# Network tariff design with prosumers and electromobility: who wins, who loses?

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**Abstract**

Distributed Energy Resources (DERs), mostly in the form of solar photovoltaic (PV) or lithium-ion batteries, and electric vehicles (EVs) are emerging as three disruptive innovations in power grids. Recent studies have pointed out the potential synergies between these technologies, while others have studied the difficulty to design adequate network tariff when some consumers can adopt DERs (prosumers). In this paper, we investigate the combined effect of DERs and EVs on grid cost recovery. To study these effects, we formulate a non-cooperative game between a regulator that sets tariffs to recover grid costs and the four classes of network users depending on whether they are prosumer (resp. EV owners) or not. We study how tariff structures and the levels of EV penetration and prosuming affect tariffs. First, we find that grid cost recovery concerns caused by load-defecting prosumers installing DER can be balanced by the diffusion of EVs in the network. Second, we highlight that EVs and DERs adoptions are conflicting through the network tariff design. In particular, we find that the more a tariff structure gives incentives for DERs, the less beneficial it is for EVs.

*Keywords:* Electric vehicle, Prosumers, Distributed energy resources, Tariff design, Distribution grid

## 1. Introduction

The power sector faces deep transformations, motivated by environmental reasons and led by disruptive technologies. Within these transformations, two of the main trends can be identified: energy self-supply and electrification. On the one hand, distributed generation and storage allow some consumers[1] to produce and self-consume electricity with flexibility. On the other hand, the electrification of sectors (transport, heating) should significantly increase consumers' power consumption. To this regard, solar photovoltaic (PV)[2] and lithium-ion batteries for the first trend and electric vehicles (EVs)[R1] for the second, are the main representative technologies. Indeed, both solar PV and lithium-ion batteries have had a spectacular decline in costs (Schmidt et al., 2017; IEA, 2018; Nykvist et al., 2019). Simultaneously, solar PV and EVs have been supported by strong public policies and regulations (MIT, 2015; IEA, 2018).

In this context, the traditional organization of grids is being moved by these new technologies and network uses. This paradigm shift of electricity use is challenging the current economic rules of power grids, with fears of system efficiency losses and fairness matters between consumers (Eid et al., 2014). Nevertheless, smart association of these new technologies could bring economic gains for users as for the power system

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[1] In this paper, such consumers will be designated by the term *prosumers*.

[2] *Abbreviations*: EV, electric vehicle; TV, traditional vehicle; PV, photovoltaic; DER, distributed energy resources; DSO, distribution system operator; SOC, state of charge; EVIC, EV incremental costs.

(Richardson, 2013; Hoarau and Perez, 2018). Therefore new regulations are needed to cope with these issues while ensuring a well-functioning power system. Among these, the design of network charges is a particularly crucial issue (Pérez-Arriaga et al., 2017).

This paper investigates the tariff design of low-voltage distribution grids with high levels of adoption DERs (solar PV and batteries) and EVs~~electric vehicles (EVs)~~[R1], which is still a rather unexplored issue in the literature (Pollitt, 2018). More precisely, it studies the interactions of the behavior of prosumers that are able to invest in distributed energy resources (DERs)[3], with the adoption of electric vehicles that significantly increases the electric consumption of their owners[4]. The tariff design process is modeled as a non-cooperative game between various classes of network users and a regulator who enforces the network cost recovery. Numerical case studies are conducted with different scenarios of EV diffusion and prosuming and different tariff structures. The impacts on network tariffs of increased proportions of prosumers and electric vehicle owners in the network with different tariff structures are investigated. We describe precisely how network costs are shared between the different users. Along with this, we provide evidences of conflicts between DER adoption and EV adoption through the grid costs recovery enforcement by the regulator. These conflicts generally translates into either cross-subsidy from EV owners to prosumers or by decrease of the profitability of DER investments. We also determine how the tariff structure drives those conflicts. We found that the more a tariff structure gives incentives for DERs, the less beneficial it is for EVs, and vice-versa. In addition, the appendices of this paper provide results on the robustness of the previously described mechanisms to (1) alternative tariff structures and (2) variable components in the grid costs structure.

The paper is organized as follows. First, the motivations of these research questions are presented with a literature review on three related research topics. Then, the modeling framework and the assumptions of the associated simulations are described. Results are presented on section 4 which discusses (1) the impact of EV and prosuming on tariff design, (2) the spillovers between EV and DER adoption through tariff design. Last section concludes the paper and discusses policy implications of this study.

## 2. Literature review

The contribution of this paper is at the intersection of three strands of literature. The first deals with designing network tariffs when grid users acquire DERs. The second one studies the integration of EVs in power grids. The interaction between electric vehicles and DERs constitutes the third body of literature. In this section, we briefly present these three strands, and we review the elements of modeling needed to study the interactions between tariff design, electric mobility and prosuming.

Volumetric tariff with net-metering have been the traditional way of recovering distribution network costs. However, many scholars have evidenced that under such tariff structure, DERs and especially solar PV, leads to inefficiencies and fairness issues between network users (Eid et al., 2014; Simshauser, 2016; Jenkins and Pérez-Arriaga, 2017). Indeed, prosumers become able to react to electricity prices to minimize their bill by investing in solar PV. They save on energy costs as well as network costs with a volumetric with net-metering tariff. At some point, this could lead to threaten the financial balance of distribution system operator (DSO). To prevent this, regulators would have to increase tariff levels and this for all users. This results in an increase of traditional (passive) users' bill and hence a sensible fairness issue between network users. Numerous studies have investigated alternative tariffs that would integrate solar PV both efficiently and fairly. For instance, (Simshauser, 2016) has argued that capacity tariffs should remove the over-incentives on solar PV brought by volumetric tariffs. However, this issue is still controversial in the literature (Brown and Sappington, 2018; Passey et al., 2017). For instance, (Kubli, 2018; Schittekatte et al., 2018) have indicated that capacity tariffs give incentives for the adoption of low-cost lithium-ion batteries, which could also create similar fairness and efficiency issues. This strand of literature mainly focuses on tariff design with technologies that allow users to reduce their consumption (energy or peak power). To the

[3] By investing in DERs, prosumers may seek to minimize their electricity costs and are hence able to react to changes in network tariffs.

[4] For instance, (Andersen et al., 2017) has shown that for an household from the EU, charging an electric vehicle at home can increase power consumption almost by a factor two.

best of our knowledge, no study has considered adoption of technologies that would significantly increase power consumption of users, such as electric vehicles.

Although EVs represent a potential huge source of revenues for electric utilities (Kempton and Letendre, 1997), numerous studies have pointed out that a disorganized deployment of EVs in power grids could severely affect the stability of networks[5] and hence increase total network costs (Clement-Nyns et al., 2010; Fernandez et al., 2011; Muratori, 2018; Verzijlbergh et al., 2012). Nevertheless, such effects are dependent on the robustness of the network (Neaimeh et al., 2015). Moreover, the flexibility of the EV battery provides a wide range of options to mitigate these impacts on grids, thanks to so-called smart charging strategies (García Villalobos, 2016). Assessing the economic and regulatory incentives to make EV drivers and fleet managers to such uses is therefore a crucial issue for efficient integrations of EVs (Eid et al., 2016; Knezović et al., 2017). Among these regulations, electricity prices can give strong incentives to adopt smart charging. Network tariffs can therefore play a significant role, that yet needs to be described. We contribute to this research field by assessing how the electricity costs of EV owners vary with the network tariff design and how large EV diffusion could affect the tariff design.

Finally, we contribute to the literature on the interaction between EVs, solar PV and distributed storage, which has gathered much attention recently (Richardson, 2013; Hoarau and Perez, 2018). This research topic is motivated by the following reasons. Electric vehicles need low-cost power for charging and require a low-carbon energy to have a significant environmental benefit against internal combustion vehicles (Fang et al., 2018). PV generation needs flexible storage to face its variability and intermittency. Moreover, local PV generation could alleviate electric vehicles' impact on power grids (Islam et al., 2016). Nevertheless, (Munkhammar et al., 2015) have pointed out that since EV charging should be synchronized with PV generation hours, there should not be much synergy between EV and PV in residential areas, where EVs are away most of the day. However, (Alirezaei et al., 2016; Kaschub et al., 2016) have shown that low-cost home batteries could bypass this issue and ensure significant economic and environmental gains. Generally, there is a lack of studies that integrate economic and regulatory aspects of couplings between EVs and DERs (Hoarau and Perez, 2018). This paper fills one gap in this strand of literature by investigating the effects of network tariff design on the interactions between EVs and DERs. There are few papers that simultaneously take into account EVs, DERs and network tariffs. (Kaschub et al., 2016) study how the profitability of home systems comprising solar PV and batteries was affected by EV charging and retail tariff, but there is no feedback on the tariff design. In a recent paper, (Küfeoğlu et al., 2018) developed a case study on tariff study for British distribution grids and assessed that EVs were counterbalancing the increasing effect on tariffs induced by solar PV, but the authors neither consider batteries or load flexibility.

A difficulty in the modeling of tariff design with EV and DERs is to consider key-elements of the three fields that have been previously discussed. Studying the integration of EVs in power grids require to model the effect of the EV charging patterns on the single EV owner's load profile and aggregate effect of EVs on the network peak power and network costs. At the same time, investigating the interactions between EVs and DERs needs to model precisely the consumption of users and how they invest and optimize their consumption (in energy and power) with electricity prices. Designing efficient and fair network tariffs requires to take into account the newly conflicting aspect of this problem. One of the main missions of the regulator is to ensure the cost recovery of utilities in charge of distribution systems operations. In the network, some users are now able to react to changes in their electricity costs by investing in DERs. Such conflicting situation can be modeled by non-cooperative games. More precisely, a non-cooperative game between the regulator and network users would be the appropriate methodology. Such games have been applied for the studies of smart grids organized by an aggregator such as in (Yu and Hong, 2016; Tushar et al., 2012). Such modeling methods allow to evaluate both distributive aspects and welfare aspects of the tariff design (Brown et al., 2017; Schittekatte and Meeus, 2018). In a neighboring study on this paper, (Küfeoğlu et al., 2018) models different penetration levels of solar PV and EVs and their implications on the network tariffs. But the authors neither model the precise load profiles of users, nor the reaction of some users to network tariff to optimize their consumption, nor emit welfare considerations.

[5]Typical effect of massive uncoordinated EV charging in distribution network are increased power loss and reduction of transformers lifetimes.

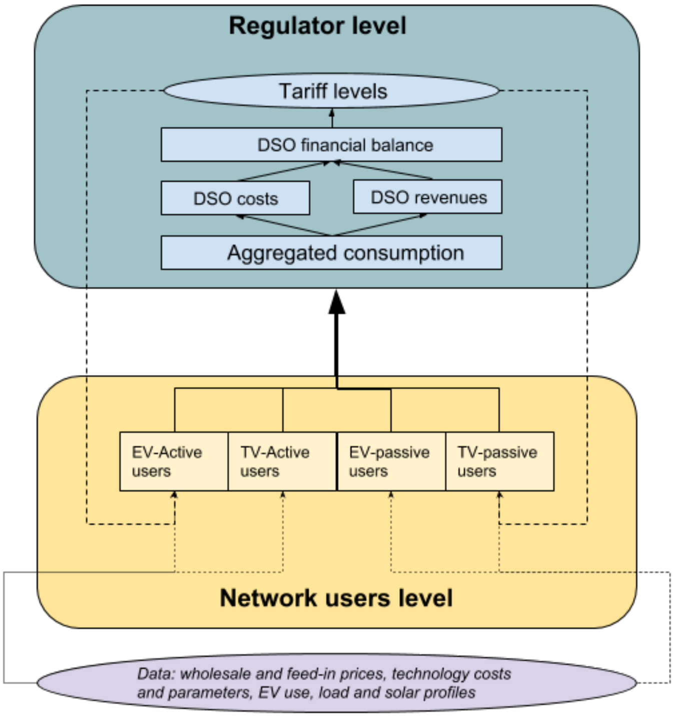


Figure 1: Model structure

## 3. Methods and data

This section presents the methodology adopted in this paper. A detailed explanation of the modeling of tariff design is followed by the description of the data used in the numerical case study.

### *3.1. Model*

#### *3.1.1. Overview*

This paper models a regulator that designs tariffs in a low-voltage residential grid in a stylized framework. As pointed out earlier, one of his main missions is to design tariffs paid by network users that will remunerate the DSO so that it recovers its costs. In the previously defined context, he needs to anticipate the behavior of some grid users that would push back by installing DERs in their home in reaction of increased electricity prices. Moreover, the regulator takes into account the precise effect of the adoption of other new technologies by users (namely EVs in this paper).

The chosen approach of this paper is a game-theoretical model which is similar to the one used in (Schittekatte et al., 2018; Schittekatte and Meeus, 2018; von Appen and Braun, 2018). The model is summarized in Figure 1. More precisely, the interaction between the regulator that designs network tariff and users of grid users is modeled by a non-cooperative game. As different tariff structures are considered by the regulator, typical load profiles of network users need to be precisely modeled. Four kinds of representative network users are considered, depending on whether they are prosumers or passive users, and whether they own an EV or a traditional vehicle (TV)[6]. A description of user types is shown on table 1. Rational representative users are considered. Prosumers are able to minimize their electricity consumption by investing in DERs and to optimize the energy flows of their houses. On the contrary, passive users are not able to do so[7].

[6]The user type "TV owners" includes more generally all users that do not own a private EV at home.

[7]This inability has several causes, such as lacks of space for DER installation, cash access for investing, unavailable information, etc.

| | Passive network user | Prosumer |
|---|---|---|
| Traditional vehicle owner | TV-passive user - *Traditional user*<br>• do not minimize electricity costs<br>• may not invest in DERs<br>• proportion: $(1-p^P)(1-p^{EV})$ | TV-prosumer - *Regular prosumer*<br>• minimize electricity costs<br>• may invest in DERs<br>• proportion: $p^P(1-p^{EV})$ |
| Electric vehicle owner | EV-passive user - *Green commuter*<br>• do not minimize electricity costs<br>• dumb charging of EV<br>• may not invest in DERs<br>• proportion: $(1-p^P)p^{EV}$ | EV-prosumer - *Full innovator*<br>• minimize electricity costs<br>• smart charging of EV<br>• may invest in DERs<br>• proportion: $p^P p^{EV}$ |

Table 1: Description of the different network users with their attributes

Such differentiation has been widely used in the literature (Brown et al., 2017; Gautier et al., 2018). We assume that only EV owners that are also prosumers can optimize their EV charging (*smart charging*). The proportion $p^P$ of prosumer is assumed to be independent of proportion $p^{EV}$ of EV owners[8]. To simplify, we assume that all network users have the same typical electric consumption and that this consumption is strictly inflexible. It is important to notice the asymmetry between EVs and DERs in this approach. DER adoption is mainly motivated by electricity prices (Karakaya and Sriwannawit, 2015). On the contrary, charging costs and electricity prices are not acknowledged as an important barrier to EV adoption~~EV adoption is uncorrelated to electricity prices, mainly because electricity prices represent a small part of EV total ownership cost (Breetz and Salon, 2018; Palmer et al., 2018).~~[R1][9] The model is solved numerically[10] by an iterative method[11], where each level takes in argument the output of the other level until the algorithm converges[12].

### *3.1.2. Regulator level*

In the upper level, the tariff design process is simplified. The sole objective of the regulator is to balance the budget of the DSO. The DSO only reports its costs and the aggregated[13] consumption of the whole network[14]. Beside this reporting, the DSO is passive in the tariff design process. In the most part of the paper, we consider only sunk distribution network costs. This important assumption is motivated by the traditional 'fit-and-forget' approach of grid planning that has led to over-dimensioned grid with large costs (Pollitt, 2018). This assumption will be relaxed in the Appendix D. The tariff design is defined as follows. First, the regulator chooses a tariff structure. This structure is a policy choice and is therefore exogenous in the model. Network tariffs are usually decomposed in three parts : volumetric (in €/kWh), capacity (in €/kW) and fixed (in €). In the case where users are able to self-consume and/or feed-in power back

[8]However, some correlation of adoption both DERs and EV has been evidenced in some regions (Delmas et al., 2017).

[9]Main current barriers to EV adoption are the upfront purchasing cost of the vehicle, the limited driving range of the vehicle and the lack of charging infrastructure (Li et al., 2017). Moreover, electricity prices represent a small share of the total cost of ownership of EVs - less than 10% based on (Breetz and Salon, 2018; Palmer et al., 2018). As this paper deals with network tariffs which account for 30-60% of the retail electricity price, it seems reasonable to consider that changes of tariffs won't impact EV adoption levels[R1].

[10]Note that this model can not be solved analytically, unless a simple ad-hoc DER investment function is assumed.

[11]The model is solved in Python using CVXPY (Diamond and Boyd, 2016).

[12]For most of the simulations, less than 10 iterations were needed.

[13]Note that this aggregation allows a rough classification of representative network users.

[14]Among others, the regulation can incentivize the DSO to certain efficiency practices regarding grid reinforcements or renewable curtailment (Abdelmotteleb et al., 2018; von Appen and Braun, 2018). Such considerations are beyond the scope of this paper.

to the grid, net-metering has been generally applied. With net-metering, the volumetric part of the tariff applies to the net electricity consumed (*i.e.* electricity consumed minus electricity produced)[15]. Network tariff design is described in the model with three types of structure (volumetric, capacity and fixed). This allows a precise understanding of the particular effect of each part of the tariff[16].

$$C_N = R_V + R_C + R_F \tag{1a}$$

$$R_V = \epsilon_V \sum_i p_i t_V \sum_t (F_{i,t}^{G,-} - \delta_m F_{i,t}^{G,+}) \Delta T \tag{1b}$$

$$R_C = \epsilon_C t_C \sum_i p_i \bar{P}_i \tag{1c}$$

$$R_F = (1 - \epsilon_V - \epsilon_C) \sum_i p_i t_F \tag{1d}$$

Equations 1(a-d) describe the DSO cost recovery constraint[17]. The regulator enforces that the overall networks costs $C_N$ should match the revenues of the DSO by setting tariffs $t_V, t_C, t_F$. These revenues are composed of volumetric (energy) charges revenues $R_V$, capacity charges revenues $R_C$ and fixed charges revenues $R_F$. Parameters $\epsilon_V, \epsilon_C, \delta_m$ describe the composition of the tariff. For pure volumetric tariff, $\epsilon_V = 1, \epsilon_C = 0$. For pure capacity tariff $\epsilon_V = 0, \epsilon_C = 1$. For fixed tariff, $\epsilon_V = 0, \epsilon_C = 0$. With net-metering ($\delta_m = 1$), the user is charged on its net consumption (with $F_{i,t}^{G,-}$ and $F_{i,t}^{G,+}$ the power flows from and to the grid of user $i$ at time $t$, and $\Delta T$ an annualization factor[R2]), meaning that her self-production (*e.g.* from solar PV) is subtracted from its consumption on a yearly basis[18]. Without net-metering, volumetric charges apply to the total power flows of the user (consumption added to self-consumption). With capacity tariffs, the user is charged based on its annual peak load $\bar{P}_i$. $p_i$ is the proportion of user $i$ in the network, which is exogenous in our model.

#### *3.1.3. Network users level*

In the lower level, network users minimize their electricity costs depending on their user class (EV-prosumer, EV-passive, TV-prosumer or TV-passive) as follows:

$$\text{Minimize (Electricity costs)}_i = \text{(Energy costs)}_i + \text{(Network charges)}_i + \text{(DERs costs)}_i + \text{Taxes} \tag{2}$$

With:

$$\text{(Energy costs)}_i = \sum_t \left( c^{G,-} F_{i,t}^{G,+} - c^{G,+} F_{i,t}^{G,-} \right) \tag{3}$$

$$\text{(Network costs)}_i = \epsilon_V t_V \sum_t \left( F_{i,t}^{G,-} - \delta_m F_{i,t}^{G,+} \right) + t_C \bar{P}_i + t_F \tag{4}$$

$$\text{(DER costs)}_i = c^S S_i + c^B B_i \tag{5}$$

Equation 3 describes the energy charges component of the user's bill. It is composed of the total power bought from the grid at cost $c^{G,-}$ minus the total power sold to the grid at price $c^{G,+}$[19]. $F_{i,t}^{G,-}$ and $F_{i,t}^{G,+}$ represent the amount of energy bought from and sold to the grid. Equation 4 refers to the network charges

[15]Without net-metering, the volumetric tariff applies to the total electricity that went through the house power lines (*i.e.* consumed electricity plus produced electricity). We consider this tariff structure only in the appendix.

[16]Note that if most countries implemented a mixed structure, pure tariffs are adopted by several countries such as Holland (100% power) or Romania (100% energy) in the EU. Other tariff structures are considered in Appendix C.

[17]All parameters and variables are described in the Appendix A.

[18]Note that net-metering could also applied on a lower time frame (monthly, weekly...).

[19]Note that although they could be easily included, dynamic tariffs are not considered in this paper.

component of the user's bill. Note that in the case of a volumetric net-metering tariff, network charges cannot be negative by regulation, which imposes an additional constraint. The investments costs in PV panels and batteries of the prosumer constitutes the DER costs in equation 5. PV capacity and battery annualized cost are $c^S$ and $c^B$. These technology costs are described in the section 3.2 on data.

$$L_{i,t} = F_{i,t}^{G,-} - F_{i,t}^{G,+} + S_i y_{i,t}^S + F_{i,t}^{B,-} - F_{i,t}^{B,+} + F_{i,t}^{EV,-} - F_{i,t}^{EV,+} \tag{6a}$$

$$F_{i,t}^{G,+} + F_{i,t}^{G,-} \leq \bar{P}_i \tag{6b}$$

$$\sum_t \left(F_{i,t}^{G,-} - F_{i,t}^{G,+}\right) \geq 0 \tag{6c}$$

Equations 6(a-c) represent the physical constraints on power flows at the house level. The first constraint represents power conservation at the house level (equation 6a), that enforces at every time $t$ the equality between the user's regular load $L_{i,t}$, solar PV self-production ($S_i y_{i,t}^S$), the net energy flows from the battery ($F_{i,t}^{B,-} - F_{i,t}^{B,+}$) and the EV ($F_{i,t}^{EV,-} - F_{i,t}^{EV,+}$). Equation 6b defines the peak power $\bar{P}_i$ of the user, which is the maximum total power (sum of grid power injection and withdrawal). To prevent having negative network charges, the total net electricity called from the network is assumed to be positive (equation 6c)[20].

$$S_i \leq \bar{S}_i \tag{7}$$

Equation 7 adds an upper bound on prosumers' solar PV capacity. This hypothesis is motivated by practical constraints that users face when installing solar PV. Indeed, users may have insufficient space for installing solar panels.

$$B_i \leq \bar{B}_i \tag{8a}$$

$$SOC_{i,t}^B = \eta^{B,+} dt F_{i,t}^{B,+} - \frac{dt}{\eta^{B,-}} F_{i,t}^{B,-} + (1 - \varphi^B dt) SOC_{i,t-1}^B \tag{8b}$$

$$SOC_{i,1}^B = \eta^{B,+} dt F_{i,1}^{B,+} - \frac{dt}{\eta^{B,-}} F_{i,1}^{B,-} + (1 - \varphi^B dt) SOC_{i,0}^B \tag{8c}$$

$$SOC_{i,t_{max}}^B = SOC_{i,0}^B \tag{8d}$$

$$SOC_{i,t}^B \leq B_i \tag{8e}$$

$$F_{i,t}^{B,+} \leq \nu^{B,+} B_i \tag{8f}$$

$$F_{i,t}^{B,-} \leq \nu^{B,-} B_i \tag{8g}$$

Equations 8(a-g) refer to the battery constraints. As for solar PV, we allow the battery capacity to be bounded by $\bar{B}_i$[21]. Equations 8(b-c) describes the battery dynamics that comprises bidirectional flows and leakage. Charging and discharging involve losses that are characterized by efficiency factors $\eta^{B,+}$ (charging) and $\eta^{B,+}$ (discharging). A periodic condition is imposed in equation 8d. The initial state of charge (SOC) of the battery is set to zero. This enables the user to extract the maximal value from its battery. Equation 8e indicates that the SOC cannot exceed the battery capacity. Equation 8(f-g) refers to charging and discharging powers are limited by physical constraints of the battery, characterized by maximum rates of charging/discharging $\nu^{B,+}$ and $\nu^{B,-}$.

[20] Note that this constraint only matters when volumetric and especially with net-metering, is implemented.

[21] Nevertheless, we do not impose a limit on battery investments

$$SOC_{i,t}^{EV} = \eta^{EV,+} dt F_{i,t}^{EV,+} - \frac{dt}{\eta^{EV,-}} F_{i,t}^{EV,-} + (1 - \varphi^{EV} dt) SOC_{i,t-1}^{EV} \quad (9a)$$

$$SOC_{i,1}^{EV} = \eta^{EV,+} dt F_{i,t}^{EV,+} - \frac{dt}{\eta^{EV,-}} F_{i,1}^{EV,-} + (1 - \varphi^{EV} dt) SOC_{i,t_{max}}^{EV} \quad (9b)$$

$$SOC_{i,t}^{EV} \leq K_i^{EV} \quad (9c)$$

$$F_{i,t}^{EV,+} \leq h_{i,t}^{EV} \nu^{EV,+} K_i^{EV} \quad (9d)$$

$$F_{i,t}^{EV,-} \leq h_{i,t}^{EV} \nu^{EV,-} K_i^{EV} \quad (9e)$$

$$SOC_{i,t_d}^{EV} = SOC_i^{EV,d} \quad (9f)$$

$$SOC_{i,t_a}^{EV} = SOC_i^{EV,d} - \frac{\chi^{EV} d}{K_i^{EV}} \quad (9g)$$

$$SOC_{i,t}^{EV} \geq SOC_{min}^{EV} \quad (9h)$$

To simplify the modeling, the following assumptions are made regarding EV charging. The EV battery dynamics, described in equations 9(a-h), are roughly similar to the stand-alone battery dynamics. It is assumed that all EVs have the same travel patterns. They travel every day the distance $d$, which translates into an additional electricity need of $\chi^{EV} d$ for the user, with $\chi^{EV}$ the engine efficiency of the EV and $K^{EV}$ the capacity of the EV battery. Every day, the EV unplugs and leaves at $t_d$ and come back and plugs at $t_r$. As drivers are supposed to be commuting every day, EVs are away from home most of the day. In addition, it is assumed that EV mainly charges at home. The boolean function $h_{i,t}^{EV}$ returns 1 when the EV is plugged at home and 0 else. This assumption is motivated by empirical evidences on early EV adopters (Langbroek et al., 2017). Similarly to the standalone battery dynamics, a periodic condition is also imposed in equation 9c. Passive EV owners plug their vehicle at maximum power as soon as they have come back home (*dumb charging*). Note that this dumb charging of the EV most likely happens during the house peak load. The plugging power is assumed to be modest (3kW), which is consistent with the current plugs provided by EV manufacturers for domestic use (García Villalobos, 2016). Only EV-prosumers include the vehicle battery in their process of electricity costs minimization. In this case, the EV charging is flexible (*smart charging*) and in addition it is assumed that EV-prosumers are able to discharge their EV battery to power their house, without any damage on the battery[22]. It is likely that EV owners could charge their vehicle smartly without being able to invest in DERs. To limit the number of agents' behaviors, such option is not considered in this paper[23]. It is assumed that the EV battery has the same technical parameters as the stand-alone battery. It is assumed that EV owners require a minimal state-of-charge $SOC_{min}^{EV}$ for their battery.

Finally, all variables of the model are positive :

$$F_{i,t}^{G,-}, F_{i,t}^{G,+}, F_{i,t}^{B,+}, F_{i,t}^{B,+}, F_{i,t}^{EV,-}, F_{i,t}^{EV,+}, SOC_{i,t}^{B}, SOC_{i,t}^{EV}, S_i, B_i, \bar{P}_i \geq 0 \quad (10)$$

### *3.1.4. Evaluation methods*

The interaction between tariff design and the different network users' behavior are analyzed with different proxies. In this study, we focus on three aspects. First, the impact of EV and DER penetrations on network tariff levels, is computed with the variation of network tariff. This tariff variation has been interpreted in term of fairness between prosumers and passive users in the literature on tariff design with DERs (Schittekatte and Meeus, 2018). The reference case is defined by the scenario with 100% TV-passive users (*i.e.* without either EV nor prosumers).

[22] This assumption may be strong, but several studies have demonstrated that discharging the EV battery is far from being strictly costly for the battery (Apostolaki-Iosifidou et al., 2017; Thompson, 2018).

[23] As EV are assumed to be away from home during sunny hours, smart charging can only save on yearly capacity charges by shifting the EV load every day. This implies a high level of commitment that we assume passive user do not have.

| Proxy | Description |
|---|---|
| Tariff variation | network tariff variation relatively to the reference case (without either EV nor prosumer) |
| EVIC *(prosumer)* | cost difference between EV-prosumers and TV-prosumers |
| EVIC *(passive)* | difference between passive EV-[R2]owner's costs and passive TV owner's costs |
| DER payback time ($TV$) | payback time of DER investments made by TV-prosumers |
| Solar PV capacity ($TV$) | solar capacity installed by TV-prosumers |
| Battery capacity ($TV$) | battery capacity installed by TV-prosumers |

Table 2: Proxies used to evaluate tariff designs

$$\text{Tariff Variation} = \frac{\text{Tariff}(p^P, p^{EV})}{\text{Tariff}(0,0)} - 1 \tag{11}$$

To quantify the spillovers of DER adoption on EVs ownership costs, we define as proxies EV incremental costs for prosumers and passive users as follows:

$$\text{EV incremental cost}(prosumer) = \frac{\text{Costs}^T(EV\text{-}prosumer) - \text{Costs}^T(TV\text{-}prosumer)}{\text{Costs}^{ref}(EV\text{-}prosumer) - \text{Costs}^{ref}(TV\text{-}prosumer)} \tag{12a}$$

$$\text{EV incremental cost}(passive) = \frac{\text{Costs}^T(EV\text{-}passive) - \text{Costs}^T(TV\text{-}passive)}{\text{Costs}^{ref}(EV\text{-}passive) - \text{Costs}^{ref}(TV\text{-}passive)} \tag{12b}$$

EV incremental costs (EVIC) of prosumers (resp. passive users) are first defined by the difference of electricity costs of EV-prosumers (resp. EV-passive users) and TV-prosumers (resp. TV-passive users). These differences are then normalized by the same cost difference using the tariffs of the reference case[24]. For passive users, the EVIC can be identified as the charging costs of the vehicle. Nevertheless, for prosumers, the EVIC may also include additional costs or revenues due to additional DER investments.

Third, the impacts of EV diffusion on DERs adoption and profitability are assessed with the characteristic of prosumers without EV (TV-prosumers). DER adoption is directly measured by the installed capacities in solar PV and battery of the prosumer. DER profitability is assessed by the payback time[25] of the DER investment, defined by the ratio of the initial DERs investments costs over the saving in the electricity costs brought by these investments. Such savings are defined by the difference between the TV-passive user's bill with the TV-prosumer's bill :

$$\text{DER Payback time} = \frac{\text{Total DER initial investment cost}}{\text{Costs}(TV\text{-}passive\ user) - \text{Costs}(TV\text{-}prosumer)} \tag{13}$$

*3.2. Data*

As the goal of this paper is to analyze the links between the design of network tariffs and grid users behaviors and technologies, generic numerical examples are computed. They are based on stylized facts on power consumption in Europe, technologies costs and technical parameters.

The basic load of users represented with typical two-day load profile designed for this numerical experiment (shown in Figure 2-left). Each daily profile incorporates one low peak in the morning and a high peak in the evening. The two days are chosen to capture seasonal consumption pattern. The whole profile is calibrated to reach an annual consumption of 6500kWh/year and a peak power of 4kW, which are medium estimates between yearly household consumption in Europe and in the US (ACER, 2016).

[24] Note that for this proxy, the network tariffs of the reference case are tariffs with a fixed tariff structure.
[25] Other proxies are possible to consider as the net present value, internal rate of return...

| Cost types | Proportion in bill | Cost per year |
|---|---|---|
| Energy costs | 45% | 520€/year |
| Network costs | 35% | 400€/year |
| Other charges | 20% | 230€/year |
| Total electricity cost | 0.18€/kWh | 1150€/year |

Table 3: Electricity bill of a TV-passive user in the reference case

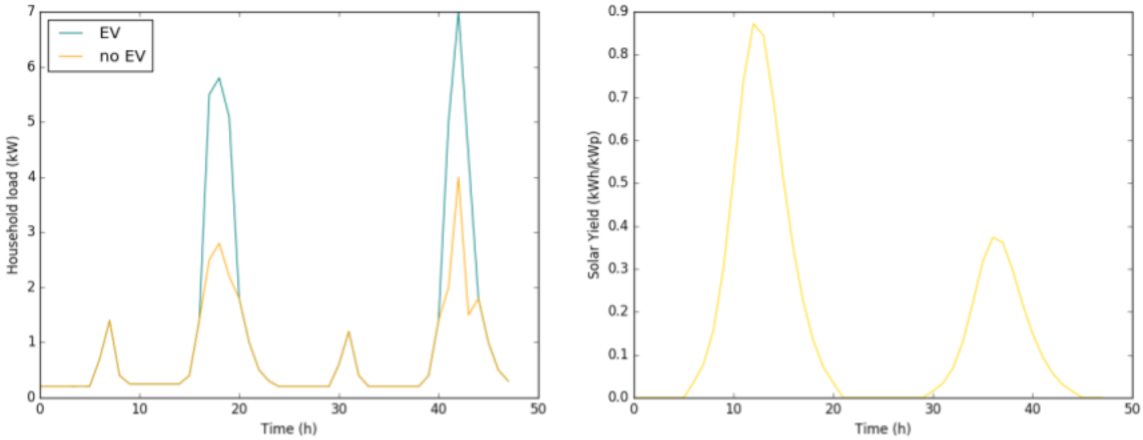


Figure 2: Daily demand load profile of passive users (left, in kWh) with TV (yellow) and EV (blue); solar yield for prosumers (right, in kWh/kWp)

The default electricity bill is defined by the situation without either prosumer nor EV owner in the network. Parameters are shown in Table 3. The bill is computed over one year from the two-days net consumption profile, with an annualization factor $\Delta T$ of 182.5. The default bill is decomposed as follows : 45% for energy purchases, 35% for network utilization and 20% for other charges and taxes. Such decomposition is close to the one used in (Schittekatte and Meeus, 2018) and reflects an average composition of European electricity based on (ACER, 2016). It is assumed that the regulator has complete information regarding network costs. As discussed earlier, network costs are assumed to be sunk. This hypothesis will be relaxed in the appendix. It is assumed that taxes on electricity are fixed and independent from energy consumption. The final electricity cost is 0.18€/kWh, which is between the average European prices (0.21€/kWh) and the average US prices (0.125 €/kWh).

A two-day solar yield per kWp of PV installed, shown in Figure 2-right, is calibrated on a yearly production of 1160kWh/kWp and meant to capture winter/summer patterns. In line with (Schittekatte et al., 2016) the efficiency of standalone and EV batteries charging and discharging is set at 90%. The EV battery capacity is set at 40kWh, which is largely sufficient for daily travels. As EV battery quality is much higher than stand-alone home batteries, we assume that there is no leakage in the EV battery while the standalone battery has leakage rate of $2\%/h$.

We assume relatively low investments costs of solar PV and lithium-ion batteries, which is in line with studies on the short-term future development of these technologies (Lazard, 2018a,b). Investment costs of PV and batteries are set to be respectively 1300€/kWp and 200€/kWh based on (Schittekatte et al., 2018). Lifetimes of PV panels and batteries are respectively 20 and 10 years. With a usual discount rate of 5%, annual costs for solar PV and batteries capacities are 104 €/kWp/year and 26 €/kWh/year. To avoid over-incentives on solar PV caused by excessively high feed-in tariffs combined with low price of PV panels, feed-in tariff is set at low enough level (4c/kWh in the simulations) to exclude significant investment in solar PV or battery with null network tariff.

As already stated earlier, EV adoption is assumed to be exogenous in the model. Again, simplifying

| Tariff structure | Proportion of EV owners | Proportion of prosumers | **Tariff Variation (%)** |
|---|---|---|---|
| Volumetric | 5% | 5% | 2.6 |
| | | 25% | 29.2 |
| | 25% | 5% | -9.4 |
| | | 25% | 15.2 |
| Capacity | 5% | 5% | -0.61 |
| | | 25% | 13.5 |
| | 25% | 5% | -12.9 |
| | | 25% | 0.63 |

Table 4: Network tariff variation relative to the reference case. Variations are given for capacity and volumetric with net-metering tariff structure, 5-25% EV owners and 5-25% prosumers.

assumptions are used for transport, since in the end, only the yearly peak load and the yearly energy consumption matters for network tariff design. In our setup, EVs leave home at 7am and come back at 5pm[26]. The daily travel distance of EV owners is set at 40km, which is a typical order of magnitude for Europe (Pasaoglu et al., 2014). It can be also considered that EV owners drive over longer distances, but charge more frequently at workplace or at a commercial charging station. The EV engine efficiency $\chi^{EV}$ is set at 0.2kWh/km. In this setting, a passive EV owner consumes 45% more energy and has a 75% higher peak load compared to a traditional passive TV owner.

Finally, four scenarios of penetration of EVs and prosumers will be considered. Low penetrations will be modeled as 5% of users and 25% for high penetration. If "low" (resp. "high") penetrations can be identified to short (resp. long) term, high penetrations (of EVs and/or prosumers) can potentially occur in specific locations despite low penetrations on larger scales (*e.g.* in California, Norway...).

## 4. Results

### *4.1. Impacts of prosumers and EVs penetration on network charges*

This section focuses on tariff variations caused by prosumers or EV owners. Table 4 shows the variations of tariff levels relatively to the reference case without either prosumers nor EV owners. Four major highlights are described in what follow.

First, for both tariff structures and for both EV penetration scenarios, increased proportions of prosumers have an increasing effect on network tariff. With volumetric tariff structure and for both EV penetration scenarios, a 20% increase in proportion of prosumers results in a 24-27% increase in tariffs. Under capacity tariff, such increase is in the range 13-14% for a 20% increase in proportion of prosumers. Such results are well-identified in the literature and have been discussed in section 3. Indeed, both tariff structures give incentives to invest in DERs. As shown in Appendix B, volumetric with net-metering tariff incentivizes prosumers to invest in solar PV to save on network charges. Capacity tariffs incentivize both solar PV and battery capacities to lower prosumers' peak load. For both tariff structures, prosumers' DERs results in a decrease of DSO's revenues. As grid costs stay constant, the regulator has to increase tariff levels to balance the DSO's budget.

Second, for both tariff structures and for prosuming scenarios, increased EV penetration has a decreasing effect on network tariffs. Under volumetric tariff structure, and for both prosuming scenarios, a 20% increase in proportion of EV owners leads to a 12-14% tariff decrease. With capacity tariff, the same increase in EV penetration leads to a 12-13% decrease. This result can be interpreted as follows. Getting an EV and charging at home significantly increases its user' energy consumption and peak load (in our setup, respectively by 45 and 75%). Hence, higher penetration of EVs in the network increases the DSO's revenues. Again, as grid costs are all sunk, the regulator lowers tariffs to minimize electricity costs of network users while ensuring DSO's cost recovery.

[26]Several studies have pointed out that early evening charging is currently the most common way (Langbroek et al., 2017).

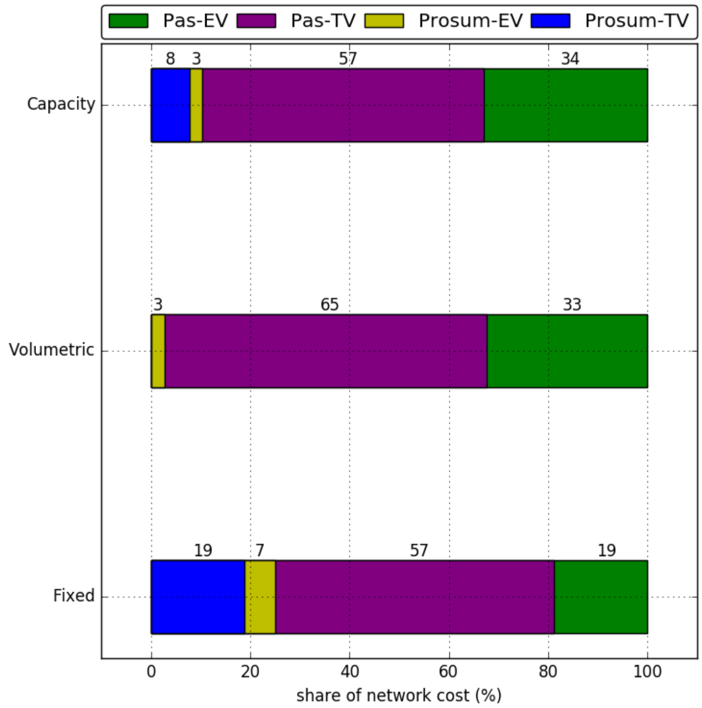


Figure 3: Distribution of DSO's costs between the four classes of network users for the case with 25% EV owners and 25% prosumers. Three tariff structures are considered : volumetric, capacity and fixed.

Third, these two previous effects seem to balance each other. With capacity tariff, same proportions of EV owners and prosumers in the network leave tariffs almost unchanged compared to the reference situation. Indeed, in the 5%-5% and in the 25%-25% scenarios, network tariffs only deviate by 0.6%. With the volumetric tariff structure, network tariff deviates slightly in the 5%-5% scenario, but by 15% in the 25%-25% scenario. However, in this scenario, tariff has increased by 15% compared to the reference case. Although this partly contradicts the previous results, it is important to note that the decrease of tariff induced by EV is larger when proportion of prosumers is large. Indeed, the decreases of tariff induced by 20% additional EV owners are respectively 12% and 14% in the 5%-5% and in the 25%-25% scenarios.
An other way to analyze the effects of EVs and prosuming on network tariffs is to represent how grid costs are shared between users. Figure 3 shows this distribution for the 25%-25% scenario. Three network tariff structures are considered with a pure fixed tariff in addition to the pure volumetric and capacity tariffs. With fixed tariff, every user pays the same fee for grid access regardless of their power consumption. Hence, the proportion of the user class is equal to the share of this user class in grid costs recovery. In our set-up fixed tariff does not give incentives neither for solar PV or for batteries, since network charges cannot be avoided by prosumers. With volumetric tariff, prosumers, especially TV-prosumers have withdrawn their contribution to grid costs recovery. Indeed, solar PV investments allowed these users to completely escape the network charges they were paying without their solar panels. The resulting missing revenues for the DSO are then filled by passive users. TV-passive and EV-passive users respectively bear 65% and 33% of grid cost, while 57% and 19% under the fixed tariff structure. Under capacity tariff, similar results are found with a reduced share of prosumers and an increase share of passive users in grid costs recovery. These latter results clearly illustrate the non-cooperative behavior of prosumers in the regulation grid costs recovery. Indeed with both capacity and volumetric tariff, prosuming leads to free-ride network access, at the expense of passive users.

Fourth, it is important to assess how network tariff structures affect the combined effects of EV and prosuming on network tariffs. In this study, we focused on volumetric with net-metering and capacity tariff structures as they are the most characteristic forms of current network tariff designs. The results described in Table 4 have shown that tariff variations are smaller under capacity tariff structure than under volumetric tariff, for all EV/prosuming scenarios. These results can be interpreted as follows. On the one hand, volumetric structure gives higher incentives to adopt DERs. As shown in the Appendix B, prosumers invest in their maximal possible[27] solar PV capacity even for low tariffs level. On the contrary, solar PV and battery investments are much more progressive under capacity tariffs. Hence volumetric tariff structure results in higher missing revenues for DSO than with capacity tariffs. On the other hand, EV owners are more sensitive to capacity tariffs as in our setting, their peak power is increased by 75%[28] while energy consumption is increased by 45%[29]. Hence electric vehicles represent a larger source of revenues for the network operator under capacity tariff. In addition, fixed tariffs are the least costly tariff structure for passive EV owners, while they do not give any incentives for DERs.

This last result highlights a crucial issue. Depending on the tariff structure, prosumers benefit and EV owners get penalized and vice-versa. Next section will detail this highlight by investigating the conflicts between EVs and DERs adoption through tariff design. Finally, it is important to note that the numerical results shown in this section are dependent on several assumptions. The appendix provides results that demonstrate that the mechanisms described in this section are also valid in the case of (1) other tariff structures and (2) variable grid costs structure.

### *4.2. Conflicting effects between EVs and DERs adoptions*

As discussed earlier, EVs and DERs are identified as crucial technologies in the energy transition. While these technologies will meet in power grids, their economic characteristics are asymmetrical in several ways. First, the adoption of DERs is strongly dependent on electricity prices, contrary to the current EV adoption patterns. Second, DERs adoption is even more incentivized by high electricity prices, while high electricity prices will increase the total cost of ownership of the EV. In the context of tariff design, such asymmetry leads to a conflicting situation between EVs and DERs adoptions. In this section, we extend the previous analysis to investigate (1) how EV incremental costs are affected by prosuming and (2) how DER adoption and profitability are affected by EV adoption.

| Tariff structure | Proportion of EV owners | Proportion of prosumers | **EVIC (%)** (prosumer) | **EVIC (%)** (passive) |
|---|---|---|---|---|
| Volumetric | 5% | 5% | 178 | 179 |
| | | 25% | 194 | 199 |
| | 25% | 5% | 170 | 170 |
| | | 25% | 186 | 189 |
| Capacity | 5% | 5% | 73.0 | 215 |
| | | 25% | 73.2 | 231 |
| | 25% | 5% | 72.8 | 200 |
| | | 25% | 73.0 | 216 |

Table 5: EV incremental costs (EVIC) for EV-prosumers and EV-passive users.

First, EV incremental costs are increased by DER adoption. In Table 5, EV incremental costs as defined earlier for passive users and prosumers are shown for the four scenarios of EV diffusion and prosuming, and for the two tariff structures. For both volumetric tariffs and whichever the proportion of EV owners

[27]Note that solar PV capacity is constrained in our model by equations (7c) and (8).
[28]Note that standard plug power can be much higher (*e.g.* 7kW, 22kW (Codani et al., 2016)).
[29]In opposition to the charging power, this increase is more probable to be lesser than higher, since the vehicle can charge elsewhere.

and prosumers, there are no significant differences in incremental costs between EV-prosumers and EV-passive users. For instance, with the 20% increase in prosumers, EV incremental costs increase by 16-20%. On the contrary, the capacity tariff shows huge differences in EVIC between EV-prosumer and EV-passive users. EV-passive users face a 15% increase in their EVIC for all scenarios when the proportion of prosumer increases. Results show differences for EV-prosumer costs. For all scenarios, the EV incremental costs of a EV-prosumer are almost three times higher than for passive EV owners. Indeed, smart charging of EV-prosumer allows them to significantly lower their peak for free, even without investing in stand-alone batteries. Nevertheless, in our scenarios, EV-prosumers represent a small fractions of all users. Although we assumed EV adoption to be independent from charging costs, these latter represent a rather small part in the total cost of ownership of EVs (Breetz and Salon, 2018; Palmer et al., 2018). This increase can be interpreted as a cross-subsidy from EV owners to all other users through network tariffs, and especially prosumers.

| Tariff structure | Prosumer proportion | EV owners proportion | **DER payback time ($y$)** | **Solar PV capacity (kWp)** | **Battery capacity (kWh)** |
|---|---|---|---|---|---|
| Volumetric | 5% | 5% | 10.52 | 4.48 | 0.0 |
| | | 25% | 8.82 | 1.83 | 0.0 |
| | 25% | 5% | 9.92 | 4.48 | 0.0 |
| | | 25% | 9.64 | 4.48 | 0.0 |
| Capacity | 5% | 5% | 6.17 | 1.19 | 2.93 |
| | | 25% | 6.73 | 1.19 | 2.93 |
| | 25% | 5% | 5.63 | 1.19 | 2.93 |
| | | 25% | 6.12 | 1.19 | 2.93 |

Table 6: DER payback time, solar PV and battery capacity of the TV-passive user.

Second, DER adoption and profitability are affected by EV diffusion. Table 6 shows the different proxies defined earlier, *i.e.* solar PV and battery capacities installed by TV-prosumers, and the payback time of TV-prosumer's investments in DERs. With the capacity tariff structure, increases of the proportion of prosumers have similar effects for both EV penetration scenarios. When the proportion of prosumers increase by 20%, the payback time of DER investments increase by 0.6 year while solar PV and battery capacity stay constant. With volumetric tariff, the same increase in EV penetration has different effects. In the 5% EV penetration, solar PV adoption, the only DER adopted by prosumers with volumetric tariffs, decrease from 4.5kWp to 1.8kWp while the related payback time decrease. In the 25% EV scenario, solar PV adoption stay unchanged, but solar PV payback time increase by 0.8 year. The interpretation of the following results are similar. In every case, the increase in EV penetration has a lowering effect on network tariffs. As DER adoption is determined by electricity prices, the effect results in reducing the prosumer's valuation of DER investment.

## 5. Conclusion and policy implications

This paper has studied several aspects of network tariff design with DERs (solar PV and batteries) and EVs (with flexible and dumb charging) within a stylized non-cooperative game including four types of network users (prosumers with and without EV, passive users with and without EV). It enlightened several mechanisms that have relevant policy implications. First, EVs and DERs adoptions show counterbalancing effects through the grid costs recovery problem. When grid costs are sunk, EVs therefore decrease the risk of the death spiral of distribution utilities as they constitute a large source of revenues. Then, through the recovery of grid costs, DERs and EVs induce spillovers on each other. These are mainly due to the asymmetrical characteristics of both technology uses. High electricity prices are the main driver of DER adoption. On the other hand, EV adoption would be facilitated by low electricity prices, although it is currently largely independent from them. This study has shown that with the main tariff structure (volumetric and capacity), EVs and DERs may be conflicting by inducing negative externalities on each other. This latter finding contradicts a part of the literature on EV/DERs synergies.

Changing regulation makes winners and losers. In this study, winners (or free riders in this case), manage to escape network charges, leaving losers bearing the cost of the whole network. Regulation of network charges mainly consists in choosing a tariff structure. It has been shown that with volumetric tariff with net-metering, EV owners are the losers as they pay much more than what they would have had with other tariffs. On the contrary, prosumers are the winners. Depending on the proportion of EVs in the network, the lowering trends on equity can be compensated. With capacity tariffs, DERs are less incentivized for prosumers, but EV owners are much more sensitive to peak load charges. The fact that the situation EV owners may get worse needs to be discussed in term of public acceptance. Moreover, it may penalize a technology which is currently strongly pushed by policies. Nevertheless, EV adopters are generally affluent and therefore could perceive this situation lightly.

The implications of these mechanisms for policy making are twofold. First, by focusing only on the impacts of DER diffusion, the debate on network tariff design has eluded the trend of electrification. As including electrification leads to less dramatic outcomes, this could incite regulators to be less willing to modify tariff structures too soon. Second, a precise investigation of the winners and losers (in term of both user groups and technologies) of a tariff design change should be made. Indeed, the evaluation of tariff designs in term of efficiency and equity may hide the existence of conflicting effects between some technologies that are deemed valuable for society. We therefore think that the EV industry should consider this issue carefully and participate on network tariffs.

Finally, this paper calls for several works in the future. This study assumed that EV and DERs were the only drivers of power consumption of network users. Other flexible or inflexible consumption sources would be added by electrification of other sectors (heating) or removed with sobriety or energy efficiency of appliances. A realistic case study on specific distribution grids should include these consumption sources to compute the DSO's revenues. Hence the effect of DERs and electrification (EVs, heat pump) on tariff design. Such case studies could also include other grids than only low-voltage residential grids, as considered in this study. Indeed, as such distribution grids would include large buildings and workplaces, EV charging profile and solar yields could be more synchronized. This would allow to include the appropriate conditions for EV/DER synergies. Then, we assumed simple roles for the regulator and for the DSO. Our framework could be enhanced by making the tariff structure endogenous based on the regulator's goals. For instance, such goals could be to favor certain type of network users. Including an active management of the grid by the DSO would also be a relevant enrichment. ~~preferences and an an active management of the grid by the DSO.~~[R1]. Furthermore, more diverse tariff structures, including dynamic tariffs, should be investigated. Finally, the conflicts between policies that promote EVs and policies that incentivize renewables should be studied in detail. Taking into consideration other support mechanisms of renewables that also end up in increasing the retail price of electricity would therefore be appropriate.

## Appendix A. Notations

| Notation | Set |
|---|---|
| $i$ | User index |
| $t$ | Time slot |

| Notation | Variable |
|---|---|
| $t_V$ | Volumetric tariff (€/kWh) |
| $t_C$ | Capacity tariff (€/kW) |
| $t_F$ | Fixed tariff (€) |
| $\bar{P}_i$ | Maximum peak power of user $i$ (kW) |
| $S_i$ | installed solar PV capacity by user $i$ (kWp) |
| $B_i$ | installed battery capacity by user $i$ (kWh) |
| $F_{i,t}^{G,+}$ | power flow to~~from~~[R2] the grid of user $i$ at $t$ (kWh) |
| $F_{i,t}^{G,-}$ | power flow from~~to~~[R2] the grid of user $i$ at $t$ (kWh) |
| $F_{i,t}^{B,+}$ | power flow in the fixed battery of user $i$ at $t$ (kWh) |
| $F_{i,t}^{B,-}$ | power flow from the fixed battery of user $i$ at $t$ (kWh) |
| $F_{i,t}^{EV,+}$ | power flow in the EV battery of user $i$ at $t$ (kWh) |
| $F_{i,t}^{EV,-}$ | power flow from the EV battery of user $i$ at $t$ (kWh) |
| $SOC_{i,t}^{B}$ | state of charge of the fixed battery of user $i$ at $t$ (kWh) |
| $SOC_{i,t}^{EV}$ | state of charge of the EV battery of user $i$ at $t$ (kWh) |

| Notation | Parameter |
|---|---|
| $dt$ | time step (h) |
| $\epsilon_V$ | volumetric tariff fraction (%) |
| $\epsilon_C$ | capacity tariff fraction (%) |
| $\delta_m$ | net-metering indicator |
| $\Delta T$ | annualization factor |
| $L_{i,t}$ | regular load of user $i$ at $t$ (kWh) |
| $y_{i,t}^{S}$ | solar yield at $t$ for user $i$ (kWh/kWp) |
| $c^{G,-}$ | feed-in tariff~~grid electricity price~~[R2] (€/kWh) |
| $c^{G,+}$ | grid electricity price~~feed-in tariff~~[R2] (€/kWh) |
| $\eta^{B,-}$ | efficiency of battery discharging (%) |
| $\eta^{B,+}$ | efficiency of battery charging (%) |
| $\eta^{EV,-}$ | efficiency of EV discharging (%) |
| $\eta^{EV,+}$ | efficiency of EV charging (%) |
| $\nu^{B,-}$ | ramp down ratio of the battery (%) |
| $\nu^{B,+}$ | ramp up ratio of the battery (%) |
| $\nu^{EV,-}$ | ramp down ratio of the EV battery (%) |
| $\nu^{EV,+}$ | ramp up ratio of the EV battery (%) |
| $\varphi^{B}$ | stand-alone leakage rate (%) |
| $\varphi^{EV}$ | EV battery leakage rate (%) |
| $\bar{S}_i$ | maximum solar capacity available to user $i$ (kWp) |
| $\bar{B}_i$ | maximum battery capacity (kWh) |
| $K_i^{EV}$ | capacity of the EV battery of user $i$ (kWh) |
| $c^{S}$ | annualized cost of solar PV (€/kWp) |
| $c^{B}$ | annualized cost of stand-alone battery (€/kWh) |

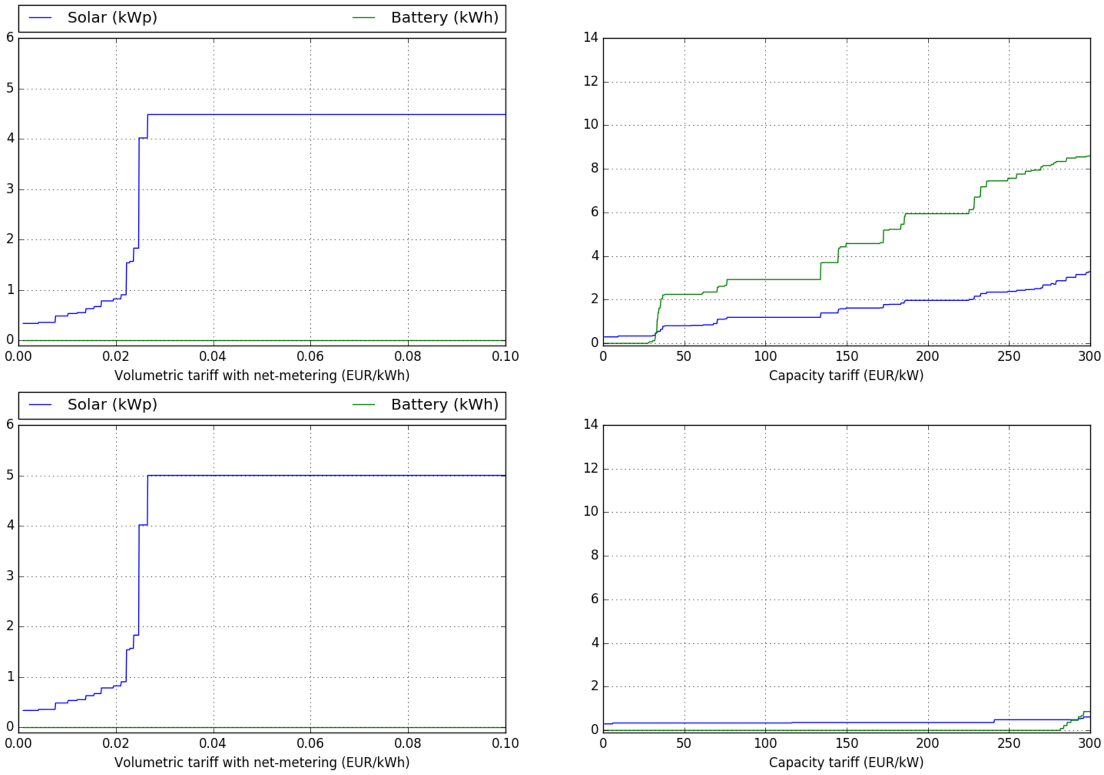


Figure B.4: Optimal solar PV and battery investment functions of TV-prosumers (up) and EV-prosumers (down) function of the tariff level for volumetric (left) and capacity (right) tariff structures.

## Appendix B. Optimal investment of prosumers

In our bi-level framework, the regulator (upper level) anticipates the reaction of prosumers (lower level) to set network tariffs. Such tariff level corresponds to the equilibrium of the non-cooperative game. These optimal investments functions of EV-prosumers and TV-prosumers are shown on Figure B.4 for volumetric and capacity tariff structures. With volumetric tariff, only solar PV is incentivized and the reaction function has almost a threshold. With capacity tariff, both solar PV and batteries are incentivized. Contrary to the volumetric tariff, the optimal investment function is much smoother. Furthermore, with the volumetric structure, prosumers with EV have similar investment decisions to TV-prosumers. Under capacity tariff, EV-prosumers only invest in DER if capacity tariffs are high enough. Indeed, a smart charging of the EV is sufficient to avoid much of the network tariff.

## Appendix C. Impacts of alternative tariff structures

Previously, we only considered pure tariff structures. In this section, we consider different tariff structures. First, we consider another type of pure tariff structure, the volumetric tariff without net-metering. Second, we investigate the impacts of mixed volumetric/capacity tariffs.

### *Appendix C.1. Volumetric tariff without net-metering*

Another possible tariff is the volumetric tariff without net-metering as defined in (Schittekatte et al., 2018). With this tariff, prosumers are charged for their feed-in to the grid. Table C.7 shows the tariff variation of the model with the four scenarios of prosuming/EV penetration. These results indicate that the effects of EV become dominant, as prosumers invest in little DER capacities. Indeed, such tariff gives incentives for solar PV only if the produced power is self-consumed.

| Tariff structure | Proportion of EV owners | Proportion of prosumers | **Tariff Variation (%)** |
|---|---|---|---|
| Volumetric | 5% | 5% | -1.95 |
| | | 25% | -10.7 |
| | 25% | 5% | 0.05 |
| | | 25% | -9.04 |

Table C.7: Network tariff variation relatively to the reference case, under volumetric without net-metering tariff structure. Variations are given for C and VNM tariff structure, 5 and 25% EV owners and 5-25% prosumers.

*Appendix C.2. Mixed energy-capacity tariffs*

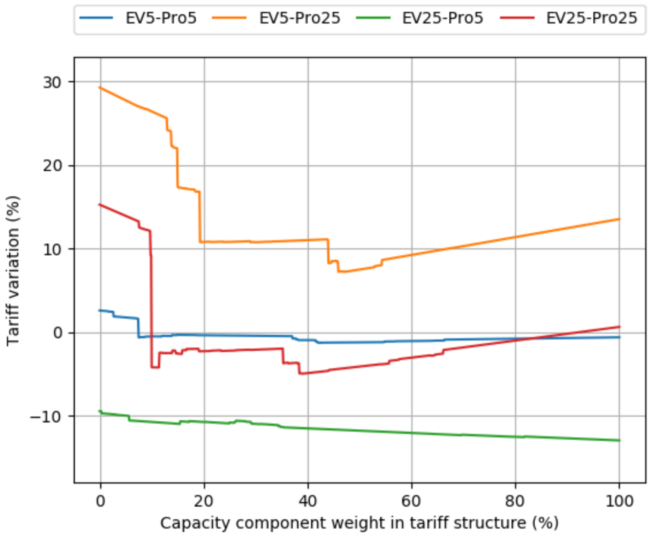


Figure C.5: Evolution of tariff variations with the share of capacity tariff in the tariff structure. The usual four scenarios of prosuming and EV penetration are considered.

In our framework, mixed tariff structure can be modeled with a pair $(\epsilon_V, \epsilon_C)$. Without a fixed component in the tariff structure, mixed volumetric/capacity tariffs are then defined with $\epsilon_V = 1 - \epsilon_C$. Figure C.5 shows the evolution of tariff variation with the capacity component $\epsilon_C$. Three observations are made about these results on mixed volumetric/capacity. First, scenarios with small proportion of prosumers shows small tariff variations for the whole range of mixed tariff structures. Tariffs decrease with higher capacity components as EV owners pays more for their peak load. On the other hand, scenarios with high proportion of prosumers shows non-linear dependence with the capacity component. A minimal tariff variation is achieved for capacity components in the range 20-40%. Indeed, this range of tariff structure is enough to limit both over-incentives for solar PV and for battery.

## Appendix D. Impacts of variable grid costs

In the previous sections, we assumed that grid costs were only sunk costs. This hypothesis is adopted by several studies in the field (Schittekatte et al., 2018). Nevertheless some other studies consider a variable cost component such as (Schittekatte and Meeus, 2018). Moreover, several works have inferred that large electric vehicles diffusion, by increasing the network peak load, could significantly increase grid costs (Clement-Nyns et al., 2010; Muratori, 2018). We discuss the consequences of such possibility in this section.

$$C_N(P_{tot}) = \alpha_S C_{sunk} + (1 - \alpha_S) C_{var}(P_{tot}) \tag{D.1}$$

Grid costs function is defined in equation D.1, with $C_{sunk}$ and $C_{var}$ the sunk and variable components of grid costs. $C_{var}$ depends on the network peak load. $\alpha_S$ is the fraction of sunk grid costs. It is assumed that the variable component of network costs is linear and calibrated with the reference level where there are neither prosumers or EVs in the network:

$$C_{var}(P_{tot}) = C_{sunk}\frac{P_{tot}}{P_{tot}^{ref}} \tag{D.2}$$

With $P_{tot}^{ref}$ the network peak load of the reference case. This way, we have $C_N(P_{tot}^{ref}) = C_{sunk}$.

We focus on a situation where a network has variable costs (20%), which is in line with several studies in the literature. Such a variable component represents the additional costs due to increased damages in the grid or additional reinforcements that have to be made to the grid. For instance, (Simshauser, 2016; Pollitt, 2018) estimate the variable component of network costs to 20%. (Fernandez et al., 2011) estimates the worst case scenario to 15% grid costs increase due to high EV penetration. In our model formulation, load peaks of network users are exactly coincident. Remember that getting an EV leads to a 75% increase of the EV owner's peak load. Hence a 25% penetration of EVs with no prosumers leads to a 19% increase of network peak load. Then this increase in peak load results in a 4% increase in grid costs.

| Tariff structure | Proportion of EV owners | Proportion of prosumers | **Tariff Variation (%)** |
|---|---|---|---|
| Volumetric | 5% | 5% | 10.3 |
| | | 25% | 38.3 |
| | 25% | 5% | 3.7 |
| | | 25% | 26.9 |
| Capacity | 5% | 5% | 6.2 |
| | | 25% | 17.5 |
| | 25% | 5% | -3.7 |
| | | 25% | 7 |

Table D.8: Tariff variations for variable grid costs (20%). The previous prosuming/EV scenarios are considered. The reference is still the 0%-0% EV/prosumers case

Two main highlights can be drawn from results shown in table D.8. First, as EVs increase the peak load of their user, they increase the network peak load. This increase leads to higher grid costs, which are then reflected on network tariffs. However, this increase in grid costs is not entirely transmitted on tariffs since they decrease by 6-14% in both prosuming scenarios. Again, as EV owners consume much more power than TV owners, they also pay much more network charges. In these settings, EV owners increase the financial revenues of the DSO more than they increase grid costs. On the contrary, tariff variations caused by prosumers are larger with this variable grid costs structure. Indeed, DSO missing revenues because of prosumers is even more severe that grid costs are higher due to EV penetration, which leads to even higher tariffs. In summary, a grid costs structure with a variable component do not change significantly change our previous results.


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## List of changes

Added (R1): (EVs) . . . 1
Replaced (R1): EVs . . . 2
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