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Tariff-based regulatory sandboxes for EV smart charging: Impacts on the tariff and the power system in a national framework

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Summary

Electrification of private transport is a fundamental step for decarbonizing mobility. Electric vehicles (EV) can be a burden for the power system if vehicle-grid integration is not implemented by design. Market-based smart charging projects are effective, but their massive diffusion is limited. A fundamental instrument toward a large adoption of smart charging is the inclusion of smart charging-oriented measures in regulatory sandboxes, conveniently acting on electricity tariff. This paper presents a set of possible toolboxes for smart charging to show the potential that regulatory measures can have on steering the infrastructure deployment and the charging activity. Each proposed toolbox addresses a specific charging mode, including domestic, workplace, and public access charging. Proposed measures are target-oriented and evaluated based on their environmental, technical, and economic impacts. These include the carbon footprint of the electricity used for EV charging, the impact in terms of peak power withdrawal from the public grid and the charging cost born by EV users. Additionally, the assessment about the impact of prospected measures on the electricity tariffs' income is provided. Results show the possibility of reducing the evening EV-related peak load by 30% to 50% via home smart charging. Also, a 10% decrease in carbon footprint is achieved by valley-filling with work charging. Charging at the destination can reduce the system cost for the new distribution infrastructure, dropping the number of new dedicated connection points for public charging. The cost of incentives is partially repayable considering the additional EV penetration fostered by the reduced charging costs.

KEYWORDS

duck curve, electric mobility, electricity bill, electricity tariff, smart charging, valley-filling

1 | INTRODUCTION

Sales of electric vehicles (EV) experienced an exponential growth in the second decade of 21st century.[1] Scenarios for 2030 show an increasingly fast expansion of this market.[2] Electrification can support the decarbonization of the transport system, since EVs hold a lower carbon footprint on their lifecycle with respect to internal combustion engine (ICE) vehicles, especially when coupled with renewable power generation.[3] Therefore, within the

European decarbonization strategy recently updated with the EU Green Deal, the transition to an electrified mobility is addressed as one of the key points for reducing greenhouse gases (GHG) emissions.[4]

In the future, the total number of passenger cars is expected to decrease under the pressure of a major exploitation of public transport means and shared mobility. Indeed, sustainable mobility can be achieved via a change of paradigm, decreasing the modal share of private cars toward other forms of transport.[5] While this is still the case in the long-term, COVID-19 crisis constrained most of the global population to stay separated as far as possible, and some impacts can potentially last in the long run.[6] Consequently, private transportation is expected to maintain a preponderant role in the next future. In 2020, COVID-19 crisis, while pushing down European car sales by 10%, contributed to increase by 120% EV car sales (+0.8 million registrations)[7]; the same trend (+0.9 million registrations) has shown in 2021.[8] This suggests that the recovery plan set up by EU authorities could be a golden opportunity to effectively shift the private transport sector toward electric. Drivers for the diffusion of EVs in a country are several and most of them can be steered by policymaking. Among the main drivers there are the presence of financial incentives and the diffusion of charging infrastructure.[9,10] Also, a lower electricity cost proved to be linked with the increment of EV sales.[10]

EVs also introduce some issues, such as the burden that new electric loads generate on power system. EV could enhance the ramp rate of the evening load curve, contributing to the formation of the so-called "duck curve". To cope with this, vehicle-grid integration (VGI) is addressed at various levels, including different kinds of regulatory, technical, or pricing practices gathered under the concept of smart charging.[11]

The literature widely investigated smart charging in the different charging modes. Home smart charging has been proposed for the coordination of large residential EV populations.[12] Smart charging strategies on the working place devoted to peak load reduction[13] or, oppositely, valley-filling,[14,15] are studied. Peak shaving can move the EV charging-related load from peak to off-peak periods (eg, the nighttime). With valley-filling, instead, the EV charging process can increase the load in those hours of maximum nonprogrammable RES production, contrasting the residual load reduction. The net load reduction is potentially detrimental for the system (eg, in largely PV penetrated systems).[16,17] Public charging, for instance in large parking lots, can be smartened for improving logics of self-consumption and therefore provide RES integration.[18,19] One of the ultimate goals for smart charging can be the provision of flexibility and ancillary services with EVs, often aggregated and considered as portable energy storage systems.[20,21] Algorithms used to implement peak-shaving and valley-filling practices can have a different level of complexity: a lower complexity, coordinated with the presence of powerful policy tools, is generally likely to increase the adhesion to the smart charging practice.[22,23] Despite literature highlights that the simpler is the scheme, the wider is the participation, most of the contributions focus on smart charging with provision of services to the system following a sophisticated scheduling[24–26] and foreseeing the participation of the EV owner to ancillary services markets (by means of an aggregator). The challenges are, in this case, both technological and related to the involvement of the end-users (ie, the service must be paid and, in general, the achievable margin is limited). Simpler schemes are proposed, instead, by regulatory sandboxes and experimentations acting on the electricity tariff.[27]

The previous studies either neglect actions to be implemented to steer EV charging toward smart charging or consider market projects involving flexibility provision. EVs, as other distributed energy resources (DERs), will likely face difficulties in being integrated quickly in the flexibility markets.[28,29] Instead, it is fundamental that the VGI occurs "by design" and involves most of the EVs. For fostering the larger affluence to smart charging, regulation can involve a larger turnout of users with respect to the flexibility markets, providing convenient price signals by acting directly on the electricity tariff.[23,24] The possibility of steering the EV charging with tailor-made, yet cost-reflective regulatory measures is less analysed than market-based solutions. This can guide the EV charging infrastructure deployment: since different electric customers are generally associated to diverse charging mode (eg, home, work, and public charging), a cost-reflective tariff could lead to deploy different shares of poles and prioritising the deployment of the infrastructure that entails lower impacts (ie, costs) on power systems.[30]

The main impact on the power systems is related to the EV charging load profile. The impact of dumb vs smart charging is assessed in Reference 31 over a portion of medium voltage (MV) network, suggesting that smart charging can prevent overload. Nevertheless, it is known that the additional load is not the only issue of a large deployment of EVs, especially when considering the topology of the network. Indeed, the cost of infrastructure can increase in case either a new dedicated point of delivery (PoD) is foreseen or an existing connection point is reinforced to host larger power demand.[32] At a national level, the impact of EV demand on the power system is estimated in Reference 33 for Italy and Germany. The benefits of passing from dumb to smart charging are assessed in terms of CO_2 reduction and avoided curtailment of variable RES. Nevertheless, the size of incentives needed for turning dumb into smart charging is not considered, thus the possible massive adoption of smart charging is uncertain. Two policy recommendations are proposed: the introduction of time-of-use (ToU) tariffs and the aggregation of EVs in a virtual power plant (VPP) managed by a Balancing Service Provider (BSP). To assess the cost of a tariff revision for incentivizing some EV charging modes, a proper model considering the tariff components (mainly including the network costs) should be developed.[34] Few studies are found estimating the variation on a national tariff income (in million €) of an extended electricity tariff redesign,[35,36] and none on the EV charging.

This study aims at assessing the power of an intervention on the electricity tariff by the regulator for steering EV charging infrastructure deployment and charging activity toward smart charging.[37,38] The effect of EV charging on the Italian power system and on the electricity tariff prospected on 2030 is estimated by a set of different perspectives, with and without a set of regulatory incentives to foster smart charging. Different policy toolboxes will be described and tested: they could be implemented in regulatory sandboxes, pilot projects or new policies. Toolboxes are target oriented since they are proposed for pursuing a wide set of final targets: for mitigating the additional burden from EV on the power system; for increasing environmental compatibility of EV charging; for addressing different smart charging methods; for cancelling price distortion that some electric user categories could experience. This is done assessing the difference between a reference Base Case and some toolbox cases, where some or all the prospected measures are implemented. A comprehensive sensitivity analysis is proposed on the recognized key performance indexes (KPI), dealing with costs (for the system, the network, and the EV user), and the environmental impact.

The knowledge gap that is filled is the estimation of the impacts - both positive (ie, better VGI) and possibly negative (ie, the cost of incentives on the national tariff income) - of an introduction of tariff-based measures for steering the EV charging toward smart charging. Tariff can guide this by design (ie, starting from guiding the deployment of the charging infrastructure). As previously stated, the literature mostly focuses on market experiences, including specific plant layouts (eg, increasing the self-consumption in a smart energy district) or participation to ancillary services markets: for what said before, these are useful but niche solutions. The regulation is instead an enabler for the massive implementation of smart charging since it can guide both the deployment of the charging infrastructure (ie, if a charging mode is more convenient, the charging pole will be deployed under the PoD of a specific electric user) and the charging events (eg, in case a user benefits of a lower tariff in a certain time, it will concentrate the charging events). Therefore, studying the system effects of extensive smart charging, especially in a pioneering country for what concerns regulation of power systems,[39] is considered of large interest: if the quantitative results in this paper are valid for Italy, the proposed methodology can be extended internationally.

The analyzed positive impacts include the effects on the power system in terms of EV-related load profile, carbon intensity of EV charging, and the relationship between deployment of charging poles and new connections to grid. The negative side of the coin considers the cost of the incentives and its reflection on the electricity tariff income at a national level.

The remainder of the paper is structured as follows. Section 2 describes how the electricity tariff can steer dumb charging toward smart charging in the different charging modes. Then, it presents the Italian electricity tariff structure and the corresponding costs for EV charging. Section 3 focuses on the modeling tools used in the analysis, presenting a Base Case and three different policy toolboxes. Section 4 reports the results obtained, addressing economical, systemic, and environmental aspects related to EV diffusion. Eventually, in Section 5, the paper concludes that policy toolboxes under the form of experimentation, sandboxes, and pilot regulations, can effectively enhance private electric mobility, while trying to contain the costs borne by final customers in the bill.

2 | STEERING THE EV CHARGING WITH THE ELECTRICITY TARIFF

Charging activity has been largely studied and correlated to end-user behaviours,[40] identifying in the literature the so-called charging modes.[41] It is possibly to distinguish:

- home charging, which typically takes place connecting the EV at the domestic premises,
- charging at the working place, that is, used both for companies' fleets and employees' private cars,
- public access charging, which considers all the charging modalities where an EV user can access the infrastructure in public areas.

These three main charging modes are common at international level: indeed, with few or no adaptations, a charging profile obtained by national users can be applied to other countries.[42,43] Generally, the first two charging modes occur at a private PoD, only accessible by authorized people that are relevant either to the household or to the company. Public access to charging poles can be provided, too. Two different categories of public access, and thus two charging modes, can be recognized. Some businesses offer EV charging as a benefit for their customers. This public access mode is known as "charging at the destination". It is a business to consumers (B2C) service: a PoD, owned by a business (eg, a supermarket or a hotel), is exploited to feed EVs owned by customers of that business. Often, charging at the destination is granted for free or at a low price, for instance to increase fidelity of the customers. On the other hand, a tout-court public charging, with a dedicated PoD, is more traditionally associated to public charging poles on the streets. These dedicated PoDs (and this charging mode) are usually involved in the strategic planning of EV infrastructure.[44] Often, full public charging is the most expensive way of charging (ie, it shows an expensive electricity tariff), since it entails higher fixed costs (eg, related to the tariff for the connection of a new PoD).

Charging modes can be incentivized or hindered while planning the deployment of the charging infrastructure, for instance to reduce the system cost or to foster smart charging. The electricity tariff is the main instrument for National Regulatory Authorities (NRAs) to steer the EV charging habits and to increase the VGI starting from guiding the diffusion of the infrastructure. The electricity tariff concept usually includes two components: network costs and general system charges. Bearing in mind that the regulation principles impose the cost reflectivity of tariffs,[45] an accurate design of the electricity tariff can enhance both the social welfare and the efficient integration of new resources in the power system.[46] To this aim, innovative regulation frameworks have been recently implemented in many EU countries, addressing diverse energy sectors, with the goal of testing and upscaling new policy rules.[47] They are commonly known as regulatory sandboxes, pilot regulations or regulatory experiments, depending on the application field, the scope, and the participants.[48] An EV-related regulatory experimentation could exploit, for instance, ToU tariffs or discounts on fixed or capacity-related components. Also, a specific electricity tariff for EV charging can be proposed[49]: this is done in Portugal[50] and in Italy,[51] where a tariff is proposed to dedicated PoDs that host public electric vehicle supply equipment (EVSE). The budget constraint principle implies the need for the electricity network tariff income to remunerate network costs faced by regulated firms, namely distribution and transmission system operators (DSOs and TSOs).[34] Therefore, when preparing and implementing regulatory sandboxes, it is necessary to carefully assess the impact of new rules (and eventual incentives) on the tariff income at a national level.[52] This is also confirmed, in Italy, by the roll-out of second generations smart meters, where a TOTEX approach was adopted.[53] The Italian authority (ARERA) granted a fast-track approval to those plans which demonstrated to have a tariff-invariant impact with respect to first generation meters substitution through a counter factual test.[54]

Some countries are considered pioneers in regulatory experimentation in energy: among these, Italy.[27] These countries can be taken as reference to check how the regulatory experimentation can evolve in the European context. This is also suggested by the Agency for the Cooperation of Energy Regulators (ACER): the resulting lessons from regulatory experimentation should be shared between NRAs to avoid the need to replicate pilots in each Member State and to accelerate decisions on whether a regulation or legislation needs to be adapted.[55]

2.1 | Italian electricity tariffs and EV charging costs

In Italy, the electric customers are represented by a large portfolio of different user types: each type has its own electricity tariff, given by the network costs and the general system charges.[56] Users are clustered based on the maximum available power at the PoD and the voltage level that can be low (LV), medium (MV), and high (HV). Furthermore, the Italian regulation distinguishes between different users' categories: domestic users having a dedicated domestic tariff ("TD"); specific users, such as public lighting in LV ("BTIP"), in MV ("MTIP") and electric vehicle charging in LV ("BTVE"); other uses, including the rest of commercial, industrial, administrative buildings and users, in both LV ("BTA*n*") and MV ("MTA*n*"), where the *n* increases as the contracted power level increases. Overall, there are around 15 user types, corresponding to 15 different tariffs. The electricity tariff includes network costs and system charges and is based on a trinomial structure, having three terms characterized by three metered quantities: a variable (also known as volumetric) energy-based (€/kWh), a capacity or power-based (€/kW/y), and a fixed term (€/PoD/y). Generally, the power-based tariff is directly related to the peak power. This can be fixed, coincident with the maximum power available at the PoD (ie, the contracted power), or variable. This latter case applies to contracted powers above 30 kW (both at LV and higher voltage levels): for these users, the power quota varies monthly depending on the maximum monthly value of the power withdrawn from the public grid.

ARERA already implemented some measures specifically addressing EV charging management, mainly by sending price signals to different users.[57] Since 2010, ARERA has introduced a dedicated tariff for public access EV charging poles connected at LV ("BTVE"). This tariff is completely volumetric (€/kWh), meaning that power (€/kW) and fixed (€/PoD) terms are null; this has been done to reduce fixed costs of public charging poles that are characterized by low utilization rates, thus potentially bearing large costs even if they withdraw a small amount of energy from the network. Also, this reflects the fact that EV charging is a power-intensive activity, often characterized by limited energy consumption at high power rates.[58,59] More recently, ARERA started a pilot regulation related to EV smart charging at home: domestic consumers can withdraw more power (typically passing from 3 to 6 kW) during off-peak hours (ie, nighttime, Sundays, and holidays) with a full discount on the additional power quota of the tariff that they should pay.[60]

With the presented measures, ARERA aims at pursuing the following targets.

- Thanks to BTVE, dedicated PoDs hosting EVSE for public access can be deployed with no fixed costs for what concerns the bill tariff. This helps developing a public charging infrastructure also in rural areas and, in general, where the utilization rate is lower.
- Thanks to the discount on the off-peak power increment, a share of the load could be moved from peak to off-peak hours. Therefore, the purpose of this measure is to implement a smart charging strategy for peak-shaving.

Tariff's fixed costs entail potential issues also in case of home charging, in case the car garage is connected to a PoD different form the household one. Indeed, in this case, the contracted power for the garage PoD should be high, with a limited energy consumption, eventually leading to an expensive specific cost for electricity.[51]

For defining the foreground of the study, the components of the charging costs are presented in Figure 1. The costs are related to the direct energy costs, to the electricity tariff (including network costs and system charges), and to taxes (including VAT and some excises). In addition to this, the charging point operator (CPO) margin is present: as previously mentioned, this could be positive (eg, for public charging), negative (eg, in case of charging at the destination at a discounted price), or zero (eg, in case of home charging at a private wallbox). The remainder of the paper will deal with energy, tariff, and taxes (the light orange part in Figure 1, listing the direct electricity cost components), leaving aside non-electricity related costs (eg, the charging point operator margin). Indeed, the focus of the analysis is the power system and the possible role of NRAs and policymakers in steering the EV charging: the business perspective should not influence the results of the work.

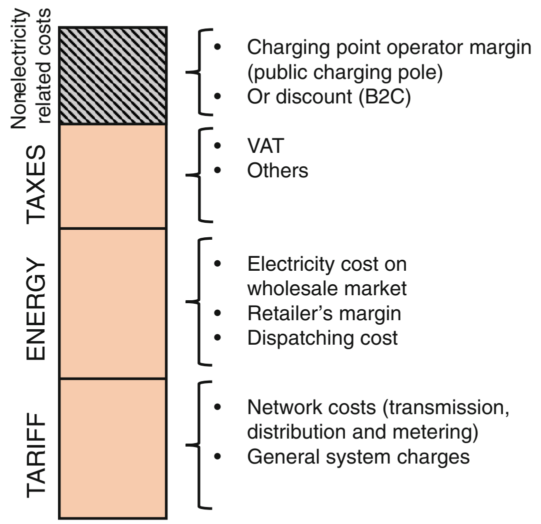


FIGURE 1 Components of the total costs for electricity in EV charging

3 | MATERIALS AND METHODS

The study aims at describing the impact of EV penetration on the Italian power system and on the electricity tariff income. Furthermore, it depicts the effects of a set of policy measures (namely a "toolbox") on EV charging habits, addressing possible benefits and drawbacks on marginal electricity demand, on system costs and on the environmental impact of electric mobility. They are estimated through a specific model that allows to calculate the hourly marginal load profile in a standard working day according to different EV penetration scenarios in 2030. A thorough investigation on the Italian electricity users and tariffs allows to correlate the demand for electric mobility to the charging poles' contracted power and to the number of new PoDs dedicated to EV charging. This information is necessary to assess the impact on the overall tariff income of EV-related withdrawal.

The tariff model is fed with all the components related to every relevant user type present in the Italian regulatory framework in 2021.[61] The components include the fixed (€/PoD/y), power (€/kW/y), and variable (€/kWh) quotas for both network costs (transmission, distribution and metering fees) and general system charges (mainly related to RES incentives financing). Multiplying each quota respectively by the PoDs' number, the peak power (in MW) and the energy volume (in GWh), it is possible to obtain the total EV-related tariff income. The following paragraphs describe how to get the energy, power and PoDs related to each use case and user type. To perform a preliminary check of the model's accuracy, an example has been carried out estimating the amount of tariff income for the overall portfolio of Italian users. Data related to Italian customers, divided by user types, are published by ARERA.[62] Gathering them for 2019, it is possible to compare the calculated income with the estimation made by the Italian ministerial energy research center (RSE)[34] (further evaluations will instead refer to electricity tariffs values updated to 2021). The study[34] estimates the total income, considering both network costs and general system charges, in 22.2 B€ for 2019; instead, the model exploited in this study returns a total income for the same year of 24.3 B€, hence overestimating by 8.5% with respect to RSE's figure. This overshoot could be partially explained by the fact that the developed model disregards the reliefs and discounts granted to some specific classes of electric users (eg, energy poverty measures).[61] In any case, the accuracy is considered acceptable for the scope of the work.

Afterward, some regulatory toolboxes with measures tailor-made for smartening the EV charging process are introduced. Hence, some measures are implemented in three toolbox cases: Home Charging, Work Charging and Public Access Charging. The effect of the adopted measures on the load profile, the tariff income, and some other relevant KPIs are evaluated with respect to the Base Case by means of an organic sensitivity analysis.*

3.1 | The base case

A literature review of EV penetration scenarios in Italy at 2030 has been carried out, selecting institutional[64,65] and research[59,66] sources, and considering both battery electric vehicle (BEV) and plug-in hybrid electric vehicles (PHEV). The adopted scenario of EV penetration for the analysis is computed as the mean of literature-based forecasts (see it in darker colors in Figure 2).

The adopted scenario considers 3.59 million BEV and 1.35 million PHEV, for a total almost 5 million of EV. The electric drive fraction (*ED*) of PHEV is considered equal to 70%.[1,67,68] The characteristics of the circulating fleet are taken from,[69] where the share of each car segment is considered to define the average electricity consumption (in kWh/100 km) of the fleet. That figure is updated to 2030 considering 1% year on year increase in the EVs efficiency, a conservative number with respect to recent estimations.[70,71] Therefore, the calculated average electricity consumption (*ec*) at 2030 is 15.1 kWh/100 km. The yearly mileage (*M*) of Italian average cars is 11 885 km as per 2019 data.[72] The data are used to compute the overall yearly energy demand (*E*, in GWh) by EVs in 2030.

$$\mathrm{E} = (N_{\mathrm{BEV}} \times e + N_{\mathrm{PHEV}} \times e \times \mathrm{ED})/106 \tag{1}$$

$$e = ec \times M \tag{2}$$

where N_{BEV} and N_{PHEV} are the units of BEV and PHEV in the reference scenario as reported before; e is the yearly energy demand for a BEV (in kWh); and ED is the electric drive fraction (70%). To conveniently compute the energy consumption for home charging, we also assume one EV per house.

Knowing the overall energy demand, the charging behavior of EV users must be modeled to estimate the charging load profile.[40,44] To do this, a breakdown of charging operations is hypothesized, coherently with the diverse charging modes reported above. Commercial, institutional, and academic literature[41,73–75] has been

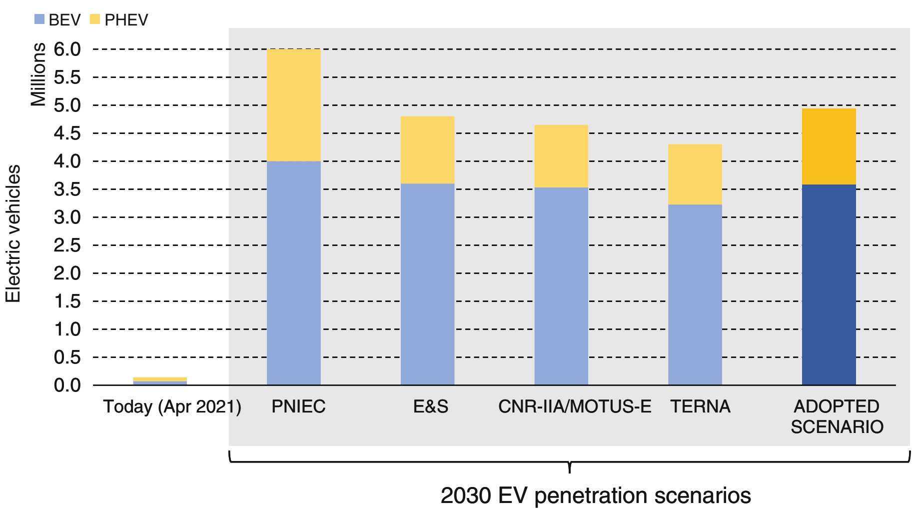


FIGURE 2 Italian EV penetration in 2021 (from public data) and 2030 scenarios

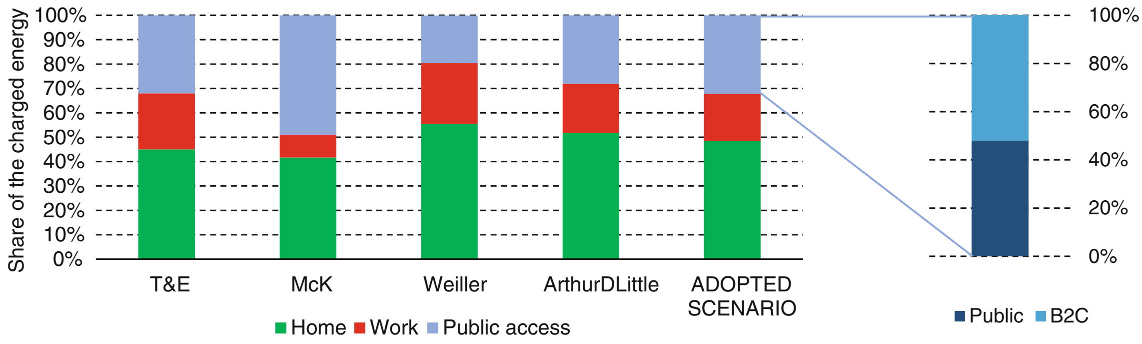


FIGURE 3 Charging mode breakdown in 2030

investigated to propose a realistic estimation of the different EV charging modalities between domestic, work and public access in 2030. Furthermore, public access charging mode splits in B2C (also known as charging at the destination) and public (charging poles located on the public land). Home charging is commonly considered the most diffused charging modes. Public charging is nowadays limited, but it is expected to increase its share by 2030; among this, around half of public access charging is B2C.[75] The adopted charging mode breakdown is shown in Figure 3, with 48% of home charging, 19% of work charging, and 32% of public access charging (15% public, 17% B2C).

The study focuses on a working day. Since working days and holidays have different load profiles, a fixed ratio is considered between working days and holidays energy demand ($r_{w/h}$).[76] To find the daily energy demand (E_d), Equation (3) is proposed. Then, to have the energy demand for each charging mode (m) in the standard working day ($E_{d,m}$), E_d is multiplied by the shares (S_m) shown in Figure 3.

$$E_d = E/\left(n_w + n_h/r_{w/h}\right) \tag{3}$$

$$E_{d,m} = E_d \times S_m. \tag{4}$$

where n_w is the number of working days in a year (251) and n_h is the number of holidays, including weekends and bank holidays (114); $r_{w/h}$ is 1.32,[76] meaning that on a working day the energy demand for EV charging is 132% with respect to holiday. The charging modes (m) are listed in first column of Table 1.

Afterward, hourly profiles for each charging mode in a working day are retrieved from literature. They are shown in Figure 4 as normalized profiles with respect to the daily modal energy consumption (ie, the integral of the hourly values over the day is 100%). Home charging profile (in green) is an average of literature sources (in gray).[12,77–80] The same is for work charging (in red).[76,80,81] B2C profile refers to the possibility of charging in the parking lot of a destination (eg, a supermarket). Therefore, it is associated to the average hourly visitors' profile for a popular Italian supermarket firm in Milan, retrieved from.[82] The profile obtained this way is averaged with,[83] and the obtained profile is presented in light blue. Eventually, public charging profile is presented in dark blue.[76,80,84,85]

TABLE 1 Electric user codes adopted for charging operation

m	Code 1	Code 2
home	TD (80%)	BTA2 (20%)
work	MTA2 (70%)	BTA6 (30%)
B2C	MTA3 (70%)	BTA6 (30%)
public	BTVE (39%)	BTA6 (61%)

The hourly load profiles obtained are rescaled so that their integral over time is equal to $E_{d,m}$. Their summation returns the hourly load profile for EV charging in a standard working day (whose integral in time is equal to E_d).

As previously introduced, to estimate the total income of the electricity tariff, the regulatory framework in Italy for 2021 is investigated.[56] Electricity tariff in Italy is based on diverse user types identified by a code; for each type, the tariff is based on a trinomial structure whose terms are related to energy (€/kWh), power (€/kW/y), and PoD (€/PoD/y). The energy demand for each charging mode is allocated on the convenient user type as reported in Table 1.

As introduced before, home charging is mainly related to the domestic tariff ("TD"), addressing those users who have a single PoD for both house and garage. A non-negligible share of houses has a dedicated PoD for the garage. According to the Italian regulation, they are included in the category of "other uses," characterized by "BTA*n*" tariffs. The contracted power is assumed to be 3 kW; therefore, the associated code is "BTA2". Charging

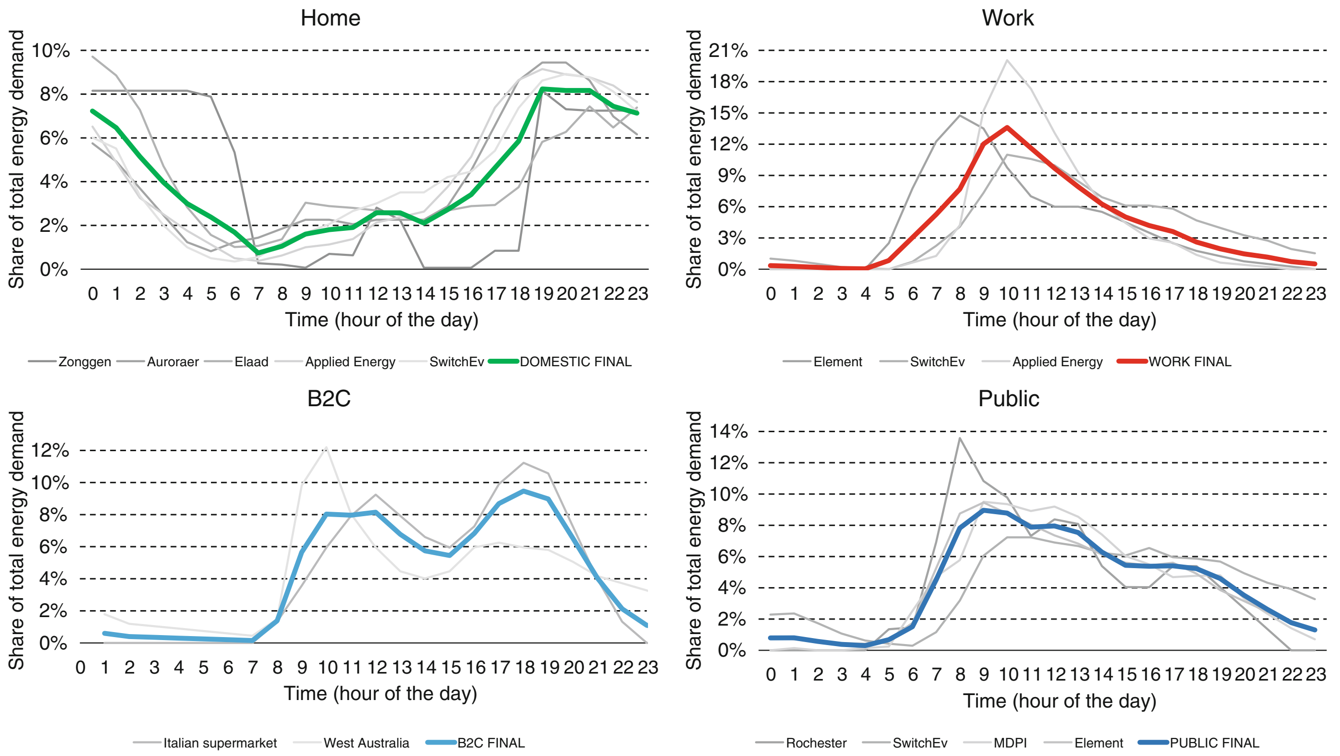


FIGURE 4 Normalized hourly load profiles for each charging modes

at the working place is associated to the company premises, that could be at LV with a contracted power larger than 16 kW ("BTA6") or at MV with a power below 500 kW ("MTA2"). B2C charging is mainly associated to mass retailers that install charging poles available for customers in their parking lot. These premises are associated to large-scale MV users, with a peak withdrawal above 500 kW ("MTA3"). A portion of B2C charging is also associated to smaller shops with a LV contract ("BTA6"). Finally, public charging is represented by LV users, including also fast charging. The dedicated tariff for the electric mobility[51] in LV is partially adopted ("BTVE"). Actually, this conveniently abates fixed costs in case of low utilization rates (u): utilization rate represents the yearly energy demand of a charging pole divided by the maximum energy that can be delivered in one year (ie, the contracted power times 8760 h). For high u, the traditional ("BTA6") LV tariff becomes more convenient; knowing this, given an average assumed utilization rate for public charging poles in Italy equal to 10%, a distribution of u for each charging pole is elaborated (depending on location, pricing rules, etc.) following.[86] Then, considering that "BTA6" tariff is more convenient than "BTVE" for u greater than 6.5%,[61] we can estimate the portion of public access charging poles adopting each tariff. We have that, for u equal to 10% as in the Italian case, 61% of poles conveniently adopt "BTA6" and the remainder is with "BTVE". All the public charging is considered to occur at LV. MV public access charging is related to B2C charging. This could be the case, for example, of motorway fast charging stations integrated in restaurants or shops of motorway service areas.

To estimate the power quota of the tariff, the variation of contracted power due to EV charging for each electric user must be conveniently estimated. As introduced before, the maximum available power at the PoD for LV user is fixed in the contract. Instead, large users (ie, power > 30 kW, either in LV or MV) generally pay for the peak power absorbed monthly. Therefore, the increment of power for each electric user is related to the maximum value of marginal absorbed power in peak hours for each charging mode ($\Delta P_{\mathrm{peak,m}}$), where peak hours are considered as per "F1" band in Italian tariff (7 AM - 11 PM). Then, the increment in contracted power for each tariff n (ΔP_{n}) is computed by taking in account the share of each tariff reported in the second and third columns of Table 1 (S_{n}).

$$\Delta P_{\mathrm{n}} = \Delta P_{\mathrm{peak,m}} \times S\mathrm{n}. \tag{5}$$

As described, the variation in power for a domestic user or a small user (in LV) is associated to an enhanced contracted power of a fixed step. In Italy, most of domestic users have a contracted power of 3 kW. Another typical contracted power, for historical reasons, is 4.5 kW.[62] Therefore, we can estimate a share of users increasing their contracted power of 1.5 kW coherent with the power increase for domestic tariff estimated based on

Equation (5) (ΔP_{TD}). In case of separate car garage, it is estimated that 45% of car garage is in "BTA1," thus with a contracted power of 1.5 kW, based on an elaboration on ARERA's data.[62] In these cases, home charging requires at least the upgrade to "BTA2," with 3 kW of contracted power. This is treated as a power increment of 1.5 kW per user.

For public charging, the increase in contracted power depends on the average Italian utilization rate (u) of the charging poles.

$$u = E \times S_{public} / (P_p \times 8760) \tag{6}$$

where P_p is the overall contracted power of the public poles. As previously mentioned, a $u = 10\%$ is considered. We are aware that research hypothesizes value around 4% to 5% in a mature market,[87] but a larger value seems more coherent with the expected increase in public charging share in 2030. Equation (6) can be used to estimate contracted power for public charging (P_p). Then, the number of new PoD is estimated by assuming an average of 14 kW per PoD.

These data and assumptions are used to estimate the marginal electricity tariff income related to EV charging in 2030. Instead, to compute the total energy-related costs for EV users, considering the components highlighted in Figure 1, data reported in Table 2 are assumed. The remaining components (energy cost and taxes) require less effort since they present a pure volumetric cost.

The cost of electricity is reported as the total marginal cost of electricity for EV charging, that is, considering fixed and variable costs for tariff, energy and taxes and reporting it in €/kWh. It is obtained by dividing the overall additional cost by the energy charged.

3.2 | Proposed regulatory toolboxes

Some policy measures are introduced aiming at reducing the impact on the power system of EV charging operations and providing economic and environmental benefits to the society. These measures are split in toolboxes each one addressing a different charging mode (ie, home, work, and public access) (see Table 3).

TABLE 2 Adopted data for the electricity cost components

Data	Unit	Value	Source
Energy cost LV	€/kWh	0.102	88
Energy cost MV and public	€/kWh	0.075	89
Taxes (VAT)	%	22% (10% for "TD" residential)	56

TABLE 3 Proposed regulatory measures

Toolbox	#	Measure name	Description of the measure	Expected effect
Home	1	Home off-peak power increment	TD and BTA2 users holding an EV can absorb up to 6 kW in off-peak hours without paying extra-power quota	Peak-shaving on the evening peak (and ramp)
	2	BTA2 straight tariff decrease	BTA2 tariff is reduced to get it equal to non-residential domestic tariff	Eliminate charging cost distortion for domestic users having a dedicated PoD for their car garage
Work	3	Work peak power increment	Working places do not pay extra-power quota for EV charging occurring in peak hours	Valley-filling during the daytime to exploit the PV production and cope with the reduced residual load
Public access	4	Discount on occupancy tax + promotion of B2C charging	The connection of EVSE to an existing business PoD is not subject to the occupancy tax. Besides, a promotion campaign is carried out to increase shop owners' awareness on the possibility of installing EVSE	Decrease the number of dedicated PoDs for public charging

3.2.1 | Home toolbox

Home toolbox cases is composed by two measures. Measure #1 allows the "TD" and "BTA2" user to absorb from grid a power up to 6 kW during off-peak hours (F3 band in Italy, from 11 PM to 7 AM) without further costs for the contracted power increment. This toolbox acts on the most common EV charging mode (almost 50% modal share). The aim is to decrease the impact on the power system of the peak shown in Figure 4 for domestic charging (6-9 PM). This measure is already implemented by a pilot regulation in Italy.[60] In a more general perspective, this measure implements a basic domestic smart charging aiming at peak-shaving. Therefore, a proper profile is achieved by averaging literature results[77,90–92] with a profile obtained modifying the home charging presented in green in Figure 4. Modification is done by doubling the off-peak (11 PM to 7 AM) withdrawal and dividing by 1.5 the demand in the remaining hours. The result is shown in Figure 5, where the adopted profile is in green, and the sources are in different shades of gray. Over the total home charging demand, a participation coefficient of 20% is assumed, meaning that one fifth of total home charging follows this smart profile, while the rest keeps following the "dumb" curve for home charging presented in Figure 4.

The achievement of this profile should be obtained with relatively low technological and end-user effort. Indeed, a document of the pilot regulation shows that there is a long list of home EVSE compatible with the Measure.[93]

Measure #2 proposes to reduce "BTA2" tariff to get it equal to the nonresidential domestic tariff ("TD"). This is because a distortion on the home charging costs has been detected for those users with a separate PoD for the car garage.[94] This can hinder the possibility of home charging at a reasonable cost for a relevant part of EV users, especially in urban areas.

The economic benefits foreseen by this toolbox should reduce the system costs and therefore the tariff's income. The income decreases due to missing power quotas for the increment in contracted power (indeed, the share of domestic users paying for "TD" power increase is considered to be 0 in the home toolbox cases) and income loss in the "BTA2" EV-related income. The estimation of these costs corresponds to the difference between the EV-related tariff income in Base Case and in the home toolbox cases.

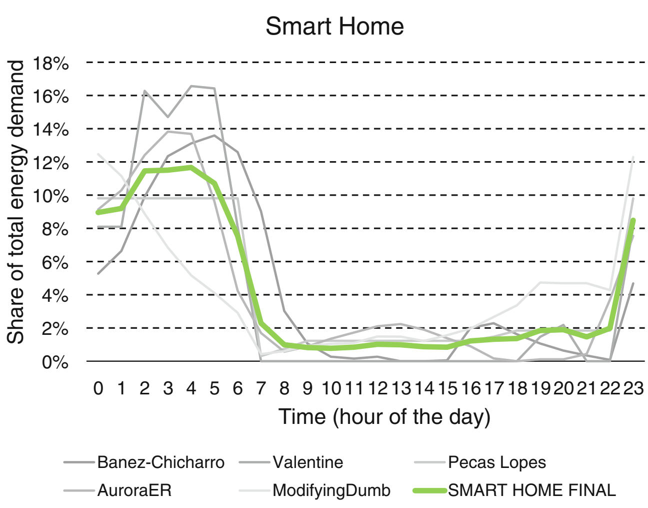


FIGURE 5 Smart home charging normalized profile

3.2.2 | Work toolbox

The work toolbox cases includes a measure to exploit the partial simultaneity of work charging and PV generation. Indeed, this can help decreasing the carbon intensity of electric mobility in a widely RES-penetrated system; also, it is related to a process of smart charging for valley-filling. The proposed Measure #3 consists in the possibility of a 100% discount on the extra power withdrawn during peak periods in case of EV charging at work. Therefore, the incremental value of the work charging load profile for "MTA2" and "BTA6" users hosting charging poles is not subject to the tariff's extra-power quota. The Measure could be associated to the definition of a list of compatible EVSE, as done for Measure #1, to ease the access to the pilot regulation. To assess the environmental performance of EV charging, an essential study on the carbon intensity of Italian production mix in 2030 is performed. The input data are the generating mix in 2030 as targeted in the Italian National Energy and Climate Plan (NECP),[64] the average hourly power profile of PV and wind generation and the load profile of a working day as reported by the Italian TSO.[95] The load profile subtracted of the PV and wind generation is the so-called residual load. The hourly residual load is satisfied according to the corresponding hourly generation mix in Italy. The carbon intensity (in g_{CO2eq}/kWh) of each electricity source is given by the lifecycle emissions presented in Annex III of the IPCC report.[96] Figure 6 presents the target mix for Italy in 2030, the hourly load profile, as satisfied by the different generating sources, and the hourly carbon intensity. It is possible to see that carbon intensity is dominated by natural gas generation. Indeed, in daytime, when PV generation is at its peak, a lower amount of gas plants is operated and the carbon intensity drops. This justifies a valley-filling smart charging aimed to increase the load when the carbon intensity is lower.

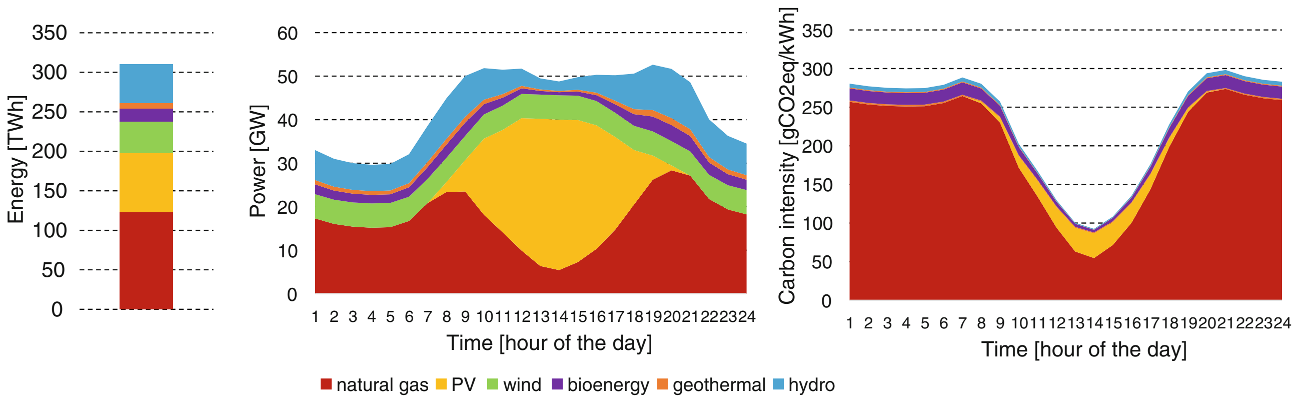


FIGURE 6 The energy (left), power (mid) and carbon intensity (right) estimation for Italian power system in 2030

The average carbon intensity of electricity for EV charging (CI) is computed as the sum of the hourly product of the EV charging demand and the electricity carbon intensity, divided by the total energy demand E_d.

$$CI = \frac{1}{E_d} \times \left(\sum_{h=0}^{23} \Delta P_h \times CI_h \right) \quad (7)$$

where ΔP_h is the hourly load profile for EV charging at hour h and CI_h is the carbon intensity of the generating mix at hour h.

3.2.3 | Public access toolbox

The public access toolbox cases guides the public charging infrastructure development coherently with the its integration within the distribution network. One of the main issues of public access charging is the proliferation of new dedicated PoDs. In a public Consultation Document (DCO 318/2019/R/eel[57]), the Authority proposes a principle stating that, wherever applicable, the charging infrastructure should be implemented under already existing PoDs, without creating new dedicated PoDs. This entails both benefits for the users (eg, the fixed costs spread on a larger amount of energy) and the system, since an already existing PoD could allow inclusion in logics of demand response, the exploitation of self-consumption and lower infrastructural development costs. B2C charging mode, since it occurs at the destinations, can be compatible with the installation of EVSE in already existing PoDs. On the other hand, public charging needs (almost) always a dedicated new connection. Hence, measure #4 is implemented to increase the ratio of B2C charging over the total public access charging. It foresees two sub-measures that do not directly apply on the electricity tariff.

- First, a discount on the occupancy tax can be proposed. In Italy, a yearly fee in the order of some tens of euros per m^2 per year is paid to the city administration for deploying infrastructure on the public land, included the EVSE.[97] This can be discounted partially or totally based on a City Council decision. This decision can be subject to the connection of the EVSE to an existing PoD.
- Second, a large information and promotion campaign could be operated addressing both shop managers and local administrations, raising awareness on the possibility of deploying EVSE at the destinations, with benefits for the final users and charging point operators (CPO).

The aim of these measures is increasing the amount of B2C poles, so the B2C/public charging ratio. To assess the benefits of a different penetration of these measures, the number of dedicated PoDs (ie, based on Equation (6), considering the marginal power for public charging and 14 kW of contracted power per PoD) and the average cost of public access charging (as the weighted average of B2C and public charging cost) are computed. The system cost of Measure #4, as the sum of the discount on occupancy fee and the cost of the information campaign, are not computed: for the framework of this study, Measure #4 has no cost on the electricity tariff income, since it is supposed that this burden is sustained by general taxation.

4 | RESULTS

4.1 | Base case reference scenario

For the Base Case, the load profile of the EV charging operation in a standard working day is shown in Figure 8 (left part). It represents the EV-related hourly load profile of the system in 2030. This can be added on top to the system load. Two peaks can be seen: a morning peak around 10 AM (1508 MW) and an evening peak at 7 PM (1478 MW). It is well known that, while the morning peak occurs in a period of generally low residual load,[98] the evening peak increases the load burden on power system and enhances the so-called duck curve.[99]

To assess the impact of the new load on the system (in terms of new PoDs, peak power and energy demand) and on the electricity tariff income, an organic set of output data from the developed model is given in Table 4. The largest income volume is associated to home charging (as the sum of “TD residential”, “TD non-residential” and “BTA2”). Excluding home charging, “BTA6” is the most exploited tariff among remaining PoDs (with 1.6 TWh and 1.1 GW), being relevant for both work and public access charging. Indeed, it is possible to conclude that a large share of EV charging will be operated at LV: only 2 TWh on a total of 8 TWh are charged at MV, and only 650 MW out of 4.5 GW of peak power increase is expected at MV. New dedicated PoDs only relates to public charging (see “BTVE” and “BTA6” columns): a total of 95 thousand new dedicated PoDs are estimated. The total EV-related income is 686 M€, the contracted power is 4.5 GW (around 3 times the actual peak demand shown in the left part of Figure 8) and the yearly energy demand (E) is 8.1 TWh.

The charging cost is computed for every relevant user type. Results are shown in Figure 12, left part. It is worth noting that these are the marginal costs for EV charging in some use cases in which there is already a PoD, a contracted power, and an energy demand. Therefore, for instance, the cost is very low for B2C charging at a large mall (“MTA3”), where usually there is a high electricity consumption level already present, hence the economic weight of fixed costs is reduced. On the opposite, the cost is high in a car garage with a dedicated PoD (“BTA2”), characterized by a very small (close to zero) as-is energy demand (eg, only for lighting) and high fixed costs. Among the three components of electricity cost, fixed costs are only typical for the tariff. Summarizing, in the Base Case the electricity charging cost is low for home and MV (B2C and work charging) charging, being below 0.2 €/kWh. Oppositely, public charging (“BTVE”) and home charging with a dedicated PoD show a very high price, around 0.3 €/kWh. The former issue (public charging with “BTVE”) is enhanced by the charging point operator's margin, that should be added on top to the computed cost, leading to a very high price for public charging. The latter issue (dedicated PoD for home charging) will be addressed by the home toolbox. Also, the EV charging gives an undesired, strong contribution to the evening load ramp. The next toolboxes operate to shave this evening peak.

4.2 | Home toolbox cases impact

The home toolbox cases operates on the “dumb” home charging profile to propose a simplified smart charging coherent with the experimentation ongoing in Italy as of 2022.[60] Home chargers joining the smart charging follow the load profile presented in Figure 5. The target of the measure is to shave the evening peak generated by dumb home EV charging. The results are proposed in Figure 7, where the decrease in the evening peak (in MW) is correlated with the adhesion to the smart charging. The system cost of the incentive is a missing revenue: the users joining the smart charging do not pay any power-related tariff for the increased contracted power (ie, the components in €/kW/y for the power increment are null). A total estimated cost of the incentive is given in the diagram: this is an upper boundary, considering that all the EV users involved in the smart charging would have, instead, paid for the power increment in case the incentive was not in place (instead, it is worth noting that in the Base Case only 12% of home EV users are supposed to increase their contracted power).

The impact on the load profile of a 50% participation to domestic smart charging with respect to the Base Case is shown in Figure 8. This means that half of the EV users decided to depart from standard toward smart charging, also nudged by the incentive on the tariff. Hence, the total home charging demand is equally split

TABLE 4 Summary table of the impact on tariff income and the power system of EV in base case

User type	TD residential	TD non-residential	BTVE	BTA2	BTA6	MTA2	MTA3	TOT
Voltage level	LV	LV	LV	LV	LV	MV	MV	
EV-related tariff income [M€]	152.50	22.34	78.30	118.01	163.88	87.27	63.36	685.67
Dedicated PoD [kPoD]	0	0	39	0	54	0	0	95
Contracted power [MW]	776	101	547	1321	1132	422	245	4544
Energy demand [GWh]	2751	357	489	777	1649	1133	943	8099

between smart and standard home charging. As can be seen, the evening peak is drastically reduced.

In case of large adhesion (80%), the smart charging can shave the EV peak by one-third (more than 500 MW). A specific cost of peak shaving, in €/MW of decrease, can be estimated: in case of a 20% adhesion to smart charging, the yearly cost of the incentive is around 210 k€/MW. As said before, this is the maximum estimation of the missing revenue related to the discount of the power quota of the tariff and it can prevent the need for additional capacity.

Beside this, a further measure of the home toolbox cases concerns the decrease in the "BTA2" tariff for car garages, to have a tariff with the same specific weight

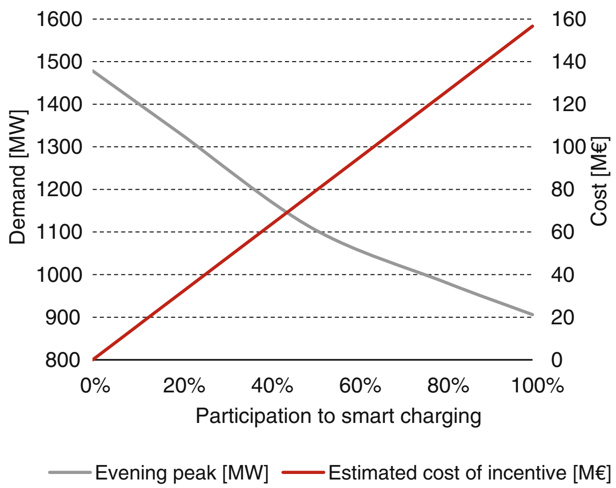
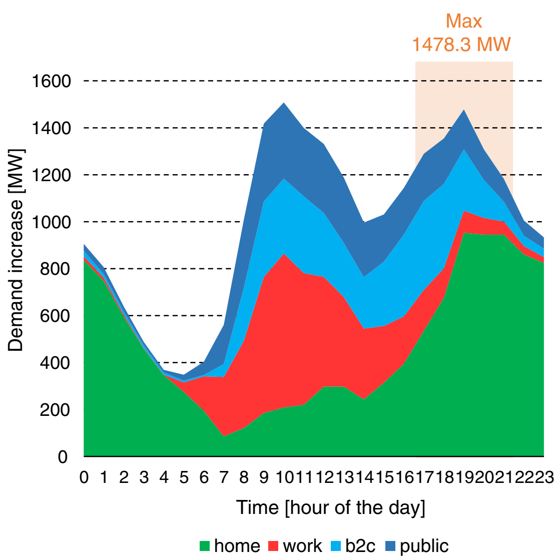


FIGURE 7 Impact on evening load peak and tariff costs of home toolbox smart charging

(considering the actual €/kWh for electricity for charging) on the electricity charging cost of the "TD" tariff for nonresidential owners. It is worth noting that this cost considers both the fixed, power, and variable quota of the tariff and spreads them on the total energy charged, to have in the end the same €/kWh. In Table 5 "BTA2" (as-is, in 2021[61]) and the "BTA2*" (to-be, the decreased tariff) components are listed. As it can be seen, the as-is components are all divided by 2.77. The results on the final cost of electricity for charging with "BTA2*" is provided in Figure 12 (right part), together with the effect of the other measures: the marginal cost for charging in a car garage passed from 0.31 €/kWh of the Base Case to 0.19 €/kWh, thus deleting the above-cited price distortion. The cost of this incentive, estimated as the impact on the 2030 tariff income of the introduction of "BTA2*", is of 77.9 M€.

4.3 | Work toolbox cases impact

The work toolbox cases is proposed as a simplified way of integrating NP-RES in systems with a wide penetration of PV. It incentivizes the industrial and office electric users to host EV charging by discounting the power quota on the increased withdrawn power during daytime. By doing this, Measure #3 exploits the partial contemporaneity of peak PV generation and peak demand of work charging. Results are reported in terms of average carbon intensity of EV charging with respect to the share of work charging over total (see Figure 9): the carbon intensity linearly decreases with a larger work charging share, obtaining a −9.3% passing from 0% to 60% of charging at work. This



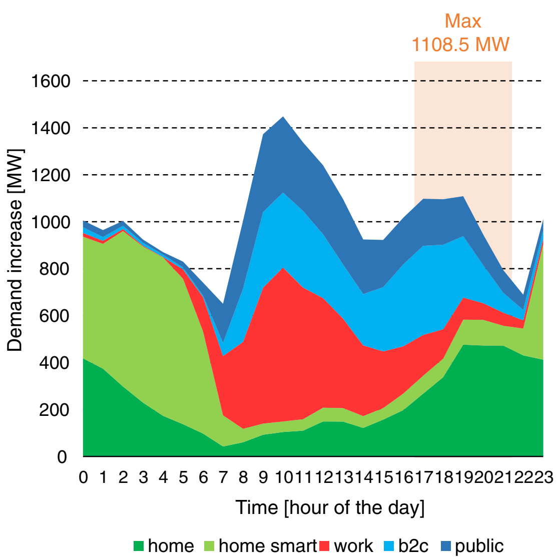


FIGURE 8 The hourly load profile for base case (left part) and for home toolbox with 50% of smart charging participation (right part)

TABLE 5 Tariff for car garage with a separate PoD as-is and to-be

User type	BTA2	BTA2*
Fixed quota [€/PoD/y]	49.562	17.917
Power quota [€/kW/y]	55.829	20.182
Variable quota [€/kWh]	0.061	0.022

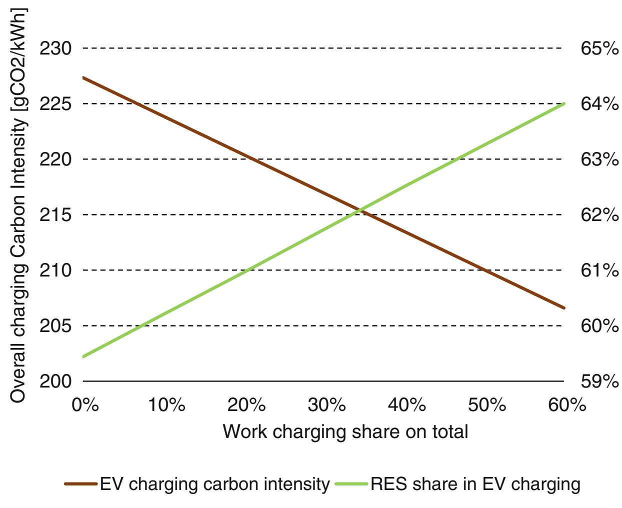


FIGURE 9 Carbon intensity and RES share of EV charging with the work toolbox

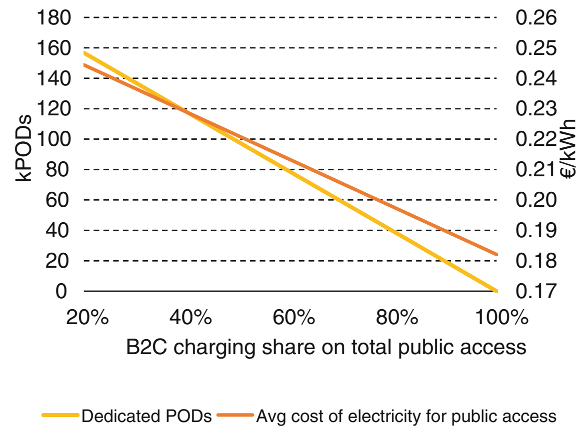


FIGURE 10 B2C charging impact on dedicated PoDs for EV charging and charging costs

is due to the larger RES share in the electricity for EV charging, given by the similar pattern of work charging and PV generation. The results are subject to the adopted data on the generating mix, as presented in Figure 6 and coherently with the Italian NECP.

This kind of valley-filling smart charging would be largely important in a mid to long-term scenario, in case of decreasing residual load (up to negative values) during the daytime,[98] inducing also reverse flow phenomena on distribution grids. In addition, this simplified approach is obtained with low effort from EV users, and it does not exploit active EVSE technologies: indeed, the load profile considered is the same as in Figure 4, top left, thus the "dumb" profile for work charging. This is only partially overlapping the PV generation profile (see Figure 6): for instance, the PV generation peak is at 1 to 2 PM, while the work charging demand peaks at 10 AM. Therefore, this simplified (by design) smart charging could have in principle a large and easy adhesion, yet its positive outcome can be improved in a subsequent step enhancing its implementation complexity and targeting a more precise overlapping of the load profile peak and the carbon intensity valley (ie, delaying the peak charging power to 1 to 2 PM).

4.4 | Public access toolbox cases impact

The public access toolbox case aims at steering the public access charging from public dedicated PoDs to B2C charging stations. This is to obtain the following results, as described by the Italian NRA.[57]

- The EV-dedicated PoD number decreases if B2C charging mode is preferred, since the public charging is considered to imply a new dedicated PoD, while B2C charging is hosted under the already-existing commercial premises' PoD.
- The cost of public access charging decreases with a larger B2C share, since the fixed costs of tariff are spread on a larger energy demand.

The results obtained by increasing the share of B2C charging with respect to public are shown in Figure 10. In the sensitivity analysis presented, the share of public access charging on total does not change (ie, 32%), yet the effects of a different B2C/public access ratio are shown. The number of dedicated PoDs can decrease from the Base Case (95 kPoDs) to be equal to zero. Vice versa, it increases if a lower B2C mode share is achieved. The same trend is exhibited for the average public access charging cost, ranging from almost 0.25 to 0.18 €/kWh in case of 100% B2C/public access.

It is worth noting that this amount of new PoDs is obtained for a share of public charging of around 30% on the total demand for EV charging. In addition, it must be noticed that the costs of this toolbox cannot directly be referred to tariff income: Measure #4 foresees a discount on the occupancy fees for the EVSE insisting on public land and belonging to a business, together with an information campaign for managers and local authorities.

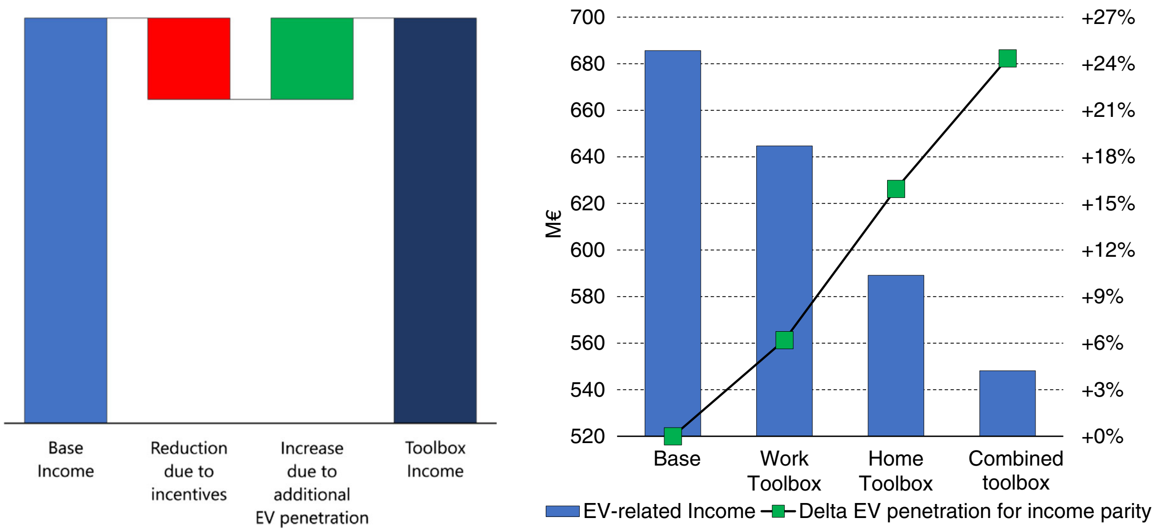


FIGURE 11 Graphical explanation of the concept of income parity (left part), and comparative analysis of toolbox income and EV penetration for income parity

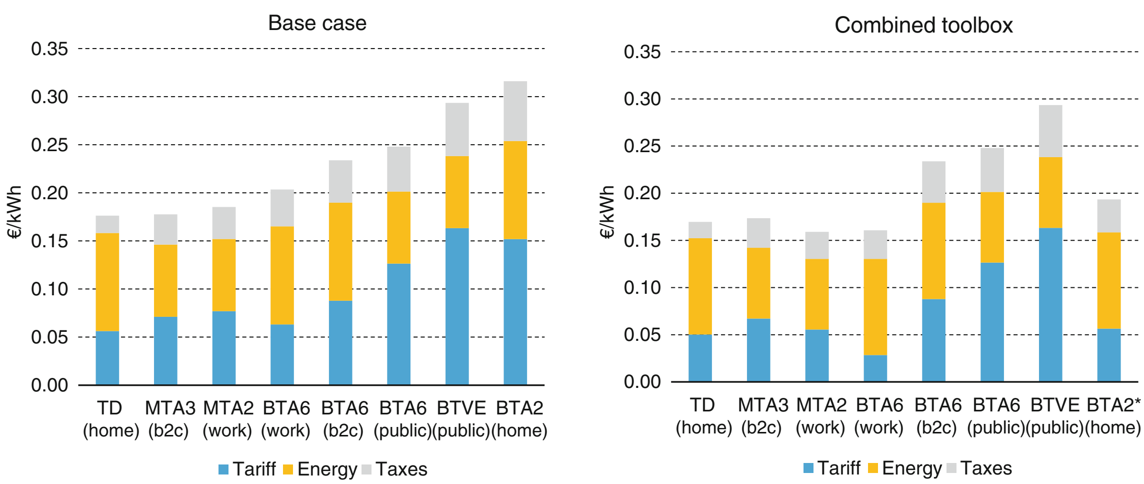


FIGURE 12 Electricity charging cost comparison: Base case (left part) vs combined toolbox (right part)

Related costs can be financed by general purpose taxation.

4.5 | Combining home and work toolbox cases: The combined toolbox

In the end, the impact of the application of the combined toolbox, considering both the Home and Work measures (Measures #1 to #3), is presented. The combined toolbox helps settling the price distortion and shaving the evening peak. The cost of each toolbox (reduction in the tariff income) can be observed in Figure 11. In principle, the income can result invariant in case a larger EV penetration is achieved. Indeed, the cost of the incentives can be balanced by the increase of electricity consumption (and therefore the enhanced income) given by a larger number of EVs, as described in,[63] and as graphically presented in Figure 11 (left part). The targeted EV additional penetration for achieving the income parity can be seen in Figure 11 for each toolbox (right part). For instance, the home toolbox should entail a 16% increase in the EV diffusion to repay the cost of the incentive. As previously presented, the specific cost of the peak shaving implemented in the home toolbox is 210 k€/MW. In case the home toolbox entails a + 10% EV penetration, its net cost would reduce to around 70 k€/MW. This price is compatible with the remuneration of the capacity market in Italy for 2022: 75 k€/MW.[100] This means that a peak shaving by domestic smart charging can be economically interesting if associated with an incentive that pushes new users to the transition toward EV.

It is interesting that the benefits obtained with the toolbox are not frustrated by the larger EV penetration. For instance, considering Measure #1, the evening EV-related peak in the Base Case is 1478 MW. In case of 20% adhesion to home smart charging, the peak is shaved to 1330 MW. To cover the cost of Measure #1 only, the EV penetration should increase by 5%, bringing the evening peak back to 1400 MW: still 78 MW lower than the Base Case, showing the effectiveness of the smart charging measure.

The decreased cost for charging could stimulate the EV penetration,[10] thus leading to an accelerate scenario for EV penetration. Even the +24% penetration (for a total of 6.1 million EV) estimated for obtaining income parity with the combined toolbox is compatible with some scenarios.[59] One target could be designing measures to foster a larger penetration of EVs, de facto constituting tariff-invariant measures. The panorama of charging cost is presented in Figure 12 (right part) graphically compared with the charging cost with no measures (left part). As it can be seen, the cost of home charging at a car garage with a separate PoD is decreased, as well as the use cases related to work charging.

5 | CONCLUSION

The study presented a detailed analysis of the EV penetration impact on the electricity tariff and on the system load profile, considering a base scenario for Italy in 2030. The motivation for a study on tariff-based measures relies in the observation that, usually, smart charging is considered as an add-on to electric mobility that can be proposed by the market with projects that are developed ex-post the diffusion of EV and the deployment of the charging infrastructure. In these cases, smart charging follows complex control strategies that can be realistically implemented on a limited number of EVs and involve few EV users. Oppositely, the regulation can play a major role in steering the EV charging and the charging infrastructure deployment by conveniently acting on the electricity tariff: this way, smart charging is implemented by design and involves the many.

Therefore, this study presented an organic set of policy toolboxes that are representative of the portfolio of tools in the hands of the regulation. The recognized EV risks are to generate burden shifting (ie, there are no emissions at the exhaust, but there are still emissions at the power plant) and to be detrimental for the power system (eg, increasing the power demand in peak hours). These measures show that the involvement of a large turnout of users in smart charging could allow EVs to become sustainable and to support the system. The measures are mainly aimed to enhance vehicle integration with the grid, reducing the possible burden on the system and on the distribution grid; decrease the carbon intensity of EV charging operations; decrease the electricity cost for some specific use cases that suffer a very high charging cost. This last point is related to the possible price distortions that arise for some EV users, featuring unreasonably high charging costs: it is the duty of the regulator to guarantee that EVs are suitable for all the users without discrimination.

The effectiveness of the proposed regulatory measures is assessed by a comprehensive sensitivity analysis. A significant outcome is related to the implementation of home smart charging for peak shaving. In case of a massive adhesion, the proposed scheme, already subject of a pilot regulation in Italy,[60] can reduce EV-related load during the evening peak, thus helping to flatten the "duck curve". Quantitatively, the achievable reduction on the 2030's evening peak ranges from −70 MW (in case of 10% demand-side participation) to −500 MW (in case of 80% participation): this represents more than 1/3 of the total EV demand in the evening. Apparently, this large participation is only achievable in case the regulation proposes incentives or imposes obligations to adopt a certain charging behavior.

Valley-filling has been associated to work charging, given the natural simultaneity of work charging demand and PV generation. Valley-filling can be powerful for supporting the power system, for decreasing the charging costs, and for reducing the carbon intensity of EV charging: 10% less g_{CO2eq}/kWh can be obtained, and this outcome can improve in case of either a more complex smart charging protocol or a larger PV penetration. Indeed, valley-filling can be suitable on the long term to welcome a very high penetration of variable RES (eg, looking at 2050 as target year), in substitution to the massive use of stationary energy storage.

For what concerns the charging at poles with public access, it has been shown that the wider diffusion of charging at the destinations is a way to limit the new connection points dedicated to EVSE: oppositely, with a higher degree of public charging, new PoDs are foreseen. The figure ranges from +156 kPoDs (in case public charging represents 25% of the overall charging demand) to +39 kPoDs (with public charging at 6%): to have a comparison 156 kPoDs would represent a + 3% of nondomestic PoDs in Italy for a negligible energy demand (around 0.6% with respect to the national electricity consumption). In addition, the cost of public charging for the end-user is higher than B2C: considering 2019 market prices, the average cost for public charging is 0.26 €/kWh (this number is pure cost, it disregards the CPO margin, that should be added to obtain the price to the end-user). This can be compared with an average cost of charging at the destination of 0.18 €/kWh (−30%). Given the much lower cost of charging at the destination, an increase of this modal share entails economic benefits for consumers, too.

It is worth noting that for each measure, an estimation of the possible system cost is given. This cannot be considered a nonrepayable cost. Indeed, the reduction in the average cost of charging thanks to the implemented economic incentives is supposed to foster EV penetration and the larger energy consumption due to more EV can increase both the market and the tariff income, paying-back in the end the incentives. The marginal EV penetration that is necessary to have parity with the tariff income in the Base Case (no incentives) is assessed. The toolbox related to home smart charging demonstrated to be the most expensive: it should entail a 16% increase in the EV diffusion to be completely repaid. In case the home toolbox only entails a +10% EV penetration, its net cost would be 70 k€/MW of evening peak shaved: this price is compatible with the awarded prices in the Italian capacity market. The proposed instrument for assessing the tariff income parity could support the policymakers in sizing the incentives compatibly with expected effects on the end-user economic convenience for EVs.

The smart charging could be of support for both the transmission system operator (TSO) and the distribution system operator (DSO). For instance, the TSO can consider smart charging as a tool for manipulating the load profile and improve VGI: the flexibility provided by EV can be exploited in several ways, for instance the already detailed peak shaving approach. It is well known, anyway, that the EV diffusion will affect most the DSOs.[101] The large number of new connections at low voltage can imply a massive and diffused need for network reinforcement. In addition, DSOs can be worried by the simultaneous demand that can be expected in residential areas, for instance at the end of business. Some of the previously implemented measures can support the DSO in orientating both the deployment of the infrastructure and the charging activity in a direction that is compatible with the system needs and limits. The increased responsibility and new central role of the DSO can lead, in some situations and in some specific areas, to the need for a local flexibility market or to local tariff measures directly acting on the distribution component of the network costs to incentivize smart charging.

The limitations of this study include the adoption of a set of assumptions to get to a whole-of-tariff result. These assumptions are based on expert advice and on an extensive literature review. Plus, the sensitivity analysis is included to relax some of the main hypotheses. The sensitivity analysis also shows the power and flexibility of the developed model: this can be suitable for tailor made studies, both helping regulators, system operators or other stakeholders of the electricity market to get insights on this fast-evolving system.

Further studies can adopt the developed models for detailed studies of the potential of valley-filling or peak shaving practices in some specific areas. Non-interconnected islands, already featuring massive variable RES and characterized by distance ranges compatible with EV and micro electric mobility, can benefit of specific regulation that can support their fast decarbonization. In metropolitan areas, traffic data could be used to reconstruct local demands and tailor regulatory measures for different situations. Also, the compatibility of some smart charging techniques with the ancillary services markets can be assessed, bearing in mind the difficulty in involving a major turnout of DERs in these markets. Eventually, the developed tariff model could be extended to other technologies supporting the energy transition, such as heat pumps, to assess the impact on the tariff income of dedicated economic nudges enhancing the electrification.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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ENDNOTE

* A preliminary edition of this study, related to 2025 as the target year, was published in Reference 63.

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