PROVISION OF FLEXIBILITY SERVICES THROUGH ENERGY COMMUNITIES

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ABSTRACT

Nowadays, the proportion of Distributed Energy Resources (DERs) is growing fast. The grid needs a new design that enhances the power system. In this regards, a new form of local initiative, called of energy communities, can boost the transition by providing optimal integration of prosumers into the system. This paper presents a methodology for the provision of flexibility services delivered as market services to mitigate congestion problems at the distribution level through energy communities. Peaks shaving, backup power and power ramp rate reduction are formulated as services in this study. New business models can be developed in relation with this technological, regulatory and economic framework. This paper illustrates with a test case that energy communities are able to provide grid services, as well as leading to a considerable enhancement of community welfare and commitment.

INTRODUCTION

Background and challenge

Nowadays residential customers can install their own Distributed Energy Resources (DERs), becoming energy prosumers and having potentially some forms of storage capabilities. Prosumers can play a key role in the power systems if properly integrated and incentivized. For this reason decentralized approach based on community and Peer-to-Peer (P2P) concepts has been proposed for electricity markets [1]. In this regard, energy communities based on P2P structures are emerging [2, 3] as groups of prosumers in a neighborhood, exhibiting a high degree of ownership and control of energy projects. The new paradigm of P2P markets assumes a bottom-up and collaborative market organization, where each actor (e.g. prosumers, renewable producers, traditional actors) trades energy in a distributed manner. In this sense, peers have more freedom to choose their trading partners than the centralized organization governing the current markets.

At the same time, the steady operation of Distribution System Operators (DSOs) will be undermined [4] by the growing penetration of distributed renewable energy without proper integration. Hence, congestion becomes one of the most pressing matters in future distribution grids [5]. The grid reinforcement represents a costly measure to DSOs pursue in this new paradigm [6]. Thus, the recent investigation of active distribution management claims that DSOs have to pursue alternative solutions [6], where a market-based approach that procures flexible services is a possibility. Energy communities are relevant assets for flexibility service markets that can mitigate congestion [4].

Contribution of this study

The existing regulatory framework is less inclined to assume a complete decentralized electricity market [7], although the first attempts point to this future paradigm. Therefore, this paper deals with a setup appropriated to the current regulatory framework, where we assumed energy communities formed by a group of prosumers geographically close, as well as connected to the same grid node. We assume that controllable loads and DERs support the prosumers. The community can also rely on the flexibility of an Electric Energy Storage (EES), working as virtual buffer. The recent advances on Information and Communication Technology devices support energy community where all prosumers, down to the appliance level, may then trade as well as procure flexible services according to DSO request.

In this paper, the P2P market design follows the community-based model in [8], where community members form an energy collective to share electricity according to a common economic-social agreement. There is a supervisory node managing the energy trading among members. Additionally, it works as a bottleneck when it comes to the interaction with the remaining system. The contribution of the paper is a methodology for energy communities to provide flexibility services, delivered as market services, for mitigating congestion problems at the distribution level. In this regard, the supervisor node of our community acts as the Smart Energy Service Provider (SESP) introduced in [4], which is an intermediate between the community and the flexibility service markets. Hence, a business model has also been proposed for ruling the SESP and community relationship.

After this introductory section, the next section introduces the energy community model with the respective mathematical formulation. Then the third section presents a test case based on the Australian market and discusses the results. The fourth section introduces the proposed business model for the SESP actor. The last section gathers the main conclusions with this study.

ENERGY COMMUNITY MODEL

Flexibility service markets

In this paper, the energy community can procure three different services. *Peak shaving* service is used to shave the demand peaks and not exceeding the line capacity of the system. This offers the opportunity to defer the cost of network expansion and increasing the utilization of the grid asset. The service will be activated between 4 pm and 10 pm during the high demand seasons. The second treated service, *power ramp rate reduction*, is a control strategy to smooth the fluctuating behavior of the power produced by intermittent renewable generation (e.g. wind farms or PV solar panels). During these ramping events, this service mitigates power fluctuations that could lead to grid instability, voltage variation, etc. The final service is the *backup energy*, which is activated in case of grid failure or disconnection from the grid. It can be used to maintain the energy community in "islanding" operation behind-the-meter. Since the model is optimized by each day, modeling backup power service in the response to real-time signal results to be complicated. Therefore, we assumed that the community will be informed about the DSO planned outages. According to the gathered information of planned outages in the New South Wales region in Australia, defining the duration of disconnection, it was possible to assess the necessary flexibility under scheduled delivery through the energy community. Moreover, this investigation can give a hint on the community flexibility capability to react to blackouts caused by environmental circumstances.

Exchange of energy and information

Different exchanges occur among the actors involved in our community-based model. Most interactions take place inside the community due to the ability of prosumers to share their surplus electricity with the other peers through P2P exchanges. Figure 1 depicts the diagram representing all exchanges of energy and information in this paper.

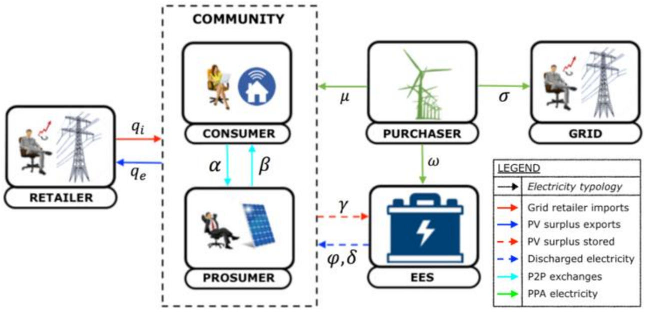

Figure 1. Exchange energy and information on the community-based model.

The community members can receive electricity from their retailer at fixed tariff and the prosumers can sell their surplus at Feed-in-Tariff (FiT) price. The SESP has an agreement with a local wind producer to consume energy at a fixed price. The SESP is also the EES owner for simplicity. The prosumer can store the energy surplus into the EES, whenever the self-consumption or P2P trading with others is not possible. Later, the prosumer can share this energy with other community members. Finally, the EES can store the energy from the local wind produce, and use it later on the community members.

Community-based market model

The model was formulated as an economic dispatch for the next day with an objective function translating the individual objective of SESP and community members. In this approach, a member can be a prosumer or consumer. It is considered the hypothetical revenues as negative costs. Before introducing the mathematical model, parameters and variables are shown.

Parameter	***Description***	***Unit***
p	PV electricity produced	kWh
GC	General consumption	kWh
CL	Controllable load quota	kWh
P_w	Available wind power	kWh
Q^{DSO}	Maximum grid demand requested by DSO	kWh
η_{ch}	Charging efficiency	%
η_{dis}	Discharging efficiency	%
e_{max}	Maximum EES energy capacity	%
$P_{ch_{max}}$	Maximum charged power	kW
$P_{dis_{max}}$	Maximum discharged power	kW
λ_{buy}	Retailer electricity price	$/kWh
λ_{sell}	FiT PV electricity price	$/kWh
$\lambda_{surplus}$	PV electricity price stored	$/kWh
λ_{fee}	PV electricity price discharged	$/kWh
λ_{PPA}	PPA wind electricity price	$/kWh
λ_{int}	Price of discharged electricity	$/kWh
$\lambda_{p1,p2}$	Penalization factors degradation	$/kWh
λ_w/λ_{PV}	Penalization for power ramp reduction	$/kWh
τ	Transaction cost for P2P trades	$/kWh

Variables	***Description***	***Unit***
c	Electricity consumed	kWh
q_i	Electricity grid imports	kWh
q_e	Electricity grid exports	kWh
α	Electricity P2P imported	kWh
β	Electricity P2P exported	kWh
γ	PV surplus charged in EES	kWh
φ	PV surplus discharged to the community	kWh
μ	Wind electricity sold to the community	kWh
σ	Wind electricity sold to the grid	kWh
ω	Wind electricity stored in EES	kWh
δ	Wind electricity discharged from EES	kWh

The function Z translates the total cost for the SESP and the community, as seen below

$$\min Z = \sum_{t=1}^{T}\sum_{i=1}^{N} f(X_C) + \sum_{t=1}^{T}\sum_{i=1}^{N} g(X_M) + \sum_{t=1}^{T} \rho(SoC_t) \qquad (1)$$

where, $X_C = (p_{i,t}, c_{i,t}, q_{i_{i,t}}, q_{e_{i,t}}, \alpha_{i,t}, \beta_{i,t})$ and $X_M = (q_{i_{i,t}}, q_{e_{i,t}}, \alpha_{i,t}, \beta_{i,t}, \gamma_{i,t}, \varphi_{i,t}, \mu_{i,t}, \omega_t, \delta_{i,t})$ for each member i and for each time-step t. f, g and ρ are respectively the member i, the SESP and the penalization model functions. The function f includes the individual utility curve of member i and its costs for exchanging energy within the community, as presented below

$$f(X_C) = h_i \cdot (p_i + c_i)^2 + d_i \cdot (p_i + c_i)^2 + \tau \cdot (\alpha_i - \beta_i) + \lambda_{buy} \cdot q_{i_i} + \lambda_{sell} \cdot q_{e_i} \qquad (2)$$

where, p_i is positive and represents the PV energy production, while c_i is negative and represents the energy consumption. Function g represents community manager interface. It aims to minimize the energy costs and maximize the revenues of the community battery.

$$g(X_C) = \sum_{t=1}^{T}\sum_{i=1}^{N}\Big(\big(\lambda_{buy}\cdot q_{i_{i,t}}\big) + \big(\lambda_{sell}\cdot q_{e_{i,t}}\big) + \big(\lambda_{surplus}\cdot \gamma_{i,t}\big) + \big(\lambda_{fee}\cdot \varphi_{i,t}\big) + \big(\lambda_{PPA}\cdot \mu_{i,t}\big) + \big(\lambda_{int}\cdot \delta_{i,t}\big)\Big) + \sum_{t=1}^{T}(\lambda_{PPA}\cdot \omega_t) \quad (3)$$

In addition, the penalization model function ρ is added to model the degradation that can affect the battery life.

$$\rho(SoC_t) = \lambda_{\rho 1}\cdot\sum_{t=1}^{T}\left|\frac{SoC_t - 0.5}{T}\right|^2 + \lambda_{\rho 2}\cdot\sum_{t=1}^{T}\left|\frac{SoC_t - SoC_{t-1}}{T}\right| \quad (4)$$

The electricity balances within the community, for each member *i* and within the P2P trading, are formulated as

$$\sum_{i=1}^{N}(p_{i,t} + c_{i,t}) = -\sum_{i=1}^{N}(q_{i_{i,t}} + q_{e_{i,t}} + \gamma_{i,t} + \mu_{i,t} + \omega_t + \delta_{i,t}) \quad (5)$$

$$p_{i,t} + c_{i,t} + \alpha_{i,t} + \beta_{i,t} + q_{i_{i,t}} + q_{e_{i,t}} + \gamma_{i,t} + \varphi_{i,t} + \mu_{i,t} + \delta_{i,t} = 0, \quad \forall\, t\ in\ T, \forall\, i\ in\ N \quad (6)$$

$$\sum_{i=1}^{N}\alpha_{i,t} + \sum_{i=1}^{N}\beta_{i,t} = 0, \qquad \forall\, t\ in\ T \quad (7)$$

The following constraints represent the available quota of controllable consumption for each customer in each time-step and the daily total.

$$\big(GC_{i,t} + 2CL_{i,t} + p_{i,t}\big) \le c_{i,t} \le \big(GC_{i,t} + p_{i,t}\big), \quad \forall\, t\ in\ T, \forall\, i\ in\ N \quad (8)$$

$$\sum_{t=1}^{T}(c_{i,t} - GC_{i,t}) \le \sum_{t=1}^{T} CL_{i,t}\ , \qquad \forall\, i\ in \quad (9)$$

Equations (10) and (11) reflect the technological limits of the battery round-trip efficiency. Equations (12) and (13) represents the EES power flows, while Equations (14) and (15) assure that charge and discharge do not occur simultaneously.

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\varphi_{i,t} \le \eta_{ch}\eta_{dis}\sum_{t=1}^{T}\sum_{i=1}^{N}\gamma_{i,t}\ , \qquad \forall\, t\ in\ T \quad (10)$$

$$\sum_{t=1}^{T}\omega_{i,t} \ge \eta_{ch}\eta_{ch}\sum_{t=1}^{T}\sum_{i=1}^{N}\delta_{i,t}\ , \qquad \forall\, t\ in\ T \quad (11)$$

$$P_{ch_t} = \sum_{i=1}^{N}\gamma_{i,t} + \omega_t, \qquad \forall\, t\ in\ T \quad (12)$$

$$P_{dis_t} = \sum_{i=1}^{N}\varphi_{i,t} + \sum_{i=1}^{N}\delta_{i,t}, \qquad \forall\, t\ in\ T \quad (13)$$

$$P_{ch_t} \le P_{ch_{max}}\cdot X_t \qquad \forall\, t\ in\ T \quad (14)$$

$$P_{dis_t} \le P_{dis_{max}}\cdot (1 - X_t) \qquad \forall\, t\ in\ T \quad (15)$$

Constraint (16) is the updated status of the EES capacity, while SoC used in (4) is equal to e_t divided by e_{max} represents the State-of-Charge of the battery.

$$e_t = e_{t-1} + \eta_{ch}\cdot\Delta t\cdot P_{ch_t} - \frac{1}{\eta_{dis}}\cdot\Delta t\cdot P_{dis_t}\ , \quad \forall\, t\ in\ T \quad (16)$$

The following equation is used to constrain wind power availability.

$$(\omega_t + \sigma_t) + \sum_{i=1}^{N}\mu_{i,t} = P_{w_t}, \qquad \forall\, t\ in\ T \quad (17)$$

The signs of the variables have been specified as follows.

$$c_{i,t}, q_{e_{i,t}}, \beta_{i,t}, \gamma_{i,t}, \sigma_t \le 0 \qquad \forall\, t\ in\ T \quad (18)$$

$$p_{i,t}, q_{i_{i,t}}, \alpha_{i,t}, \varphi_{i,t}, \omega_t, \delta_{i,t}, \mu_{i,t} \ge 0 \qquad \forall\, t\ in\ T \quad (19)$$

In order to carry out the Economic Dispatch, Gurobi Optimizer has been used as commercial optimization solver in Python to solve this mixed-integer quadratic programming (MIQP) problem.

Grid services modeling

In order to apply each service provision, additional terms have been added to the mathematical model. *Peak shaving* has been implemented as a hard constraint in which the grid imports are constrained by the requested threshold form the DSO, illustrated as follows.

$$\sum_{i=1}^{N} q_{i_{i,t}} \le Q_t^{DSO}, \quad (21)$$

Power ramp reduction was defined as extra penalization function in (1) to mitigate the extreme slopes of wind and solar injection into the grid. The additional ramp function R is applied at the objective function.

$$R\left(q_{e_{i,t}}, \sigma_t\right) = \lambda_w\cdot\sum_{t=1}^{T}\sum_{i=!}^{N}\left|\frac{q_{e_{i,t}} - q_{e_{i,(t-j)}}}{T}\right| + \lambda_{PV}\cdot\sum_{t=1}^{T}\left|\frac{\sigma_t - \sigma_{t-j}}{T}\right| \quad (22)$$

Backup power was introduced with an additional constraint representing the disconnection from the grid.

$$\sum_{i=1}^{N}(q_{i_{i,t}} + q_{e_{i,t}}) + \sigma_t = 0, \quad (23)$$

CASE STUDY

The case study is a community, following the model previously described, composed by 10 prosumers with fixed, flexible loads and PV panels. The community relies on a single large storage, instead of having multiple customer batteries. In this way, the community EES capacity can be optimally sized. The SESP has a Power Purchase Agreement (PPA) contract with the local wind producer. These PPAs have been defined as "Behind-the-meter" by [9] in which a fixed price of energy is secured to the community while supporting the wind turbine financing. The community model results are then compared with a baseline model in which each prosumer trades individually the PV production surplus, as well as consuming individually from retailer or local purchaser.

Dataset

The case study uses a public dataset of real prosumers profile in Australia [10]. The data collected from the Australian DSO contains electricity profiles of 300 prosumers with a time-step of 30 minutes between July 2012 and June 2013. The dataset contains time series of fixed, flexible load and PV generation. It has been assumed that the flexible load can be automatically activated without a direct customer control. We assume a single wind turbine of 5.8 kW, assuming a generation profile collected from Australia in [11]. The commercial model Tesla Power Wall 2, with 13.5kWh/5kW energy/power ratio, 89% of round-trip efficiency and cost of 9600 $, was considered as the community battery.

The import and FiT prices have been collected from the largest Australian retailer, Origin Energy. Additionally, according to the retailer's scheme, there is a daily charge of 1$ for infrastructure usage for each customer. It is assumed a quadratic utility curve for each prosumer, translating the price to pay per P2P exchange inside the community, with a small transaction fee. As regards the

Table 1. Electricity prices of the model.

Community electricity flow		Price [\$/kWh]
Description	**Parameter**	
Grid import	λ_{buy}	0.31
PV surplus export	λ_{sell}	0.09
PV surplus stored	$\lambda_{surplus}$	0.10
Battery discharge	$\lambda_{int}, \lambda_{fee}$	0.15
P2P exchange	λ_{P2P}	[0.09 - 0.31]
Wind exchange	λ_{PPA}	0.10

community battery, the price of the electricity discharged differs from the charging price, reflecting a fee to reimburse the battery degradation costs and transaction costs. Table 1 shows the prices used in this case study.

Results

Peak shaving provision

Over one-year period, the baseline model achieved a half-hourly maximum community consumption of 16.3 kW. The next step investigated different levels of peak shaving provision. The presented results correspond to a peak shaving service to 70% of the maximum consumption, i.e. equal to 11.4 kW. It was found out that this peak shaving service was activated in 39 days of our simulation. The number of activations would be significantly reduced for a more moderate service provision. Figure 2 presents the outcomes of peak shaving activation during a typical day in July with low PV and wind power production.

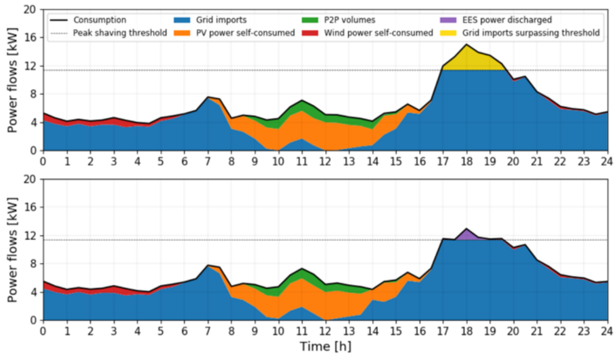

Figure 2. Baseline (above) and peak shaving scenario (below).

Under these conditions, the majority of this service is secured by the flexible load of prosumers, which results in the community reducing the grid-imported energy. In fact, the flexible consumption assists the provision for a share close to 69% yearly. The remaining service was procured through the community battery, necessary to deliver optimally the service the whole simulation year. This is due to periods with low controllable consumption quota and low PV and wind power generation.

Power ramp reduction

In this service model, the wind turbine capacity has been increased to 20 kW capacity for reaching considerable ramping power injection. Figure 3 shows the ramping service provided by the community when there is a week with high wind power production.

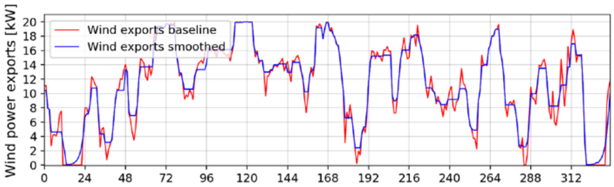

Figure 3. Wind power ramp provision 13th-19th May 2013.

Similar smoothing pattern is achieved for the PV electricity injection, as shown in Figure 4.

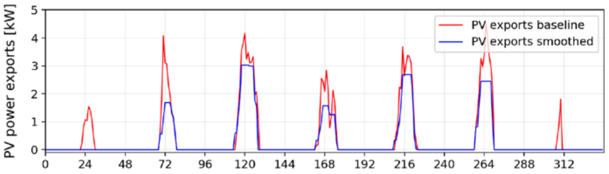

Figure 4. PV power ramp provision 15th-21st March 2013.

In general, EES and flexible loads provide notable ramping capabilities that compensate spiky variations in the wind and PV power production.

Backup power service

The objective is to assess the potential days in which the energy community can behave in islanding mode for at least 6 hours. Figure 5 shows the histogram of the monthly portion that the community can be isolated from the grid.

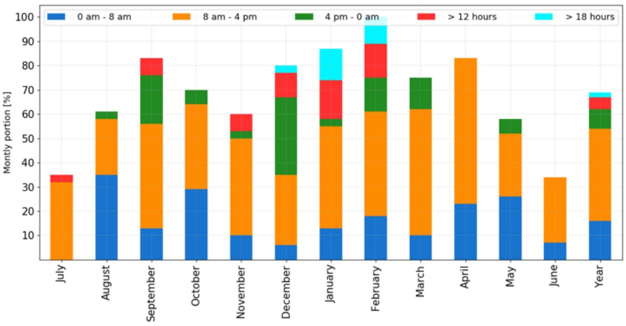

Figure 5. Histogram of the islanding mode per month.

As can be observed, the level of provision depends on the local generation and community flexibility. Clearly, in winter the back power provision is limited due to the low solar irradiance and wind availability. In general, backup power for at least 6 hours daily can be performed approximately 70% of the year. The greatest share of the off-grid hours in each month occurs between 8 am and 4 pm, hours with considerably low grid demand. The energy community could react to programmed out of service requests, as well as hypothetically blackouts. However, wind and solar forecast would be essential.

BUSINESS MODEL OUTLINE

In this paper, we focus on a business model for the peak shaving service. Table 2 presents the economic outcomes of this service, as well as the baseline model.

Table 2. Annual economical results.

Description	***Peak shaving***	***Baseline***
Community spending [$]	-16,250	-20,118
Community revenue [$]	175	1,093
Retailer revenue [$]	9,455	13,888
PV self-consumed [%]	99.2	48.4
Wind self-consumed [%]	83.4	76.5
Emissions [kg_{CO2}]	25,017	36,743

The service provision has considerable benefits that does not affect the community economic results in respect to the baseline model. On the contrary, the community spending is reduced benefiting prosumers welfare, along with decreasing the retailer revenues. On average, the bills for each prosumer has been decreased by about 300$. The community revenues are lowered because the internal volumes are considered both costs and revenues. A notable result is that the emissions are drastically decreased thanks to a higher renewable electricity self-consumed.

This study assumes that the SESP is a non-profit agent for the community. However, the community members pay an annual membership to use the platform in addition to the compensation fee for the battery degradation. On the other hand, the community is not remunerated for its delivered service. [12] recommends 800$ of remuneration from the DSO for kW shaved in respect to the maximum demand threshold. According to our results, the SESP would earn 3920$ per year because of the 4.9 kW size-power shaved, which compensates its investment on the community EES. The business would become profitable during the third year. However, it is noteworthy that the SESP could receive penalties on failing the service delivery, and even, ending the contract after four failures. Moreover, the DSO remuneration could vary. The DSO must assess if it is more convenient to remunerate a SESP for deferring the grid expansion or to invest in new lines.

CONCLUSION

This paper proves the attractiveness of the energy community as an integrated part of the active distribution management done by the DSO, through a portfolio of flexible services modeled in this study. Energy communities can efficiently provide high quality energy for power grid by efficiently integrating prosumers into the system. At the same time, the community welfare and commitment can be increased. The test case shows that energy communities are able to decrease by 30% the peak demands. Energy communities can smooth the intermittent energy injection improving the grid stability. Moreover, backup power can be delivered for 70% of the year for at least 6 hours daily. Business models defined for service provision can become potentially profitable in the future, as well as enhance the resilience of prosumers against congestion problems in the distribution grid. At the same time, the battery lifespan can be safeguarded because of integrating a penalization function in the model that corresponds to the hidden costs of battery operation.

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