Which combination of battery capacity and charging power for battery electric vehicles: urban versus rural French case studies

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WHICH COMBINATION OF BATTERY CAPACITY AND CHARGING POWER FOR BATTERY ELECTRIC VEHICLES: URBAN VERSUS RURAL FRENCH CASE STUDIES

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Abstract

Battery Electric Vehicles (BEVs) are essential for reducing greenhouse gas emissions related to the transport sector towards meeting global emissions targets. Although this technology is gaining much attention, techno-economic barriers hinder the widespread of BEVs, namely the high investments, the limited autonomy, and the lack of public-charging infrastructure. A bigger battery leads simultaneously to more autonomy and higher-priced BEV, due to the battery-pack cost. Deploying more public chargers, a solution for limited autonomy BEVs, is facing other obstacles: vehicle-charger adaptability in terms of charging power, and additional investments for charging operators. Therefore, this paper aims to find the most cost-efficient solution(s) of battery capacity and charging power combination(s), considering techno-economic factors. Based on French travel surveys data, we simulate the needs of 12 scenarios of 5,000 identical privately-purchased BEVs, by changing their battery capacity for both urban and rural areas, before determining the optimal number of charging stations. We then analyze the BEV owner and the charging operator business models in order to conclude with win-win situations for both parties. Results show cheaper investments in charging infrastructure, especially 22 kW charger, rather than in bigger batteries. For urban (rural) areas, purchasing a 35 to 50 kWh BEV (65 kWh BEV for rural) and deploying 22 and 50 kW chargers (50 kW for rural) proves the most cost-efficient and profitable solutions for both BEV owners and charging operators. We finally recommend charging operators to review their charging tariffs, and to take into account the acceptability of customer.

Keywords: Battery range, Charging infrastructure, Electric vehicles, Innovative business model, Techno-economic scenarios

Highlights

1. Each battery size is compatible with a dedicated charging power speed. And bigger battery capacity will always require more charging stations compatible.
2. We show benefits of the BEV customer and those of charging operator are antagonists.
3. 35-50 kWh BEV and deploying 22-50 kW chargers is the cost-efficient solution for urban needs.
4. 65 kWh BEV and deploying 50 kW chargers is the cost-efficient solution for rural needs.
5. Future reviews of charging tariffs and pricing method is recommended.

1. Introduction

In order to reach ambitious climate change mitigation targets, the Intergovernmental Panel on Climate Change (IPCC) called for a reduction of greenhouse gas emissions (GHG) emissions, especially in the energy and transportation sectors that are currently heavily fossil-fuel dependent (IEA, 2019; IPCC, 2018). The transportation sector, which is responsible for 20% of global CO2 emissions, of which 72% are emitted by road transportation, should become emission-free by 2050, in order to reach world ambitions (IPCC, 2018). Electric vehicles (EVs), including Battery EVs (BEVs) and Plug-in EVs (PHEVs), have the potential to improve the environmental landscape of personal-road transportation because of their non-fossil-fuel dependency. During the last few years, EVs have attracted much attention thanks to their CO2 benefits, pushing governments to promote this technology as an auspicious solution (Amjad et al., 2018). However, switching to electric mobility has remained limited due to the economic hurdle posed by the high price of the vehicle, the technical issues of non-mature battery technology, and the non-optimized charging infrastructure of different powers.

Eliminating these barriers, however, involves a trade-off: while bigger battery could provide a more significant range, this comes with higher investments. Besides the high price, the additional capacity will only be used for occasional long-distance trips (Funke et al., 2019). High penetration of charging infrastructure, a solution for the range anxiety of the driver, also comes with a trade-off between lower purchase costs for the consumer and higher investments for deploying this network. While determining the optimal battery size of BEVs and optimizing the charging network have received widespread attention in the literature, it remains unclear where should we invest: in bigger batteries or more charging infrastructure. Since this question has rarely been analyzed in details by considering different types of chargers, specificities of different territories, it is essential to compare the two solutions using a cost-efficient methodology based on real data.

The EV ecosystem is composed of three prominent stakeholders, the automotive industry, the charging point operator, and the client, which seek to achieve different objectives. The objective of the automotive industry is to maximize their sales, especially the electric ones, in order to minimize the penalty of the Corporate Average Fuel Economy (CAFE) engagement. The customer's dual goals are to minimize purchase and operating costs, and the time spent charging the vehicle. The charging operator aims to deploy the optimal number of chargers and to minimize purchase and operating costs.

Since the goals of these members of the BEV ecosystem are antagonists, it is crucial to determine which combination of battery capacity and charging power is the most cost-efficient for the client and the charging operator, given that the sales of the automotive industry will increase if the client is satisfied. Therefore, the novelty of our paper is to simulate the trade-off between the BEV customer and the charging operator, in order to introduce a roadmap identifying the right path to invest, thanks to the determination of win-win situations for both parties.

To achieve this, we have analyzed and compared the business model of the BEV owner, and that of the charging infrastructure operator, based on daily trips of BEVs in French urban and rural areas. The business models we computed are based on (Funke et al., 2019), with the use of the Equivalent Annual Cost (EAC) method - i.e. the cost of owning, operating, and maintaining an asset over its entire lifetime - which we upgraded to address different charging powers, and to analyze the costs regarding different parties of the BEV ecosystem. The EAC is highly relevant since BEVs and charging infrastructure do not share identical lifetimes nor owning, operating, and maintaining costs.

Results show cheaper investments in charging infrastructure, especially 22 kW chargers, rather than in bigger batteries. For urban (*for rural*) areas, purchasing a 35 to 50 kWh BEV (*65 kWh BEV for rural*), and deploying 22 and 50 kW chargers (*50 kW for rural*), prove the most cost-efficient and profitable solutions for both BEV owners and charging operators.

The paper is structured as follow: Section 2 presents the literature review. Section 3 discusses the methodology, the data, and the techno-economic parameters. The results of the study are presented in Section 4. The conclusion, discussion and future works are drawn up in Section 5.

2. Literature Review

The literature devoted to our research question is divided into three main streams. The first discusses the optimal battery capacity for a BEV. Secondly, a group of publications quantifies the deployment of charging infrastructure. Lastly, the third stream compares the investment in both technologies.

2.1. Optimal Battery Capacity for a BEV

Determining the exact need for autonomy requires a large dataset of trips, for a large number of drivers, over a long period of study. This is because the travelled kilometres could change with social and driving behaviours changes. The publications used three primary sources as input data: surveys, data on long-mileage trips, and GPS-based trips. The first source uses large databases from surveys and questionnaires at a national scale. (Zhang et al., 2013) used the Californian dataset of 20,295 privately owned vehicles travelling 83,005 single daily trips or 7.85 trips each, from the 2009 National Household Travel Survey (NHTS). They found that 88% of the trips could be operated using a BEV with a 60-mile range (approx. 97 km), taking into account only at-home charging. Similarly, (Zhou et al., 2020) conducted a stated preference survey, and analyzed its data using the Latent Class model to predict the different recharging behaviours of two clusters of BEV drivers in Bejing. They concluded that a range of 300 miles (approx. 483 km) is needed to cover the travel demands of 90% of the drivers, while a 100-mile (approx. 161 km) range battery is able to satisfy the need of 80% of the drivers.

Next group of publications is based on data of long-mileage trips. Since data on BEV trips are still rare, especially for long-distance trips, (Weiss et al., 2014) used three mobility surveys: the German Mobility Panel, car mileage and fuel consumption, and the long-distance travel survey INVERMO, and concluded that only 16% of private vehicle data exceeded the mileage of 100 km for 1-4 days a year. Similarly, (Gnann et al., 2016) ascertained, based on German of ICEV drivers' long trip database, that the trip distances of 65% of the drivers did not exceed 100 km, throughout one year.

The last group of publications used GPS-based data of trips in a bottom-up approach. (Pearre et al., 2011) analyzed the driving patterns of 484 ICEVs, over one year, in the United States of America, and assumed that these drivers would not change their behaviour after switching into BEV. They found that, in one day, 9% of users never exceeded 100 miles, and 21% never exceeded 150 miles. This percentage could increase up to 32% of the drivers if they were willing to adapt during longer-mileage trips. (Neubauer and Wood, 2014) claimed, after analyzing the trips by 317 ICEVs over one year, that a 120 km-range BEV could fill the needs of 75% of the drivers without public-charging infrastructure, and could rise to 90% with available charging infrastructure. (Meinrenken et al., 2020) concluded that the optimal range of the battery would be approximately 158 km, based on 412 cars and GPS data for 384,869 individual trips while maximizing GHG savings.

2.2. Deployment of Charging Infrastructures

The question of charging station locations has been extensively studied in the literature. Research has focused on optimizing the locations of charging infrastructure based on various objectives: minimizing the cost (Yang et al., 2017), minimizing the travelled distance (Sathaye and Kelley, 2013), maximizing the coverage (Wang and Wang, 2010), minimizing failed trips (Alhazmi et al., 2017), minimizing the distance between demand and charging sites (Sathaye and Kelley, 2013). Various optimization methods are elaborated in the state-of-the-arts that reviewed spatial localization methodologies for the electric vehicle charging infrastructure (Pagany et al., 2019; Shareef et al., 2016; Shen et al., 2019).

These articles only focus on the charging infrastructure geo-localization, taking into account a set of data related to the BEVs, such as the battery capacity or autonomy. These studies do not consider the BEV battery capacity evolution in their parameters, nor its influence on the charging infrastructure deployment.

2.3. Comparison of Investments in Both Technologies.

The comparison between deploying charging infrastructure and increasing battery capacity is rarely studied in the literature. (Jabbari and Mackenzie, 2017) examined the trade-off between DC fast charging[1] facilities and BEVs, using a theoretical queuing model, and cost of deployment. They concluded that high reliability of access and high utilization rate of charging stations could be achieved by installing a large number of chargers. (Wood et al., 2015) studied various fast-charging infrastructure deployment scenarios and found that it is more costly to add 100 km to the BEV autonomy than to deploying more fast-charging infrastructure. Indeed, analyzing the effects of these deployment scenarios would require a greater understanding of both the nature of individual trips and charging behaviour.

The originality of (Funke et al., 2019)'s study is to combine all the three streams presented above: identification of BEV needs for German long-milage trips, determining the number of needed fast chargers, and comparing both of them, using a techno-economic approach, in order to address this trade-off. They compared the EAC of owning a BEV, and of expanding the fast-charging infrastructure, for doubled and tripled battery size of BEVs. They concluded that the investments in only fast charging infrastructure (50 and 150 kW chargers) are low compared to the investments in larger batteries, due to the high price of 1 kWh battery pack (350€/kWh). While (Funke et al., 2019) made significant improvements in this field, questions remain as to the socio-techno-economic assumptions.

[1] The difference between AC (Alternative Current) charging and DC (Direct Current) charging is where the AC power gets converted; in the car or by the charger.

First, a variety of BEV types could be available on the market with different battery capacities, and each type is compatible with specified charging power. While some vehicles, especially small-battery ones, can only charge using a 7 or a 22 kW chargers, due to their non-compatibility with fast charging technology, while others can use all types of charging powers, mostly BEVs with battery capacity higher than 50 kWh. Next, the question of the trade-off between battery capacity and charging infrastructure cost comparison for daily needs, such as home-work trips, was not elaborated in the literature. Lastly, the question of the optimum battery capacity or the optimum deployment of charging infrastructure was only studied regarding one actor: the society, the charging point operator, or the BEV customer, neglecting the fact that their interests are antagonists, and only a small numbers of solutions to this trade-off could be profitable for all actors in the BEV ecosystem.

The goal of this paper is to close these research gaps and to study the trade-off between bigger batteries and the availability of various power chargers for drivers.

3. Methodology and Data

In this paper, we applied a techno-economic model to identify the investments related to bigger batteries, and the investments related to extending the charging infrastructure network, inspired by (Funke et al., 2019)'s methodology.

As illustrated in Figure 1, BEV needs have been estimated based on different databases (Section 3.1). Then, the number of charging stations has been identified, based on M/M/2 queue model, taking into account a maximum waiting time of 15 minutes (Section 3.2). After, we compared the BEV customer and the charging operators business models before concluding profitable solutions for both parties (Section 3.3). Finally, different data and techno-economic parameters are elaborated (Section 3.4).

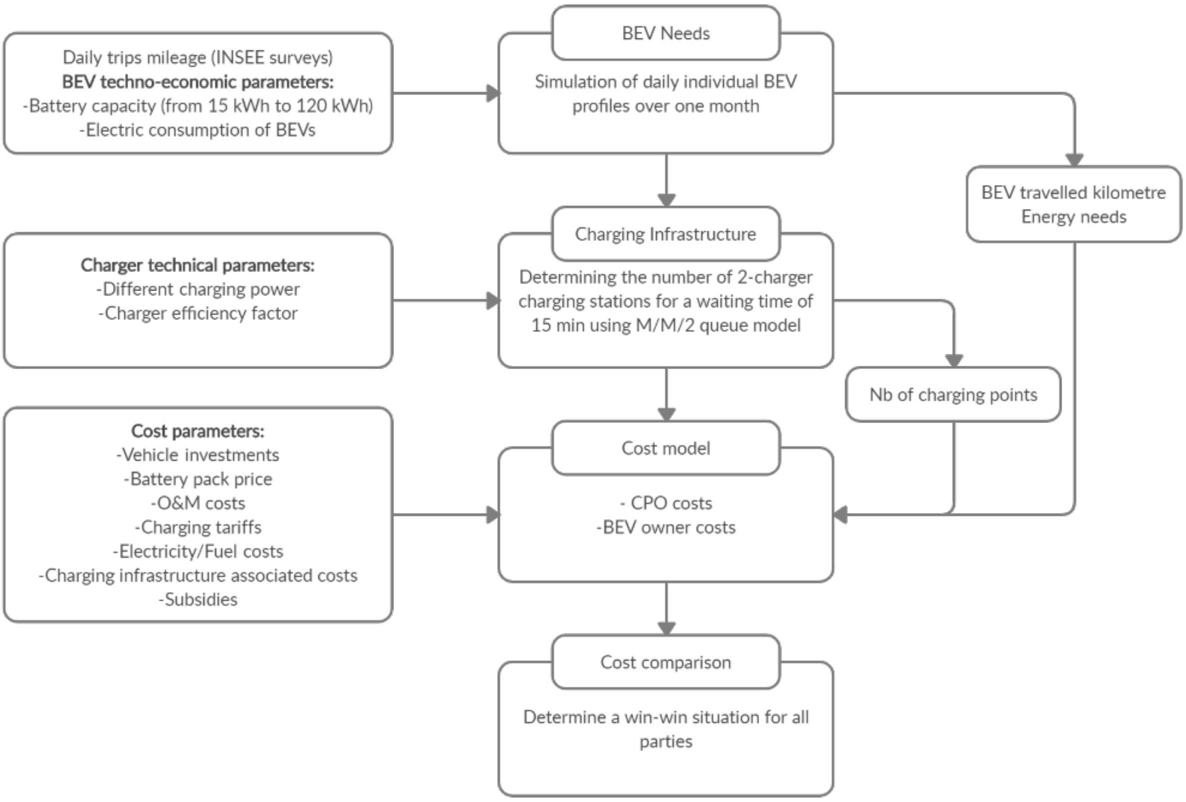

Figure 1 Model overview

3.1. Modelling the BEV Charging Needs

This step 1 allows us to estimate the BEVs energy needs in an urban, and a rural area separately, based on different sources. Twelve scenarios of 5,000 individual-identical private BEV profiles each were simulated based on their daily trips travelled kilometre to determine the energy needs over one year. We then increased the battery capacity by 5 kWh from a scenario to another.

It should be noted that we only studied private BEVs, which have limited travel mileage compared to commercial BEVs such as taxis or delivery vans. In order to determine the Worldwide harmonized Light vehicles Test Procedures (WLTP) needs, a conversion factor from real to WLTP standards was used for daily home-work-home trips (Source: Groupe PSA). Since using an optimized charging strategy, especially reaching full State of Charge (SoC), may lead to an increase in the lifetime of the battery (Redondo-Iglesias et al., 2019), the SoC of the battery should always stay between 20% and 80%. A random initial SoC is given to all BEVs. In other words, we consider that drivers will charge their vehicles to 80% if the next day's SoC would reach 20% (or less) before returning home. The SoC is then calculated, taking into account technical parameters such as energy consumption (c_i^e), the kilometres travelled (VKT), and a random variable (a) (Equation 1). After simulating all the BEV driving profiles, we determine the yearly charged energy every BEV profile for the twelve scenarios.

The present work is focused on the usage of the public charging infrastructure, even though we cannot neglect private chargers, which are a popular option (according to surveys and questionnaires, 90% to 95% of BEVs drivers use home charging to fill their battery - TOI, 2018). For our study, we do not consider household having one or more private parking places for vehicles who installed at home charger and then will not use public infrastructure. Since the type of accommodation differs with the urbanity degree, we consider two values for drivers who will access the public charging infrastructure: one for each urban and rural areas.

$$SoC_{i,j} = \begin{cases} SoC_{i,j} - \left(\dfrac{a * VKT(j+1) * c_i^e}{c_i^{batt}}\right) * 100 \;\; if\ (SoC_{i,j+1} \geq 20\%) \\ 80 \quad if\ (SoC_{i,j+1} \leq 20\%) \end{cases} \tag{1}$$

Where:

- $i = 1, \dots, N$ is the driving profile
- j is the day

3.2. *Modelling the Charging Infrastructure Demand*

There are many charging techniques (Grauers et al., 2013): stationary charging (plug-in or wireless), battery swapping, and dynamic charging while driving (conductive or inductive). This paper will cover the plug-in stationary charging technique, using “a charger”. The charging time depends not only on the charger power (amperage) but also on the battery capacity, the battery SoC, the vehicle technology (AC/DC conversion) and the charging cable (Hardman et al., 2018). We can identify and qualify a charging point by its location, power, socket model, and current type (AC/DC, single or triple phase).

According to the international standard IEC 61851, the slowest is Mode 1, usually installed in private homes, which has a power of 3 kW using AC we do not consider in this study. The power of Mode 2 chargers is between 3 and 22 kW at AC, and they are generally found in either private homes or private or public parking spaces (such as parking lots). A Mode 3 charger operates up to 50 kW, using DC, and is generally not found in private homes. Preferably, these charging points are installed in public spaces and parking lots. Finally, ultra-fast Mode 4 chargers operate at powers above 50 kW using DC and are generally installed on inter-city corridors (highways) (Circutor, 2020).

In our study, we consider that every BEV size segment will charge at the maximum speed level. Therefore, a BEV with a battery capacity less than 20 kWh will use a 7 kW charger; those between 20 kWh and 45 kWh will use a 22 kW charger due to their non-compatibility with fast charging technology. BEVs, with a battery capacity higher than 50 kWh, are compatible with fast charging technology (50 kW). We do not consider slow and ultra-fast chargers because 3.7 kW chargers are generally installed at home, and more than 50 kW chargers are used for long-distance trips.

The need for charging infrastructure is deduced from the previous steps based on the sum of all daily energy charged by BEVs. Then, we determine the number of charging stations to be installed in order to cover the demand based on a queuing model. On the one hand, users want to find a vacant charging point when they arrive at a charging site. On the other hand, charging infrastructure operators cannot install an excessive number of on-street chargers due to the charger price that is increasingly expensive for high power. Therefore, we determined the number of on-street two-charger stations using the M/M/s queueing model, neglecting the limited-parking lots constraint, and under the constraint of an average maximal waiting time of 15 minutes.

The critical input parameters of a queue are the arrival rate and the service rate. The BEVs arrival rate, λ [#BEVs/hour], is deduced from the number of BEVs that cannot charge at home, and are obliged to use the charging stations. We consider that the BEVs arrival rate is equal on all charging stations, and the stations have two identical chargers (s=2). We also consider, just like in reality, that there is no arrival for BEVs to charging stations 00:00 to 06:00 am. 62% of the BEVs arrive from 02:00 pm to 7:00 pm, known as peak hours, Figure 2 (Groupe Alpha et al., 2018). Besides, we identified for every battery-capacity scenario a specific average arrival rate.

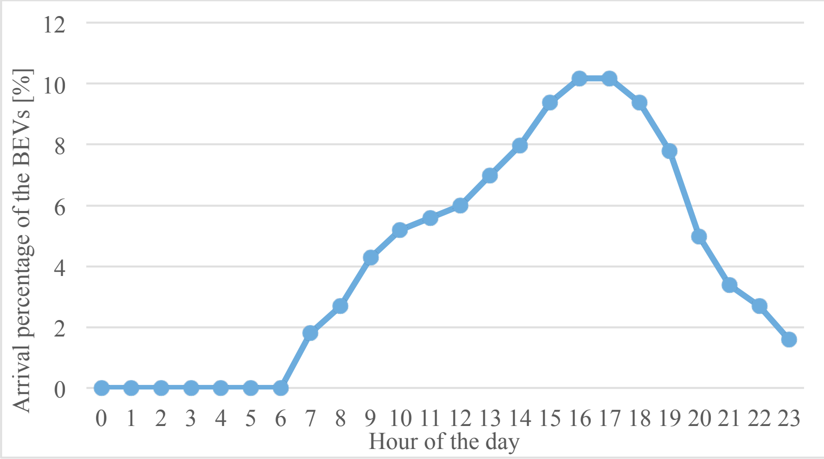

Figure 2 BEV arrival percentage

The service rate, μ [BEV/hour], was derived from the charging need model (Step 1: section 3.1) and was calculated based on the charging power for every battery capacity scenario. As mentioned before, the BEV will charge if its SoC is near 20%. μ is the reciprocal value of the average charging time estimated in our study, taking into account an efficiency factor of $\eta_{charger}$=85% for 7, 22, and 50 kW chargers. Therefore, we calculated a service rate for every battery capacity scenario.

Finally, since we have defined a minimal level of quality of service, we ensure that the waiting time for users remains limited. Therefore, the average waiting time ($W_q^{M/M/2}$) of 15 minutes maximum was applied in order to determine the number of stations for every charging power. For more information on queuing models, please refer to (Bhat, 2015).

3.3. *Cost Model*

The method aims to minimize the total cost of both charging infrastructure and the BEV, which was calculated for every driving profile 'i' based on the assumptions discussed earlier in this paper. Based on (Funke et al., 2019), we decided to use the EAC method for BEVs and charging infrastructure, by upgrading it to address different charging powers, and analyzing the costs regarding different parties of the BEV ecosystem, and two different territories.

3.3.1. The Business Model of the BEV Customer

Regarding the business model of the BEV customer, we compare the difference between purchasing a BEV and a conventional ICEV, for every profile and every scenario, and we concluded the average associated profits using ΔEAC_i as shown in Equation (2).

$$\boldsymbol{\Delta EAC_i = EAC_{BEV,i} - EAC_{ICEV,i}} \tag{2}$$

Equation 3 applies to all types of vehicles, electric or conventional. As shown, it is composed of the sum of amortized investments of the car body and the battery capacity, annual operating and maintenance costs that differ for every driving profile due to the individual $aVKT_i$, charging or refuelling costs and the CO2 emissions cost for ICEVs, as noted in (Gnann, 2015; Plötz et al., 2014). Note there are no battery costs, subsidies, nor subscription fees to access the charging infrastructure for a conventional vehicle. Table 1 details the techno-economic parameters of Equation 3, and all the values are presented in Appendix A.

$$EAC_{VEH,i} = \frac{(1+r_{VEH})^{T_{VEH}} * r_{VEH}}{(1+r_{VEH})^{T_{VEH}} - 1}\left(I_{VEH,z} + c_{batt,i} * p_{1kWh} - c_{BEV,subsidies}\right) + aVKT_i * \left(c_{VEH,O\&M,z} + c_{VEH,charging}\right) + c_{BEV,card} + LCA_{ICEV,z} * p_{CO2} \quad (3)$$

Where:

$$c_{VEH,charging} = \begin{cases} c_{f,el} * \frac{cons_{VEH,z}}{P_z * \eta}; if\ VEH = BEV \\ c_{f,el} * cons_{VEH,z}; if\ VEH = ICEV \end{cases}$$

- $i = 1, \dots, N$ is the driving profile
- $z = \begin{cases} Small\ ; if\ c_{batt} \le 20\ kWh \\ Medium; if\ 20\ kWh < c_{batt} < 50\ kWh \\ Large\ ; if\ c_{batt} \ge 50\ kWh \end{cases}$

Table 1 Techno-economic parameters of EAC_{VEH}

$EAC_{VEH,i}$	**Equivalent Annual Cost of the driving profile 'i'**	**[€/Year]**
r_{VEH}	Interest rate	[-]
T_{VEH}	Lifetime	[Years]
$I_{VEH,z}$	Vehicle investment of Type z (w/o battery)	[€]
$c_{batt,i}$	Battery capacity	[kWh]
p_{1kWh}	Price of 1 kWh	[€/kWh]
$c_{BEV,subsidies}$	Subsidies	[€]
$aVKT_i$	Annual Vehicle Km Travelled	[km/Year]
$c_{VEH,O\&M,z}$	Operation and Maintenance cost of a vehicle Type 'z'	[€/km]
$c_{VEH,charging}$	Charging fees	[€/Year]
$c_{f,el}$	Fuel/Electricity cost	[€/l] or [€/min]
$cons_{VEH,z}$	Fuel/Electricity consumption	[l/km] or [kWh/km]
P_z	Associated charging power	[kW]
η	The efficiency of the charging point	[-]
$c_{BEV,card}$	Subscription fee to access the charging infrastructure	[€/year]
$LCA_{ICEV,z}$	Life Cycle Assessment of ICEV Type 'z'	[tCO2/Year]
p_{CO2}	Price of 1 tonne of CO2	[€/tCO2]

3.3.2. Charging Point Operator Business Model

Before detailing the business model, it is essential to underline that the charging operator is in a situation of natural monopoly on the market, because of supporting fixed investment cost in their network. Also, we consider that, based on a benchmark of charging operators in Appendix A, that these firms use the third-degree price discrimination, because they fix their charging prices differently based on the category of clients, thus, on the used charging power and the battery capacity of the BEV. Equation 4 allows us to assess the profitability of its business model.

$$\boldsymbol{EAC_{CPO} = \sum_{i=1}^{N} EAC_{CPO,i}} \tag{4}$$

Where:

- $i = 1, \ldots, N$ is the charging point

In the most general case, the costs for the CPO are those related to the charging infrastructure that includes the investments related to the charger, civil engineering works, installation costs, and grid reinforcement. Besides, operation and maintenance costs, the electricity bill (per kWh consumed), and communication costs are added to the business model. We exclude costs for accessing the market place and personnel costs, due to the limited existing data; therefore, they will not be added to the formula.

Regarding the revenues, the operator receives governmental subsidies for installing new charging stations and revenues from the BEV customer per charging event and a subscription fee. Table 2 details the techno-economic parameters of Equation 5, and values are presented in Appendix A.

$$EAC_{CPO,j} = \left(\frac{(1+r_{CPO})^{T_{CPO}} * r_{CPO}}{(1+r_{CPO})^{T_{CPO}} - 1} \left(I_{CP,z} + I_{CPO,Civil\,works,z} + I_{CPO,Installation,z} + I_{CPO,Grid\,connections,z} - c_{CPO,subsidies} \right) + c_{CPO,O\&M} + c_{CPO,MB} + c_{CPO,com} \right) - \sum_{k=1}^{r} \left(c_{CPO,charging,k} + c_{CPO,card,k} - c_{CPO,elec} * YCE_k \right) \tag{5}$$

Where:

- j is the charger
- $z = \begin{cases} 7\ kW \\ 22\ kW \\ 50\ kW \end{cases}$
- $k = 1, \ldots, r$ is the BEV that uses the studied charger

Table 2 Techno-economic parameters of EAC_{CPO}

$EAC_{CPO,j}$	**Equivalent Annual Cost of a charger 'j'**	**[€/Year]**
r_{CPO}	Interest rate	[-]
T_{CPO}	Lifetime	[Years]
$I_{CP,z}$	Charging point investment of Type 'z'	[€]
$I_{CPO,Civil\ works,z}$	Civil works investment of Type 'z'	[€]
$I_{CSO,Installation,z}$	Installation investment of Type 'z'	[€]
$I_{CPO,Grid\ connections,z}$	Grid connections investment of Type 'z'	[€]
$c_{CPO,subsidies,z}$	Subsidies of Type 'z'	[€]
$c_{CPO,O\&M,z}$	Operation and Maintenance cost of Type 'z'	[€]
$c_{CPO,MB}$	Metering and billing cost	[€]
$c_{CPO,com}$	Communication cost	[€]
r	The number of BEV that use one charger	[-]
$c_{CPO,charging,k}$	Charging cost for the driver of the vehicle 'k' (=$c_{BEV,charging,k}$)	[€]
$c_{CPO,card,k}$	Subscription fee to access the charging infrastructure 'k' (=$c_{BEV,card}$)	[€/Year]
$c_{CPO,elec}$	Electricity cost for the CPO	[€/kWh]
YCE_k	Yearly Charged Energy of BEV 'k'	[kWh/Year]

3.4. Data and Techno-Economic Parameters

To determine the travelled kilometres, we used data from surveys done by The French National Institute of Statistics and Economic Studies (INSEE, 2008), which provides the travelled mileage during the weekends (e.g. 25 km for a Saturday, and 20 km for a Sunday). We used additional metadata on daily home-work trips was reported by (ENTD, 2020) for regular home-work trips per town. The vehicle-travelled kilometre per day is on average 32 km/day for urban areas compared to 135 km/day for rural areas. These "real" mileages were converted into WLTP autonomy-scale by multiplying them using a factor: 0.75 for city trips, 1 for roads, and 2 for highways (source: Groupe PSA). Generally, the individual-annual kilometre travelled for regular daily trips varies between 7,000 km/year and 12,000 km/year for urban areas and between 12,000 km/year and 42,500 km/year for rural areas.

Regarding techno-economic-environmental parameters, vehicles were reported into three sizes depending on their battery capacity. Since a comparison between a BEV and an ICEV is made for the driver, we should compare the same type of vehicle. Therefore, all the parameters of both electric and conventional vehicles are divided into three types and detailed in Appendix A (Tables 4 and 5). These parameters include energy consumption: electricity for BEV and fuel for ICEV, investments (without the battery), operation and maintenance costs, and life cycle assessment. We assumed in our study that the duration of vehicle ownership is 9.5 years for both BEV and ICEV (ACEA, 2019). We consider the price of one kWh pack of battery capacity as 150 €/kWh, and the price of 1 tonne of CO2 as 100€ (Fox et al., 2017; Quinet et al., 2009). A 6,000€ governmental subsidy in France is offered to the BEV customer if the battery capacity is less than 50 kWh. This amount decreases to 3,000 € if the battery capacity is between 50 kWh and 70 kWh, and is cancelled for large BEVs with 70 kWh and more (French Government, 2020)[2].

The EAC of the charging point operator includes the amortized investments needed for charging infrastructure during the ownership of 15 years. The investment is the sum of the charger price, civil engineering works, installation costs, and grid reinforcement, which are summarised in Table 6 of Appendix A. Similarly to the BEV customer, governmental subsidies (called ADVENIR in France) are offered to CPOs: 40% of the charger price for deploying a slow charger and 1,500€ for normal and fast ones (Advenir, 2020). The annual costs for operations and maintenance are assumed to be 10% of the charges price, communication costs are 100€ per charger, and metering and billing 188€ per charger (Groupe Alpha et al., 2018). An efficiency factor of 85% is applied to the conversion between the charger and the battery.

The charging/refuelling tariffs are fixed based on the French market. The fuel cost is fixed as 1.518€/l (French Ministry of Economy and Finance, 2020), and the charging pass costs 5€/BEV/month. Charging tariffs are set as follow: 1€/hour using a 7 kW charger, 1.5€ for the first hour and 0.2€/minute after the first hour for a 22 kW charger, and 2€ for the access to a 50 kW charger, plus a cost of 0.247€/min (Chargemap, 2020). The industrial electricity bought by the charging operator is 0.18€/kWh (Eurostat, 2020). A maximal interest rate for purchasing a BEV or ICEV is 3%, for the charging points is 5%.

4. Results

Results relating to the identification of a cost-efficient trade-off between longer BEV ranges and more charging stations are presented in three steps. First, we simulate a fleet of BEVs to identify energy needs (Section 4.1). Second, we quantify the number of charging stations (Section 4.2). Third, results compare the investments in both technologies and detailing the business models of the different parties of the BEV ecosystem (Section 4.3).

4.1. Individual Driving Profiles

[2] We took into account the governmental subsidies before the COVID19 crisis.

In order to quantify the electric needs of the BEVs, we simulated 12 scenarios of 5,000 identical BEVs per scenario, separately for urban and rural case studies. We increased the battery capacity from 15 kWh to 120 kWh from a scenario to another. We modelled the individual driving profiles taking into account socio-technical parameters, namely daily travelled kilometre (ENTD, 2020; INSEE, 2008), and electricity consumption (Gnann, 2015) that vary with the size of the vehicle. The daily travelled kilometres for "home-work-home" trips on weekdays is on average 35 km/day for urban needs and 135 km/day for rural needs. Besides, the travelled kilometres during weekends fluctuate between 18 and 23 km for Saturdays, and between 26 and 33 km for Sundays. Generally, the annual vehicle kilometres travelled for daily purposes vary between 7,000 and 12,000 km for urban needs, and between 12,600 and 42,400 km for rural needs. Real travelled kilometres are then converted to electric needs (WLTP) using a factor.

Aside, in order to calculate the needs of each BEV, we consider the driver will not charge his vehicle unless the SoC of the next day will drop below 20%, and if needed, will charge to 80%. Since each type of BEV could only charge using a well-defined charging power, the charging duration of a single charging event increases with battery capacity contrary to the frequency of events. BEV with a battery capacity between 15 kWh and 35 kWh were excluded due to their limited autonomy.

4.2. Charging Infrastructure Demand

As mentioned earlier in this paper, some BEVs are not compatible with fast charging technology. For this reason, a BEV with a battery capacity between 15 kWh and 20 kWh uses a 7 kW charger, BEV with a battery capacity between 25 kWh and 45 kWh uses a 22 kW charger. A BEV, with a battery capacity between 50 kWh and 120 kWh, is compatible with fast charging technology (50 kW). Figure 3 presents how many BEVs an available charging point (CP) could serve.

Simulation results, in Figure 3, show that for less need for infrastructure for higher charging power. However, the required number of chargers increases with bigger battery capacities that use the same charging power. This is due to the 15 minutes maximum waiting time constraint additionally to the increase in the charging duration of one event. Besides, results show that one CP could serve more BEVs in urban areas than in rural ones; thus, fewer needs of deploying charging infrastructure by comparing the two areas.

Regarding the urban needs, on average, one 7 kW CP could serve up to 18 small-battery BEVs, one 22 kW CP up to 46 medium-battery BEVs, and one 50 kW CP up to 80 large-battery BEVs. In contrary, for rural needs, one 22 kW CP could serve up to 8 medium-battery BEVs, and one 50 kW CP to 26 large-battery BEVs.

Altogether, we concluded that BEVs with a more extended range that uses the same charger speed rely more on charging infrastructure. However, if we compare the results of different charging powers, it is clear that the need for charging infrastructure becomes lower for a 50 kW charger than a 22 kW and 7 W chargers. At present, deploying charging infrastructure is based on technical factors and neglects some psychological factors, such as range anxiety, due to the limited data. For this reason, the number of charging points might vary.

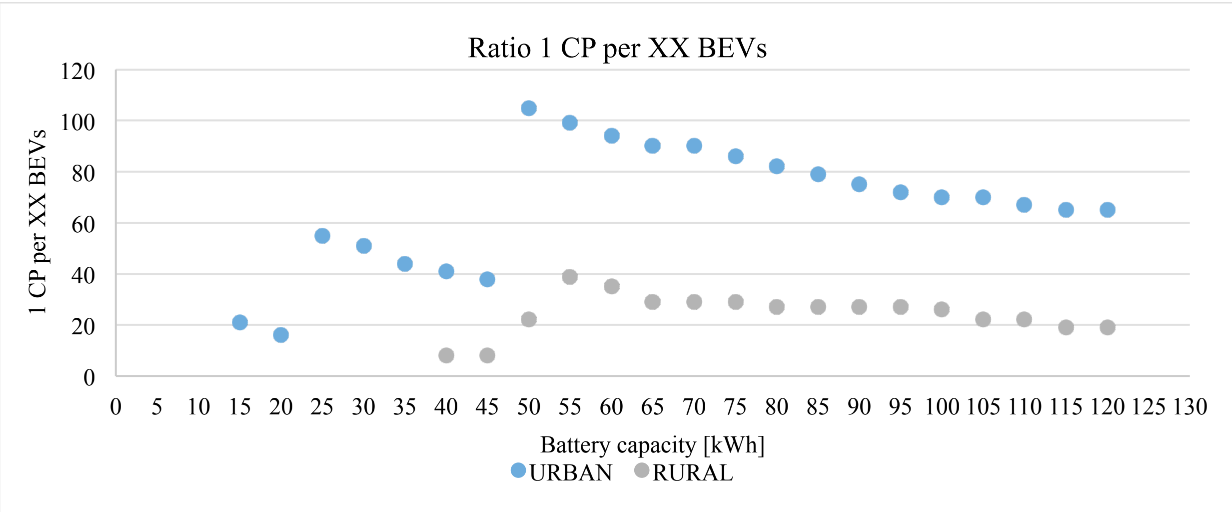

Figure 3 Number of BEV that use one charging point as function of battery capacity

4.3. Costs Models

In order to identify the most cost-efficient trade-off between bigger batteries and charging stations, we compare the investments in both technologies that could help us to draw general conclusions, especially for policy recommendations. Then, we develop the business models of the BEV customer, the charging point operator, in order to determine the most cost-efficient solution for both parties.

4.3.1. Investments Comparison of Bigger Batteries and Charging Infrastructure

We compared the investments of adding 50 and 100 km of autonomy, and those of the deployment of 7, 22, and 50 kW chargers per BEV. Figure 4 presents the comparison of investing in both technologies. Results show that the costs of investing in longer ranges are higher than those in charging points of different powers.

At today's battery capacity prices, the cost of adding 50 km of autonomy can vary between 1200€/BEV and 1600€/BEV. Similarly, for a range extension of 100 km, the investments add up to several thousands of euros (from 2400 €/BEV to 3200€/BEV). The investments in added autonomy vary between two values given that the electricity consumption of BEVs increases with bigger battery capacity. The price of one pack of 1 kWh is fixed at 150 €/kWh.

Regarding charging infrastructure, associated investments are considered to be equally distributed across all BEVs. The required investments of 7 kW chargers vary from 125€/BEV to 165€/BEV for urban needs and do not exist in rural needs, due to the limited autonomy of small–battery BEVs. Also, the investments of 22 kW chargers vary from 70€/BEV to 105€/BEV for urban needs and between 490€/BEV to 505€/BEV for rural needs. Similarly, those of 50 kW chargers alter from 240€/BEV to 390€/BEV for urban areas and between 645€/BEV to 1330€/BEV. These investments range between two values given that an optimal number of charging stations is identified for every battery capacity.

Generally, it is cheaper to deploy more charging points, of different powers, than to extend the BEV range; except for rural needs because adding 5 km to the battery range comes with a lower cost than deploying 50 kW chargers. Among the three charging powers, lower costs for 22 kW chargers are the cheapest thanks to both limited investments and the number of BEVs that use one charger.

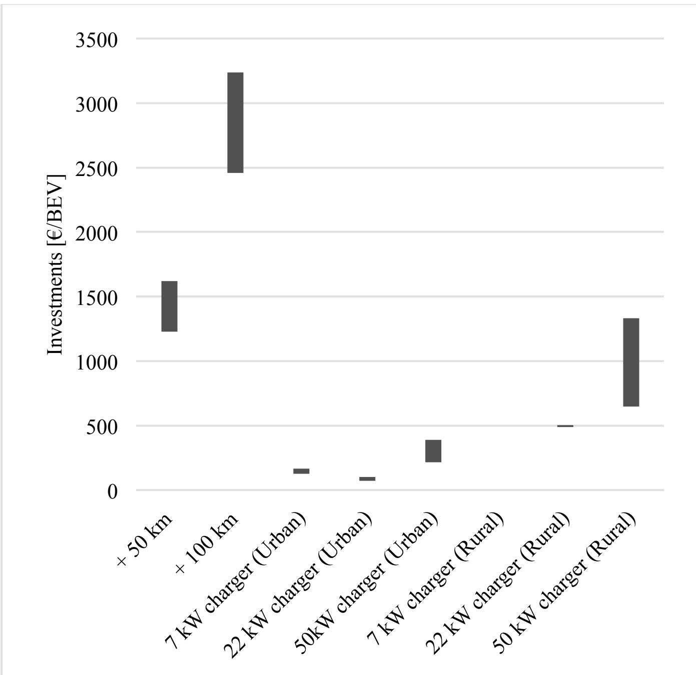

Figure 4 Range of investments for extending the range of BEVs vs. those in charging infrastructure

4.3.2. The Business Model of the BEV Customer

From the BEV customer's perspective, we first analyze the difference between the EAC of purchasing a BEV and an ICEV for the customer, hereafter noted as ΔEAC. A positive ΔEAC indicates that a BEV comes with higher costs than an ICEV. Figure 5 indicates the average ΔEAC and the monthly charging duration for every battery capacity, for both urban and rural case studies.

Regarding the urban needs (Figure 5), results show that negative ΔEAC is guaranteed for purchasing a BEV with a battery capacity between 15 kWh and 50 kWh. Indeed, purchasing a 15 kWh BEV is the most cost-efficient for the customer (with the lowest ΔEAC: -1120€/BEV/Year). Nevertheless, the driver will spend around 10 hours/month to charge his vehicle. For medium-battery BEV, ΔEAC has a negative value between 35 kWh and 45 kWh while the charging duration fluctuates around 5 hours/month. For large-battery BEV, a 50 kWh vehicle comes with a dual-advantage: lower cost than an ICEV (ΔEAC=-105€/BEV/Year) and low charging duration (3 hours/month). BEV with battery capacity more than 55 kWh are not economical for the client (positive ΔEAC), even so the charging duration does not exceed 3 hours/month.

For rural needs (Figure 5) (and after excluding BEVs with a battery capacity between 15 kWh and 35 kWh due to their limited autonomy), results show that purchasing a 40-45 kWh vehicle is not economical since $\Delta EAC > 0.$ A 50 kWh BEV comes with the lowest costs (ΔEAC=-1030€/BEV/Year) but with high charging durations (>24hours/month). The autonomy of 40 to 50 kWh BEV presents a potential risk of blackout during the "home-work-home" trip, depending on the driver's choice and the usual rural trips. Therefore, even though purchasing a 50 kWh vehicle is the most cost-efficient, it could not be suitable for some drivers due to limited range. The most cost-efficient solution for the rural areas will depend on the driver's trips. A 55-65 kWh BEV could not only satisfy the driving needs but also comes with the lowest monthly charging duration. Yet, its ΔEAC is positive.

To conclude, our results indicate, for the customer, that there is a trade-off between cost and charging duration: small-battery BEV, contrary to large-battery BEV, is the most cost-efficient solution but comes with high charging duration. If the client is searching for an economical solution rather than a luxurious one, purchasing a BEV with a battery capacity between 15 kWh and 50 kWh is cost-efficient for urban needs (ΔEAC is negative). In contrary, for rural needs, several choices could be interesting for the driver based on his/her daily trips. Yet, the less risky solution is 55-65 kWh BEV with the required autonomy and a minimum ΔEAC.

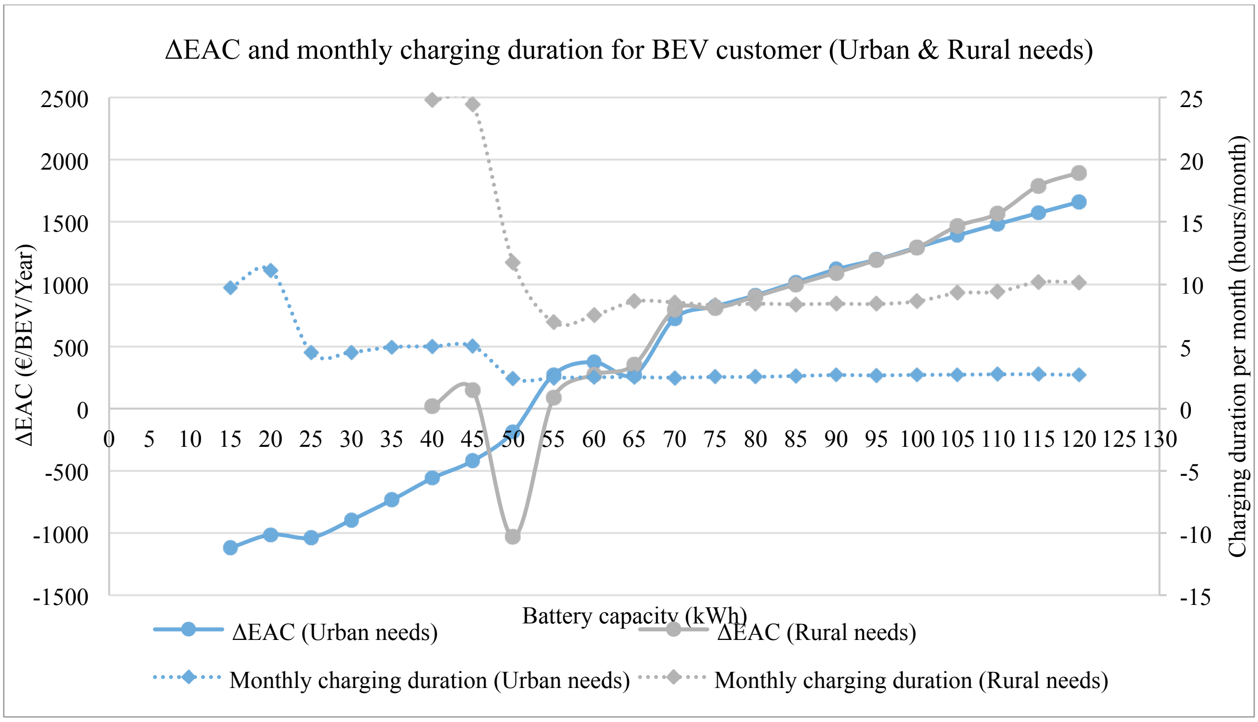

Figure 5 The business model and the monthly charging duration for the BEV customer

4.3.3. The Business Model of the Charging Point Operator

Regarding the Charging Point Operator, we calculated the EAC of the whole infrastructure, in both urban and rural areas. Results are given in Figure 6. Remember, negative costs are profits, each BEV is only compatible with one charging power, and charging pricing differs with charging powers (Benchmark of offers is provided in Appendix A Table 3). It is assumed that all BEVs' customers purchased a subscription card to access the charging infrastructure. Simulations point out that this business could be profitable in case of deployment of the optimal number of chargers, and using the right pricing method with the right tariffs.

Regarding urban needs, Figure 6 indicates that deploying slow charging infrastructure is not profitable for the operator, due to a high number of required chargers (Figure 6), resulting in higher charging tariffs than 1€/hour. Regarding the 22 kW infrastructure, a fleet of BEVs with a battery capacity of 25 and 30 kWh is not profitable for the operator. Since the charging duration does not exceed 1 hour, it is recommended to review the first-hour tariff in order to avoid positive costs. It becomes profitable for the operator to deploy these chargers for battery capacity between 35 and 45 kWh, which charging durations exceed one hour. These profits increase with bigger battery capacity because of the exceeded minute pricing method.

Regarding the fast charging infrastructure, the operator generates profits by deploying 50 kW chargers and based on the used tariffs. It is essential to stress on the fact that the profits slightly decrease with broader autonomy. Overall, the operator receives profits for a fleet of 35 to 120 kWh BEVs, with a maximum at 50 kWh, because of two main reasons: the 2-hour charging duration per vehicle and the "per exceeded minute" pricing method. Urban and rural share the same results.

To sum up, based on our tariffs, a fleet of 35-120 kWh vehicles for urban (40-120 kWh vehicles for rural) that use 22 kW and 50 kW charging infrastructure generate profits for the operator, especially for the 50 kWh case. These results underline the fact that the charging operator could have a profitable business model if the optimal number of chargers is deployed, and the right pricing method and tariffs are used. Future researches should consider revising charging tariffs especially for 7 kW and for the first hour of 22 kW chargers.

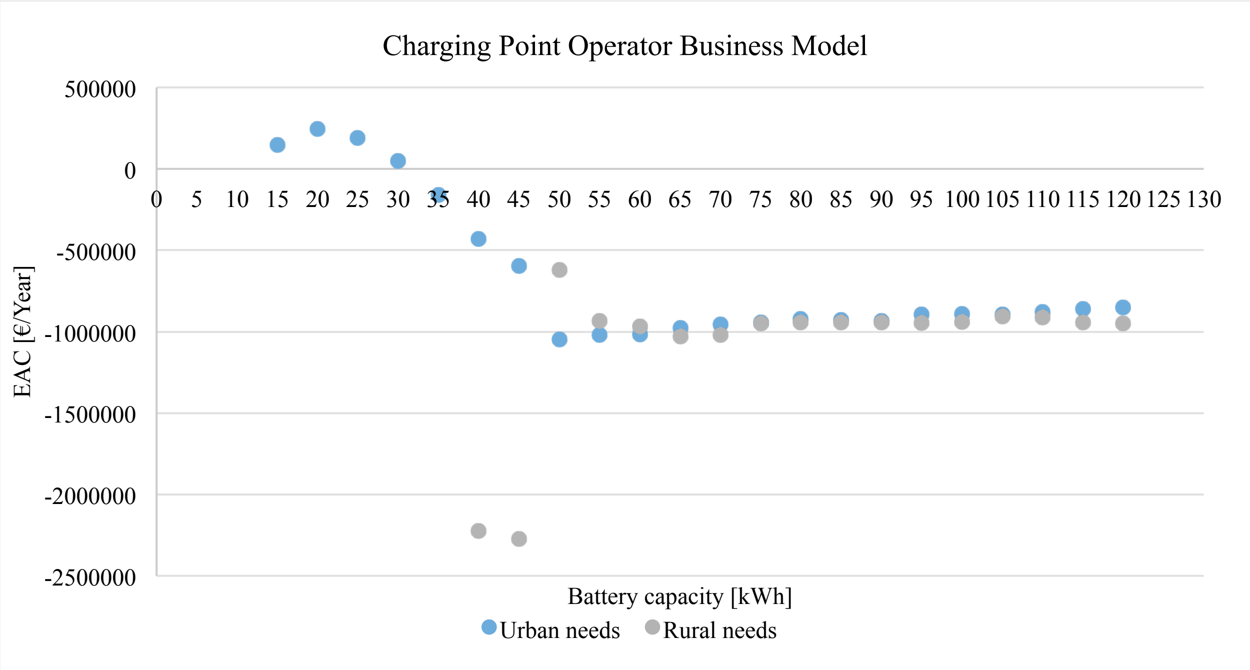

Figure 6 The business model of the Charging Point Operator

4.3.4. Win-Win Situations

Regarding the urban needs, two solutions could be profitable for the ecosystem: 35-45 kWh BEV and deploying 22 kW chargers; or 50 kWh BEV and deploying 50 kW chargers. Similarly, for rural needs, we conclude with two solutions based on the driver's daily travelled kilometres. The first one is a 50 kWh BEV and deploying 22 kW chargers, that does not only come with the lowest costs for the driver but also with the highest profits for the charging operator. This choice could be risky for some drivers due to limited autonomy. Therefore, the second safe choice is a 55-65 kWh BEV and deploying 50 kW chargers.

4.4. Sensitivity tests

In order to strengthen our results, we apply three sensitivity tests to validate its robustness against changes in charging behaviour and charging pricing methods. First, we took different scenarios of the utilization of charging powers by mixing the adaptability between chargers and BEV battery size. Second, we changed the pricing method. Third, we increased the charging tariffs by 50% in order to evaluate the influence on BEV drivers.

4.4.1. Mixing the charging powers and the BEV battery size

In this study, small-battery BEVs use the 7 kW chargers, medium-battery BEVs use 22 kW, and large-battery BEVs use 50kW to charge (Scenario 0). Since it could depend on the drivers' charging behaviour, we studied three additional scenarios by mixing the usage of chargers with the battery sizes. Therefore, we defined three additional scenarios: Scenario 1 when all BEVs charge using 7 kW chargers, Scenario 2 using 22 kW, and Scenario 3 using 50 kW chargers (even that some BEVs do not have the fast charging technology). Results show that the benefits of the customer and those of the operator are antagonists but in line with our conclusions (Figures 7-8-9-10). For urban needs, BEVs, with battery capacity between 35 kWh and 50 kWh, are the most cost-efficient with the deployment of 22 kW or 50 kW chargers.

Regarding the rural needs, a 40-65 kWh BEV presents a win-win solution for the customer and the operator at the same time. The choice of the battery size will depend on the driver's daily trips.

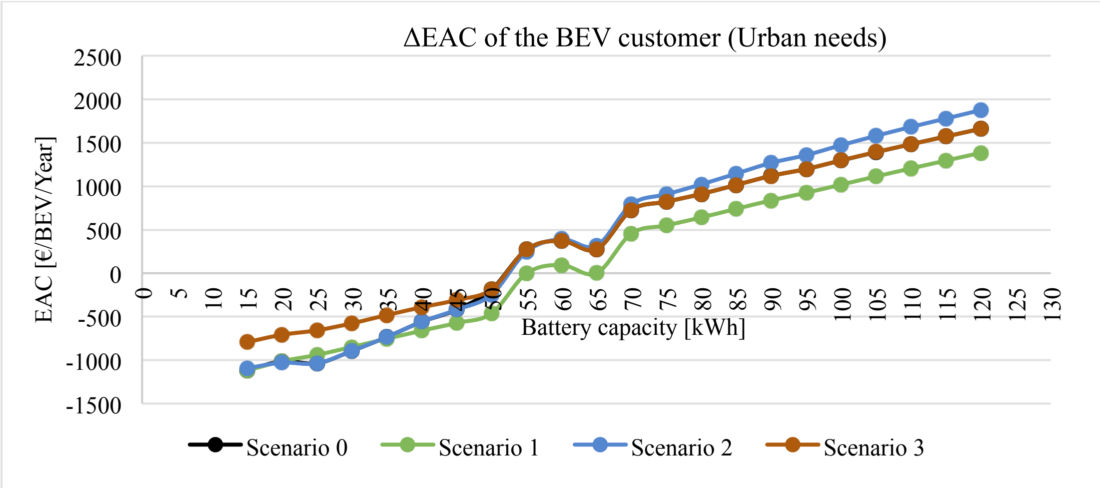

Figure 7 Sensitivity test 1 results on the BEV customer for urban needs

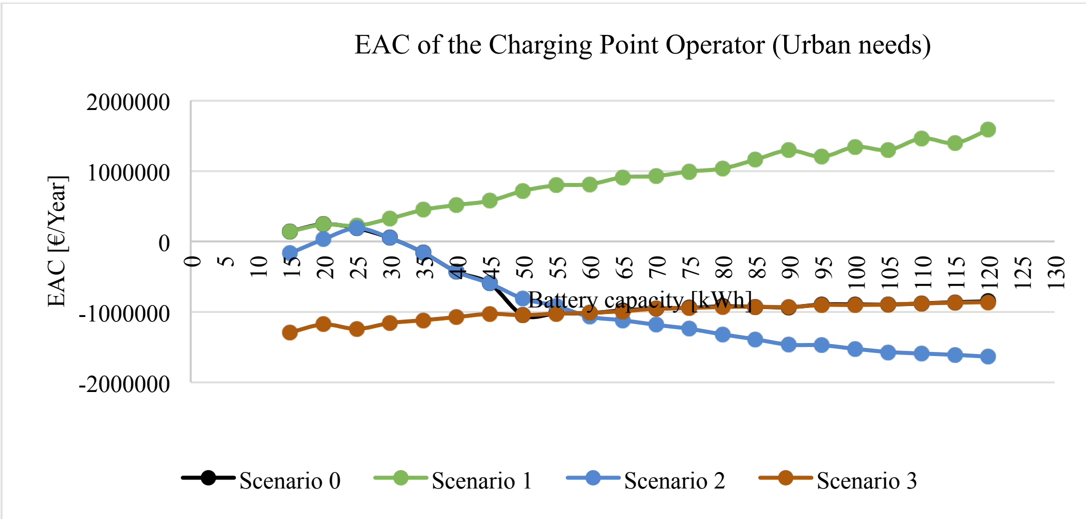

Figure 8 Sensitivity test 1 results on the charging point operator for urban needs

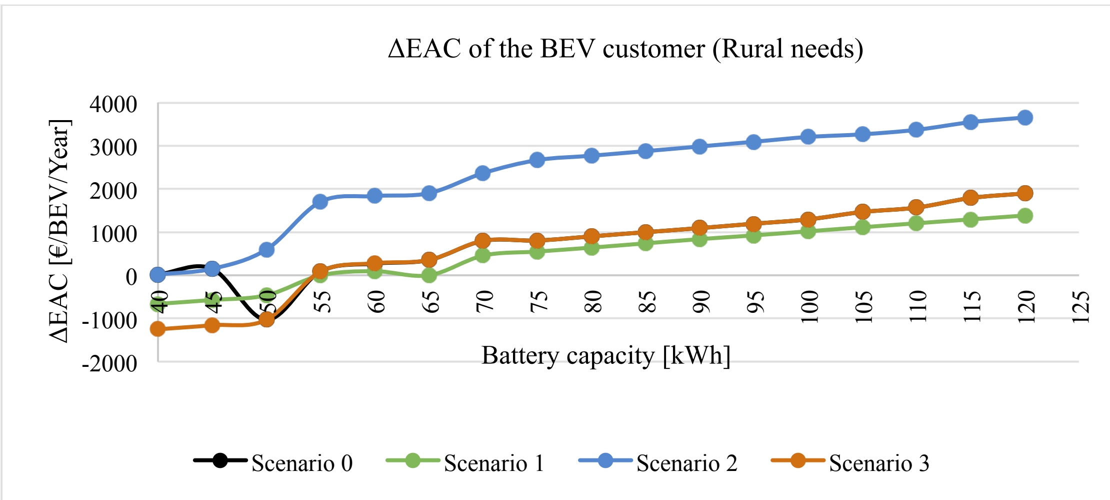

Figure 9 Sensitivity test 1 results on the BEV customer for rural needs

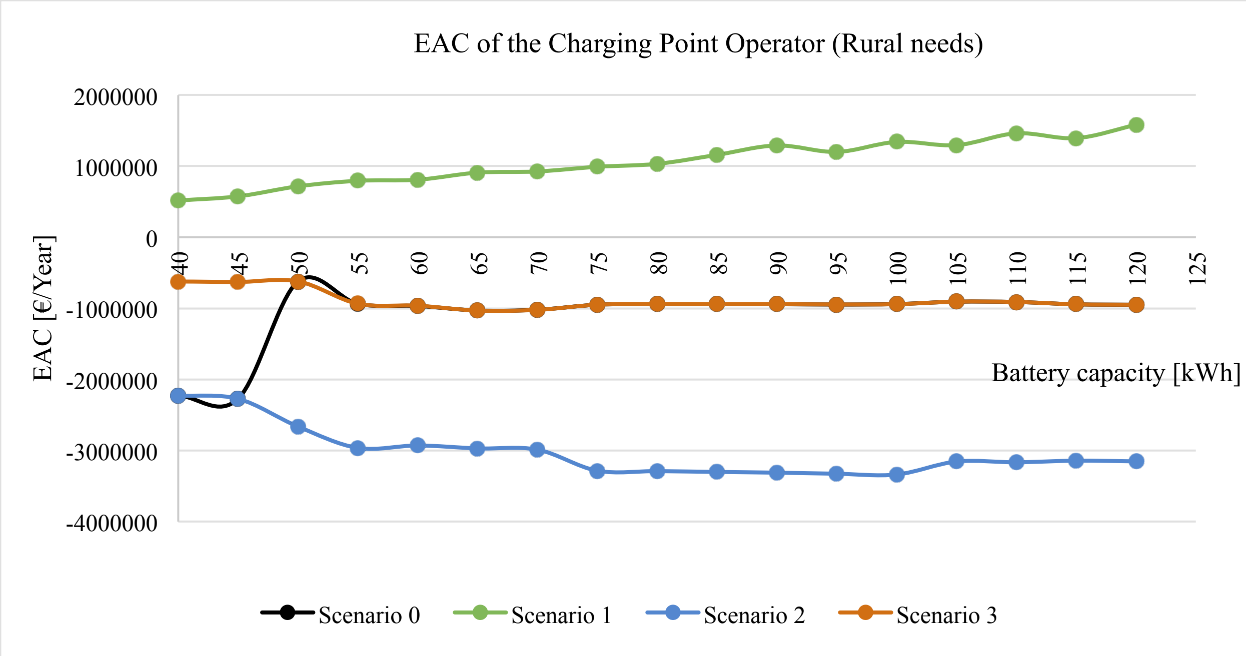

Figure 10 Sensitivity test 1 results on the charging point operator for rural needs

4.4.2. Changing the Pricing Methods

Different pricing methods are available on the market: a tariff per hour, a fixed tariff for the first hour and every exceeded minute, and an access fee to the charging station and per minute (Appendix A Table 1). For robustness, we changed the pricing method for medium and large-battery BEVs. The scenarios are defined in Table 8.

Table 3 Sensitivity test 2 scenarios

Scenario #	**Scenario 0**	**Scenario 1**
Small BEV	1€/hour	1€/hour
Medium BEV	1.5€ for the first hour 0.2€ per exceeded minute	1.5€ for the access 0.2€ per minute
Large BEV	2€ for the access 0.247€ per minute	2€ for the first hour 0.247€ per exceeded minute

Results (Figure 11 and 12) show, for urban needs, a "per exceeded minute" pricing method that comes with more profit for the customer rather than "an access fee + per minute" pricing method, on the contrary, to the operator. Two solutions could be a cost-efficient for both parties: (35-40 kWh BEV; 22 kW chargers; "per exceeded minute" pricing method) or (50 kWh BEV; 50 kW chargers; "an access fee + per minute").

For rural needs, no conclusion could be drawn, since no win-win situation is detected. Therefore, we share the same solution as elaborate in Section 4.3.3. We recommend as future studies, to investigate about a profitable solution for both BEV customer and charging operator for the rural case study.

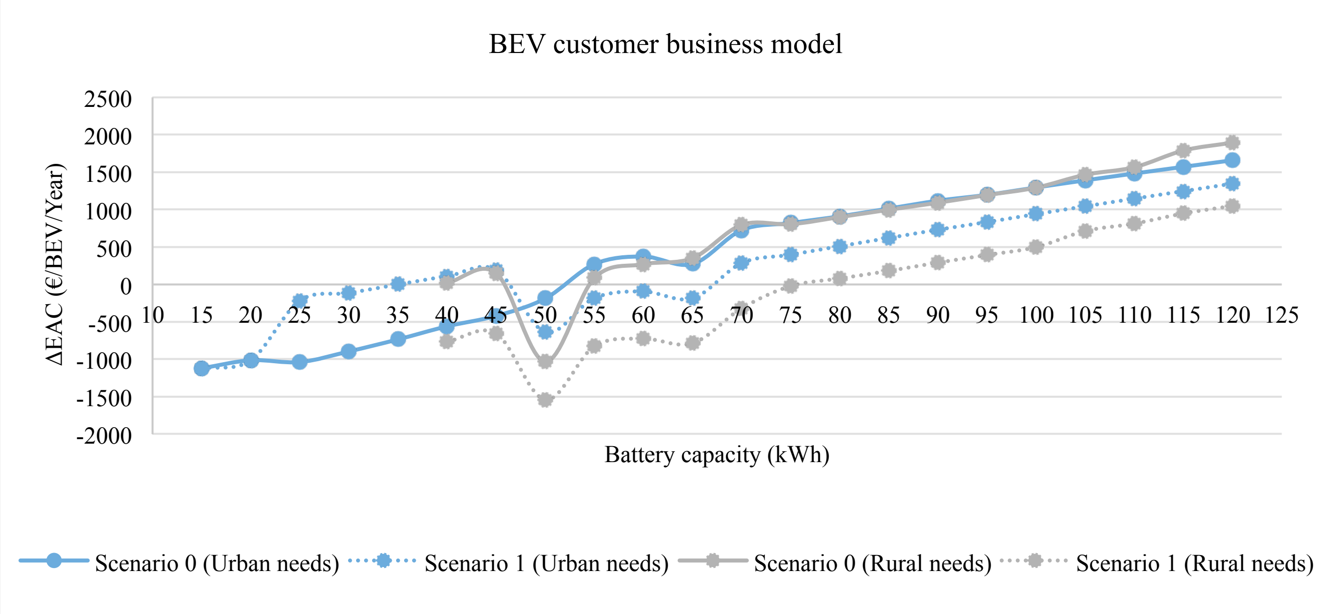

Figure 11 Sensitivity test 2 results on the BEV customer

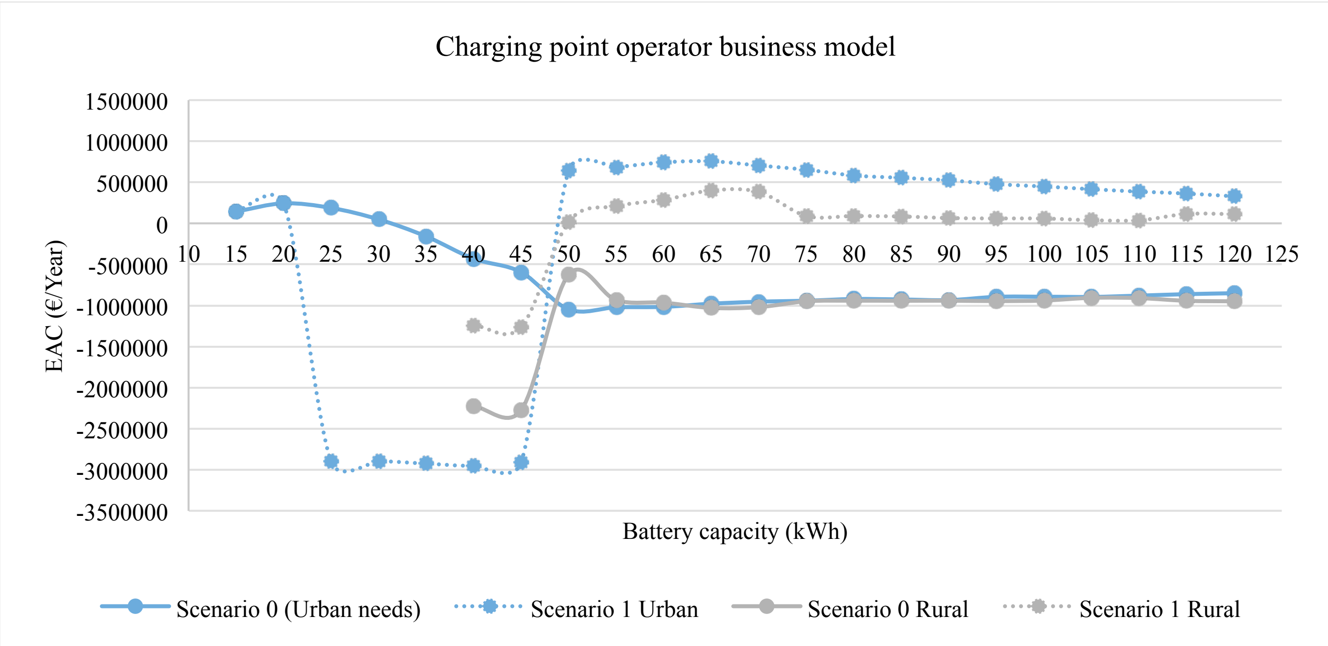

Figure 12 Sensitivity test 2 results on the charging point operator

4.4.3. Increasing the Charging Tariffs

As a third sensitivity test, we increased the charging tariffs by 50% in order to measure the influence on the BEV customer (Figure 13). Results of the rural case study show high price elasticity of demand (ε<-1 : the variation of the ΔEAC is higher than 50% for all battery capacities). Regarding urban needs, the elasticity is high for medium-battery BEVs (ε<-1) contrary to small-battery and large-battery BEVs (-1<ε<0).

Since increasing the tariffs could be highly demand elastic, BEV customers could change their driving behaviour. It is then recommended, for operators, to review the charging tariffs, and to consider the driver's point of view towards similar variations.

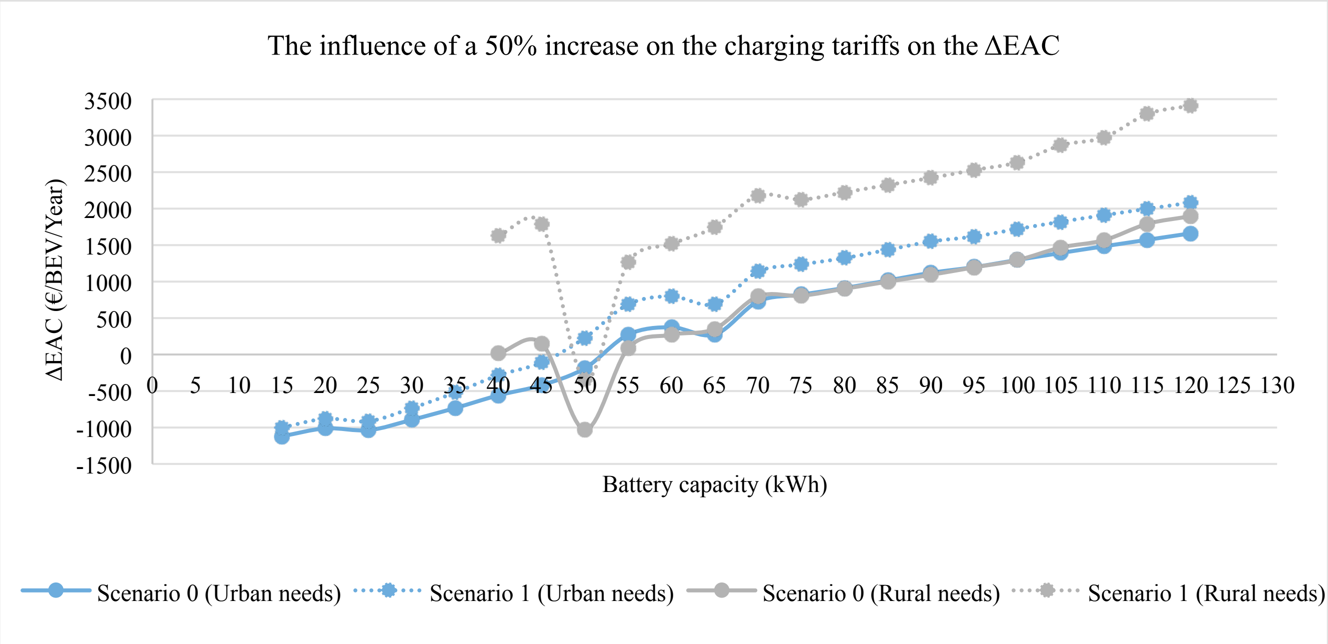

Figure 13 Sensitivity test 3 results on the BEV customer

5. Conclusion and Discussion

In order to reach global ambitions regarding GHG emissions, the growth in the BEV market share is inescapable. Range anxiety, a primary barrier to BEV adoption, could be solved using two interdependent and complementary options: by increasing the battery capacity and/or by enlarging the charging network. This study presents a novel approach to answer the issue by calculating the EAC of different battery capacity scenarios. We modelled the usage of public infrastructure by simulating 5,000 privately purchased BEVs, taking into account their daily driving needs for both urban and rural French areas scenarios, and by neglecting long-mileage trips (e.g. vacations). We also categorized the vehicles into three parts based on their battery capacity: small-battery BEVs that can only charge using 7 kW chargers, medium-battery

BEVs using 22 kW chargers, and large-battery BEVs that can connect to 50 kW fast-chargers. The model could be applied to different territories by changing the values of these parameters. However, it does not deliver a geo-spatial allocation of charging infrastructure..

Our analyses showed that the specific investments [€/BEV] in the deployment of charging infrastructure, especially for 22 kW chargers, is lower than that of expanding the BEV range by 50 km and 100 km. We found that bigger batteries do not pay off, since additional investments will apply. In our study, the operator uses the third type of discrimination while fixing its charging tariffs, because the pricing depends on the power of the charger, and thus on the battery capacity. Our outcomes demonstrate the fact that the battery capacity and charging points are correlated since the charger usage depends on the battery size.

After detailing and comparing the different business models of the parties of the BEV ecosystem, the analyses for urban needs showed that 35 kWh to 50 kWh BEVs with the deployment of 22 and 50 kW chargers is cost-efficient. The used pricing method is a variable one, taxed by exceed minute after one hour of charging. In contrary, for rural needs, the results showed two solutions depending on the driver's trips: a 50 kWh BEV with 22 kW chargers that comes with the lowest cost for the customer but could not be the right choice for some drivers due to the limited autonomy. A second solution is a 55-65 kWh BEV use 50 kW chargers, which comes with a minimum positive ΔEAC but a more significant autonomy, using a fixed pricing method: a fee for the access added to a tariff per minute of charging.

Although the design of our model presents a dual analysis for both parties (i.e. BEV driver and the charging infrastructure operator), it has some limitations due to several assumptions related to driving and charging behaviours, due to the lack of data and parameter calibration choices. We, therefore, applied several sensitivity tests, in order to measure the effect of different scenarios variations on the results, by i) mixing the charging powers and the BEV size, by ii) changing the pricing method, and by iii) increasing the charging tariffs. The results of the sensitivity tests were in line with our general conclusions for both urban and rural areas.

In future work, the assumption of driving and charging behaviour should be considered, because the driver could change their attitudes in terms of additional trips, such as home-school travels, other activity centres, malls, etc. where semi-public charging stations could be available. For this reason, the arrival rate to the charging stations may change, causing a different number of chargers. Also, when simulating BEV profiles, we neglected comfort parameters such as heating, cooling, lights, and radio, that may increase the energy demand of BEVs. Besides driving behaviour, some hypotheses about installation and techno-economic grid parameters are not considered. The question related to grid expansion is under discussion because specific technical problems could be resolved by smart charging such as peak demands, especially for fast charging infrastructure. Also, we did not consider external parameters such as the land price in the operator's business model, due to no-spatial model and the high variety of these prices. Overall, it is vital to use real-world data that reflect the driving and charging behaviours of BEV drivers, such as trip mileage, arrival rates, and actual charging durations. Finally, based on these real-data, charging tariffs and the pricing methods should be revised, taking into account an oligopolistic market where competition between charging operators stakes.

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References

ACEA, 2019. ACEA Report Vehicles in use-Europe 2019 [WWW Document]. URL https://www.acea.be/uploads/publications/ACEA_Report_Vehicles_in_use-Europe_2019.pdf (accessed 10.13.20).

Advenir, project, 2020. ADVENIR | Primes CEE pour points de recharge des véhicules électriques [WWW Document]. ADVENIR. URL https://advenir.mobi/ (accessed 10.26.20).

Alhazmi, Y.A., Mostafa, H.A., Salama, M.M.A., 2017. Optimal allocation for electric vehicle charging stations using Trip Success Ratio. Int. J. Electr. Power Energy Syst. 91, 101–116. https://doi.org/10.1016/j.ijepes.2017.03.009

Alizécharge, 2020. Alizé Charge - Bornes de recharge pour voitures électriques [WWW Document]. URL https://alizecharge.com/fr/ (accessed 10.27.20).

Amjad, M., Ahmad, A., Rehmani, M.H., Umer, T., 2018. A review of EVs charging: From the perspective of energy optimization, optimization approaches, and charging techniques. Transp. Res. Part Transp. Environ. 62, 386–417. https://doi.org/10.1016/j.trd.2018.03.006

Bhat, U.N., 2015. An Introduction to Queueing Theory: Modeling and Analysis in Applications, 2nd ed, Statistics for Industry and Technology. Birkhäuser Basel. https://doi.org/10.1007/978-0-8176-8421-1

Capturing the Usage of the German Car Fleet for a One Year Period to Evaluate the Suitability of Battery Electric Vehicles – A Model based Approach - ScienceDirect

[WWW Document], n.d. URL https://www-sciencedirect-com.ezproxy.universite-paris-saclay.fr/science/article/pii/S2352146514000155 (accessed 3.8.20).
Carbone4, 2018. La France amorce le virage vers le véhicule électrique [WWW Document]. URL http://www.carbone4.com/wp-content/uploads/2018/09/Publication-Carbone-4-Mobilite-electrique.pdf (accessed 10.26.20).
chargemap, 2020. Chargemap - bornes de recharge pour voitures électriques [WWW Document]. URL https://fr.chargemap.com/ (accessed 10.26.20).
circutor, 2020. Modes de charge (IEC-61851-1) [WWW Document]. URL http://circutor.es/fr/formation/vehicule-electrique/modes-de-charge-iec-61851-1 (accessed 10.29.20).
ENTD, 2020. Enquête sur la mobilité des personnes 2018-2019 | Données et études statistiques [WWW Document]. URL https://www.statistiques.developpement-durable.gouv.fr/enquete-sur-la-mobilite-des-personnes-2018-2019 (accessed 7.28.20).
Eurostat, 2020. Statistiques sur le prix de l'énergie - Statistics Explained [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_price_statistics/fr&oldid=291900 (accessed 10.13.20).
Fox, J., Axsen, J., Jaccard, M., 2017. Picking Winners: Modelling the Costs of Technology-specific Climate Policy in the U.S. Passenger Vehicle Sector. Ecol. Econ. 137, 133–147. https://doi.org/10.1016/j.ecolecon.2017.03.002
French Government, 2020. Bonus écologique pour un véhicule électrique ou hybride (voiture, vélo...) [WWW Document]. URL https://www.service-public.fr/particuliers/vosdroits/F34014 (accessed 10.26.20).
French Ministry of Economy and Finance, 2020. Données publiques [WWW Document]. URL https://www.prix-carburants.gouv.fr/rubrique/opendata/ (accessed 7.27.20).
Funke, S.Á., Plötz, P., Wietschel, M., 2019. Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany. Appl. Energy 235, 888–899. https://doi.org/10.1016/j.apenergy.2018.10.134
Gnann, T., 2015. Market diffusion of plug-in electric vehicles and their charging infrastructure, Book series "Innovation potentials." Fraunhofer-Verl, Stuttgart.
Gnann, T., Goldbach, D., Jakobsson, N., Plötz, P., Bennehag, A., Sprei, F., 2016. A Model for Public Fast Charging Infrastructure Needs. World Electr. Veh. J. 8, 943–954. https://doi.org/10.3390/wevj8040943
Groupe Alpha, INTERGROS (France), France, Direction générale des entreprises (2014-....), 2018. L'impact des mutations technologiques et de la digitalisation sur le modèle économique du commerce de gros. Direction générale des entreprises, Paris.
IEA, 2019. Global Electric Vehicle Outlook 2019 [WWW Document]. IEA. URL https://www.iea.org/reports/global-ev-outlook-2019 (accessed 6.17.20).
INSEE, 2008. Présentation statistique − Enquête nationale transports et déplacements 2007/2008 | Insee [WWW Document]. URL https://www.insee.fr/fr/metadonnees/source/operation/s1367/presentation (accessed 10.22.20).
IPCC, 2018. Allen, M.R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M.Wairiu, and K. Zickfeld, 2018: Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors,

J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Jabbari, P., Mackenzie, D., 2017. EV Everywhere or EV Anytime? Co-locating Multiple DC Fast Chargers to Improve Both Operator Cost and Access Reliability.

Madina, C., Zamora, I., Zabala, E., 2016. Methodology for assessing electric vehicle charging infrastructure business models. Energy Policy 89, 284–293. https://doi.org/10.1016/j.enpol.2015.12.007

Meinrenken, C.J., Shou, Z., Di, X., 2020. Using GPS-data to determine optimum electric vehicle ranges: A Michigan case study. Transp. Res. Part Transp. Environ. 78, 102203. https://doi.org/10.1016/j.trd.2019.102203

Neubauer, J., Wood, E., 2014. Thru-life impacts of driver aggression, climate, cabin thermal management, and battery thermal management on battery electric vehicle utility. J. Power Sources 259, 262–275. https://doi.org/10.1016/j.jpowsour.2014.02.083

Pagany, R., Camargo, L.R., Dorner, W., 2019. A review of spatial localization methodologies for the electric vehicle charging infrastructure. Int. J. Sustain. Transp. 13, 433–449. https://doi.org/10.1080/15568318.2018.1481243

Pearre, N.S., Kempton, W., Guensler, R.L., Elango, V.V., 2011. Electric vehicles: How much range is required for a day's driving? Transp. Res. Part C Emerg. Technol. 19, 1171–1184. https://doi.org/10.1016/j.trc.2010.12.010

Plötz, P., Gnann, T., Wietschel, M., 2014. Modelling market diffusion of electric vehicles with real world driving data — Part I: Model structure and validation. Ecol. Econ. 107, 411–421. https://doi.org/10.1016/j.ecolecon.2014.09.021

Quinet, A., Baumstark, L., Centre d'analyse stratégique (France), 2009. La valeur tutélaire du carbone. Documentation française, Paris.

Sathaye, N., Kelley, S., 2013. An approach for the optimal planning of electric vehicle infrastructure for highway corridors. Transp. Res. Part E Logist. Transp. Rev. 59, 15–33. https://doi.org/10.1016/j.tre.2013.08.003

Shareef, H., Islam, Md.M., Mohamed, A., 2016. A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles. Renew. Sustain. Energy Rev. 64, 403–420. https://doi.org/10.1016/j.rser.2016.06.033

Shen, Z.-J.M., Feng, B., Mao, C., Ran, L., 2019. Optimization models for electric vehicle service operations: A literature review. Transp. Res. Part B Methodol. 128, 462–477. https://doi.org/10.1016/j.trb.2019.08.006

Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M.J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J.J. Schauer, D. Sperling, and G. Tiwari, 2014: Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., n.d.

Wang, Y.-W., Wang, C.-R., 2010. Locating passenger vehicle refueling stations. Transp. Res. Part E Logist. Transp. Rev. 46, 791–801. https://doi.org/10.1016/j.tre.2009.12.001

Wiederer and Philip, 2010. Wiederer, A., Philip, R., 2010. Policy options for electric vehicle chargin infrastructure in C40 cities.Transportation Clinton Climate Initiative. [WWW Document]. URL https://www.innovations.harvard.edu/policy-options-electric-vehicle-charging-infrastructure-c40-cities (accessed 4.20.20).

Wood, E., Neubauer, J., Burton, E., 2015. Quantifying the Effect of Fast Charger Deployments on Electric Vehicle Utility and Travel Patterns via Advanced

Simulation: Preprint (No. NREL/CP-5400-63423). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.4271/2015-01-1687
Yang, J., Dong, J., Hu, L., 2017. A data-driven optimization-based approach for siting and sizing of electric taxi charging stations. Transp. Res. Part C Emerg. Technol. 77, 462–477. https://doi.org/10.1016/j.trc.2017.02.014
Zhang, L., Brown, T., Samuelsen, S., 2013. Evaluation of charging infrastructure requirements and operating costs for plug-in electric vehicles. J. Power Sources 240, 515–524. https://doi.org/10.1016/j.jpowsour.2013.04.048
Zhou, Y., Wen, R., Wang, H., Cai, H., 2020. Optimal battery electric vehicles range: A study considering heterogeneous travel patterns, charging behaviors, and access to charging infrastructure. Energy 197, 116945. https://doi.org/10.1016/j.energy.2020.116945

Appendix A: Techno-economic parameters of the business models

Table 4 Charging tariffs of different operators

	Access fee	P = 7 kW	P = 22 kW	P = 50 kW	Availability on the market	Source
Belib		1 €/hour *	0,022 €/min 0,293 €/min after 1 hour		++	(chargemap, 2020)
Indigo		0,036 €/min	0,036 €/min		+	
Virta			0,218 €/min		-	
Freshmile	2,2 €/event **	0,011 €/min (no access fee)	0,935 €/min after 1 hour		+	
New motion		0,027 €/min	0,053 €/min		+	
EFFIA	4,4 €/event	0,587 €/min	0,587 €/min		+	
Izivia	4,396 €/event	0,053 €/min after 1 hour	0,053 €/min after 1 hour		+	
Electric 55 charging		0,026 €/min			-	
Corri-door	1,452 €/event			0,247 €/min	++	
Seymaborne	0,88 €/event	0,023 €/min	0,068 €/min		-	
Total				0,428 €/min	+	
ZEborne				0,218 €/min	-	
Alizé			0,04 €/min	3,75 €/20 min After, 0,1875 €/min	+	(Alizécharge, 2020)
Unknown 1				5 €/45min		(Groupe Alpha et al., 2018)
Unknown 2			0,06 €/min			
Unknown 3				0,7 €/5min		
*** Sometimes free from 08:00 pm to 08:00 am; ** Sometimes not applicable**						

Table 5 BEV techno-economic parameters

Variables		**Small BEV**	**Medium BEV**	**Large BEV**	**Source**
$\boldsymbol{P_{Type,i}}$	Charging power [kW]	7 kW	22 kW	50 kW	
$\boldsymbol{\eta}$	Efficiency factor [%]		85%		
$\boldsymbol{r_{BEV}}$	Interest rate [%]		3%		(Funke et al., 2019)
$\boldsymbol{T_{BEV}}$	Lifetime [Years]		9.5		(ACEA, 2019)
$\boldsymbol{I_{BEV,veh}}$	Vehicle investment [€]	10480	17600	30930	(Gnann, 2015)
$\boldsymbol{c_{batt,i}}$	Battery capacity [kWh]		*Variable*		
$\boldsymbol{c_{BEV,subsidies}}$	Subsidies [€]		6000€/BEV for c_{batt}≤50 kWh 3000€/BEV for 50 kWh≤c_{batt}≤70 kWh 0€/BEV for c_{batt}>70 kWh		(French Government, 2020)
$\boldsymbol{p_{1kWh}}$	Price of 1 kWh [€/kWh]		150€/kWh		Own sources
$\boldsymbol{aVKT_i}$	Annual Vehicle Km Travelled [km]		*Depends on every BEV profile*		(ENTD, 2020)
$\boldsymbol{c_{BEV,charging}}$	Charging fees [€/hour]	1€/hour	1.5€ for the	2€ for the 1st	(chargemap, 2020)

			1st hour 0.2€/min	hour 0.247€/min	
$cons_i$	Electricity consumption [kWh/km]	0.164 kWh/km	0.201 kWh/km	0.216 kWh/km	(Gnann, 2015)
$c_{BEV,O\&M}$	Operation and Maintenance cost [€/km]	0.021€/km	0.040€/km	0.062€/km	(Gnann, 2015)
$c_{BEV,card}$	Card cost [€/year]	5€/month	5€/month	5€/month	(Wiederer and Philip, 2010)

Table 6 ICEV techno-economic parameters

Variables		Small ICEV	Medium ICEV	Large ICEV	Source
r_{ICEV}	Interest rate [%]		5%		(Funke et al., 2019)
T_{ICEV}	Lifetime [Years]		11		(Funke et al., 2019)
$I_{ICEV,veh}$	Vehicle investment [€]	12600	19480	32980	(Gnann, 2015)
$aVKT_i$	Annual Vehicle Km Travelled [km]		*Depends on every BEV profile*		INSEE surveys
$cons_i$	Fuel consumption [L/km]	0.046 L/km	0.057 L/km	0.071 L/km	(Gnann, 2015)
c_{fuel}	Fuel cost [€/L]		1.518 €/L		(Funke et al., 2019)
$c_{ICEV,O\&M}$	Operation and Maintenance cost [€/km]	0.018€/km	0.048€/km	0.076€/km	(Gnann, 2015)
$LCA_{ICEV,i}$	Life Cycle Assessment [tCO2/ICEV]	21.15	32.1	44.8	(Carbone4, 2018, p. 4)
p_{CO2}	CO2 price [€/tCO2]		100 €/tCO2		(Quinet et al., 2009)

Table 7 Charging infrastructure techno-economic parameters

Variables		Slow charger	Normal charger	Fast charger	Source
	Power of the charger	**7 kW**	**22 kW**	**50 kW**	
r_{CPO}	Interest rate [%]		5%		(Funke et al., 2019)
T_{CPO}	Lifetime [Years]		15		(Funke et al., 2019)
I_{CPO}	Charging infrastructure investment [€]	2500€	4000€	25300€	(Groupe Alpha et al., 2018)
$I_{CPO,Civil\ works}$	Civil works investment [€]	1063€	1063€	1553€	
$I_{CPO,Installation}$	Installation investment [€]	817€	817€	1822€	
$I_{CPO,Grid\ connections}$	Grid connections investment [€]	957€	957€	1611€	
$c_{CPO,subsidies}$	Subsidies [€]	40% of I_{CI}	1500€	1500€	(Advenir, 2020)
$c_{CPO,com}$	Communication cost [€]	100€	100€	100€	(Madina et al., 2016)
$c_{CPO,M}$	Metering and billing cost [€]	188€	188€	188€	(Madina et al., 2016)
$c_{CPO,O\&M}$	Operation and Maintenance cost [€/km]		10% of I_{CI}		Literature
$c_{CPO,elec}$	Electricity cost for the CSO [€/kWh]		0.18€/kWh		(Eurostat, 2020)
YCE_i	Yearly Charged Energy of BEV 'j' [kWh]		*Depends on every BEV profile*		Our study
$c_{CPO,charging}$	Electricity cost [€/kWh] Paid by the driver	1€/hour	1.5€ for the 1st hour 0.2€/min	2€ to access 0.247€/min	(chargemap, 2020)
$c_{CPO,card}$	Card cost [€/year]	5€/month	5€/month	5€/month	(Wiederer and Philip, 2010)

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