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Blockchain-based Transactive Energy Framework for Connected Virtual Power Plants

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***Abstract*—Emerging technologies are helping to accelerate the ongoing energy transition. At the forefront of these new technologies is blockchain, which has the potential to disrupt energy trading markets. This paper explores this potential by presenting an innovative multi-level Transactive Energy (TE) optimization model for the scheduling of Distributed Energy Resources (DERs) within connected Virtual Power Plants (VPPs). The model allows for energy transactions within a given VPP as well as between connected VPPs. A blockchain based smart contract layer is applied on top of the TE optimization model to automate and record energy transactions. The model is formulated to adhere to the new regulations for the self-generation and self-consumption of energy in Portugal. This new set of regulations can ease barriers to entry for consumers and increase their active participation in energy markets. Results show a decrease in energy costs for consumers and increased generation of locally produced electricity. This model shows that blockchain based smart contracts can be successfully integrated into a hierarchical energy trading model, which respects the novel energy regulation. This combination of technologies can be used to increase consumer participation, lower energy bills, and increase the penetration of locally generated electricity from renewable energy sources.**

***Index Terms*—Virtual Power Plants, Transactive Energy, Smart Contracts, Blockchain, Prosumers.**

NOMENCLATURE

A. Sets/Indices

$t \in \Omega^T$	Time period
$s \in \Omega^S$	Scenarios
$w \in \Omega^W$	Prosumers $w = \{1,2,3\}$
$c \in \Omega^C$	Controllable appliances $c = \{HVAC, WM, DW\}$
$f \in \Omega^F$	Variable operation phases of controllable appliances

B. Parameters

$CE_{w,s}^{ESS}$	Charging efficiency of the Prosumer w's ESS
$CE_{w,s}^{EV}$	Charging efficiency of the Prosumer w's EV
$\eta_{w,t}^{EV,disch}$	Discharging efficiency of the EV of prosumer w
$InfLoad_{w,t}$	Inflexible load of household w in period t [kW].
$N_{w,s,c'}$	Periods of operation for the controllable appliance c of prosumer w
$P_{w,f,c,s}^{phase}$	Power consumed by controllable appliance c of prosumer w while in phase f [kW].
$P_{w,t,s}^{PV,prod}$	Available power of the PV system of household w in period t [kW].
$R_{w,s}^{ESS,charg}$	Charging rate of ESS of prosumer w [kW].
$R_{w,s}^{ESS,disch}$	Discharging rate of ESS of prosumer w [kW].
$R_{w,s}^{EV,charg}$	Charging rate of EV of prosumer w [kW].
$R_{w,s}^{EV,disch}$	Discharging rate of EV of prosumer w [kW].
$SOC_{w,s}^{ESS,ini}$	Initial SOE of the ESS of prosumer w [kWh].
$SOC_{w,s}^{ESS,max}$	Maximum SOE of the ESS of prosumer w [kWh].
$SOC_{w}^{ESS,min}$	Minimum SOE of the ESS of prosumer w [kWh].
$SOC_{w,s}^{EV,ini}$	Initial SOE of the EV of prosumer w [kWh].
$SOC_{w,s}^{EV,max}$	Maximum SOE of the EV of prosumer w [kWh].
$SOC_{w,s}^{EV,min}$	Minimum SOE of the EV of prosumer w [kWh].
$T_{w,s}^{a}$	Arrival time of the EV of prosumer w.
$T_{w,s}^{d}$	Departure period of the EV of prosumer w.
$T_{w,f,c,s}^{dur}$	Duration of phase f of controllable appliance c of prosumer w [number of ΔT-hour periods].
$\lambda_{t,s}^{pur}$	Energy buying price [€/MWh]
$\lambda_{t,s}^{sold}$	Energy selling price [€/MWh]
ΔT	Time interval duration [t].

C. Variables

$P_{w,t,s}^{pur,grid}$	Portion of total power procured from the grid by prosumer w in period t [kW].
$P_{w,t,s}^{pur,local}$	Portion of power procured from the local neighborhood by prosumer w in period t [kW].
$P_{w,t,s}^{pur,T}$	Total power procured by prosumer w in period t [kW].
$P_{t,w,s}^{ESS,charge}$	Charging power of ESS of prosumer w in period t [kW].
$P_{w,t,s}^{ESS,disch}$	Discharging power of ESS of prosumer w in period t [kW].
$P_{w,t,s}^{ESS,used}$	ESS discharging power of prosumer w used to satisfy self-consumption in period t [kW].
$P_{t,w,s}^{EV,charge}$	Charging power of EV of prosumer w in period t [kW].
$P_{w,t,s}^{EV,disch}$	Discharging power of EV of prosumer w in period t [kW].
$P_{w,t,s}^{EV,used}$	Portion of the EV discharging power of prosumer w used to satisfy self-consumption in period t [kW].
$P_{w,t',c,s}^{mach}$	Power consumed by controllable appliance c of prosumer w while in period t [kW].
$P_{w,t,s}^{PV,used}$	Portion of the PV power of prosumer w used to satisfy self-consumption in period t [kW].

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$P_{w,t,s}^{sold,ESS}$	Portion of the ESS discharging power of prosumer w sold to the grid or the neighbourhood in period t [kW].
$P_{w,t,s}^{sold,EV}$	Portion of the EV discharging power of prosumer w sold to the grid or neighborhood in period t [kW]
$P_{w,t,s}^{sold,grid}$	Portion of the power injected to grid by prosumer w that flows back to the grid in period t [kW].
$P_{w,t,s}^{sold,local}$	Portion of the power injected to grid by prosumer w that is used in neighborhood in period t [kW].
$P_{w,t,s}^{sold,PV}$	Portion of the PV power of prosumer w sold to the grid or the neighborhood in period t [kW].
$P_{w,h,s}^{sold,T}$	Power injected by prosumer w in period t [kW].
$SOC_{t,w,s}^{ESS}$	SOE of ESS from prosumer w in period t [kWh].
$SOC_{t,w,s}^{EV}$	SOE of EV from prosumer w in period t [kWh].
$x_{w,s,t'}^{1}$	Binary variable. 1 if the neighborhood is drawing power from the grid in period t; else 0
$x_{w,s,t'}^{2}$	Binary variable. 1 if the power flows from grid to prosumers/if EV is charging (w = {1, 2, 3}) for prosumer w in period t; else 0.
$x_{w,s,t'}^{3}$	Binary variable. 1 if the power flows from grid to prosumers/ if ESS is charging (w = {1, 2, 3}) for prosumer w in period t; else 0.
$x_{w,s,t,f,c}^{phase}$	Binary variables. 1 if phase f of controllable appliance c in prosumer w is beginning/ongoing/finishing $(x = \{y, u, z\})$ in period t; else 0.

I. Introduction

THE emergence of Distributed Energy Resources (DERs) has created new opportunities and challenges for all stakeholders within the power system [1]. This new paradigm grants consumers the possibility to actively engage in the energy system through the production of electricity through DERs thus becoming prosumers, consumers who also produce electricity [2]. Emerging technologies such as blockchain have the potential to broaden the role that active consumers can play [3]. This new role also brings increased challenges in terms of balancing the supply and demand of electricity which is increasingly being generated by intermittent renewable energy sources (RES). To ease this balancing challenges, virtual power plants (VPPs) have been proposed [4]. VPPs have emerged as a concept to aggregate a diverse number of disparate DERs to act as a single entity when participating in energy markets [5]. The VPP will combine the separate generation and demand profiles of the underlying DERs to create a single load or generation profile which reduces the complexity associated with controlling a large number of DERs [6]. VPPs can have different structures and operational goals depending on their architecture [7]. These VPPs can group consumers into various levels according to scale and location. These different levels are then managed by a designated authority which helps reduce the challenges associated with managing an electric power system with a large number of small-scale intermittent generators [8].

This concept of multi-level VPPs participating in energy markets is shown in Fig. 1 which shows the proposed multi-level VPP model used in this paper. At the lower level, the local VPP operators are responsible for intra-VPP energy trading.

At the higher level, the global VPP operator is responsible for inter-VPP energy trading and coordinating with the local VPP operators. The global VPP operator also liaises directly with the system operator, the external grid, and the market facilitator agents. The figure shows that each VPP is composed of several different consumers including residential and service buildings with different portfolios of DERs and load demand profiles.

Within the VPPs, prosumers play a significant role and lead to an increase in the number and type of DERs available [9]. VPPs can reduce the complexity associated with bidding into energy markets, increase consumer participation, improve system reliability and flexibility, and increase the penetration of renewable energy sources within the power system [10], [11].

VPPs increase the number and type of transactions within energy markets and this increase in transactions brings about its challenges. One control framework to help manage these challenges is Transactive Energy (TE) [12]. This framework is designed for the control and coordination of many DERs owned by various entities and users. The TE framework uses market-based approaches to incentivize the trading of both energy and information between participants [13]. TE mechanisms can use price, comfort, technical and environmental signals to coordinate energy markets across the entire power system infrastructure [14].

A thorough review of the TE concept has been presented by [15], where the authors clearly identify the need for multi-layer TE models to maximize the benefits of this control framework. This paper uses the principles of TE to coordinate energy trading both within VPPs and between VPPs. The application of TE to VPPs has been suggested by past work, such as [16] as a number of disparate DERs can be optimized to participate in energy trading.

Within TE systems there is a large amount of data transfer between the participants. This may raise questions about data privacy and security or even impact the operation of transactive energy markets [17]. Blockchain technology can provide some solutions to these problems and is therefore well suited to TE systems [18]. Within TE systems multiple interconnected layers transmit information between each other. A blockchain system can therefore easily become part of the network layer of a TE system. Thus, the nexus between VPPs, prosumers, TE systems and blockchain has emerged as an interesting field of study, both academically and commercially. Despite this increase in interest, there are several areas where more research is needed.

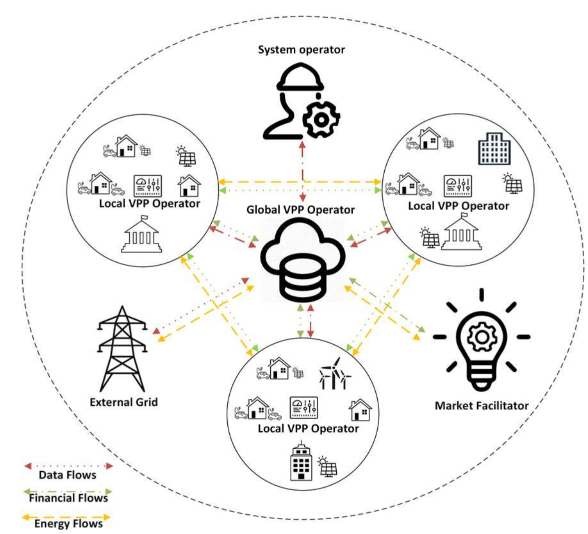

Fig. 1: Multi-level energy trading market

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A. State of the Art

This section introduces and critically discusses several existing papers which deal with the optimization and scheduling of consumer-owned DERs in small-scale energy markets. This is done to highlight how the proposed paper addresses certain research gaps and extends the state-of-the-art. The contributions of each of these papers are summarized in Table I, which compares and contrasts existing research with the proposed model.

A decentralized optimization model for energy trading within local energy markets using Hyperledger implementation of the blockchain was developed by [19]. The model considered a single layer of energy trading among residential consumers with a variety of DERs, including heat pumps. The authors consider two different trading strategies, namely matching supply, and demand and then a strategy that encourages nearby peers to engage in energy trading thus reducing system losses.

Blockchain was applied for load and generation aggregation in [20]. The smart contracts were used to record the consumers' energy usage and any potential flexibility that the consumer may offer to the system, the authors used the Hyperledger blockchain implementation. Optimal scheduling of consumer-owned DERs was not considered.

In [21], a two-stage transactive energy model for the optimization of prosumer’s flexibility was developed. This nested market considered several consumer-owned DERs and a local flexibility market to minimize costs for the stakeholders. The model considered many customers (1 million) with different customer participation levels. The model did not incorporate blockchain-based smart contracts.

A model incorporating both transactive energy principles and blockchain was developed by [18]. The model applied a blockchain layer over an energy trading layer to enable the transactive energy mechanism. The model used ADMM but did not consider nested energy trading among different VPPs.

A standalone blockchain-based energy trading platform using Remix and Ethereum was developed by [22]. This model did not consider optimal scheduling of consumer-owned DERs or any energy trading. However, a detailed analysis of the processing time and performance of the developed smart contract trading scheme was proposed.

A VPP model considering prosumers and using blockchain was developed by [23]. This model considered Energy Storage Systems (ESS) and used hierarchical VPP trading layers to minimize the energy cost of prosumers using a knapsack solution algorithm. The blockchain layer was developed in Ethereum to help manage and record energy transactions amongst consumers and VPPS. Uncertainty was not considered, and neither were Electric Vehicles (EVs).

A decentralized energy management platform for prosumers incorporating blockchain was developed by [24]. The system used Ethereum as the underlying blockchain system to support the decentralized optimization of DERs. The model did not consider multi-level trading amongst the VPPs or regulations.

The above paragraphs and Table I show that there is a large and growing body of literature that investigates the potential for VPP to integrate blockchain systems into their operations. The table shows that very few papers consider a multi-level trading system. This multi-level system can ease both computational complexity and fluctuations in both electricity demand and supply. In addition, a research gap that was identified is that none of the papers considered a current regulatory regime of the relevant area. Designing the energy trading system according to relevant legislation and regulations is important if the trading system is to be successfully implemented.

B. Paper Contributions

In the preceding section, existing literature was critically examined to demonstrate various shortcomings and research gaps.

TABLE I
COMPARISON WITH RELEVANT LITERATURE

Paper	Type of optimization	DERS considered	Multi-level trading	Blockchain Considered	Consensus mechanism	Blockchain implementation	Regulatory framework	Objective function
[18]	Mixed integer programming	EES, EV, HVAC, PV	Yes	No	None	None	No	Cost minimization
[15]	Alternating direction method of multipliers	HVAC, RES, ESS	No	Yes	Practical Byzantine-fault tolerance	Quorum	No	Cost minimization
[19]	None	ESS	No	Yes	Proof of work	Ethereum and Remix	No	None
[20]	Pure integer non-linear Program	PV, ESS	Yes	Yes	Proof of work	Ethereum	No	Cost minimization
[17]	None	None	No	Yes	Hyperledger consensus	Hyperledger fabric	No	None
[21]	Alternating direction method of multipliers	HVAC BESS	No	Yes	Proof of authority	Ethereum	No	Cost minimization
[16]	Alternating direction method of multipliers	EV, BESS, Heat Pump	No	Yes	Hyperledger consensus	Hyperledger fabric	No	Cost minimization
This paper	**Mixed integer linear programming**	**EV, ESS, HVAC, PV**	**Yes**	**Yes**	**Proof of work**	**Ethereum and Remix**	**Yes**	**Cost minimization**

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This paper addresses the following research question; how can blockchain be used in conjunction with emerging energy regulations to facilitate the active participation of prosumers in VPPs? To answer this research question, the paper has the following contributions:

- Develop a MILP based energy management model for prosumers in active distribution networks.
- Create a hierarchical VPP trading model to allow for intra and inter VPP energy trading and facilitate localized energy balancing.
- Utilize smart contracts from Blockchain technology to automate and record energy transactions amongst the users. This can increase reliability, transparency, and ease of use for the consumers.
- Examine the effects of Portuguese energy regulation on self-consumption on the operation of a VPP.

This paper extends the research carried out in [25]**.** The existing paper designed, validated, and implemented the energy management framework for a group of connected prosumers allowing for peer-to-peer energy trading. The current work extends this model to account for various types of consumers, including large service buildings, such as schools. In addition, the multi-layer structure of the model is introduced allowing for energy trading between different VPP. The recording and verification of the energy trades using blockchain-based smart contracts is also a novel aspect of this paper. Finally, the paper uses recent Portuguese energy regulations to design a realistic case study and investigate the impacts of the regulatory framework on consumers and system operators.

C. Paper structure

The rest of the paper is laid out in the following manner: Section III introduces blockchain-based smart contracts and highlights their potential in the energy system. In addition, Section III discusses the recent Portuguese energy regulations dealing with self-generation and consumption. Section IV contains the mathematical formulation of the MILP model and the structure of the smart contracts. Section V presents the case studies and discusses the results obtained from the model. Finally, the conclusions drawn from the research are shown in Section VI.

II. Background Information

This paper presents a hierarchical energy trading model for several VPPs using blockchain to automate and record energy trading transactions within the VPPs and then between the VPPs. The model is developed according to recent Portuguese energy regulations. In this section, a brief background of both blockchain-based smart contracts and the recent Portuguese regulations concerning self-generation and consumption are presented.

A. Blockchain

Blockchain has emerged as an interesting Information and Communication Technology (ICT) with diverse applications, including in the power sector. Within the power sector, blockchain has largely been used in energy trading applications, especially in decentralized or peer to peer energy trading [3].

In short, a blockchain is a collection of distributed databases of records that continually grows as new records are added. These records are secure, transparent, and tamper-proof [26].

Thus this chain of immutable blocks of recorded transactions can provide trust between individuals without the need for a central third party overseeing the market [3].

Within blockchain, smart contracts are electronic contracts that can be automatically executed should certain criteria be met. These smart contracts are simple programs that can be created to suit the needs of the individuals involved in the transaction.

Rules and conditions may be written into the smart contracts which can interact with the underlying blockchain network and structure the transaction without the need for human intervention or third-party authentication. These smart contracts have the potential to enable decentralized energy trading amongst peers based on their preferences. Using smart contracts, this energy trading will be secure, automated and fairly carried out [26].

B. Portuguese Energy Regulation

In October 2019, the Portuguese government released novel legislation relating to 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) [27].

This was enacted through the Decree Law 162/2019 of the 25th of October [28]. This law is concerned with the legal framework for the installation and use of small-scale DERs with or without connection to the public electricity distribution system.

The law aims to remove unnecessary burdens from consumers who would like to produce, consume, store, share and sell electricity. It encompasses peer-to-peer energy trading and renewable energy communities but crucially the law introduces the so-called Market Facilitator (MF). This agent is a supplier or purchaser who is under obligation to buy or purchase energy produced by DERs under market conditions [28].

The concept of MF was included in this energy trading model and its effects on the market outcomes will be studied. To make full use of energy trading platforms, new applications of ICT technologies are needed and as discussed above, blockchain can be one element of these novel platforms.

Further consideration of the Portuguese legislation in this model is the energy mix considered in the VPPs. The PNEC plan calls for a significant increase in the use of renewable energy, especially solar PV. The plan calls for an increase from 1.8 GW of installed PV capacity in 2020 to 9.9 GW installed by 2030. Thus, the VPPs considered in this model have significant penetrations of solar PV following the goals laid out in PNEC.

III. System Development

A. Model Overview

The model used in this paper has two integrated layers, the first deals with energy trading and the second, network layer, sits on top to coordinate and record energy transactions using smart contracts. The first layer uses a stochastic mixed-integer linear programming (MILP) optimization model to investigate the potential for both intra- and inter-VPP energy trading.

The second layer is the network layer which automates and records the transactions. The model considers various sources of uncertainty and variability, such as PV production and departure and arrival times of EVs. The multi-layer approach of this model is shown in Fig. 2. This shows the interconnected layers which optimize the scheduling of DERs and work together to facilitate and record energy trading while respecting the constraints of the underlying physical infrastructure layer. The figure shows that while each layer can be independent, by utilizing the principles of TE, a more complete model can be developed, and this provides a deeper understanding of the model functions and the roles that the consumers can have.

B. Energy Trading model

This model is operated using a two-stage optimization approach. Initially, the model is applied to a single VPP to optimize the energy trading between connected consumers, prosumers or producers. The results of this stage are then passed up to the second stage of the model with deals with energy trading between connected VPPs. The objective function is to minimize the total costs of prosumers shown in (1).

$$Min\,Total\,Prosumers\,Cost = \sum_{s} \rho_s \sum_{w} \sum_{t} \left(\lambda_{t,s}^{pur} \cdot P_{w,t,s}^{pur,T} \cdot \Delta T - \lambda_{t,s}^{sold} \cdot P_{w,t,s}^{sold,T} \cdot \Delta T\right) \quad (1)$$

In (2) – (4), the set of restrictions regarding the power exchange in the neighborhood is shown. The power purchased may come from the grid or a prosumer shown in (2) and in (3), the power sold may go to the grid or another prosumer in the neighborhood. The energy transaction in the neighborhood is represented by (4), where the power purchased must be equal to the power sold.

$$P_{w,t,s}^{pur,T} = P_{w,t,s}^{pur,grid} + P_{w,t,s}^{pur,local} \quad (2)$$

$$P_{w,t,s}^{sold,T} = P_{w,t,s}^{sold,grid} + P_{w,t,s}^{sold,local} \quad (3)$$

$$\sum_{w} P_{w,t,s}^{pur,neighb} = \sum_{w} P_{w,t,s}^{sold,neighb} \quad (4)$$

In (5) the power balance equation for each prosumer is presented. Energy transactions between prosumers and the network are represented by (6) – (8), where parameter N may impose limits on the amount of power coming from the grid.

$$P_{w,t,s}^{pur,T} + P_{w,t,s}^{PV,used} + P_{w,t,s}^{EV,used} + P_{w,t,s}^{ESS,used} = InfLoad_{w,t,s} + P_{w,t,s}^{EV,charge} + P_{w,t,s}^{ESS,charge} + \sum_{c} P_{w,t',c,s}^{mach} \quad (5)$$

$$P_{w,t,s}^{sold,T} = P_{w,t,s}^{sold,PV} + P_{w,t,s}^{sold,EV} + P_{w,t,s}^{sold,ESS} \quad (6)$$

$$P_{w,t,s}^{pur,T} \leq N \cdot x_{w,t',s}^{2} \quad (7)$$

$$P_{w,t,s}^{pur,T} \leq N \cdot (1 - x_{w,t',s}^{2}) \quad (8)$$

In (9) – (10) control flexible appliances such as the dishwasher (DW) and washing machine (WM), considering that they operate in predefined cycles and that consumption during an operational phase for each prosumer is known. However, operational periods may change depending on the best price and the defaults of the prosumers, for example, the number of times to trade during the day [19], [20].

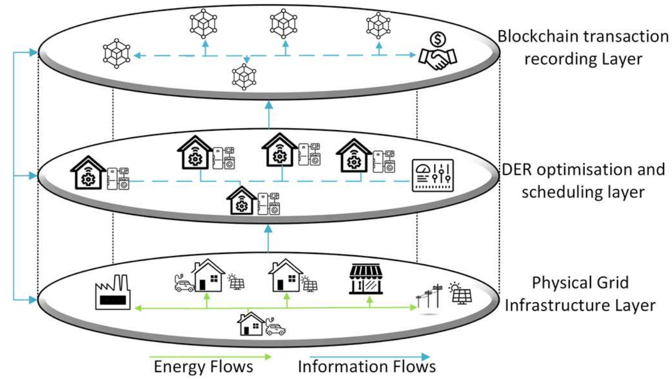

Fig. 2: Layers within the transactive energy market

$$P_{w,t',c,s}^{mach} = \sum_{f} \left(x_{w,t,f,c,s}^{phase} \cdot P_{w,f,c,s}^{phase}\right) \quad (9)$$

$$\sum_{f} x_{w,t,f,c,s}^{phase} \leq 1 \quad (10)$$

$$y_{w,t,f,c,s}^{phase} \leq 1 \quad (11)$$

$$y_{w,t,f,c,s}^{phase} = y_{w,f,c,s,(t+T_{w,f,c,s}^{dur})'}^{phase} \quad (12)$$

$$y_{w,t,f,c,s}^{phase} - z_{w,t,f,c,s}^{phase} = x_{w,t,f,c,s}^{phase} - x_{w,f,c,s,(t-1)'}^{phase} \quad (13)$$

$$z_{w,t,f,c,s}^{phase} = y_{w,t',s,f+1,c}^{phase} \quad (14)$$

$$\sum_{t} y_{w,t,f,c,s}^{phase} = N_{w,c,s} \quad (15)$$

The EV model used is presented in (16)– (21), where the EV discharging power can go either to the network or to the home (16). In (17) and (18), the charging and discharging limits are presented. The state-of-charge (SOC) is defined by (19) and (20).

$$P_{w,t,s}^{EV,used} + P_{w,t,s}^{sold,EV} = \eta_{w,s}^{EV,disch} \cdot P_{w,t,s}^{EV,disch} \quad (16)$$

$$0 \leq P_{w,t,s}^{EV,charg} \leq R_{w,s}^{EV,charg} \cdot x_{w,t'}^{3} \quad w \in \left[T_{w,s}^{a}, T_{w,s}^{d}\right] \quad (17)$$

$$0 \leq P_{w,t,s}^{EV,disch} \leq R_{w,s}^{EV,disch}\left(1 - x_{w,t'}^{3}\right) \quad w \in \left[T_{w,s}^{a}, T_{w,s}^{d}\right] \quad (18)$$

$$SOC_{t,w,s}^{EV} = SOC_{t,w,s}^{EV,ini} + CE_{w,s}^{EV} \cdot P_{t,w,s}^{EV,charge} \cdot \Delta T - P_{t,w,s}^{EV,disch} \cdot \Delta T \quad \forall w, if\ t = T_{w,s}^{a} \quad (19)$$

$$SOC_{t,w,s}^{EV} = SOC_{t-1,w,s}^{EV,ini} + CE_{t,s}^{EV} \cdot P_{t,w,s}^{EV,charge} \cdot \Delta T - P_{t,w,s}^{EV,disch} \cdot \Delta T \quad \forall w, t \in t = \left[T_{w,s}^{a} - T_{w,s}^{b}\right] \quad (20)$$

$$SOC_{w,s}^{EV,min} \leq SOC_{t,w,s}^{EV} \leq SOC_{w,s}^{EV,max} \quad \forall w, t \in t = \left[T_{w,s}^{a} - T_{w,s}^{b}\right] \quad (21)$$

$$SOC_{t,w,s}^{EV} = SOC_{t,w,s}^{EV,max} \quad \forall w, if\ t = T_{w,s}^{d} \quad (22)$$

In (23) – (28), the ESS of each prosumer is modelled. This formulation is similar to how the EVs were described.

$$P_{w,t,s}^{ESS,used} + P_{w,t,s}^{sold,ESS} = \eta_{w,s}^{ESS,disch} \cdot P_{w,t,s}^{ESS,disch} \quad (23)$$

$$0 \leq P_{w,t,s}^{ESS,charg} \leq R_{w,s}^{ESS,charg} \cdot x_{w,s,t'}^{4}\ \forall w, t \quad (24)$$

$$0 \leq P_{w,t,s}^{ESS,disch} \leq R_{w,s}^{ESS,disch}\left(1 - x_{w,s,t'}^{4}\right) \forall w, t \quad (25)$$

$$SOC^{ESS}_{t,w,s} = SOC^{ESS}_{t-1,w,s} + CE^{ESS}_{w,s} \cdot P^{ESS,charge}_{t,w,s} \cdot \Delta T - P^{ESS,disch}_{t,w,s} \cdot \Delta T \qquad \forall w, t \geq 1 \tag{26}$$

$$SOC^{ESS}_{t,w,s} = SOC^{ESS,ini}_{w,s} \qquad \forall w \; if \; t = 1 \tag{27}$$

$$SOC^{ESS,min}_{w,s} \leq SOC^{ESS}_{t,w,s} \leq SOC^{ESS,max}_{w,s} \quad \forall w, t \tag{28}$$

PV production by the prosumer is presented in (29), where PV production can be used by the prosumer or sold to the grid. A simplified heating, ventilating and air conditioning (HVAC) model is presented in (30) - (32) based on temperature control.

$$P^{PV,used}_{w,h,s} + P^{PV,sold}_{w,h,s} = P^{PV,prod}_{w,h,s} \qquad \forall w, t \tag{29}$$

$$\theta_{w,t+1} = \beta_{w,s} \cdot \theta_{w,t,s} + \left(1 - \beta_{w,s}\right)\left(\theta^{O}_{w,t,s} + COP_{w,s} \cdot R_{w,s} \cdot P^{HVAC}_{w,t,s}\right) \tag{30}$$

where $\beta_{w,s} = e^{-\Delta t / R_w * C_w}$

$$\theta^{min}_{w} \leq \theta_{w,t+1} \leq \theta^{max}_{w}, \forall w, t \tag{31}$$

$$0 \leq D^{HVAC}_{w,t} \leq P^{HVAC}_{w,t}, \forall w, t \tag{32}$$

In this model, uncertainty is accounted for using scenario generation. Two sources of uncertainty, solar generation, and demand were considered in the model. Three scenarios for each parameter were developed. This resulted in nine scenarios which were reduced using k-means clustering techniques as is described in [29].

The model is programmed in GAMS 24.0 and solved using the CPLEX 12.0 solver. The simulations are conducted on an HP Z820 workstation with two 3.1GHz E5-2687W processors and 256 GB of RAM.

C. Smart Contract Layer

The second layer of this transactive energy model introduces the blockchain-based smart contract layer to the underlying MILP model to automate and record the energy transactions both within VPPs and between the connected VPPs.

This layer is designed to sit atop the energy management layer and receive data related to the energy trades between consumers and VPPs. This layer helps to increase the automation of energy trading, improves the transparency of trading mechanisms, and increases the security of the system through the immutable nature of blockchain.

The system of smart contracts developed for this paper was developed using Ethereum. The contracts were compiled using Solidity version 0.6.6 and deployed using Remix v0.9.4.

The flow of information between a consumer and a prosumer using the smart contract system is shown in Fig. 3. This flow of information occurs within the network layer specified in Fig. 2.

There were four types of agents operating within the smart contract layer. These are the Administrator, Consumer, Prosumer, and the Market Facilitator. These agents and their actions will be introduced in the following sections:

1) Administrator

This agent is responsible for the functioning of the VPP by allowing consumers to enter and leave the VPP. The administrator agent is responsible for ensuring that the consumers adhere to both technical and market-based requirements.

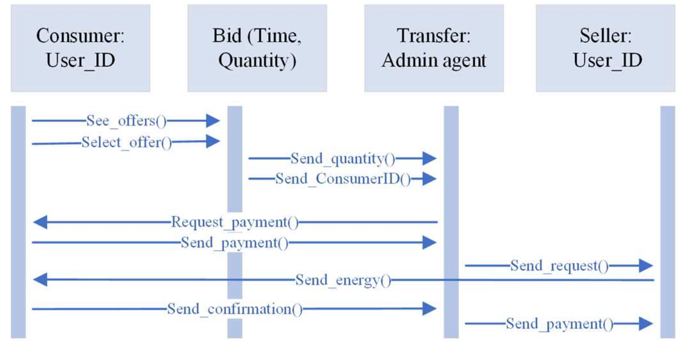

Fig. 3: Flow of information through the system within the network layer

While the presence of the administrator agent negates the promise of fully decentralized energy trading among prosumers, the authors argue that this agent is necessary as the administrator provides security and reliability to the system and may be required by the relevant energy regulation.

2) Consumer Agent

This agent represents the traditional customer role within power systems. The consumer only purchases energy, either from the external grid or from prosumers.

3) Prosumer Agent

This agent represents an active consumer who may generate, or store electricity using various types of DERS and then can sell this excess to other agents or the external grid. This agent needs to be authorized by the Administrator agent to participate in the market.

4) Market Facilitator

This agent is authorized to buy and sell energy within the VPP. This agent is a regulatory construct and has emerged from the recent changes to the regulations dealing with self-generation and self-consumption of electricity in Portugal. According to this regulatory framework, the MF acts as a supplier and purchaser of last resort to minimize any shortfalls in electricity supply or demand. Within this model, energy transactions amongst consumers are prioritized and the MF only intervenes if there is a shortage or excess of electricity within the system. This was done by setting the price charged by the MF at a higher level than the energy traded

IV. Case Study and Results

A. Case Study Details

This paper used three VPPs to investigate the impacts of transactive energy trading. Each VPP had 10 consumers with a different mixture of residential and service buildings. This diversity of consumer types leads to different load profiles and DER portfolios which helps to increase opportunities for energy trading within the VPP. The allocation of these DERs can be seen in Table II.

TABLE II
TOTAL NUMBER OF DERS IN THE VPPS

Device	VPP 1	VPP 2	VPP 3
EV	10	7	13
ESS	7	5	10
PV	9	3	21
HVAC	11	10	10
DW	9	10	8
WM	9	10	8

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The PV systems had a capacity of 1 kW each. The ESSs had a capacity of 3 kWh, maximum charging and discharging rate of 0.6 kW, initial state of charge (SOC) of 80%, minimum SOC of 40% and charging and discharging efficiency of 90%. The EVs had a capacity of 4 kWh, maximum charging and discharging rate of 0.6 kW and efficiency of 90% [25].

In this paper, three case studies were considered. In each case study, different levels of energy trading were considered. In the baseline case, Case 1, there was no energy trading between consumers. All the energy demand was satisfied by purchasing the energy from the external grid. Case 2 introduced intra-VPP energy trading. This allowed energy trading within the VPP but not between VPPs. Any shortage or excess of electricity was imported or sold to the MF agent. There is a fixed fee for energy trading between peers of €0.03/kWh, taken from [25].

The transaction cost for each P2P energy trade is fixed in this model, however the question of tariff design for P2P energy markets is an interesting and important field [30]. Numerous factors will influence the composition of this tariff including technical (maintenance costs), economic (taxes) or social costs (equity concerns), and these will vary depending on the local conditions.

In Case 3, inter-VPP trading was considered. In this case, the model first sought to balance any excess or shortfall from a single VPP by trading energy from the other two VPPs and only, if this excess or shortfall could not be met would the MF agent becomes active.

B. *VPP Optimization Results*

This section introduces the results of the model for each case study and then compares the operating costs.

1) *Baseline*

In the baseline model, Case 1, there was no energy trading permitted. This case study provided a baseline for the comparison of the other two cases in terms of the scheduling and operating costs of the DERs. The energy mix for VPP 1 in this case study as well as the TOU tariff used in this study are shown in Fig. 4. The negative power values in Fig. 4 are loads used in the VPP and include flexible loads and inflexible loads. The energy used to charge the ESS and EVs is also shown.

The great majority of EV and ESS charging takes place during the early hours of the morning when electricity prices are relatively low. The EVs and ESSs are discharged in the evening peak period to reduce the amount of energy bought from the external grid. The flexible loads are scheduled to occur in periods of low tariffs. In this case study, renewable energy sources accounted for 31.56% of the total load for VPP 1.

2) *Intra-VPP Trading*

This case allowed for intra-VPP energy trading between the consumers. The energy supply of VPP 1 is shown in Fig. 5. This figure shows that when the TOU tariff is low, between 01:00 and 07:00 power is imported from the grid and used to charge the EVs and ESSs. Energy trading among the peers occurs when the TOU tariff is high, namely from 17:00 to 21:00. It is also during these evening hours where the EVs and ESS discharge power to help meet the evening peak load.

Comparing this case to the baseline, grid imports were reduced by 5.7% as the VPP demands could now also be met through energy trading which helped to reduce costs of electricity for the VPP.

Interestingly, a new peak load period is introduced into the system. This new peak load period, which occurs between 00:00 and 02:00 is due to the charging of the ESSs and EVs. This is an important feature to consider in future distribution grids which may contain a large penetration of EVs or ESSs.

In Case 2, VPP 3 had the most energy trading amongst consumers. These trades can be seen in the chord diagram shown in Fig. 6. This figure shows the quantity and direction of the energy traded within this VPP during the 24-hours.

The numbers and width of the arcs are proportional to the amount of energy traded with other consumers during the 24-hours. Much of the excess energy for trading is generated by Peer 9 and Peer 10. These two peers are the two service buildings within the VPP and have large installed PV systems.

In this VPP there exist different types of consumers, namely those consumers who do only consume energy such as Peer 3 and Peer 4. Some consumers are self-reliant and do not require any additional energy, such as Peer 9 and Peer 10. Then there are some consumers who, depending on the time of day, are either exporting or importing energy, for example, Peer 5 or Peer 1. With intra-VPP energy trading allowed, renewable energy sources accounted for 36.12% of the total load which is an increase of five percentage points relative to Case 1.

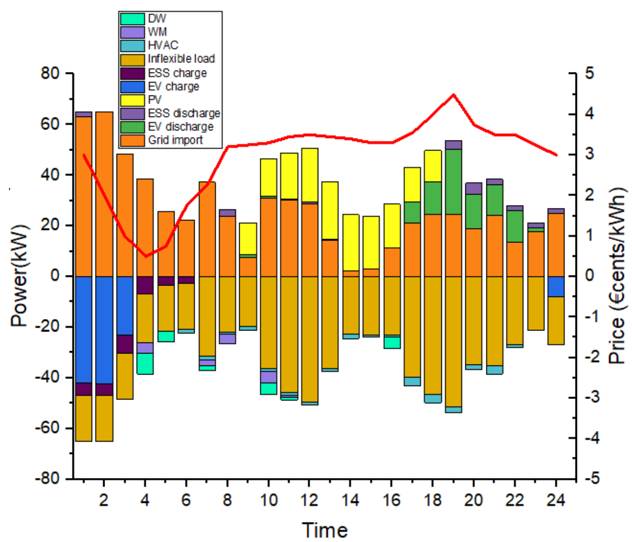

Fig. 4: Energy mix for VPP 1 in case study 1

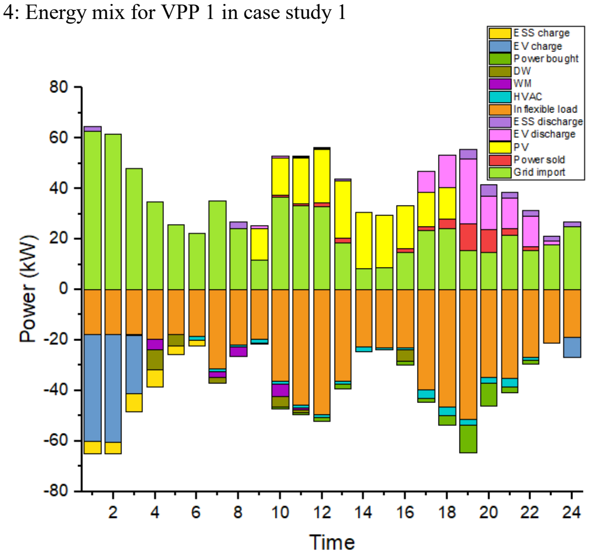

Fig. 5: Energy mix of VPP 1 in case study 2

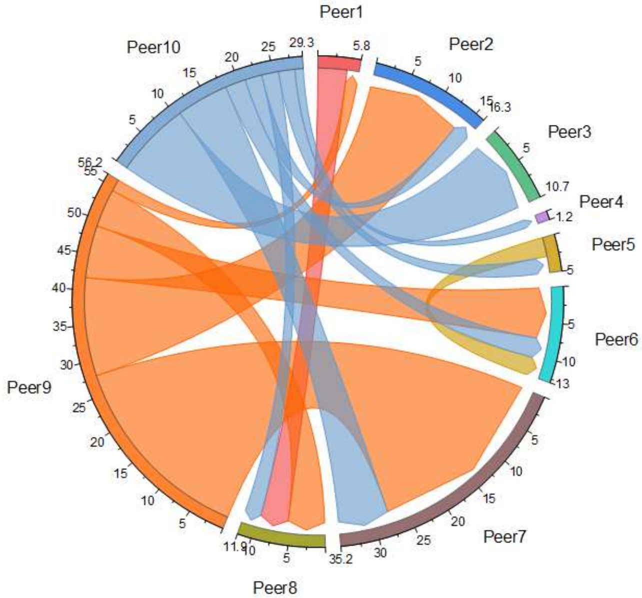

Fig. 6. Energy trades amongst peers in VPP 3 for case study 2

In this case, energy trading accounted for 5.7% of the total load for VPP 1 and across the three VPPs, energy trading accounted for 6.97% of the total load which reduced VPP costs.

VPP 3 had the highest amount of energy trading taking place in this case study. This was due to the presence of the two large service buildings with large installed PV systems. These systems increase the amount of locally produced electricity which is cheaper relative to the electricity from the external grid, therefore, promoting energy trading and the use of electricity generated within the VPP. It is expected that more PV systems will be installed in VPPs therefore this effect will become more prevalent and the scope for energy trading will increase.

3) Inter-VPP trading

The third case study allowed for the trading of energy between the VPPs. This inter-VPP trading is coordinated by the Global VPP manager as shown in Fig. 1. The flow of the energy trades was from VPP 3 to VPP2. This is likely due to the large capacity of PV installation in VPP 3 which produced excess energy and thus could be traded with VPP 2. The energy trades occurred between 14:00 and 22:00 and totaled 11.31 kWh. This was 3.5% of the energy used by VPP 2 during these hours.

The amount of renewable energy used by the VPPs, in this case, was 38.8% which is an increase relative to Case 2. Across the three VPPs in this case study, energy trading accounted for 8.3% of the total load which is an increase relative to Case 2.

Inter VPP trading further helped reduce costs due to the lower fixed fee for each local transaction.

4) Comparison

Table III shows the costs of energy for the three VPPs across the three case studies. The operating costs of the VPPs decreased between Case 1 and Case 2, i.e., with the introduction of intra-VPP trading. The cost reduction was a maximum for VPP 3 which saw a 4.3% reduction solely by allowing energy trading among the VPP members.

These cost reductions were due to a combination of lower electricity prices for locally produced electricity and from the revenue generated by trading electricity within the VPP.

TABLE III
DAILY OPERATING COSTS OF THE VPPS IN THE DIFFERENT CASE STUDIES

	Case 1 (€)	Case 2 (€)	Case 3 (€)
VPP 1	18.446	18.12	18.12
VPP 2	24.795	24.784	24.703
VPP 3	16.12	15.462	15.381
Total Cost	59.363	58.366	58.204

The cost reductions were largest for VPP 3 which had the highest number of EVs, ESSs and PV systems installed. This allowed the VPP members to optimally schedule their electric demand to avoid periods of high prices and utilize locally generated electricity, which is cheaper peak periods. This result shows the advantage of having a diverse group of customers within a VPP to take advantage of their different load profiles and DER portfolios.

In terms of the cost reduction between Case 2 and Case 3, there was a 0.72% reduction in overall costs for the VPPs. This was obtained solely by allowing VPP 3 to sell excess generation to VPP 2. Both VPPs benefited from cost reductions for VPP 2 and an increase in profits for VPP 3.

The amount of energy traded between VPPs is relatively small and this is due to the energy balancing of each VPP and the use of EVs and ESSs to store excess energy within the VPP. Additionally, each VPP only has 10 consumers or prosumers. As the number of consumers or prosumers within the VPP grows, it is expected that inter-VPP trading will increase.

5) Impact of Portuguese Energy Regulations

In this model, the impact of the new self-consumption regulations and the targets laid out in the PNEC was investigated. The significant increase in solar PV systems was modelled and this increase led to an increase in the ability of VPPs to trade excess energy as seen in the differences between VPP 2 and VPP 3.

The main impact of these regulations was the introduction of the MF agent which provided a buyer or seller of last resort for the excess energy generated by the DERs. In Case 1 and Case 2, this agent was not active as the VPPs could balance supply and demand.

However, in Case 3, with the introduction of the inter-VPP trading, there were several instances where the MF agent bought excess generation from VPP 3. The MF agent bought 2.16 kWh of electricity from Peer 10 in VPP 3 which otherwise, would not have been traded. This value is expected to grow with an increase in the number and greater diversification of prosumers in VPP. This shows the benefit of this new agent. The participation of the MF agent is thought to increase as more self-generation is brought online by active consumers.

C. Smart Contracts

In this section, the results of the case study are presented. 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.

The smart contract for the administrator agent is deployed first as this agent is then responsible for managing the other agents in the system. The deployed administrator contract is shown in Fig. 7. The figure shows that only the administrator agent can modify this contract which helps maintain the security and integrity of the model.

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```
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. 7: Deployed administrator contract

A consumer can submit a request for energy for the following 24-hour period. This request is submitted to the administrator agent for approval. An example of these requests is shown in Fig. 8. This shows the requests for energy from Peer 2 in VPP 1. The amount of energy is shown in the 'decoded input' section as a vector of values each corresponding to 1 hour for the next day. This request is encoded and only visible to the administrator agent which helps maintain the privacy and security of the system.

Once a transfer has been authorized by the respective agents, the transaction is completed and recorded. An example of a completed transaction is shown in Fig. 9. This figure 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 the originator and receiver addresses of the agents involved in the transaction. Fig. 9 also shows the acceptance by the administrator agent of an offer of excess generation from Peer 9 in VPP 1 for 1 kWh of energy. The transaction hash ensures that this trade can be tracked and verified by the members of the system which increases the transparency and reliability of the system.

These contracts are recorded and available to anyone to view and audit them, which increases the transparency of the system. The fact that both parties to the contract need to agree plus the final confirmation by the administrator agent coupled with the tamper-proof nature of blockchain data ensures that the trades are reliable and verifiable. This increases the consumers trust in the system, which can increase their participation.

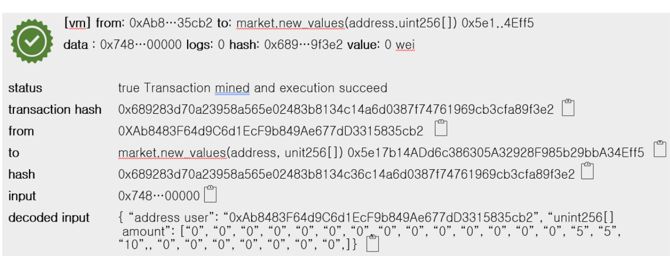

Fig. 8: Submitted energy requests from Peer 2 in VPP 1

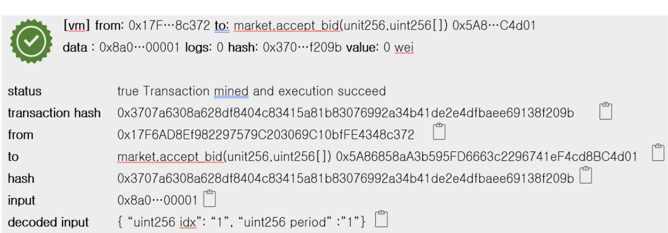

Fig. 9: Accepted bid from Peer 9 in VPP 1

Once the consumer has inputted their expected energy shortfall or excess generation, the TE market matches other peers who may be able to either buy or sell the required amount of energy. After authorization by the agents and the administrator, the transfer is carried out and recorded automatically. This automation can help reduce the input necessary from the consumers and facilitate their participation in VPPs.

V. Conclusions

In this paper, an innovative two-level transactive energy management model for three connected VPPs was developed. This MILP model optimally scheduled and managed the operation of a diverse set of DERs to minimize energy costs. The MILP model operated at two levels within the market and allowed for both intra-VPP and inter-VPP energy trading. A blockchain-based smart contracts layer was utilized on top of the energy management layer to help automate and record energy transactions. This was done to increase the reliability and transparency of the system to incentive consumer participation. Three different case studies were investigated to show the impact of different trading regimes and the impact of the new agents introduced by the self-consumption regulations in Portugal. Results showed that the operating costs of the VPPs were reduced when both intra-VPP and inter-VPP trading was allowed. Increasing the size and diversity of DERs within a VPP led to more trading and lower prices. This model has shown that blockchain-based smart contracts can be successfully integrated into a hierarchical energy trading model which respects novel energy regulations. This combination of technologies can be used to increase consumer participation, lower energy bills and increase the penetration of locally generated electricity from renewable energy sources. For future work, the technical impacts of the VPP model on the system may be investigated.

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