Optimisation of Prosumers’ Participation in Energy Transactions

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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 transaction 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 \( w \in \{1, 2, 3\} \)

\( c \in \Omega^C \) Controllable appliances \( c \in \{HVAC, WM, DW\} \)

\( f \in \Omega^F \) Variable operation phases of controllable appliances

B. Parameters

\( c_{PESS}^{W,s} \) Charging efficiency of the Prosumer \( w \)'s ESS

\( c_{PESS}^{W,s} \) Charging efficiency of the Prosumer \( w \)'s EV

\( \eta_{w,s}^{ESS,disch} \) Discharging efficiency of the ESS of prosumer \( w \)

\( \eta_{w,s}^{EV,disch} \) Discharging efficiency of the EV of prosumer \( w \)

\( \text{InfLoad}_{w,t} \) Inflexible load of household \( w \) in period \( t \) [kW].

\( N_{w,s,c} \) Periods of operation for the controllable appliance \( c \) of prosumer \( w \)

\( p_{f,\text{ase}} \) Power consumed by controllable appliance \( c \) of prosumer \( w \) in phase \( f \) [kW].

\( p_{PV,\text{prod}} \) Available power of the PV system of household \( w \) in period \( t \) [kW].

\( p_{ESS,\text{max}} \) Maximum SOE of the ESS of prosumer \( w \) [kWh].

\( p_{ESS,\text{min}} \) Minimum SOE of the ESS of prosumer \( w \) [kWh].

\( p_{EV,\text{ini}} \) Initial SOE of the EV of prosumer \( w \) [kWh].

\( p_{EV,\text{max}} \) Maximum SOE of the EV of prosumer \( w \) [kWh].

\( p_{EV,\text{min}} \) 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 \( w \).

\( p_{\text{dur}}^{w,f,c,s} \) Duration of phase \( f \) of controllable appliance \( c \) of prosumer \( w \) [number of \( \Delta T \)-hour periods].

\( p_{\text{buying price}} \) Energy buying price [\( €/\text{MWh} \)].

\( p_{\text{selling price}} \) Energy selling price [\( €/\text{MWh} \)].

Portion of total power procured from the grid by prosumer \( w \) in period \( t \) [kW].

Portion of power procured from the local neighborhood by prosumer \( w \) in period \( t \) [kW].

Total power procured by prosumer \( w \) in period \( t \) [kW].

Charging power of ESS of prosumer \( w \) in period \( t \) [kW].

Discharging power of ESS of prosumer \( w \) in period \( t \) [kW].

Charging power of EV prosumer \( w \) used to satisfy self-consumption in period \( t \) [kW].

Discharging power of EV prosumer \( w \) in period \( t \) [kW].

Total power procured by prosumer \( w \) in period \( t \) [kW].
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).

\[
\text{Min Total Prosumers Cost} = \sum_s \sum_w \sum_t (\lambda_{w,t,s} \cdot p_{w,t,s}^\text{pur,T} \cdot \Delta T - \lambda_{w,t,s}^\text{vend,T} \cdot \Delta T)
\]

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 power transaction in the neighborhood is represented by Equation (4), where the power purchased must be equal to the power sold.

\[
p_{\text{pur},w,t,s} = p_{\text{pur},\text{grid},w,t,s} + p_{\text{pur},\text{local},w,t,s}
\]

\[
p_{\text{vend},w,t,s} = p_{\text{vend},\text{grid},w,t,s} + p_{\text{vend},\text{local},w,t,s}
\]

\[
\sum_w p_{\text{pur,neigh},w,t,s} = \sum_w p_{\text{vend,neigh},w,t,s}
\]
\[
\begin{align*}
SOC_{\text{EV}, \min}^{w,s} & \leq SOC_{\text{EV}, \max}^{w,s} \\
SOC_{\text{EV}, \min}^{w,s} & \leq SOC_{\text{EV}, \max}^{w,s} \\
SOC_{t, \text{EV}}^{w,s} & = SOC_{\text{EV}, \max}^{w,s} \quad \forall w, t = T_{w,s}^d
\end{align*}
\] (21)

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

\[
\begin{align*}
p_{\text{ESS,used}}^{w,s} + p_{\text{vend,ESS}}^{w,s} = & \quad P_{\text{ESS,disch}}^{w,s} \cdot P_{\text{ESS,disch}}^{w,s} \\
0 & \leq p_{\text{ESS,charg}}^{w,s} \leq R_{\text{ESS,charg}}^{w,s} \cdot x_{w,s}^t \quad \forall w, t \\
0 & \leq p_{\text{ESS,disch}}^{w,s} \leq R_{\text{ESS,disch}}^{w,s} \cdot (1 - x_{w,s}^t) \quad \forall w, t \\
SOC_{\text{ESS}}^{w,s} & = SOC_{\text{ESS}}^{w,s,1} + CE_{\text{ESS}}^{w,s} \cdot p_{\text{ESS,charg}}^{w,s} \\
& \Delta T - p_{\text{ESS,disch}}^{w,s} \cdot \Delta T \quad \forall w, t \geq 1 \\
SOC_{\text{ESS,init}}^{w,s} & = SOC_{\text{EV,init}}^{w,s} \quad \forall w, t = 1 \\
SOC_{\text{ESS,init}}^{w,s} & \leq SOC_{\text{ESS,init}}^{w,s} \leq SOC_{\text{ESS,init}}^{w,s} \quad \forall w, t
\end{align*}
\] (22)

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.

\[
\begin{align*}
p_{\text{PV,used}}^{w,h,s} + p_{\text{vend, PV}}^{w,h,s} = & \quad P_{\text{PV,prod}}^{w,h,s} \\
\theta_{w,t+1} & = \beta_{w,s} \cdot \theta_{w,t,s} + (1 - \beta_{w,s}) \cdot \theta_{w,t,s} + COP_{\text{w,s}} \\
& \cdot R_{\text{w,s}} + P_{\text{HVAC}}^{w,t,s} \\
\theta_{w,m}^{\min} & \leq \theta_{w,t+1} \leq \theta_{w,m}^{\max} \quad \forall w, t \\
0 & \leq D_{\text{HVAC}}^{w,t} \leq P_{\text{HVAC}}^{w,t} \quad \forall w, t
\end{align*}
\] (30)

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 I. 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°C 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 specifics.
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 Case 2, 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.
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


