Reducing Neighborhood Peak Loads with a Peer-to-Peer Approach under Subscribed Capacity Tariffs

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***Abstract*—Increased power demand is a growing problem for distribution system operators (DSO) capable of causing unwanted and expensive grid upgrades. Descending prices for flexible resources and power generation such as house batteries, electric vehicles (EV) and photovoltaic (PV) cells allow for consumers to have a more active role in the energy system and possibly help avoid these expensive upgrades. In this paper we propose a peer-to-peer (P2P) market structure which allows for electricity trading between end-users to investigate how aggregated operation under different tariffs can reduce power consumption during peak hours. We developed a mixed integer linear programming (MILP) optimization model performed on a small neighborhood consisting of 30 consumers with different amounts of flexible resources to test the market structure. We simulate four different case studies, and the results show an 11% decrease in peak power import during scarcity hours and a more stable import when P2P trading is enabled under a subscription based tariff structure. The main conclusion from this study is that there is a clear potential in local electricity markets and capacity based grid tariff structures, especially when metered at neighborhood level.**

***Index Terms*—Neighborhood peak load, Prosumer, Peer-to-peer, Battery, Electrical Vehicle, Flexible loads, Grid tariffs,**

NOMENCLATURE

Sets

p	Prosumer index, $p\epsilon$[1,30]
t	Time index [hour], $t\epsilon$[1,8760]

Parameters

$\eta^{bat,ch}$	Battery charging efficiency [%]
$\eta^{bat,dis}$	Battery discharging efficiency [%]
$\eta^{EV,ch}$	EV battery charging efficiency [%]
η^{loss}	Loss when importing using P2P[%]
B^{cap}	Total battery capacity [kWh]
$B^{ch,max}$	Battery max charging power [kW]
$B^{dis,max}$	Battery max discharging power [kW]
C^{energy}	Fixed yearly price, energy tariff [NOK/year]
$C^{fixedsub}$	Fixed yearly price, subscription tariff [NOK/year]
C^{high}	Price, energy imported above sub-limit [NOK/kWh]
C^{low}	Price, energy imported below sub-limit [NOK/kWh]
C^{sub}	Subscription price [NOK/kW]
C^{tariff}	Grid tariff price, energy tariff [NOK/kWh]
C_t^{spot}	Spot price in time step t [NOK/kWh]
EV^{cap}	EV-battery capacity [kWh]
$EV^{ch,max}$	Max EV charging power [kW]
$EV^{SOC,min}$	Min EV SOC [kWh]
EV_t^{avail}	EV availability factor for time step t, $ev_t^{avail}\epsilon$[0,1]
EV_t^{cons}	EV consumption in time step t [kW]
K^{sub}	Subscribed limit [kW]
P_t^{load}	End user load in time step t [kW]
PV_t^{prod}	Production from PV-cells in time step t [kW]
T^{max}	Max temp inside water heater [°C]
T^{min}	Min temp inside water heater [°C]
W^{max}	Max power supplied to the water heater [kW]
W^{SHC}	Specific heat of water [J/kg °C]
W^{size}	Size of water heater [L]
W_t^{demand}	Water heater demand in time step t [kWh]

Variables

b^{tot}	Total electricity bill [NOK]
b_t^{ch}	Battery charging power in time step t [kW]
b_t^{dis}	Battery discharging power in time step t [kW]
b_t^{SOC}	Battery SOC in time step t [kWh]
e_t^{exp}	Energy export in time step t [kWh]
$e_t^{imp,h}$	Energy import above sub-limit in time step t [kWh]
$e_t^{imp,l}$	Energy import below sub-limit in time step t [kWh]
e_t^{imp}	Energy import in time step t [kWh]
ev_t^{ch}	EV charging power in time step t [kW]
ev_t^{SOC}	EV SOC in time step t [kWh]
n_t^{exp}	Total neighborhood export in time step t [kWh]
$n_t^{imp,h}$	Neighborhood import above sub-limit in time step t [kWh]
$n_t^{imp,l}$	Neighborhood import below sub-limit in time step t [kWh]
n_t^{imp}	Total neighborhood import in time step t [kWh]
$p_{p,t}^{exp,g}$	Prosumer grid export in time step t for prosumer p [kWh]
$p_{p,t}^{exp,p}$	Prosumer peer export in time step t for pro-

	sumer p [kWh]
$p_{p,t}^{exp}$	Total prosumer export in time step t for prosumer p [kWh]
$p_{p,t}^{imp,g}$	Prosumer grid import in time step t for prosumer p [kWh]
$p_{p,t}^{imp,h}$	Prosumer import above sub-limit in time step t for prosumer p [kWh]
$p_{p,t}^{imp,l}$	Prosumer import below sub-limit in time step t for prosumer p [kWh]
$p_{p,t}^{imp,p}$	Prosumer peer import in time step t for prosumer p [kWh]
$p_{p,t}^{imp}$	Total prosumer import in time step t for prosumer p [kWh]
t_t^{w}	Temp inside water heater in time step t [° C]
w_t^{power}	Power supplied to the water heater in time step t [kW]

I. INTRODUCTION

The increasing amount of power demand, especially due to electric vehicles, is a major concern for DSOs. Higher power demand leads to expensive upgrades for the DSOs. A possible solution to these grid expansions is to utilize flexible loads, which has been researched extensively in recent years. In addition to utilization of flexible loads, P2P trading has also been suggested as early as in 2007 in [1]. In [2] Alexandra Lüth et al. research the role of battery flexibility in a P2P market by creating an optimization model, reaching savings of up to 19.6%.

The P2P trading concept is still an area of the energy market that is still actively being investigated and needs a lot more research to be able to go commercial. Pilot projects such as the Brooklyn Microgrid project by Mengelkamp et al. [3], has achieved successful results in implementing the P2P concept in Brooklyn and has shown the technology's potential. In [4] Pierre Pinson et al. introduce consumer-centric electricity markets and highlight challenges they are facing in order to function.

The technology does not come without challenges. In [3] Mengelkamp et al. also discusses seven steps that need to be fulfilled in order for the P2P concept to work, the two biggest being blockchain and regulation. Blockchain technology is needed to make the small energy trades done in a P2P system cost-effective. Blockchain can do this by eliminating the need for a third party to approve the transactions and distributing this task to all of the nodes in the system. This, however, also comes with its challenges, one of which is discussed in [5], where Andoni et. al raises the concern for the energy used to solve the different consensus algorithms.

This paper asks how grid tariffs and P2P trading affect the energy import management of a small neighborhood. This is done by modelling a neighborhood of 30 unique households/entities that are able to trade energy locally (P2P) as well as utilize several different flexible loads. It is assumed that every minuscule energy trade is cost efficient and possible.

II. MODEL

The model arranges the neighborhood, prosumers and appliances in a hierarchical structure with the neighborhood on top. The Python-based open-source optimization language Pyomo is used to develop the model which is described in the following chapters.

A. Problem definition

The optimization program aims to optimally schedule end-user flexibility in order to minimize total costs, using a MILP formulation. Through investigating the total cost under energy based and subscription based tariffs, we illuminate how the peak load during scarcity hours are reduced. In this paper two grid tariffs are investigated: Energy based and Subscription based (Power). These are explained in detail in Chapter II-H. The optimization program minimizes the cost by utilizing flexible resources, curtailable loads and energy production (PV). The optimization problem is run for a year with an hourly resolution.

B. Neighborhood

The neighborhood consists of 30 unique load data sets with an hourly resolution for the calendar year of 2012. 28 of the data sets are small households, while the two remaining are a grocery store and a pre-school. The neighborhood model includes an energy balance consisting of total grid-import and export for all the different consumers. This does not take into account the energy traded internally between the households (P2P). The energy balance is shown in equation 1.

$$n_t^{imp} - n_t^{exp} = \sum_p (p_{p,t}^{imp,g} - p_{p,t}^{exp,g}) \tag{1}$$

When the subscription based tariff is applied, the import is split into low and high, $n_t^{imp,l}$ and $n_t^{imp,h}$, to be able to allocate the overconsumption price explained in II-H.

C. Consumer/Prosumer

All of the consumers have an associated energy balance, which includes all of the appliances available, shown in equation 2. The flexible appliances will be explained throughout this chapter.

$$\begin{aligned} p_{p,t}^{imp,p} \cdot \eta^{loss} + p_{p,t}^{imp,g} - p_{p,t}^{exp,p} - p_{p,t}^{exp,g} &= P_t^{load} \\ + b_t^{ch} - b_t^{dis} + ev_t^{ch} + w_t^{power} - PV_t^{prod} \end{aligned} \tag{2}$$

The consumer level also splits the import into low and high, $p_t^{imp,l}$ and $p_t^{imp,h}$, when the subscription based tariff is applied.

D. Battery

The battery is modeled to emulate the Tesla Powerwall 2 unit [6] with a maximum capacity of 13.5 kWh, maximum power input/output of 7 kW and a charge/discharge efficiency of 95%. It is assumed that the battery starts completely discharged with a state-of-charge (SOC) at zero. Battery SOC evolution, min and max charging power limitations and max SOC limits are shown equation 3.

$$b_t^{SOC} = b_{t-1}^{SOC} + b_t^{ch} \cdot \eta^{bat,ch} - \frac{b_t^{dis}}{\eta^{bat,dis}} \tag{3a}$$

$$b_t^{ch} < B^{ch,max} \tag{3b}$$

$$b_t^{dis} < B^{dis,max} \tag{3c}$$

$$0 < b_t^{SOC} < B^{cap} \tag{3d}$$

E. Electric vehicle

The EV is modeled as a curtailable load, meaning it does not have the option of bi-directional charging. The EV chosen for this paper has a maximum capacity of 80 kWh and an efficiency of 90%. In order for the EV to always be charged when the consumer needs it, a lower limit for the SOC is set at 60 kWh. The consumption for the EV is modeled based on the average yearly Norwegian mileage for personal vehicles from Statistics Norway (SSB). Four different usage patterns were created to reflect different types of consumers. It is assumed that the EV starts with a SOC at 70 kWh. Equation 4 describes the EV SOC evolution, charging limitations under availability conditions, and min and max SOC limits.

$$ev_t^{SOC} = ev_{t-1}^{SOC} + ev_t^{ch} \cdot \eta^{EV,ch} - EV_t^{cons} \tag{4a}$$

$$ev_t^{ch} < EV^{ch,max} \cdot EV_t^{avail} \tag{4b}$$

$$EV^{SOC,min} < ev_t^{SOC} < EV^{cap} \tag{4c}$$

F. Water heater

The water heater (WH) represents a typically sized commodity at 200 liters with the consumption equal to a small household. To model the demand of such a WH the standard found in [7] is used. The min and max temperatures are set to 55°C and 90 °C, respectively. The WH will act as a curtailable load and is described in equation 5 with temperature evolution, max input power and min/max temperature limits.

$$t_t^w = t_{t-1}^w - \frac{W_t^{demand}}{W^{size} \cdot C^{Water}} + \frac{w_t^{power}}{W^{size} \cdot C^{Water}} \tag{5a}$$

$$w_t^{power} < W^{max} \tag{5b}$$

$$T^{min} < t_t^w < T^{max} \tag{5c}$$

G. PV cells

Irradiation and temperature data from a weather station close to Trondheim, Norway was used to calculate output from the PV-cells. In total the PV-cells cover 37.84m^2 and produce 0.19 kW/m^2 giving a total of 7.2 kW of maximum theoretical power output. The data time resolution is hourly. The calculations are explained in detail in [8].

H. Grid tariffs

The energy based grid tariff charges the consumer based on energy consumption. This is the current grid tariff applied to the majority of consumers in Norway, with exception of bigger consumers such as industry and corporate customers. It consists of a price per kWh the consumer imports from the grid and a fixed yearly cost. The price ranges for the energy based tariff is collected from NVE for 2012 [9] and are shown in Table I. This study does not include taxes as it owuld be the same for both tariff structures.

TABLE I
ENERGY TARIFF PRICE RANGES [9]

Price parameter		**Cost**
Energy price [NOK/kW]	C^{tariff}	0.197
Fixed yearly price [NOK/year]	C^{energy}	1900

To incentivize consumers to lower power consumption and thereby lowering power peaks in the system, a subscription based grid tariff has been proposed [10]. This charges the consumer based on power and not energy imported. The consumer will subscribe to a certain amount of kW and pay a low price per kWh as long as they keep their consumption below this power limit. Once they import above the subscribed limit the grid tariff cost per kWh will increase. The subscription based structure also includes a fixed yearly cost.

The energy price, overconsumption price and fixed yearly price shown in Table II are identical to the ones suggested by NVE in [10]. The subscription price is calculated on the basis of the electricity bill the consumer/neighborhood attains under the energy tariff without any form of flexibility or optimization. The total electricity bill should be equal for both tariff structures when the average consumption is the same to cover the cost of the DSO. The calculated subscription cost for the different types of consumers as well as the neighborhood can be seen in Table II.

TABLE II
PRICE RANGES FOR THE SUBSCRIPTION BASED STRUCTURE [10]

Price parameter		**Cost**
Energy price [NOK/kWh]	C^{low}	0.05
Overconsumption price [NOK/kWh]	C^{high}	1.00
Fixed yearly price [NOK/year]	$C^{fixedsub}$	1900
Subscription price [NOK/kW]	C^{sub}	
Neighborhood		1057.83
Grocery store		962.24
Residential		866.69
Pre school		513.82

I. Objective function

The objective functions represent the yearly electricity bill b^{tot} for either the consumer or the entire neighborhood. For the energy based grid tariff the objective function is described in equation 6 with import/export and price elements.

$$
\begin{aligned}
min \sum_t (e_t^{imp} \cdot (C_t^{spot} + C^{tariff})) \\
- \sum_t (e_t^{exp} \cdot C_t^{spot}) + C^{energy}
\end{aligned}
\tag{6}
$$

e_t^{imp} and e_t^{exp} is equal to n_t^{imp} and n_t^{exp} for the neighborhood level and $p_{p,t}^{imp}$ and $p_{p,t}^{exp}$ for the consumer level. For the subscription based grid tariff equation 7 describes the objective function with import/export and price elements.

$$
\begin{aligned}
min \sum_t ((e_t^{imp} - e_t^{exp}) \cdot C_t^{spot}) \\
+ \sum_t (e_t^{imp,l} \cdot C^{low} + e_t^{imp,h} \cdot C^{high}) \\
+ C^{sub} \cdot K^{sub} + C^{fixedsub}
\end{aligned}
\tag{7}
$$

e_t^{imp} and e_t^{exp} equals n_t^{imp} and n_t^{exp} for the neighborhood level and p_t^{imp} and p_t^{exp} for the consumer level. $e_{imp,l}$ and $e_t^{imp,h}$ will similarly be equal $n_t^{imp,l}$ and $n_t^{imp,h}$ and $p_t^{imp,l}$ and $p_t^{imp,h}$ determined by the level of the grid tariff.

III. CASE STUDIES

In this paper four different case studies are tested. All of which are based on load data for 30 different households in Steinkjaer, Norway. The load profiles include mostly small apartments with an average power consumption between 0.64-3.5 kW, but also a pre-school and a grocery store with an average between 10-31 kW. As explained in Chapter II, the available flexible appliances are battery, EV and WH. The flexible resources and PV-cells, are distributed throughout the neighborhood resulting in some consumers having more flexibility than others, but all consumers will have some sort of flexibility through the WH. An overview of the appliances can be seen i Table III.

TABLE III
APPLIANCES IN THE NEIGHBORHOOD

Appliance	Amount
Water heater	30
Electric vehicle	15
Battery	5
PV-cell	10

The two grid tariff structures will be applied on two levels: Neighborhood level and Consumer level. On the neighborhood level all of the consumers will contribute to a common electricity bill and therefore also work together to minimize it. For the consumer level all consumers are working individually and is unaffected by the operation of the other households. P2P trading will only be available for the consumers when the tariffs are applied at the neighborhood level. A summary of the four different case studies can be seen in Table IV.

TABLE IV
SUMMARY OF CASE STUDIES

Case	Tariff level	Tariff	P2P
Case 1	Consumer	Energy	No
Case 2	Neighborhood	Energy	Yes
Case 3	Consumer	Subscription	No
Case 4	Neighborhood	Subscription	Yes

A reference case was used to derive the price ranges of the tariff structures as well as to observe the effects of flexibility and P2P functionalities. The reference case includes the original Steinkjaer load curves, WH consumption and usage patterns for the EVs. The reference case has no form of optimization. It is assumed that the original load curves do not include WHs and that all WHs follow the same usage patterns mentioned in Chapter II. The reference case does not include batteries or PV.

IV. RESULTS

To be able to compare the results obtained from the different case studies the national load in Norway from 2012 is used. The 438 hours (5%) with the highest consumption represents peak load or scarcity hours. These hours are then used to collect the corresponding hours of the optimized results to see how the consumers operate during critical hours. These results are shown in figures 1 and 2, for consumer level and neighborhood level respectively, where the total import is sorted from largest to lowest with respect to the energy tariff. Figure 3 shows the duration curves for all the different case studies, and tariff structures during the peak load hours.

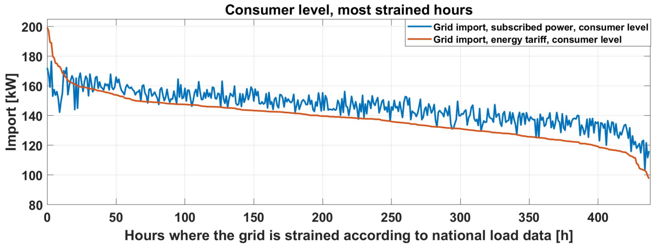

Fig. 1. Total import for the entire neighborhood with grid tariffs applied at consumer level

Figure 1 shows the neighborhood import for the two tariffs during the peak load hours of the national load with tariffs applied at consumer level. It is clear that the energy based grid tariff manages to maintain a lower level of import for most of the hours. The average import of the energy based tariff is lower than the subscription based tariff at 138 kW compared to 146 kW, but for the 25 hours with the highest import the averages are 171 kW and 167 kW, for the energy and subscription based tariffs respectively. The energy based tariff has the highest peak import of the two at 199 kW whereas the subscription tariff only reaches 177 kW, which corresponds to a 11 % decrease in peak load.

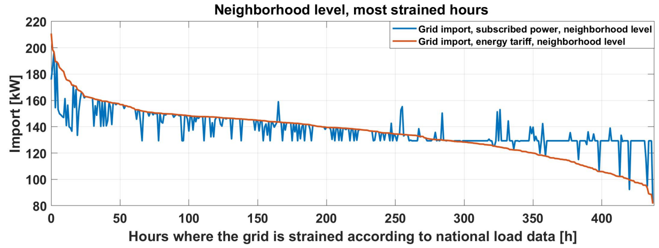

Fig. 2. Total import for the entire neighborhood with grid tariffs applied at neighborhood level

Figure 2 displays the neighborhood import with tariffs applied at neighborhood level during national peak hours. When optimizing under the subscription based grid tariff, the neighborhood import is lower until it reaches the subscription limit at 129 kW, clearly outperforming the energy based tariff with respect to reducing peak load during scarcity hours. Similarly to the case at consumer level, the energy based tariff has the highest import value during the peak hours at 211 kW compared to 196 kW for the subscription based structure, a drop of 7 %. The average import during the 25 worst hours is 179 kW for the energy tariff and 166 kW for the subscription tariff. The subscription tariff has a lower average import until the energy based tariff imports below the subscribed limit of 129 kW at 143 kW compared to 147 kW for the energy based tariff.

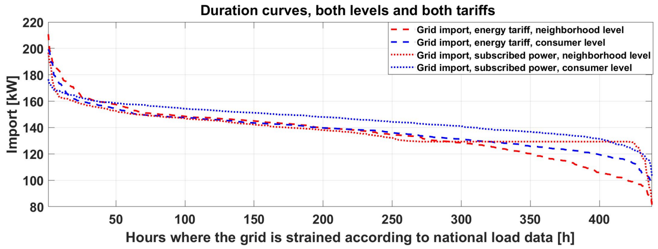

Fig. 3. Import for all four cases studies compared to the original load curve on neighborhood level.

The duration curves for the four different cases displayed in Figure 3 shows how the subscription based structure provides a more stable import for the neighborhood. This is particularly clear for the subscribed power at neighborhood level where the import is constant at the subscribed limit for over 150 hours.

To further investigate the impacts of the different grid tariffs, a day with many consecutive scarcity hours is chosen to exemplify flexibility operation. The 13th of December contains 15 hours from the selection of 438 peak load hours. This is shown in figures 4 and 5 for a prosumer and the neighborhood respectively.

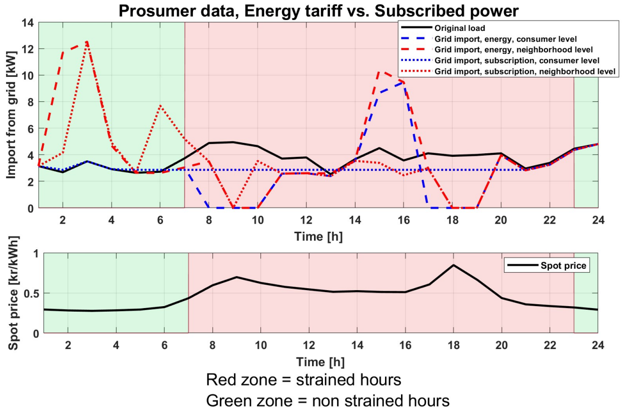

Fig. 4. Import for all four cases studies compared to the original load curve on consumer level.

Figure 4 shows how on the neighborhood level (red), both of the tariff structures import during the low load hours (01:00-07:00) to reduce load during high price hours occurring at 09:00 and 18:00. Both tariffs manage to reduce the power import at price spikes, but the energy based tariff creates a new power peak at 15:00-16:00. This is disadvantageous as this is still during the national peak hours.

When looking at the consumer level (blue) a similar scenario takes place. Both tariffs avoid the price spikes at 09:00 and 18:00, but the energy based tariff creates a new power peak at 15:00-16:00. The subscription based tariff structure manages to import at a stable rate by working towards, but preferably not over, the subscribed limit and thus distributes the load effectively. Figure 4 shows how subscribed capacity incentivizes stable net import during peak load hours, shifting large imports to low load hours, typically during the night.

An important aspect of the import curves in Figure 4 is the points where they are zero. In these time periods the prosumer is exporting electricity, but only for the neighborhood level will the prosumer be exporting this electricity to another consumer, and thus help the neighborhood as a community (P2P). This effect is visible in Figure 5 and will be discussed later.

When looking at the data for the neighborhood in Figure 5 it is also clear that the subscription based tariff is able to reduce the original load during peak hours, while the energy based tariff creates a new power peak. (Which is not necessarily worse than the two for the original load, but still worse than the subscribed power). This is the case for both neighborhood level (red) and consumer level (blue). This figure clearly shows the positive effects of P2P trading for the neighborhood. In time period 18:00-19:00 where the prosumer is exporting, the neighborhood is importing less energy from the grid for both tariffs when P2P trading is available (red) compared to when every consumer is working individually (blue).

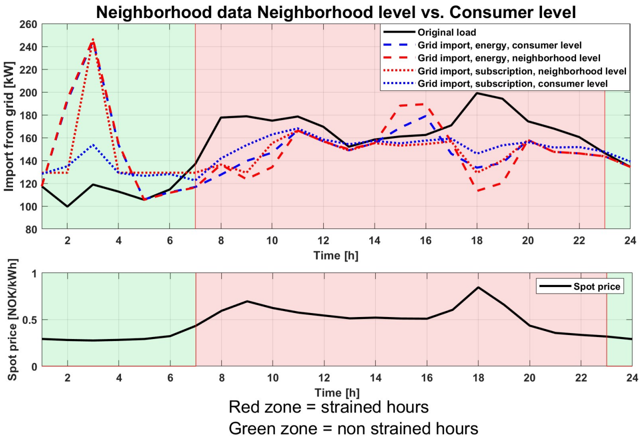

Fig. 5. Import for all four cases studies compared to the original load curve on neighborhood level.

V. Discussion

Figures 1 and 2 show that the subscription based tariff structure outperforms the energy based structure in reducing power peaks during scarcity hours for the national load. A reduction of 11% and 7% was seen for the consumer level and neighborhood level respectively. When looking at the 25 worst hours, the subscription based tariff has a lower average import at both tariff levels.

From the DSOs standpoint a stable grid is important. This makes future investments and expansions more predictable and less expensive. From Figure 3 it is clear that the subscription based tariff structure has the most stable import during scarcity hours. The results also show that aggregation outperforms consumer level metering. Figure 5 shows this effect clearly as the import is lower for both the cases where P2P trading is available. By operating under a common node, the strong prosumers are given incentive to help neighbors with less flexibility to reduce peak loads.

The difference in total cost between the subscription based tariff and the energy tariff in this paper is less than 1% for both consumer and neighborhood level. The results provided by this paper proves that the P2P technology is effective at removing power peaks during peak hours in the grid.

VI. Conclusion

The results show that the subscription based tariff structure was most effective at reducing power peaks in the 25 most critical hours. The subscription based tariff was also able to maintain a more stable import during peak load hours. Further, it was shown that tariffs applied at neighborhood level allowing for P2P trading, were most effective at lowering the total neighborhood import during scarcity hours with an 11 % peak load reduction. In conclusion, the subscription based tariff structure shows great potential for peak shaving, especially when combined with aggregated operation.

A possible improvement to the subscription based structure is to add another layer of overconsumption where if the import surpasses a certain point above the subscribed limit, the overconsumption price increases. This would further help keep power peaks to a minimum. Exploring the willingness to pay for local electricity (P2P) could also be interesting.

The current study aims to give an idea of how different grid tariff structures and a peer-to-peer market design can be used to reduce peak loads, and is thus deterministic and shows benchmark results with perfect foresight of load, PV production, prices and EV availability. Future studies could be done using stochastic programming or a sensitivity analysis in order to illuminate the consequences of not including uncertainty in the study.

This paper focuses on the duration curves and import for the neighborhood. In future research how and when the different flexible resources are being used, should be investigated to determine which are more effective and what impact they have.

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