Optimisation of Prosumers' Participation in Energy Transactions

Matthew Gough
Faculty of Engineering of the University of Porto and INESC TEC
Porto, Portugal
mattgough23@gmail.com

Sérgio F. Santos, Mohammad Javadi
INESC TEC
Porto, Portugal
sdfsantos@gmail.com
msjavadi@gmail.com

Desta Z. Fitiwi
ERSI
Dublin, Ireland
desta.fitiwi@ersi.ie

Gerardo J. Osório
C-MAST/UBI
Covilha, Portugal
gjosilva@gmail.com

Rui Castro
IST and INESC-ID
Lisbon, Portugal
rcastro@tecnico.ulisboa.pt

Mohamed Lotfi, João P. S. Catalão
Faculty of Engineering of the University of Porto and INESC TEC
Porto, Portugal
mohd.f.lotfi@gmail.com
catalao@fe.up.pt

***Abstract*—There is an ongoing paradigm shift occurring in the electricity sector. In particular, previously passive consumers are now becoming active prosumers and they can now offer important and cost-effective new forms of flexibility and demand response potential to the electricity sector and this can translate into system-wide operational and economic benefits. This work focuses on developing a model where prosumers participate in demand response programs through varying tariff schemes, and the model also quantifies the benefits of this flexibility and cost-reductions. This work includes transactive energy trading between various prosumers, the grid and the neighborhood. A stochastic tool is developed for this analysis, which also allows the quantification of the collective behavior so that the periods with the greatest demand response potential can be identified. Numerical results indicate that the optimization of energy transactions amongst the prosumers, and including the grid, leads to considerable cost reductions as well as introducing additional flexibility in the presence of demand response mechanisms.**

***Keywords*—prosumers flexibility, demand response, smart neighborhood, stochastic optimization.**

I. 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
$\eta_{w,t}^{ESS,disch}$	Discharging efficiency of the ESS of prosumer w
$\eta_{w,t}^{EV,disch}$	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
$P_{w,f,c,s}^{fase}$	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]
$\lambda_{t,s}^{vend}$	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].
$P_{w,t,s}^{ESS,used}$	Portion of the 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].

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017). G.J. Osório acknowledges the support by UIDB/00151/2020 research unit (C-MAST) funded by FCT.

978-1-7281-7455-6/20/$31.00 ©2020 IEEE

$P_{w,t,s}^{EV,used}$	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].
$P_{w,t,s}^{vend,ESS}$	Portion of the ESS discharging power of prosumer w sold to the grid or the neighborhood in period t [kW].
$P_{w,t,s}^{vend,EV}$	Portion of the EV discharging power of prosumer w sold to the grid or the neighbourhood in period t [kW]
$P_{w,t,s}^{vend,grid}$	Portion of the power injected to grid by prosumer w that flows back to the grid in period t [kW].
$P_{w,t,s}^{vend,local}$	Portion of the power injected to grid by prosumer w that is locally used in the neighborhood in period t [kW].
$P_{w,t,s}^{vend,PV}$	Portion of the PV power of prosumer w sold to the grid or to the neighbourhood in period t [kW].
$P_{w,h,s}^{vend,T}$	Total power injected to grid 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.
$x_{w,s,t,f,c}^{fase}$	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.

II. Introduction

The introduction and growth in the numbers of prosumers have led to a paradigm shift in the way that low-voltage electric networks are designed and operated [1], [2]. These prosumers (consumers of electricity who can also produce electricity) generally use Distributed Energy Resources (DERs) to generate and store electricity and a variety of appliances to manage their electric load profile to meet some predetermined goal [3].

These new DERs can interact in novel ways with the electric grid by providing various services to the system operator [4], [5]. These new services allow for increased flexibility in the operation and control of the electric grid which helps to mitigate the effects of increasing the penetration of intermittent renewable energy resources into the electric grid [6].

Additionally, these new DERs allow for bidirectional energy flows between the households and the electric grid. This may allow energy trading between households which in itself opens up a complex and novel area for research [7]. This trading between households within a certain geographic location could lead to the creation of Local Energy Markets (LEMs).

LEMs incorporate local generation, energy storage devices, demand response (DR) activities together with energy trading between prosumers, in addition to the existing grid to create an efficient market structure which can provide benefits to the consumers, generators and system operator [6].

The European Commission (EC) has recognized that Local Energy Communities (LECs) can play a significant role in energy management services [8]. As such the EC has recommended that the rules of the market and grid operation be adjusted to incentivize increased flexibility within the electricity system.

A Local Energy Market (LEM) can provide this flexibility and have the following advantages: increase in the amount of self-generated electricity, increased consumption of locally generated electricity, improving the local economy, and development of smart grids. Local markets have been used to lower customer costs and manage DR programs [9].

III. Literature Review

There exists a growing body of literature which investigated prosumer energy trading within local energy markets and the most relevant literature is highlighted below.

In [7] the effect of prosumers belonging to a local energy community and the effect of the prosumer's preferences on the behavior of the market are investigated. The results of [7] demonstrate the feasibility of these markets, even when the various preferences of the prosumers are taking into account. Examining the changing behaviors associated with demand-side load management programs are normally done to minimize the cost of energy but also keeping the comfort of the users in mind. In that respect, [10], developed a Global Model Based Anticipative Building Energy Management System (GMBA-BEMS) which aimed to balance user satisfaction and electricity costs.

The study conducted by [11] created a framework which allowed for the scheduling, sharing and bid matching between prosumers within a residential network. Various DERs (including solar PV panels, smart appliances, battery energy storage systems) were studied to examine the impact of the small-scale flexibility offered by the DERs to maximize the comfort levels of the prosumer and minimize the electricity costs using two separate multi-objective mixed integer nonlinear programming models which made use of the nondominated sorting genetic algorithm-III (NSGA-III).

A study conducted by [3] investigated the use of the continuous double auction market to promote Peer-2-Peer energy trading to unlock unused demand-side management potential. This study showed that the continuous double auction model is an effective model to promote Peer-2-Peer energy trading under differing market designs.

The study by [13] introduces a two-stage framework for energy sharing which incorporates renewable energy generators, energy storage systems and shiftable loads. The first stage uses a bilevel scheduling model to develop a robust energy sharing schedule for both prosumers and a retailer. The second stage of the model uses online optimization to optimize the hourly energy schedule of each prosumers taking the most recent state of the system into account.

A control system which uses transactive energy concepts is proposed by [14]. Various pricing schemes are used including time-of-use and distributed locational marginal pricing. Results show that the lifetime of the transformer can be extended through the use of transactive energy controls as well as a reduction in the active power losses.

IV. CONTRIBUTIONS AND PAPER ORGANIZATION

None of the previous approaches focused on the aspect of neighborhood energy transactions, and none of them took into account the different sources of uncertainty and variability other than those associated with renewable energy sources. Furthermore, this paper introduces a stochastic optimization model which uses a set of appliances and Distributed Energy Resources (DERs) owned by prosumers to determine the minimum operating cost of the grid.

The main contributions are as follows:

- A stochastic model where prosumers participate in DR actions through varying price tariff scheme and quantify the benefits of doing so in terms of added flexibility and cost reductions as a result of peak demand reduction.
- An analysis of bidirectional energy flows resulting from the interactions amongst the prosumers (smart neighborhood) and including their interactions with the grid in terms of exploiting the additional flexibility which translates into system-wide operational and economic benefits.
- Demonstration of the effects of the collective behavior of prosumers which allow for the identification of the periods where DR actions can have the largest effect.

The rest of the paper is set up in the following manner: Section 5 contains the mathematical formulation of the model. Section 6 then contains the results obtained from the model as well as a discussion of these results. Conclusions drawn from these results are presented in Section 7.

V. MATHEMATICAL FORMULATION

A. Objective Function

This work presents a stochastic mixed-integer linear programming (MILP) optimization model to perform the analysis. This model takes into account various sources of uncertainty and variability, such as PV production and departure and arrival times of EVs. The objective function is to minimize the total costs of prosumers (1).

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

B. Constraints

In (2) – (4), the set of restrictions regarding the power exchange in the neighborhood is shown. Equation (2) shows that the power purchased may come from the grid or a prosumer and that 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 Equation (4), where the power purchased must be equal to the power sold.

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

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

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

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

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

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

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

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

Equations (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].

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

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

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

$$y_{w,t,f,c,s}^{fase} = y_{w,f,c,s,(t+T_{w,f,c,s}^{dur})}^{fase}, \quad (12)$$

$$y_{w,t,f,c,s}^{fase} - z_{w,t,f,c,s}^{fase} = x_{w,t,f,c,s}^{fase} - x_{w,f,c,s,(t-1)}^{fase}, \quad (13)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$SOC_{t,w,s}^{ESS} = SOC_{t-1,w,s}^{ESS} + CE_{w,s}^{ESS} \cdot P_{t,w,s}^{ESS,charge} \cdot \Delta T - P_{t,w,s}^{ESS,disch} \cdot \Delta T \quad \forall w,t \geq 1 \qquad (26)$$

$$SOC_{t,w,s}^{ESS} = SOC_{w,s}^{EV,ini} \quad \forall w \ if \ t = 1 \qquad (27)$$

$$SOC_{w,s}^{ESS,min} \leq SOC_{t,w,s}^{ESS} \leq SOC_{w,s}^{ESS,max} \ \forall w,t \qquad (28)$$

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 according to the envisioned scenarios.

$$P_{w,h,s}^{PV,used} + P_{w,h,s}^{vend,PV} = P_{w,h,s}^{PV,prod} \qquad \forall w,t \qquad (29)$$

$$\theta_{w,t+1} = \beta_{w,s} * \theta_{w,t,s} + \left(1-\beta_{w,s}\right)\left(\theta_{w,t,s}^{O} + COP_{w,s} * R_{w,s} * P_{w,t,s}^{HVAC}\right) \qquad (30)$$

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

$$\theta_{W}^{min} \leq \theta_{w,t+1} \leq \theta_{W}^{max}, \forall w,t \qquad (31)$$

$$0 \leq D_{w,t}^{HVAC} \leq P_{w,t}^{HVAC}, \forall w,t \qquad (32)$$

VI. RESULTS AND DISCUSSION

A. *Data and Assumptions*

To demonstrate the methodology presented, a neighborhood test system is considered which consists of three houses connected through a single-phase system. In Fig. 1, a schematic representation of the system is presented. Data and results are based on 24 hours on a typical weekday. The three households are composed of a different number of people.

The first prosumer household is composed of five elements. The second and third prosumers are composed of two and four elements, respectively. All prosumers are considered to have a capacity of 1 kW of ESS, an EV, and a PV system with a maximum capacity of 2 kW. The characteristics of each technology are summarized in Table I.

In Fig. 2, the set of scenarios for the departure and arrival of each EV for each prosumer is shown. Flexible loads include the DW, the WM, and the HVAC. The main features of the DW and WM are summarized in Table II. For the operation of the HVAC, a specific set of operating periods was defined, taking into account the comfort of the house end users.

Based on these operating periods, a set of temperature variation ranges to the HVAC were defined, between 24 and 28 ºC within the predefined periods (Fig. 3).

In this work, it is assumed that the prosumers can sell power to the grid through vehicle to grid (V2G), ESS to grid (ESS2G) and PV to the grid (PV2G), self-consume (vehicle to home (V2H), ESS to home (ESS2H) and PV to home (PV2H)), or sell to the neighborhood. The 24-hour energy price signal is presented in Fig. 4 and follows the trend of demand.

The energy transaction price amongst prosumers in the neighborhood is fixed at 0.03 cents per transaction. Energy transactions are made per net metering specificities.

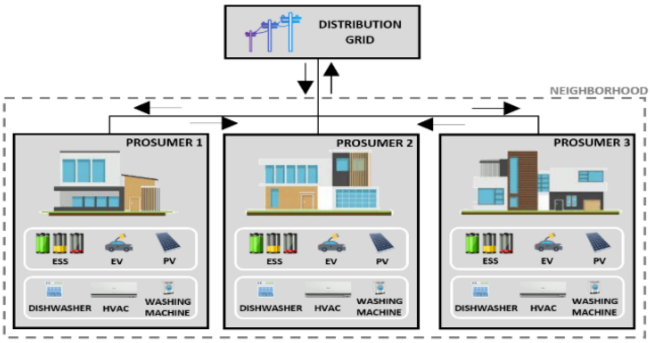

Figure 1. Schematic diagram of the considered network.

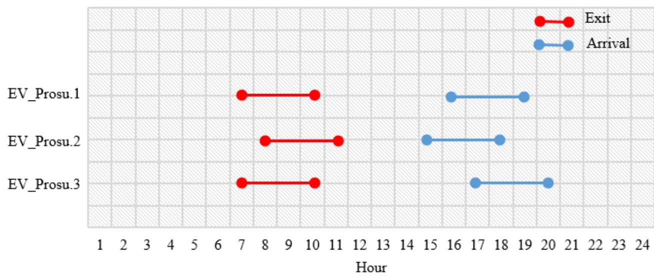

Figure 2. EV arrival and departure scenarios for the different prosumers.

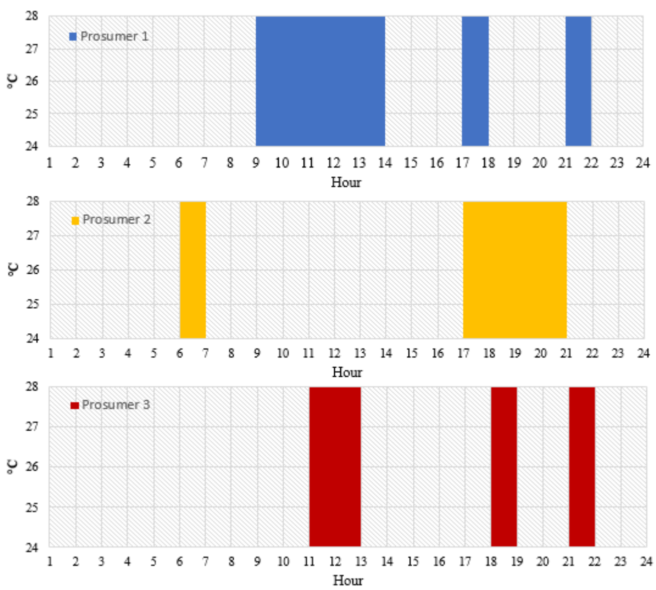

Figure 3. Prosumers HVAC temperatures scenarios.

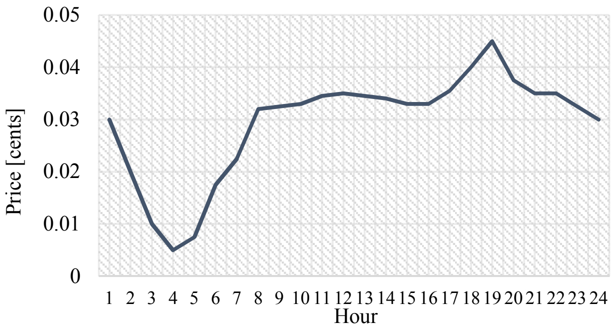

Figure 4. Price signal for 24 hours.

TABLE I. ESSS, PVS AND EVS DATA BY PROSUMER

ESS	Prosumer1	Prosumer2	Prosumer3
Battery Capacity [kWh]	4	3	3
Max Charging / Discharging Rate [kW]	0.6	0.6	0.6
Initial SOE [%]	75	80	75
Minimum SOE [%]	40	40	40
Charging / Discharging Efficiency [%]	90	90	90
PV			
Installed Capacity [kW]	1	1	1
EV			
Battery capacity [kWh]	4	3	3
Max Charging / Discharging Rate [kW]	0.6	0.6	0.6
Charging / Discharging Efficiency [%]	90	90	90

TABLE II. FLEXIBLE LOAD PARAMETERS (WM AND DW)

	Prosumer 1		Prosumer 2		Prosumer 3	
	WM	*DW*	*WM*	*DW*	*WM*	*DW*
Power [kW]	0.15	2.2	2	0.15	0.3	2.2
N. º of Phases	1	1	1	2	2	3
Duration [t]	1	1	1	1	1.5	1

B. *Discussion of Numerical Results*

In this section, the results are presented and a discussion of these results follows. Three case studies are considered in this research. The first (base) case involves consumers buying all their power from the grid, with no power generation or storage sources. In this case, the entire load is inflexible. In the second case, prosumers already can generate, store, and sell energy to the grid. Also, this case includes home energy system management systems (HEMS) in each of the households. The last case is the same as the second case, but the sale of energy between prosumers (in the neighborhood) is allowed

Table III shows the total cost of the objective function for each case, as well as the individual cost of each prosumer. As was expected, the base case has the highest costs. This is due to all the power being purchased from the grid, DR mechanisms are not considered and the entire load is inflexible.

In Case2, the total cost was reduced by 34.75%, owing to the new sources of flexibility, namely the presence of a HEMS system and the ability to generate, store, and sell energy to network, or self-consume. In Case 3 there was a 36.10% cost reduction compared to the base case, owing to the gains obtained through transactions between prosumers in the neighborhood.

Concerning EVs, each prosumer uses the energy stored in the EV in the evening peak to offset the more expensive grid power which has a peak period between 5 and 10 pm. That is, EV1, EV2, and EV3 supply 61.09%, 36.85%, and 30.27%, respectively of the total load of each prosumer in the peak period until they reach their minimum SOE. Accordingly, EVs charge at times when energy is cheaper.

Fig. 5 shows the various sources of energy for Case 2. From this, approximately 30% of the load supply is achieved whenever possible by generation sources and prosumer storage ((PV/ESS/EV) _2H_total). These systems are charged during periods when power is cheaper, taking into account the scenario constraints imposed by various appliances. Using HEMS provides greater flexibility to prosumers compared to the base case. This shows that HEMS and DR programs can facilitate cost savings.

The third case is where prosumers can sell energy to each other. The energy mix for prosumer 1 and 3 are shown in Figs. 6 and 7 respectively. Energy transactions occur between prosumers 1 and 3, principally from prosumer 3 to 1. This transaction takes place at the beginning of the peak demand period, where power from EV has lowered the needs of prosumer 3, and it is, therefore, beneficial to sell power to prosumer 1 (who buys at a lower rate than that of the grid).

Fig. 8 presents the power aggregation for Case 3. By comparing Fig. 5 with Fig. 8, it is possible to see that the summation of DER contribution stands at 31.1% which decreases the contribution of power purchased from the grid and increases grid flexibility. Although possible, there is no sale to the network, and this is because the price fluctuation between off-peak and peak hours is very small.

TABLE III. OBJECTIVE FUNCTION COST AND INDIVIDUAL PROSUMERS COST

	Case 1 [cents]	Case 2 [cents]	Case 3 [cents]
Total Prosumers Cost	793.240	517.602	506.857
Prosumer 1	272.862	178.104	170.979
Prosumer 2	254.656	158.460	158.460
Prosumer 3	265.723	181.038	177.417

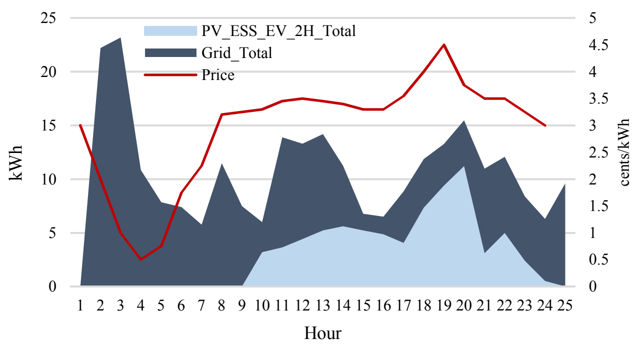

Figure 5. Energy aggregation based on source types (Case 2).

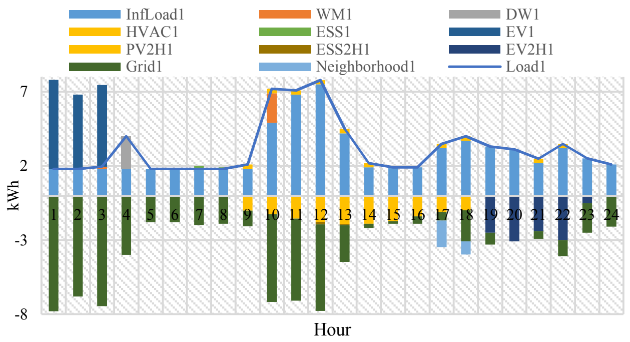

Figure 6. Prosumer 1 energy matrix (Case 3).

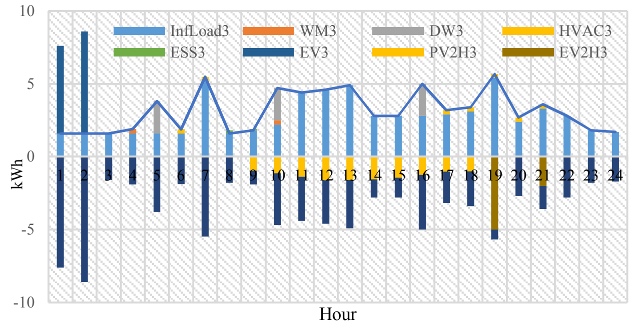

Figure 7. Prosumer 3 energy matrix (Case 3).

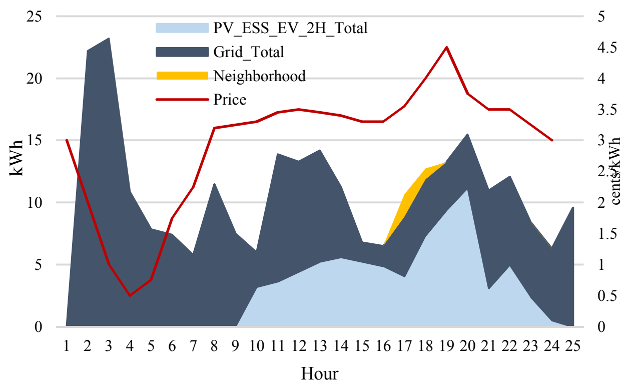

Figure 8. Energy aggregation based on source types for Case 3.

VII. Conclusions

In this work, the participation of prosumers in DR to increase system flexibility, reduce prosumers costs, evaluate bidirectional energy flows, reduce peak demand and evaluate prosumers behavior concerning DR was analyzed. To perform the analysis, a stochastic MILP model was developed considering transactive energy trading amongst the prosumers. This operational model evaluated the participation of prosumers in DR through a tariff scheme, where the model quantified the benefit in terms of flexibility and cost reduction. In this model, the prosumers had inflexible loads, flexible loads, PVs, ESSs, and EVs. Three types of energy transactions were possible: self-consumption, sale to the network, and sale in the neighborhood. The model minimized the total costs to prosumers, subject to a set of operational constraints. A test system consisting of three interconnected prosumers and the network was used. Numerical results from this study identified that the use of DR allows greater flexibility to be used in the system. This flexibility translates into cost reductions for all prosumers of at least 36%, because of the changing behavior due to DR, particularly regarding the reduction in peak demand. Thus, the peak demand for the case study presented was suppressed by at least 30% in self-consumption mode and up to 61% for one specific prosumer. In general, the power supplied by DERs was 31% when considering transactions in the neighborhood. Overall, it is evident that when DR was considered the levels of flexibility increased, whilst costs decreased further when the neighborhood was considered.

References

[1] E. Mengelkamp, S. Bose, E. Kremers, J. Eberbach, B. Hoffmann, and C. Weinhardt, "Increasing the efficiency of local energy markets through residential demand response," Energy Inform., vol. 1, no. 1, p. 11, Aug. 2018, doi: 10.1186/s42162-018-0017-3.

[2] H. Hao, C. D. Corbin, K. Kalsi, and R. G. Pratt, "Transactive Control of Commercial Buildings for Demand Response," IEEE Trans. Power Syst., vol. 32, no. 1, pp. 774–783, Jan. 2017, doi: 10.1109/TPWRS.2016.2559485.

[3] K. Chen, J. Lin, and Y. Song, "Trading strategy optimization for a prosumer in continuous double auction-based peer-to-peer market: A prediction-integration model," Appl. Energy, vol. 242, pp. 1121–1133, May 2019, doi: 10.1016/j.apenergy.2019.03.094.

[4] B. Sun, X. Kong, F. Zhang, Y. Li, Y. Qiao, and Q. Yang, "Demand-responsive virtual power plant optimization scheduling method based on competitive bidding equilibrium," Energy Procedia, vol. 158, pp. 3988–3993, Feb. 2019, doi: 10.1016/j.egypro.2019.01.842.

[5] J. Villar, R. Bessa, and M. Matos, "Flexibility products and markets: Literature review," Electr. Power Syst. Res., vol. 154, pp. 329–340, Jan. 2018, doi: 10.1016/j.epsr.2017.09.005.

[6] J. P. Iria, F. J. Soares, and M. A. Matos, "Trading Small Prosumers Flexibility in the Energy and Tertiary Reserve Markets," IEEE Trans. Smart Grid, vol. 10, no. 3, pp. 2371–2382, May 2019, doi: 10.1109/TSG.2018.2797001.

[7] I. Dukovska, N. G. Paterakis, and H. J. G. Slootweg, "Local Energy Exchange Considering Heterogeneous Prosumer Preferences," in 2018 International Conference on Smart Energy Systems and Technologies (SEST), 2018, pp. 1–6, doi: 10.1109/SEST.2018.8495865.

[8] European Commission, "Monitoring progress towards the Energy Union objectives – key indicators," European Commission, Brussels, Belgium, Working Paper, Feb. 2017.

[9] A. Lüth, J. M. Zepter, P. Crespo del Granado, and R. Egging, "Local electricity market designs for peer-to-peer trading: The role of battery flexibility," Appl. Energy, vol. 229, pp. 1233–1243, Nov. 2018, doi: 10.1016/j.apenergy.2018.08.004.

[10] R. Missaoui, H. Joumaa, S. Ploix, and S. Bacha, "Managing energy Smart Homes according to energy prices: Analysis of a Building Energy Management System," Energy Build., vol. 71, pp. 155–167, Mar. 2014, doi: 10.1016/j.enbuild.2013.12.018.

[11] A. G. Azar, H. Nazaripouya, B. Khaki, C.-C. Chu, R. Gadh, and R. H. Jacobsen, "A Non-Cooperative Framework for Coordinating a Neighbourhood of Distributed Prosumers," IEEE Trans. Ind. Inform., vol. 15, no. 5, pp. 2523–2534, May 2019, doi: 10.1109/TII.2018.2867748.

[12] T. Bragatto et al., "Statistical Analysis of Prosumer Behaviour in a Real Distribution Network Over Two Years," in 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe), 2018, pp. 1–5, doi: 10.1109/EEEIC.2018.8493764.

[13] S. Cui, Y. Wang, J. Xiao, and N. Liu, "A Two-Stage Robust Energy Sharing Management for Prosumer Microgrid," IEEE Trans. Ind. Inform., vol. 15, no. 5, pp. 2741–2752, May 2019, doi: 10.1109/TII.2018.2867878.

[14] M. K. Gray and W. G. Morsi, "A Novel Transactive Energy Framework for Prosumers with Battery Storage and Electric Vehicles," in 2018 IEEE Electrical Power and Energy Conference (EPEC), 2018, pp. 1–6, doi: 10.1109/EPEC.2018.8598368.

[15] R. Pinto, R. J. Bessa, and M. A. Matos, "Multi-period flexibility forecast for low voltage prosumers," Energy, vol. 141, pp. 2251–2263, Dec. 2017, doi: 10.1016/j.energy.2017.11.142.