Smart charging tariffs for electric vehicles

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Abstract: Electric mobility is one of the biggest challenges in the transportation sector. It is estimated that demand for electric vehicles will continue to grow, exceeding other types of power supply by 2025, and will approach 80% of all cars on the road in 2050. This increase in demand is mainly due to two relevant factors: i.e., the environmental sensitivity of users and the reduced usage costs. However, there are still several issues related to electric vehicles that do not totally convince those who must choose whether to buy an electric vehicle, among which one of the most relevant is related to the charging infrastructure. For instance, the current Italian charging infrastructure system will not be capable of supporting the forecasted electric mobility in future years. Customers, accessing the service, for different reasons, may have very different demands, and providing flat rates that are the same for all could lead to problems both on the service level guaranteed to potential customers and the profitability of the stations. This study analyses existing charging tariffs structure for AC charging and investigates their pitfalls on the effectiveness of the system. The focus is on AC charging tariffs since DC charging is usually devoted to occasionally charge of EVs for traveling long distances and thus should be located on highways paths. The main outcome of the analysis showed how mainly two different schemes are usually proposed by the operator a flat rate with a maximum monthly energy or a variable rate that depends only on the energy-charged, while power demand or time fee are not considered at all. A new smart tariff structure is proposed to incentivize virtuous charging behaviors. The analysis will be performed also through a simulation study of the new smart tariffs structure in the engineering campus of the University of Brescia, Italy.

Keywords: electric vehicles; smart charging; tariffs.

I. INTRODUCTION

In recent years, society's awareness of the climate crisis and the race for renewable sources has increased. Industrialized countries, in fact, aim to find ecologically sustainable solutions to energy production and use, investing time and money to solve this important issue. Among the various sectors involved, the most discussed one is undoubtedly the transportation sector. Electric mobility is one of the biggest challenges in the transportation sector: in 2020, passenger cars alone were responsible for 12% of CO_2 emissions at the European level. The National Integrated Energy and Climate Plan (NIPEC), updated in early 2020, also predicts that in 2030 the circulating fleet will reach 4 million electric cars (BEVs) and 2 million plug-in hybrid cars (PHEVs). The number of electric and hybrid cars is increasing each year [1], and it is estimated that demand for electric vehicles (EVs) will exceed that of any other type of power supply by 2025 and will approach 80 percent of all sold cars in 2050. This increase in demand is mainly due to two relevant factors:

- Environmental sensitivity: electric vehicles reduce pollutant emissions to zero during their use. In addition, research into cutting-edge technological solutions for battery construction and disposal is growing very fast.
- Reduced usage costs: the cost of recharging, for the same number of miles driven, is more advantageous than a conventional car. Furthermore, maintenance costs for EVs are

extremely lower than those of internal combustion cars.

However, there are still some obstacles to the purchase of EVs:

- Purchase price: according to a study conducted by Motus-E in February 2022 [2], the price of the car is the first determining factor in purchase choices. Considering that currently, the cost of electric cars is on average 30% higher than that of conventional cars, it follows that currently, the main barrier to buying an electric car is its initial cost.
- Autonomy: While one can normally get 500/1000 km on a full tank of diesel or gasoline, the range of most electric cars varies between 200 and 500 km, although upcoming cars will raise this to 400-700 km.
- Charging infrastructure: EVs need more frequent charging, hence, there is a need for a charging infrastructure system capable of covering the final demand. To date, some countries (such as Italy) do not have such an advanced infrastructure.

The focus of this paper is on the latter point. The diffusion of electric vehicles must go hand in hand with the spread of charging stations. Such devices, which can be private, semi-public, or fully public, must be structured in a complex system such as the urban one that allows their use in an easy and systematic way. The transformation of transportation towards sustainable and environmentally friendly mobility will inevitably pass through the nationwide deployment of the latest generation of rapid and ultra-rapid charging stations, without which the market for EVs will not be able to take off, despite the general predisposition of users to purchase zero-emission vehicles. Customers accessing the service, for different reasons, may have very different demands, and providing the same flat rates for all could lead to problems both on the service level and on the profitability of the stations. Therefore, this study will analyse how this very sensitive issue can be managed from the point of view of the electric rates that characterize the cost of charging while incentivizing virtuous charging behaviours.

II. Charging stations

A charging station is a device through which it is possible to recharge the battery of vehicles equipped with an electric powertrain. Different types of charging units exist, such as fixed and portable, direct o alternating current, and variable power. It's possible also to distinguish between private and public (i.e., installed by distributors or energy suppliers) charging stations. Furthermore, the public ones are generally medium or large infrastructures, which can simultaneously recharge a greater number of vehicles at a higher power than private columns. Charging operation is regulated by the legislation for charging stations for electric vehicles IEC 61851-1, which provides technical parameters to be respected for different types of electric charging stations. Four types of electrical plugs exist, two for the alternating current (AC) that allows recharging up to 43 kW and two for the direct current (DC) that allows fast recharging of up to 350 kW. [3] proposed a detailed overview of charging systems.

In Italy, there are over 35,000 charging points for electric cars [4]. Specifically, as of December 31, 2022, there were 36,772 charging points (+ 41% compared to 2021) divided into 19,334 charging columns and located at 14,048 publicly accessible locations. The distribution of electric vehicle charging points in terms of power remains largely unchanged, with 88% of charging points being alternating current (AC) and 12% being direct current (DC) [5]. The distribution of power is as follows: 73% for 43 kW as maximum power; 3% for power range 43-50 kW; 16% for 51-150 kW; and 8% for power greater than 150 kW. Geographically, about 58% of the infrastructure is in Northern Italy, 22% in the Centre, and only 20% in the South and islands. By individual regions, Lombardy, with 5,971 points, is the most virtuous and owns 16% of all installations alone. However, the number of charging points on highways is limited, although there are positive signs of improvement: data show that there are currently 496 charging points (+118 compared to December 2021), 85% of which are fast or ultra-fast charging, and only 15% are in AC. Considering the entire Italian highway network of about 7,318 km, according to ART (the Transport Regulation Authority), there are 5.3 fast or ultra-fast charging points per 100 km (6.8 if including AC as well).

III. Literature review

The proper management of EVs charging process is considered one of the most challenging issues due to the high temporal and spatial stochasticity of power demands. The boost of EVs brings challenges to charging services. Furthermore, due to the increasing battery capacity of electric vehicles, European standard electricity socket-outlets at households are not enough for a full charge cycle overnight. Hence, people tend to install (semi-) fast charging wall-boxes (up to 22 kW) which can cause critical peak loads and voltage issues whenever many electric vehicles charge simultaneously in the same area. To overcome these issues, optimization strategies for the integration of EVs in smart grids have been investigated while considering a flexible and coordinated management of the charging process (i.e., smart charging) [6]. Accordingly, allocation of charging supply infrastructure and charging price [7] are widely used to increase the EV charging efficiency and improve charging services. Literature on EVs’ charging process is vast. [8] investigated the waiting time and the service level offered by the current infrastructure and the effective performance if the number of EVs in the area will face the forecasted huge growth for traditional and smart charging processes. [9] proposes a model of energy storage systems in support of renewable generators and the integration of electric vehicle charging systems in smart grids. The availability of a PV plant resulted to be typically not enough for limiting the impact of EVs on the power grid because the charging phase could not match the PV production peak and because the total power installed is not enough for compensating the peak of EV consumption. [10] provided a general model for the estimation of the uncoordinated charging costs of EVs in the presence of distributed and intermittent generation, and variable electricity tariffs. [11] analysed control signals between the grid operators and the vehicles using different methods. The simplest implementation methods are over-the-air, wireless, direct internet links, or power line carriers. Time-of-Use (TOU) electricity pricing is an established way to reduce peak system loads: EV charging may have onboard controls that automatically begin charging according to a pre-set schedule, such as when off-peak periods begin. [12] investigated the effects of different charging scenarios on potential revenues and expenditures of EV charging managers in France and Germany in 2030 by considering aspects of user acceptance accounted for by an innovative load-shift-incentivizing tariff for EV users. [13] developed a systematic classification of charging options, considering 27 countries in the European Union together with Great Britain, Norway, and Switzerland. The results showed a wide variation in charging costs between different countries and different charging options, suggesting different policy options to reduce charging costs. Moreover, a levelized cost approach to model charging costs in the 30 European countries is employed for 13 different charging options for private passenger transport. [14] proposed a pricing scheme that assigns a session-specific energy price to each charging session at the end of the billing period. Furthermore, an online scheduling algorithm based on model predictive control to determine charging rates for each EV in real-time was also proposed. [15] developed a heuristic EV charging scheduling scheme with an emphasis on the inevitable charging behaviours of the EV users. Such scheduling incorporates priority determination using the idle time ratio and TOU period as well as priority-based time slot allocation. Moreover, accurate prioritization of EVs is realized by predicting the energy demand and idle time ratio. [16] investigated the activity duration-related charging behavioural responses of private EV travellers to charging services in an equilibrium model, concerning the operating policies related to the spatial allocation of charging opportunities and charging pricing.

IV. ELECTRICITY TARIFFS

The recharging pricing ecosystem of EVs is more competitive and diverse than that of a traditional internal combustion engine vehicle, and the consumer experience is more complex. One reason is that EV users can use both private recharging (at home or at work) and public recharging, prices are much more flexible and tend to vary depending on the recharging connector used as well as other variables.
Normal power recharging (e.g., at home) is the least expensive option, while high-power (fast) recharging is the most expensive option on the market today [17].
Current electricity tariffs for EV charging proposed by different operators can be categorized into two structures: i) a variable tariff as a function of the energy consumption, where the value of the tariff (in terms of €/kWh) increases for higher power ranges; and ii) a flat tariff per unit of the period (i.e., monthly subscription) which guarantees a certain number of kWh, not dependent on the power range. Specifically, flat rates are the preferred solution for almost all electric motorists, since they are widespread at competitive costs which therefore discourage any smart and virtuous use. Furthermore, there are no premium tariffs or penalties that incentives virtuous behaviour. Among the different offers, only one energy supplier applies tariffs that vary according to the hour (typically peak and off-peak).

V. CASE STUDY SIMULATION

A case study has been proposed to investigate which tariff should be proposed by the operator to cover the investment in improving the infrastructure (i.e., increasing the number of public charging stations) while incentivizing virtuous charging behaviors. The EV charging infrastructure considered is AC charging since it is intended to be used by employees of a public facility where the EV can be parked for several hours. To prevent opportunistic behaviors while EV charging a new tariff structure will be considered, i.e., a tariff dependent on the power demand and energy required during the charging session.

A. Problem definition

A simulation model has been developed using Anylogic software. The model is used to investigate a real-life application: i.e., the Engineering Campus of the University of Brescia, where there are 3 AC charging stations with 2 sockets, each with 22 kW. Thus, the system consists of 6 electrical outlets that allow the simultaneous use of a total power corresponding to 132 kW. The aim consists of the definition of the tariff that the operator should set in to return the investment in a specific time frame. The investment depends on the number of stations in the system and their type, as well as costs related to line activation and other fixed costs.

The first step of the proposed model consists of the estimations of the number of customers served and the number of customers who left the system based on real case observation. Priority behavior has been considered for queue management, according to which if two customers with different service times are waiting in the queue, the one who has the lowest time will have priority, and therefore will be served first. Arrival times were determined by a schedule composed of a reasonable estimate of values. Since the area is mainly frequented by students, who averagely arrive in the early morning hours or in the middle of the morning and leave in the middle of the afternoon, it was considered to include a higher value of arrivals in the morning hours (08:00 – 12:00) than in the afternoon/evening hours (15:00 – 19:00). The arrival schedule of customers is presented in Table I, for a total of 13 arrivals for each of the six charging station, which results in 26 customers per day.

TABLE I. CUSTOMERS’ ARRIVAL SCHEDULE.

Hours	00:00-08:00	08:00-09:00	09:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-15:00	15:00-19:00	19:00-24:00
Arrives	0	2	3	3	2	1	1	1	0

A value of 15 minutes of waiting time has been considered for the exit variable, which gives the possibility of cars leaving the system. Not all customers have the same characteristics: some will need more charge than others, and therefore the service time and waiting time of queuing vehicles may vary. Therefore, the customers entering the system to recharge have categorized them based on their energy and power requirements. Specifically, nine combinations have been considered: i.e., 50, 25, or 10 kWh and 5.5, 11, or 22) kW. The service time for each configuration is presented in Table II. Worse and Best Customer are the most extreme customers, as the former requires charging 50 kWh at a power level of 5.5 kW (thus with a St = 9.09 h) and the latter recharges 10 kWh with 22 kW (St = 0.45 h).

TABLE II. SERVICE TIME (ST) FOR EACH COMBINATION OF ENERGY AND POWER REQUIREMENTS.

Clients	kWh	kW	St [h]
Worse Client	50	5,5	9,09
	50	11	4,55
Client 3	25	5,5	4,55
Client 1	50	22	2,27
	25	11	2,27
Client 2	10	5,5	1,82
Client 4	25	22	1,14
	10	11	0,91
Best Client	10	22	0,45

Two indicators for the service level are considered: i) the ratio of the service time over the total time spent by the customer in the system (i.e., given by the sum of the average waiting time and the average service time; and ii) the ratio of the number of users served over the number of users entered the system. From an economic point of view, it is possible to evaluate the profit of the operator as:

$$Profit\ (€) = Energy\ need\ \left(\frac{kWh}{user}\right) \cdot (Tariff - Energy\ cost)\left(\frac{€}{kWh}\right) \cdot number\ of\ served\ users$$

B. Results

Considering three different cases where only two different types of customers can simultaneously arrive, an investment of €24,000 (i.e., 4,000€ for each one of the six recharging points), an energy cost of €0.2/kWh, a discounted payback time of 6 months and a discount rate of 6% the following economic performance and service level can be obtained (Table III) adjusting the tariffs to different customers.

TABLE III. ADJUSTED TARIFF FOR DIFFERENT TYPES OF SCENARIOS AND LINKED SERVICE LEVEL

Case	Clients	Number of clients served	Tariff (€/kWh)	Service level
1	1	8	0.66	62%
	2	8	0.47	
2	3	6	0.84	65%
	4	11	0.60	
3	Worse	6	0.88	42%
	Best	15	0.20	

The simulation shows that Case 2 is the one to be favored (lower tariffs) and penalizes Case 3 customers (higher tariffs).

VI. CONCLUSIONS

This study analysed the existing charging tariffs scheme in Italy and found mainly effort from service providers to secure flat rates with no evidence of time-of-use tariffs (the only exception is the DC Tesla Supercharger with peak and off-peak different tariffs) or power-required influences on tariffs. Thus, current charging AC tariff structures don’t incentive smart charging and leave open the door to opportunistic behaviour of the customers (i.e., customers adjusting to a very low level of power occupying the parking lot for long timings). To overcome these pitfalls in the effectiveness of the system, this study proposed a new smart tariff structure to incentivize virtuous charging behaviours. The analysis has been performed through a simulation study of the new smart tariffs structure in a specific reference use case: i.e., the engineering campus of the University of Brescia, Italy.

The current study only considered AC charging tariffs since DC charging is usually devoted to occasionally charge of EV for traveling long distances and thus should be located on highways paths.

Future research will include a sensitivity analysis on the main parameters and a more comprehensive scenario where different customers (in terms of kW and kWh required) can simultaneously arrive and the tariffs will be adapted to each customer, alternatively, the defined tariff structure could influence customer behaviour. Other extensions will include the time of use tariffs with a possible linkage to the effective electric charging tariffs at different hours and/or the inclusion of a renewable energy source (e.g., a photovoltaic system) integrated with the EV charging infrastructure [18]. Furthermore, EVs customers are mostly orienting towards flat tariffs with cap, where the price cap sets a cap on the total bill for each level of consumption. [19] also emphasized the heterogeneous preferences of residential customers for dynamic pricing schemes. The study identified a cost insurance – a price cap – as a suitable instrument for increasing the likelihood of residential customers selecting a dynamic tariff. These aspects can be included in the simulation to design reasonable and preferrable pricing schemes for different EVs customers.

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