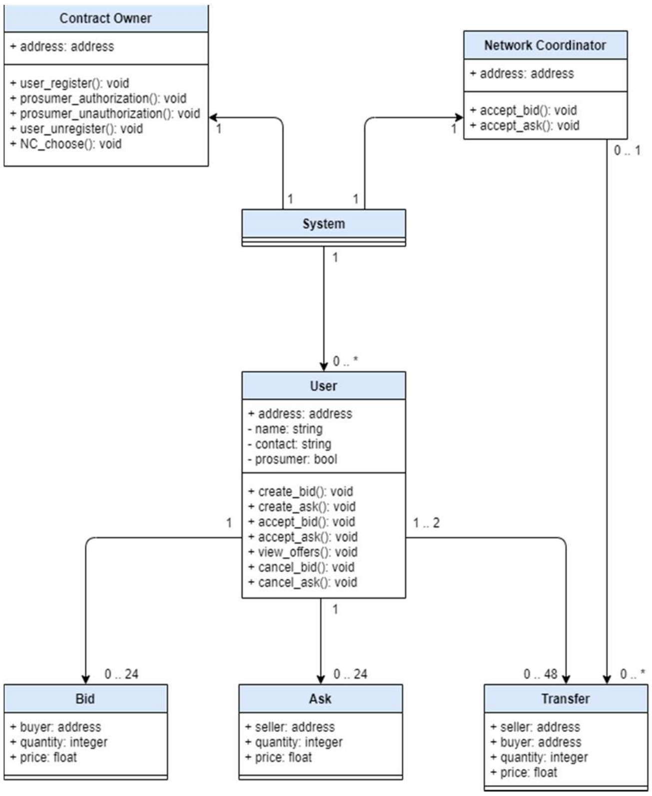

Fig. 4: Roles of various agents in the LEM.

When a bid has been accepted, the contract creates a structure which is used to store the information of the accepted bid. This includes the users who will be part of the transaction, the amount and price of energy and binary variable to declare if the transaction has been concluded or if it is still pending. These transaction structures are then stored in an array for ease of management.

Once an agreement has been reached between two parties, the amount of money is transferred to the contract and it stays there until the correct amount of electricity has been dispatched. The information relating to the money and addresses are stored in a different structure which cannot be accessed by any other party, including the administrator. If the transaction is not completed for any reason the money is transferred back to the buyer and this is recorded along with all other successful transactions.

```
contract market is service_user{

    struct order{...}
    order[][24] private list_bid;
    order[][24] private list_ask;
    struct transfer{...}
    transfer[] list_transfer;

    function create_bid(uint quantity, uint price, uint period)
        only_producer public{...}
    function cancel_bid(uint idx, uint period) public{...}
    function delete_bid(uint idx, uint period) private{...}

    function accept_bid(uint idx, uint period)
        only_user public{...}

    function make_transfer(
        address payable buyer,
        address payable seller,
        uint energy,
        uint price)
        private{...}
}
```

Fig. 5: LEM contract which records the amount and addresses of the participants in the transaction.

IV. Tests and Results

In this section, the results of the case study are presented. In addition, the barriers and issues identified during the course of the case study will be discussed. The main results identified in this section are the execution of the various smart contracts and the fact that only certain agents may access certain contracts. An in-depth presentation of the transaction fees necessary to execute the contracts will also be presented.

A. *Administrator*

To initiate the market, the administrator contract was executed and this is shown in Fig. 6. In this figure, the administrator's address is used to initiate the market and only the administrator can access this as well as change the administrator's address if needed.

B. *Users Data Management*

The successful execution of this contract allows the administrator to register consumers and grant them prosumer rights if needed. To register new users in the system the administrator will use the addresses linked to the administrator address in the accounts provided. This function can only be executed by the system's administrator and uses a total of 117.952 gas units. The transaction required to authorize a prosumer only requires the consumer's address and is carried out by the system administrator. The system will access the specific structure from the mapping and will change the Boolean value of the prosumer to be true. For this case study, three consumers were altered to be prosumers and this had a total gas cost of 53.752 units.

C. *Market Operations*

Once the various agents have been added to the system, the market transactions can take place. These transactions include executing and cancelling orders as well as the ability to accept them and make a transfer between two entities, view the list of available offers, reset the market for the next day and view the anchor price set by the MF. In this case study we have a system of five consumers and five prosumers.

The two types of orders, asks, and bids, share the same structure as both relate to an amount of energy and price. However, they are executed in different functions as these structures are stored in different arrays and certain conditions to be executed, for example, who is running the transaction.

```
[vm] from: 0x4b2...c02db to: market.accept_bid(uint256,uint256) 0x9d7...b5e99 value: 0 wei
data: 0x8a0...00001 logs: 0 hash: 0x7cf...1ff90
```

status	0x1 Transaction mined and execution succeed
transaction hash	0x7cfad16c6797d8998770ac3455be220266cf93d9857c9f2d04befcd4aa41ff90
from	0x4b20993bc481177ec7e8f571cecae8a9e22c02db
to	market.accept_bid(uint256,uint256) 0x9d7f74d0c41e726ec95884e0e97fa6129e3b5e99
gas	6000000 gas
transaction cost	168133 gas
execution cost	146541 gas

Fig. 7: Accepted offer for the puchase of energy between two participants in the LEM. .

```
contract administrator {

    address service_admin;

    event service_in_execution();
    event new_service_admin(address service_admin);

    constructor() public{...}

    modifier only_admin{...}

    function get_admin() public view
        returns (address){...}

    function change_admin(address new_admin) public
        only_admin{...}
}
```

Fig. 6: Administrator contract needed to initiate the LEM

In this case study we have a system of five consumers and five prosumers. Once the agents have submitted their offers for that time period, a market clearing price is determined and this price is used for the time period. Agents who submit offers that are not included are then forced to turn to the MF agent as the supplier/buyer of last resort.

1) Asks

To submit an ask the account must be a registered consumer to the system. The MF or the administrator cannot execute this type of contract. Prosumers may also submit asks as they are registered users to the system. The list of asks is stored in an array until the gate closing time of the market.

2) Bids

Only prosumers can submit bids of energy available. The prosumers need to state a quantity of energy available and the period in which this energy will be available.

3) Accept offer

Once a bid has been matched to a corresponding ask there will be two different functions called. One will be to accept the bid and one will be to accept the ask. The functions will only be sent to the two agents involved in the transaction. An example of a completed transaction is shown in Fig. 7. This Fig. shows the details of the transaction such as the hash codes of both the transaction and of the block in which the transaction was included, the address of the contract and also the originator and receiver addresses of the agents involved in the transaction. This message displays the consumed gas which is the fee paid to ensure that the contract is executed.

This function stores the transfer and represents the agreement between the two peers. Its parameters are the buyer's address, seller's address, the quantity of energy, and price for that quantity of energy.

This function is private and can only be accessed from other contract functions as it is not visible to users. Its functionality resides in storing the values in a specific structure, adding a Boolean as a flag to check if it was completed or not. When an order is accepted the Boolean that checks if the order was accepted is changed to the 'true' so that it cannot be accepted by any other user.

Accepting a bid consumes a total of 168.150 gas units while accepting an ask consumes a bit less, taking a total of 136.740 gas units.

D. Financial impact on the agents

The above-mentioned contracts were deployed in a case study used to simulate a small group of consumers and prosumers. This case study was simulated over 24 hours. A summary of the various bids and asks submitted by the agents for a single hour are shown in Table I. The prosumers and consumer who had accepted bids/asks then participate in a local energy market to trade the specified amounts of energy.

For the period under consideration, the anchor price is €1.1/unit. Each of the agents can submit an offer with different prices. The market clearing price is then calculated from the various offers using supply and demand curves. The offers below the market clearing price of €1.1/unit are accepted and traded amongst the prosumers while bid outside of the market clearing price are fulfilled by the MF. In this hour, there are 28 units of energy traded amongst the prosumers with the MF supplying 21 units of energy to the consumers and purchasing 24 units of energy.

A comparison between a transitional market and the developed P2P market is shown in Table II, which shows the prices of consumers if they could only buy energy from the MF and the prices they paid in this market.

For this use case, it is assumed that MF buys energy for 0.99 units of price and sells for 1.22. This corresponds to the Portuguese decree law 153/2014 which states that the renumeration for small scale DERS to the Last Resort Supplier should be set at 90% of the simple arithmetic mean of the daily closing prices for the relevant month in the Iberian wholesale energy market [15].

TABLE I: EXECUTED ORDERS BETWEEN THE CONSUMERS AND PROSUMERS

Consumers buying		**Prosumers selling**	
Quantity (kW)	***Price (€)***	***Quantity (kW)***	***Price (€)***
11	1.3	7	0.7
8	1.2	8	0.9
9	1.1	12	1
15	1	10	1.1
6	0.8	8	1.2

TABLE II: FINANCIAL IMPACT OF THE PROPOSED LEM ON CONSUMERS

Traditional market		**P2P Market**	
Agents	***Transfers (€)***	***Agents***	***Transfers (€)***
Consumers	-73.5	Consumers	-62.3
Prosumers	+22.5	Prosumers	+42.8

TABLE III: FEES INCURRED DURING THE OPERATION OF THE LEM

Function	**Gas consumed**	**Cost (Microether)**	**Cost (€)**	**Payer**
Deploy admin contract	138.608	5.27	0,0011	Admin
Deploy user contract	1.419.253	53.93	0,011	Admin
Deploy market contract	3.018.453	114.7	0,023	Admin
Register new user	117.952	4.48	0,00090	Admin
Authorize prosumer	53.752	2.04	0,00041	Admin
Submit ask	108.486	4.12	0,00083	Consumer
Submit bid	108.612	4.13	0,00083	Prosumer
Accept ask	136.740	5.2	0,0011	Seller
Accept bid	168.150	6.39	0,0013	Buyer

This was done to prioritize energy trading among the prosumers and reduce the energy traded with the MF. Using the developed local energy trading market reduced consumers costs by 15.2% and increased profit of the prosumers by 90.2%.

E. Fees

For each transaction, there were fees paid using gas. The fees for ETH are given in Szabo or Microether. For ease of understanding, the gas prices are converted to Euros. These fees are summarized in Table III. This Table uses a conversion rate of 202 Euros per ETH. Despite these extra costs associated with the transactions, overall, the impact of the LEM brings significant benefits to the consumers.

F. Portuguese regulation

This smart contract-based energy trading model highlighted the importance of the MF agent which was envisioned in the recent alteration in the Portuguese regulation dealing with consumer owned DERs. The forward thinking and proactive approach taken by the Portuguese government and the wider EU, can bring significant benefits to consumers who choose to be active in the energy sector as is highlighted in the results of this energy trading model.

V. CONCLUSION

In this paper, a blockchain-based energy trading proof-of-concept for prosumers was developed. This model used smart contracts in order to automate and execute the energy trades within a community of consumers, prosumers and a market facilitator. The design of this market was based on the recent changes in the Portuguese legal regime dealing with self-consumption by consumers using small-scale DERs. The model showed that the use of smart contracts for energy trading is possible and has the potential to provide a secure and trustworthy way of recording the transactions amongst a group of consumers. The model highlighted the role of each of the agents included in the system and showed how each one interacts with the others in order to ensure the optimal operation of the trading platform. The inclusion of the MF agent provided significant benefits to the community as can be seen from the reduction in the cost of energy for the consumers and increase in the profits made by the prosumers within the model. Within the current Portuguese regulation, P2P markets can only be formed with the inclusion of the MF agent and this work has shown that this market design can indeed have significant benefits for the consumers, even if the consumers would have higher benefits in a pure P2P market. Hence, the proposed smart contract-based trading scheme demonstrated the promise of combining blockchain and progressive energy regulation to deliver significant benefits. In terms of limitations of this model, it is a proof-of-concept and will be extended. Chief among the limitations is the choice of Blockchain and its consensus algorithm. For future work, the design of tariffs for energy trading amongst consumers will be studied, especially the role of network fees. In addition, system losses will be incorporated into the model to provide a more realistic assessment of the impacts of P2P energy trading on the distribution system.

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