A Market Framework for Enabling Electric Vehicles Flexibility Procurement at the Distribution Level Considering Grid Constraints

Gadea, Ana; Marinelli, Mattia; Zecchino, Antonio

Published in:
Proceedings of 20th Power System Computation Conference.

Link to article, DOI:
10.23919/PSCC.2018.8443012

Publication date:
2018

Document Version
Peer reviewed version

Citation (APA):
Gadea, A., Marinelli, M., & Zecchino, A. (2018). A Market Framework for Enabling Electric Vehicles Flexibility Procurement at the Distribution Level Considering Grid Constraints. In *Proceedings of 20th Power System Computation Conference.* IEEE. https://doi.org/10.23919/PSCC.2018.8443012

A Market Framework for Enabling Electric Vehicles Flexibility Procurement at the Distribution Level Considering Grid Constraints

Ana Gadea, Mattia Marinelli, Antonio Zecchino
Center for Electric Power and Energy – Department of Electrical Engineering
DTU – Technical University of Denmark
Risø Campus, Roskilde, Denmark
ana.gadea.capiscol@gmail.com; {matm, antozec}@elektro.dtu.dk

***Abstract*—In a context of extensive electrification of the transport sector, the use of flexibility services from electric vehicles (EVs) is becoming of paramount importance. This paper defines a market framework for enabling EVs flexibility at the distribution level, considering grid constraints. The main objective is to establish an adequate incentive system and proceed with an evaluation of EVs grid support for both users and DSOs, benchmarking it against the typical reinforcement solution. To exploit this framework, a billing process based on a two-price system is proposed for the controlled EV charging. The derived methodology is applied to a piece of semi-urban Danish distribution grid consisting of 42 customers. The service remuneration spans from 16 €/year to 51 €/year per customer, depending on the incentive scheme, and avoids a standard reinforcement of approximately 6200 €/year. It is demonstrated the benefit for DSOs and society, proving a technical and economic feasible solution.**

***Index Terms*—Distribution grid; electricity market; electric vehicles; flexibility procurement.**

I. INTRODUCTION

The proliferation of distributed energy resources (DERs) is transforming the operation of power systems substantially. A growing environmental awareness mainly drives this situation. In an attempt to reach the ambitious environmental targets, the electrification of the transport sector is a cornerstone. However, it jeopardizes the reliable and economical operation of power systems [1]. Characteristics as stochasticity, intermittency and bi-directionality impose additional constraints and challenges on maintaining grid balance and power quality. Traditionally, this is done via ancillary services from conventional generation units, but can also be provided via demand-response and storage solutions. Even though stationary batteries are still an expensive technology, other possibilities are arising. A smart EV integration potentially provides both storage and demand-response solutions, instead of being a mere load increase.

EVs uptake has been growing since 2010, surpassing the 2 million cars in 2016 according to IEA Global EV Outlook. Special characteristics, such as quick-response, attached battery and large idle times [2] make EVs attractive factors to consider. However, one cannot ignore the troubles that a passive EV penetration brings along. System components are not sized accordingly to this load rise since grids are long-term planned. To promote the use of system flexibility and safeguard supply at affordable prices at the same time, markets need to be redesigned. EU legislation is focused on liberalizing and interconnecting the internal electricity market, as Target Design Model lists [3]. In this context, DSOs role is highlighted [4] since most of the DERs are connected to the distribution grid. Even more, home EV charging relies on single-phase chargers which, together with the lack of regulation for per-phase connection, limits their penetration due to emerging grid issues.

System operators are responsible of guarantee stability and security of supply. Nowadays, a solution applied by DSOs to overcome load increase is via grid reinforcement. However, this is not always the most efficient solution to face the mentioned new challenges [5], due to aspects such as (1) *cost-effectiveness* –cables and transformers are expensive replacement parts, (2) *time constraints –D*SOs must submit an investment justification to the relevant authority for approval, which may be extended on time, (3) *environmental impact* –the ongoing electricity system transformation aims to mitigate climate change so not environmental friendly actions may not be consistent, and (4) *social perspective* –tariff rise to cover grid investments, long waiting time and environmental impact issues may lead to social unrest and public opposition. This context suggests that further solutions are needed, where flexibility services become an attractive alternative. It can benefit all involved parties through a more efficient and smart use of available resources.

A proved global advantage flexibility procurement endorses the transformation of current grids into so-called smart grids. This requires regulatory reforms for boosting efficiency and sharing. Such reforms suggest that system operators will be fostered to fulfill their tasks more efficiently. An example is the economic efficiency benchmark defined by the Danish Energy Regulatory Agency (DERA), which implies reductions on revenue caps of DSOs since 2007.

The authors would like to acknowledge the support of the EUDP project **ACES** – **A**cross **C**ontinent **E**lectric Vehicle **S**ervices (grant number EUDP17-I 12499). Website: www.aces-bornholm.eu

In conclusion, a smart planning for the integration of DERs is needed to shrink grid reinforcement necessity, improve system performance and ensure security of supply. A large EV integration, along with coordination of DERs and associated services, requires control systems and strategies, new market actors and regulations and efficient system and market signals. For the time being, this topic has been addressed for TSOs' further than for DSOs' services [6], [7]. In this paper, the authors aim at designing a market framework focused on the residential sector. This includes a numerical techno-economic assessment of local services and a benchmark against a grid reinforcement approach. The proposed methodology is applied to a Danish study case, which includes a piece of distribution network heavily loaded due to simultaneous EV uncontrolled charging. Network constraints and technical valuation of services are considered, based on previous works [8].

This paper is organized as follows. Section II recalls the electricity system structure and DSOs role. Section III discusses the used methodology and Section IV presents the tested case. Section V reports the results and Section VI concludes potential benefits and drawbacks of implanting the proposed concept.

II. ELECTRICITY SYSTEM AND DSOs ROLE

A. *Power System and Electricity Market*

The electricity system consists of a physical infrastructure and an electricity market. The former comprises the flow of electricity, allocating generation and transport systems, whereas the latter accounts for the movement of money. Fig. 1 illustrates a schematic overview of the contemporary electricity system structure. A centrally planned scheme lasted until early 1990s when a liberalization trend reached it. By introducing competition, energy market liberalization has led to a more efficient use of assets within power systems, bringing real, long-term benefits to customers. Regardless of liberalization, the development of power systems requires active government involvement. Some of the entities within the electricity market, as TSOs and DSOs, remained strongly regulated in Europe. Even more, they have responsibilities on both system operation and market aspects, providing non-discriminatory grid access. Thus, the new context makes necessary the re-definition of TSO-DSO interaction and their specific roles.

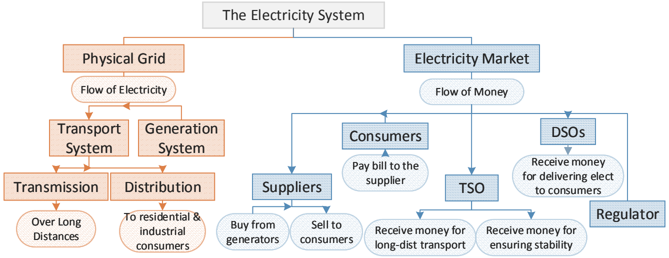


Figure 1. Schematic overview of the electricity system.

B. *Distribution System Operator: Grid Services*

The DSO is the entity concerned for operating, maintaining and developing the distribution system. It is also responsible for ensuring system ability to continuously meet reasonable demands at the distribution level. DSOs' tasks are mainly focused on long-term planning and design. This is related to the fact that they have been operating unidirectional and radial networks, where contingencies can be dealt with adequate grid planning [9]. Their concerns include finding the most efficient and affordable way for delivering electricity to consumers whilst ensuring service quality, which comprises both continuity of supply and power quality.

To achieve proper system operation, DSOs must solve grid contingencies as congestion and voltage issues. Whereas a solution to address voltage issues is often to install on-load tap changing transformers or reactive power compensation devices, to deal with congestion it is usual to upgrade overloaded components. As mentioned, reinforcements are likely to be common in the upgoing system environment, if no further actions are taken. Undesired cases will be less predominant using flexibility offered by existing agents. For instance, control EV charging scheme to provide voltage support and congestion alleviation is seen as an attractive solution [10].

C. *Distribution System Operator: Market Role*

Electricity markets operate at various levels, involving different actors. Generators compete in the wholesale market to sell power to suppliers and large consumers. Suppliers race in the retail market to sell power to end-users, such as industrials and households. Based on the focus of the study, this paper is structured around the retail market and only relevant features of it for the study´s goal are highlighted. The retail market is operated locally and is mainly focused on end-users and supplier. Prices vary from consumer to consumer, depending on the type of customer and contract. Even though it was fully liberalized in 2003, liberalization introduced competition only on retail and generation, leaving operation activities out of the free market. Producers and suppliers are commercial market players while TSOs and DSOs are neutral market facilitators.

In Denmark, a new market design was introduced in April 2016. The so-called Supplier Centric Model (SCM) is focused on increasing competition and transparency and promotes the development of new products and services. After its launch, the electricity bill was merged into a single bill sent by the supplier and the DataHub was established. This IT platform works as market data exchange mean [11] and aims to simplify and standardize communication among market players. It contains *wholesale master data* (e.g., tariff, fees, etc.), *consumer master data* (e.g., address, user category, etc.) and *metering point master data* (e.g., measuring point ID, grid area number, etc.). Through it, data flows among *DSO* –who sends data from consumers meters-, *supplier* –who use data to elaborate consumers' bills-, and *consumer* –who can checks own data.

Electricity invoices in the Danish statement can be divided in six broad categories: (1) *The supply tariff* gathers production costs and related services and is charged by the supplier. (2) *The distribution grid tariff* collects access and services at the distribution level and is charged by DSO. (3) *The transmission grid tariff* gathers access and services at high voltage system and is charged by TSO. (4) *The energy taxes* collect a range of electricity specific taxes and is levied by the state. (5) *The Value Added Tax (VAT)* which is imposed on all billed terms. (6) *The Public Service Obligation (PSO)* levied by TSO. Due to the system nature, TSO and DSOs operate as natural monopolists.

DSOs are free to set their tariffs, using a previously approved calculation method, where revenues are adjusted by an income limit. Both calculation method and income limit are fixed by DERA. Moreover, DERA sets for each DSO a benchmark economic efficiency, including a duty of quality of supply.

Based on a fast-evolving utility environment, those methods should be adapted to recognize new possibilities in the grid, enhancing flexibility procurement from DSOs. This work tries to contribute in this sense by presenting possible remuneration schemes for DSO services supplied by DERs. The proposed market framework is developed based on an analysis of the Danish residential sector and electricity bill structure. Fig. 2 breaks down a household (at. 4000 kWh/year) electricity bill in 2016, including both fixed and consumption-based terms.

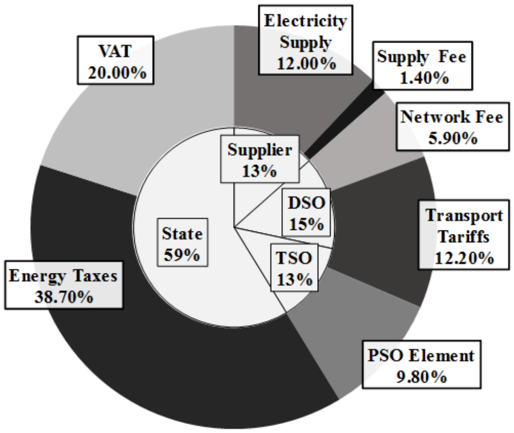


Figure 2. Standard household electricity bill composition, Denmark 2016. Data source: [12].

The graph shows the shares of each category in percentage. It is noted that almost 59% of the bill goes to the State, whereas only 12% is paid for the electricity consumed. This is charged by the supplier, together with a subscription fee of 1.4%. The transport tariff comprises 12.2%, including both distribution and transmission transport tariff. From this, the DSO takes approximately 9.1% and the TSO 3.1%. Adding the 9.8% of PSO, 12.9% of the invoice goes to the TSO. On the other hand, the DSO receives another 5.9% as network subscription fee, in addition to 9.1% of the transport tariff. The DSO is also responsible for transferring the 38.7% of tax payments to State.

III. METHODOLOGY

A. DSO Services Provided by EVs

To ensure safety operation manner of electric devices, the European standard EN50160 [13] defines limits for several grid parameters. Specifically, limits for Root Mean Square (RMS) phase-to-neutral voltage magnitude $|U_{np}|$ are established as:

$$0.90U_n \leq |U_{pn}| \leq 1.10U_n \;\; ; \;\; 0.85U_n \leq |U_{pn}| \leq 0.90U_n \quad (1)$$

for >95% and <5% of weekly 10 min intervals, respectively. Additionally, Voltage Unbalance Factor (VUF) is set as:

$$VUF[\%] = \frac{|U_{inverse}|}{|U_{direct}|} \times 100 \;\leq 2\% \quad (2)$$

where $|U_{direct}|$ and $|U_{inverse}|$ are the direct (positive) and inverse (negative) voltage symmetrical component, respectively. These terms are used for assessing voltage support in the tested study case. Regarding congestion, equipment technical limits defined by manufacturers are considered. As aforementioned, a primary goal of this study is the definition of a feasible and economical alternative to grid reinforcement by exploiting EVs flexibility. To reach that, a control strategy is applied to EVs charging processes considering congestion and voltage constraints.

Among the diverse strategies explored through the literature review, this study applies a decentralized charging schedule already proved in previous works [8]. The strategy proposed for voltage regulation support consists on both active and reactive EV power modulation responding to local voltage signals. This approach for addressing EV self-inductive voltage violation can be explained using a simple LV feeder (Fig. 3) and Equation (3), for voltage drop across the feeder. Equation (3) stated the direct impact of EV active power (P^{EV}) in voltage magnitude. Driven by this fact, adverse effects of EV charging on voltage levels can be controlled by modulating its charging rate. From (3), EV reactive power (Q^{EV}) arises as another possibility, if proper sized converter equipment is assumed. Further, the approach used for loading management is based on P^{EV} control, easing congestion by smothering out demand profile.

$$\Delta U \approx \frac{R(P_i^{PV}-P_i^{L}-P_i^{EV})+X(Q_i^{PV}-Q_i^{L}-Q_i^{EV})}{U_i} \quad (3)$$

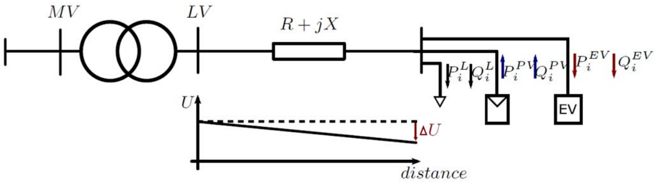


Figure 3. LV feeder with high local DERs penetration. Adapted from [8].

Hence, quality of supply when adopting large EV numbers can be supported, to some extent, by controlling P and Q injected to or consumed from the grid. Under the assumption of EV chargers equipped with voltage-dependent reactive power control (RPC), Q^{EV} modulation provides both inductive and capacitive Q depending on local voltage signals [14]. Notice that it is not sufficient to look only at X/R ratio but also the absolute value of both R and X are relevant (i.e., in short LV line, the effect of V/Q control may still effective) [15]. For P^{EV} modulation, a droop controller with current control mode (CCM) is used [16], [17]. This allows EVs response by varying charging current, according to IEC61851, and the resulting influence on P^{EV}. An impact on P^{EV} results in a slower EV charging process and, therefore, the willingness of EV owners for altering their charging patterns should be assumed. To support the effective application of the proposed combined, decentralized control scheme, the needs for a compensation framework for EV owners arise, justifying the paper's goal.

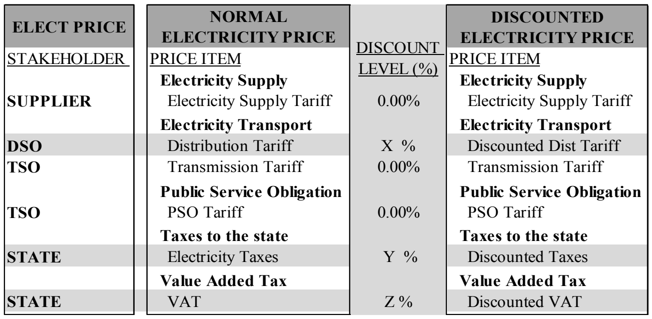
B. Market Framework for EV Flexibility Procurement

Following real trends, economic incentives are more likely at an early stage for compensation frameworks. This involves needs for varying hourly prices or fixed bilateral agreements, among others. As a status example, flex-pricing is scheduled to be rolled out in Denmark since March 2016, exposing end-users to individual hourly prices by 2020 [18]. In this paper, the economic incentive is addressed through the incorporation of EV services procurement in a defined market framework with varying prices rationale. Thus, the pricing method for the EV service delivery is a core part. This balances out flexibility procurement considering the explained EV charging controller performance and settles service supply by a two-price system, applying a discounted price to the amount of energy shifted for alleviating critical grid conditions. The final objective of the proposed method is to evaluate the technical grid benefit at a distribution level, together with the potential EV user' savings. The rationale of the designed billing process consists of, firstly identifying the amount of energy provided on schedules and the amount shifted and secondly quantify economically both terms by applying different prices. Peak and off-peak demand periods are reflected with higher and lower prices, respectively. Based on this, the energy shifted from peak (when the grid issue is detected) to later hours (when the normal stage is recovered) is assumed cheaper for the system. Both quantities are assessed as a ratio between the economic value of the EV uncontrolled charging scenario and the analogous value with PQ control. Thus, the method rewards EVs support while brings to DSOs a cost-efficient way to maintain quality and security of supply.

The mentioned two-price model is defined based on retail market dynamics and the household electricity bill structure. Three actors are identified as the most relevant for the matter: (1) *EV user*, (2) *DSO* –which would have access to a direct and fast grid support opportunity, and (3) *State* –which would benefit from substantial social benefits of smart EV integration and, in return, shall lead users engagement and legal framework definition for the new service. As for the bill structure, charged items can be clustered in consumption-based terms (price/kWh) and fixed terms (price/billing period). Due to their respective nature and the proposed methodology, reductions are assumed viable on consumption-based terms, which comprise the price per kWh paid by the end-user. Among those, for the discount design, the focus is on the price quota shared by DSO and State.

Fig. 4 summarizes the proposed two-price model drawing. The method considers reductions in distribution transport tariff (X in Fig.4) and energy taxes (Y and Z in Fig.4). The former is justified by the direct benefit on grid operation from the EV support, whilst the latter is supported by a potential welfare increase. Thus, the small discount of distribution tariff is seen as an improvement investment for a better system performance, more efficient and flexible, which are crucial aspects of the new power system. The latter is chosen as an endorsement to enable EVs flexibility procurement, due to its potential in pivotal aspects such as reaching environmental targets, a sustainable development and use of available resources and the social welfare enhancement. The reduction in the DSO invoice item is shorter, whereas the bulk is over the State quota as tax drawdown. The rationale is based on current retail market rules regarding system operators cost coverage. Besides, two incentive scheme levels have been tested. A moderated one, cutting VAT down (Z=100%), and an aggressive one, in which both VAT and energy taxes are suppressed (Y=Z=100%).

Summarizing, within the designed framework, the EV grid support is procured and rewarded when needed, contrasting with the grid reinforcement approach. From a user perspective, this method may incentive a higher engagement since the greater the participation, the more they would save in the bill. From the DSO's perspective, EV services procurement is a benefit since network contingencies are expected to take place on few months over the year when they will reward the services. Notice that the proposed market framework methodology does not require any additional contract. Instead, EV charging costs are part of the standard electricity bill and can be calculated by giving to the supplier the information regarding prices and amount of energy on schedules and shifted. The reason is to minimize the changes needed to integrate this service procurement and its market framework. Besides, the proposed two-price model is easily extrapolated to any other study case, by adjusting market stakeholders' quotas and the bill structure.



ELECT PRICE	NORMAL ELECTRICITY PRICE		DISCOUNTED ELECTRICITY PRICE
STAKEHOLDER	PRICE ITEM	DISCOUNT LEVEL (%)	PRICE ITEM
	Electricity Supply		**Electricity Supply**
SUPPLIER	Electricity Supply Tariff	0.00%	Electricity Supply Tariff
	Electricity Transport		**Electricity Transport**
DSO	Distribution Tariff	X %	Discounted Dist Tariff
TSO	Transmission Tariff	0.00%	Transmission Tariff
	Public Service Obligation		**Public Service Obligation**
TSO	PSO Tariff	0.00%	PSO Tariff
	Taxes to the state		**Taxes to the state**
STATE	Electricity Taxes	Y %	Discounted Taxes
	Value Added Tax		**Value Added Tax**
STATE	VAT	Z %	Discounted VAT

Figure 4. Price system calculation methodology. The items correspond to the charges based on consumption of Danish retail market dynamics.X,Y and Z represents variables to be adjasted with the % of item quota to discount.

C. Grid Reinforcement Calculation

This section addresses a typical DSO solution design to overcome grid contingencies caused by sharp load increases. This is issued as a reference point against which assessing the economic feasibility of EV services in a residential distribution network. Loading and voltages have been identified as primary grid issues concerning DSOs and, thus, comprise the focus in this paper. As aforementioned, nowadays, a typical solution for tracking with congestion problems is to replace affected components. To deal with voltage problem, there is a broad variety of options, such as power factor control devices, shunt capacitors or on-load tap changing transformers.

Several options for grid contingencies remedy have been modeled and simulated for the tested case. The final solution includes the installation of a switched shunt capacitor bank and the upgrading of existing MV/LV transformer and distribution line. Once the solution is properly dimensioned over an iterative process, it is economically assessed by quantifying the Capital Expenditure (CAPEX) and Operating Expenses (OPEX) terms. It is worth noting that for both cable and transformer upgrade, OPEX is accounted null, since operation and maintenance costs are assumed to remain the same for the new equipment than for the existing. The calculation procedure for CAPEX and OPEX is further detailed in [19], together with the equipment sizing. In a nutshell, a year period is considered due to availability of real grid data. For the yearly calculation, lifetime is assumed of 10 years for capacitor bank and 30 years for both transformer and cable and, hence, 3 capacitor banks are needed to meet the

30-year lifetime. Since EV integration is seen as long-term issue, no residual value of equipment at the end of study period is considered (next year period would use same equipment). Table I summarizes the annual reinforcement costs resulted.

TABLE I. SUMMARY OF ANNUAL GRID REINFORCEMENT INVESTMENT COST

Capacitor bank annual OPEX	754 €/year
Capacitor bank annual CAPEX	1,141 €/year
Total annual capacitor bank cost	**1,895 €/year**
MV/LV Transformer annual CAPEX	1,431 €/year
Total annual transformer cost	**1,431 €/year**
Distribution cable annual CAPEX	2,925 €/year
Total annual cable cost	**2,925 €/year**
Total annual grid reinforcement	**6,251 €/year**

IV. TEST CASE

A. Distribution Grid Characteristics

The methodology proposed in this paper has been applied to a study case, already used in previous works [14]. It consists of a radially run, semi-urban LV grid, based on a real network located in the Danish town of Borup. The LV grid (U_n=400V) is wired to the MV grid (U_n=10kV) through a 10.5/0.42 kV 400kVA distribution transformer and supplied by ungrounded cables divided into 13 segments with a line length of 681m. The grid consists of 4 feeders, with around 120 users as illustrated in Fig. 5. Real consumption and PV production data are available on hourly basis for a one-year period, as individual phase-by-phase data for one feeder and as aggregated load data for the remain 3 (Fig. 6). The model, simulated in DIgSILENT PowerFactory, consists of 42 household users split in 14 nodes, an aggregated load and an aggregated PV injection. Based on the DSO experience, the grid is assumed unbalanced. Phase a is loaded approximately double than b and c, so 50% of the three-phase load measured is set in phase a, 25% in phase b and 25% in phase c. An inductive power factor of 0.95 is also assumed.

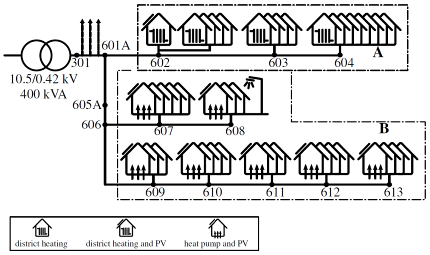


Figure 5. The topology of simulated Borup LV grid. Adapted from [8].

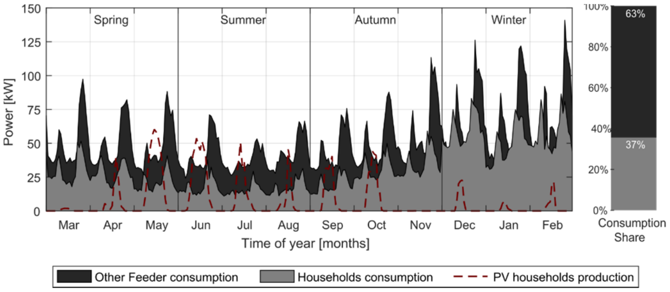


Figure 6. Consumption and production profiles in the real Borup LV grid from March 2012 to February 2013, with 0% EV penetration.

B. Electric Vehicles Integration

EVs are simulated under the assumption of each household owns a single car. The impact of the EV integration on the electricity demand profile is largely dependent upon the driving and charging user behavior. The EVs charging pattern modeled in this study is based on results from the Danish real-life project "Test-an-EV" [20], which are similar to the European "Green eMotion" [21]. Thus, charging data in this study are derived from realistic driving behavior. An adverse *dumb charging* scheme is also considered for the definition of the load profile used, under which EVs are charged as soon as they are plugged-in. To sum up, 42 daily domestic changing events are simulated.

All EVs added are assumed as Peugeot iOn, with a 16 kWh Lithium-ion battery. They are single-phase units with a max. charging rate of 3.7 kW (16A, 230V), which corresponds to Mode 2 of IEC technical standard. It is assumed the charging events start at 18:00 and end at 22:00, coinciding with households' peak demand. Over these 4 hours, charging rate profile varies as follows: first hour, EVs charge at a rate of 3 kW, increased to 3.7 kW for next two and a half hours and ending at a level of 0.2 kW for last half an hour. Daily charging amounts a total of 12.35 kWh. Hence, a 100% SOC is reached, if cars arrive home with 25% of battery capacity. Such SOC level represents a conservative situation since on average in Denmark EVs arrive to final destination with around 49% SOC. Connection points are distributed sequentially. Chargers are assumed to have RPC capability, which allows Q provision from EVs as a function of local voltage signals [15], [14].

V. RESULTS

A. Grid Constraints Analysis

Some relevant technical parameters are compared for three distinctive scenarios and chosen according to the grid services covered in this study, i.e., congestion management and voltage support. Modeled scenarios represent the following situations: (1) *No EVs* –used as base case to set up the grid operational status before EV integration, (2) *No control* –with 42 EVs integrated in the system as passive loads with fix charging pattern, and (3) *PQ control* –same case, with explained control strategy activated. One-year RMS time-domain simulation is run, with power flow calculations in intervals of 600 seconds. Considering the results obtained, EVs ability to provide adaptive voltage support and general congestion alleviation is a recognized fact. The assistance is given without significantly affect user mobility patterns, i.e., each EV reaches 100% SOC everyday with only slight deviation from base pattern (Fig. 7). The autonomous, decentralized service feature of the scheme is also confirmed. EVs assist regardless location of connection, i.e., every EV provides support in case the connection node signal requests it. Both facts are illustrated in Fig. 8.

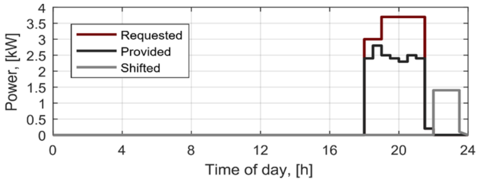


Figure 7. Energy requested, provided and shifted standard profile.

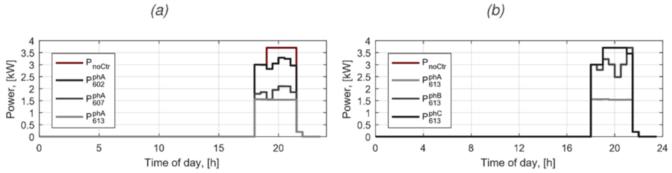


Figure 8. Controlled EV charging profile analysis *(a)* per phase for 3 representative buses: 602 (closest to feeder), 607 (middle), 613 (furthest from feeder), *(b)* of phase a, phase b and phase c connection for same bus 613.

Even though there is a slight rise in the VUF values up to 2% limit, the voltage support provided attends to specific needs of each node, mitigating the self-inductive voltage impact in a smoother way than the support provided by reinforcement. This impact mitigation and smooth support is ratified by Fig. 9, where boxplots for PQ control show a significant reduction of outliers (black lines). Regarding overloading, cable problems are sorted out whilst transformer ones are halved (Table II), merely turning out in a moderate increase in losses, due to the increase in Q flow. Hence, EVs charging control helps to keep reliable grid operation and avoid infrastructure investments.

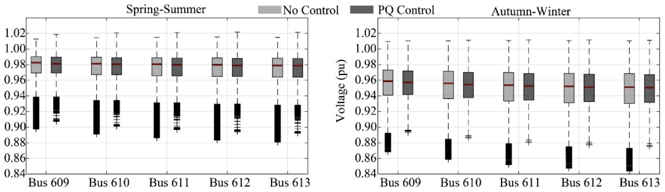


Figure 9. Phase-to-neutral voltage for selected junction points in the simulated grid during Spring-Summer and Autumn-Winter months.

TABLE II. CABLE AND TRANSFORMER LOADING

Scenario	**Maximum Loading**		**Δoverloading**
	Spring-Summer	***Winter-Autumn***	***Over year***
Cable - No control	105.03 %	124.65 %	-
Cable - PQ control	101.35 %	107.29 %	93.56 %
Trafo – No control	107.17 %	129.53 %	-
Trafo – PQ control	99.00 %	116.22 %	50.60 %

B. Economic Assessment of EV Services.

As mentioned, the application of the proposed PQ control generates a change in EV charging patterns (e.g., Fig. 7). For the economic valuation, the new EV total charging energy profile is divided into three parts: requested, provided and shifted. The amount of energy for the last two varies from car to car depending on EV connection point and grid operational situation, whereas the energy requested remains 12.35 kWh (as shown in Fig. 7 and Fig. 8). Table III lists the amount of energy requested, provided and shifted after the control activation. It can be observed a clear greater support over the Autumn-Winter than over the Spring-Summer months. This is due to a much higher consumption pattern in winter mainly due to heat pumps and null PV production. From autonomy range estimates (in km), driving needs are covered comparing with results reported by “Green eMotion” project. The different EV support procurement, dependent on connection point (shown in Fig. 8), is recognized throughout the compensation frame proposed (i.e., incentive framework is designed to offset users according to the explicit support provided). The penalization in terms of energy shifted, faced by users connected to further buses from transformer, is compensated with a higher savings in the electricity invoice. Hence, the costs that users pay for charging EVs also differ over the year and from user to user.

Table IV summarizes the amount paid, on average, per EV user for charging the car, discerning between whether DSO-based services are provided. Costs listed are estimated using a regular price of 0.31 €/kWh for energy provided on time, and a discounted price of 0.24 €/kWh, for the moderate incentive scheme (VAT-free), and of 0.11 €/kWh, for the aggressive incentive scheme (tax-free), for the energy shifted. From the results, an individual EV user can potentially save, on average, from 4 to 14 cents per charge. This spans from16 € to 51 € per year, depending on the level of incentive scheme applied. Notice that a single home charging per day per EV is considered in the calculations, assuming one daily charge.

TABLE III. ENERGY REQUIRED, PROVIDED AND SHIFTED, PER EV

Type	**EV charging energy**			
	Spring-Summer		***Autumn-Winter***	
Requested	12.35 kWh	82 km	12.35 kWh	82 km
Provided	12.08 kWh	80 km	11.38 kWh	76 km
Shifted	0.27 kWh	2 km	0.97 kWh	6 km

TABLE IV. CHARGING COST FROM EV USER PERSPECTIVE FOR EACH EV

Scenario	**EV charging cost summary**			
	Cost/day	***Cost/year***	***ΔCost/day***	***ΔCost/year***
No control	3.83 €	1,399 €	-	-
PQ ctr VAT-free	3.79 €	1,383 €	0.04 €	16 €
PQ ctr tax-free	3.69 €	1,348 €	0.14 €	51 €

For a total amount of 42 EVs and 365 days of simulation, market income from EVs charging sums up 58,758 €. By controlling them, the income is confined to approximately 58,086 €. In line with the methodology proposed, DSO and State share of the income is chosen as a relevant parameter for the study. Table V reports the daily and yearly income that DSO and State receive per EV user. Columns ‘ΔIncome’ expressed the subtraction of no control and control scenarios incomes. This embodies the economic value of EV services provision at the distribution level, estimated in around 672 €/year in case of only VAT is suppressed and 2,142 €/year in case of a totally tax-free scenario, for the 42 customers considered.

TABLE V. DSO/STATE INCOME FOR EACH EV CHARGING PROCESS

Scenario	**DSO/State EV charging income**			
	Day/EV	***Year/EV***	***ΔIncome/day***	***ΔIncome/year***
No control	2.779 €	1,014.64 €	-	-
PQ ctr VAT-free	2.736 €	998.64 €	0.04 €	16 €
PQ ctr tax-free	2.640 €	963.64 €	0.14 €	51 €

Table VI reports the socio-economic assessment carried out to compare EV services supply benchmarking against the grid reinforcement situation, from a purely economic perspective. The results reveal the potential economic benefit of using EVs capability to respond to grid issues. To conclude, the proposed framework brings an estimated service value of around 16 €/year per EV, and the consequent saving of 6,251 €/year as for grid reinforcement prevention, in case of a moderate incentive scheme is applied by the State. Even though full energy taxes quota applied on top of electricity price is suppressed, it is estimated a benefit of 4,109 €/year. The study considers also the possibility of a transformer upgrade necessity. Even in that case, economic benefit is proved (aggressive incentive scheme: 4,820–2,142=2,678 €/year). Thus, the results confirm the method proposed compensates EV users while brings to DSOs a cost-efficient way to maintain reliable grid operation. A significant potential benefit is deduced from the economic assessment. Much of the benefits arise due to a low EV service valuation, which depends directly on the amount of energy shifted. Through a combined use of P and Q control responding to the same input signal, a large grid operation improvement is achieved without significantly altering EVs users' comfort.

TABLE VI. SOCIO-ECONOMIC ANALYSIS OF DSO-SERVICES

Total grid reinforcement cost	**6,251 €/year**
EV user compensation, VAT-free strategy (X=25%, Y=0%, Z=100% in Fig.4) **Total charging cost reduction**	**672 €/year**
EV user compensation tax-free strategy (X=25%, Y=100%, Z=100% in Fig.4) **Total charging cost reduction**	**2,142 €/year**
Total social benefit, VAT-free strategy	**5,579 €/year**
Total social benefit, tax-free strategy	**4,109 €/year**

VI. CONCLUSIONS

At distribution grid level, the large additional electrical load due to EVs charging and the concurrent simultaneity with the residential peak demand result in sharp consumption increases. This may lead to severe voltage deviations and overloading conditions. Given the DSO long-term planning and its regulated nature, this reflects a need for grid reinforcements if no further solutions are implemented. Due to some constraints such as cost, time and environmental impact, the mentioned solution is not always the most efficient from a socio-economic point of view. In an attempt to avoid grid reinforcements, technical infrastructures adaptions and market and regulation redefinition are required, fostering active participation of EV users. The paper described an adequate incentive system and reported an economic evaluation of EVs grid support, defining revenues for both users and DSOs/State. The analysis was technically supported by load flow analysis to prove that the adopted methods for solving congestions and under-voltages do not violate grid constraints. Both active power and reactive power modulations are implemented along with the necessary remuneration scheme for EV distribution grid services. This solution assumes stakeholders' willingness to participate, concluding the need for a market framework for engaging the use of EV flexibility services. This paper sets an economic compensation to EV users for the services provided, based on a two-price system. Using the reinforcement solution as a benchmarking, the economic assessment of the proposed EV services shows a clear potential economic benefit for the whole society. Part of the large benefit is due to the combination of active and reactive power modulation, which results in a large operation improvement without significantly alter EV charging pattern and bringing DSOs a cost-efficient solution. In the end the value of the tested distribution grid service span from 16 to 51 €/year depending on the level adopted. Additionally, in the proposed methodology, EVs support is procured and rewarded only when needed, in contrast with the permanent feature of the grid reinforcement. This leads to a higher benefit since grid issues are focused on few weeks over a year. Even users′ revenue seems limited, Danish customers are very respondent when it comes to this type of societal participation, as proven in demand respond activities such as the EU project "Ecogrid". The mentioned market framework is focused on the EV topic, even though could be easily adapted to other appliances. In case of extrapolation to other appliances, households′ revenue from grid services will be escalated.

REFERENCES

[1] V. Marques, N. Bento, P. Moisés Costa, "The "Smart Paradox": Stimulate the deployment of smart grids with effective regulatory instruments," *Energy*, Vol. 69, Pages 96-103, 2014.

[2] W. Kempton and J. Tomic. Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of power sources*, 144(1):280–294, 2005.

[3] M. Keay. The eu target model for electricity markets: fit for purpose. Oxford Institute for Energy Studies, 2013.

[4] G.P.J. Verbong, S. Beemsterboer, and F. Sengers. "Smart grids or smart users? Involving users in developing a low carbon electricity economy." *Energy Policy* 52 (2013): 117-125.

[5] European Distribution System Operators for smart grids, "Flexibility: The role of DSOs in tomorrow's electricity market," Tech. Rep., 2014.

[6] P. Codani, M. Petit and Y. Perez, "Diversity of transmission system operators for grid integrated vehicles", in *11th International Conference on the European Energy Market (EEM)*, 2014.

[7] E. Commission, "Incorporating demand side flexibility, in particular demand response, in electricity markets," Tech. Rep., 2013.

[8] K. Knezović. Active integration of electric vehicles in the distribution network-theory, modeling and practice. PhD thesis, Technical University of Denmark, Department of Electrical Engineering, 2017.

[9] The Union of the Electricity Industry - Eurelectric. "Network tariff structure for a smart energy system". Tech. Rep., 2013.

[10] K. Knezović, M. Marinelli, A. Zecchino, P. B. Andersen, C. Traeholt, "Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration," *Energy*, Vol. 134, Pages 458-468, Sep. 2017.

[11] Energinet.dk. The danish electricity retail market - introduction to datahub and the danish supplier-centric model.

[12] Dansk Energi (Danish Energy Association). Følg strømmen, din elguide (follow the power, your electricity guide), 2016. Available http://www.danskenergi.dk/~/media/Forbruger/DinElguide.ashx.

[13] H. Markiewicz and A. Klajn, "Voltage disturbances standard EN50160," Tech. Rep., 2004.

[14] K. Knezović, M. Marinelli, Phase-wise enhanced voltage support from electric vehicles in a Danish low-voltage distribution grid, 140 (2016).

[15] A. Zecchino, M. Marinelli, "Analytical Assessment of Voltage Support via Reactive Power from new Electric Vehicles Supply Equipment in Radial Distribution Grids with Voltage-Dependent Loads," International Journal of Electrical Power & Energy Systems, vol 97, pp 17-27 (2018)

[16] S. Martinenas, K. Knezović, and M. Marinelli. Management of power quality issues in low voltage networks using electric vehicles: Experimental validation. *IEEE Transactions on Power Delivery*, 32(2):971–979, 2017.

[17] J. N. Alvarez, K. Knezović and M. Marinelli, "Analysis and Comparison of Voltage Dependent Charging Strategies for Single-Phase Electric Vehicles in an Unbalanced Danish Distribution Grid", in *2016 Proceedings of the 51st International*, pp. 1-6, Coimbra, 6-9 Sep. 2016.

[18] Neas Energy and Ea Energy Analyses, "Congestion in distribution grids. Evaluation and analysis of DSO options for congestion management in smart grids," Tech. Rep., 2014.

[19] A. Gadea. "Technical investigation and economic assessment of DSO based services from electric vehicles". MSc thesis, 2017, Technical University of Denmark, Department of Electrical Engineering, 2017.

[20] Test-en-EV consortium. Test-an-EV project: Electric vehicle (EV) data.

[21] Green eMotion consortium. Deliverable D1.10: European global analysis on the electromobility performance, technology-lead and user-friendly system, 2009.