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 generally considered a promising solution for reducing greenhouse-gas emissions. Despite increasing sales, techno-economic barriers still hinder their widespread adoption. Market stakeholders are faced with a dilemma to address these barriers, especially in terms of choices that have to be made about car battery capacity and recharging infrastructure investments. While previously considered separately, these choices are not independent and influence car price, recharging speed, and ecological impact. This paper explores various combinations of battery capacity sizes and charging power to define and compare these options. We simulate the needs of 12 scenarios of identical privately-purchased BEVs, by increasing their battery capacity, analyse the owner's and charging operator's cost models before exploring Pareto fronts to conclude with optimal combinations of battery size and charging power, taking into account French urban and rural needs separately. For urban (*rural*) areas, purchasing a 35-50-kWh (*50-kWh)* BEV and deploying 22- and 50-kW chargers (*50-kW*) proves cost-efficient solutions. Policy implications are discussed, and we recommend to revise charging tariffs and pricing methods.

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

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, responsible for 20% of global CO2 emissions, of which 72% are emitted by road transportation, should become emission-free by 2050 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 impact of personal-road transportation because of their non-fossil-fuel dependency (Amjad et al., 2018). As a result, BEVs have attracted much attention, pushing governments to promote this technology as an auspicious solution (Gnann et al., 2018).

In France, PEVs presented only about 2% of total vehicles sales in 2020 (Automobile Propre, 2020). To boost market share, the French government contributed to making EVs more attractive to consumers by offering various subsidies on both national and local scales, tax exemption, free parking, and access to bus lanes to each driver switching to electric mobility. The main subsidy is worth 5000€[1], depending on the vehicle's initial price. Besides, since the lack of charging infrastructure still presents a barrier to growth in the EV market, these authorities boosted the deployment of the infrastructure by both installing more on-street chargers (e.g. Corri-door project (EC, 2013)), and offering up to 50% of the cost of the charger for both private and public usage (e.g. ADVENIR project (Advenir, 2020)).

Although BEV sales have sharply risen in the past years because of these market-booster strategies, its sales remain limited in absolute terms. To reach BEV mass adoption, economic-, psychological-, and comfort-customer concerns are still hindering its expansion due to the vehicle investment, range anxiety of daily and long mobility needs, accessing an available on-street charger, and spending a reasonable monthly-charging time using the public infrastructure.

Eliminating these barriers involves a trade-off: while integrating bigger batteries in cars providing more range could solve the range anxiety concern by conveniently reaching one's

[1] Note that due to COVID19 crisis, and within the framework of the French recovery plan which has a section dedicated to the green transition, the French government recently increased the subsidy up to 7000€/BEV during the last quarter of 2020, according to different rules linked to the purchase price of the electric vehicle, as well as a premium for the reconversion of an old diesel (Service Public, 2020). We will only consider a maximum subsidy of 5000€.

destination, it comes with a higher vehicle-purchasing price. For instance, contrary to large-battery BEV (autonomy of around 450-630 km[3]), purchasing a small-battery BEV will come with the lowest investment, but with a high range-anxiety towards daily-mobility needs due to its limited autonomy (around 75-125 km[2]). Indeed, a large-size BEV could eliminate both daily, and vacations range distress by providing extended autonomy. However, the extra battery will occasionally be used due to the limited number of long-kilometres trips and will not pay off (Funke et al., 2019; Weiss et al., 2014). It is also accompanied by an uncertain environmental impact on society due to the battery life cycle assessment (Cox et al., 2020; Van Mierlo et al., 2017). A high engagement of high-speed charging infrastructure on highways, e.g. Corri-Door or Ionity projects in France, make long-distance travel with BEVs a reality (EC, 2013; Ionity, 2021). If one wants to keep purchasing prices low by integrating smaller batteries in the vehicle, thus limiting the impact of battery production, daily-range anxiety can only be addressed by fostering a high penetration of public charging network near accommodation places, with additional investments for the charging operator (Funke et al., 2019; Gnann et al., 2018; Greene et al., 2020).

BEV-purchasing activity faces two customer-related obstacles that depend on the accommodation area. First, higher-kilometres trips are made for rural areas than urban ones, especially under WLTP standards, making the required-BEV range diverse between these two neighbourhoods (7 km/day for Paris versus 135 km/day for Ambérieu-en-Bugey) (ENTD, 2019; INSEE, 2008). Secondly, today 90% of recharging events are done at home (AVERE, 2020) with a so-called private charger, which reveals obstacles that are now almost insurmountable for a category of customers who cannot install an at-home private charger. Private charger installation depends on the accommodation type if private parking is available and thus the area (22% of households occupied by private parking in Paris versus 70% of households occupied by private parking in Ambérieu-en-Bugey). Indeed, these customers, living in rural or peri-urban areas, are dependent on their cars due to the lack of alternative transport, such as public transportation facilities. Switching from ICEV to BEV reveals anxious towards these drivers for several reasons during their everyday trips (home-work, school-home, home-shopping): limited BEVs range, restricted availability of public charging infrastructure, which comes with various charging powers that adopt diverse charging tariffs and pricing methods, and the waiting time to access an on-street charger, especially during peak hours.

2 Ranges are measured using the Worldwide Light vehicles Test Procedures (WLTP) standards

These customers, which can be seen as BEVs late adopters, face a massive dilemma for daily trips: their battery range by limiting their investments and the obligation to use the on-street charging network. Withdrawing BEVs laggards' obstacles could ensure the massive penetration for all categories of BEV drivers.

Besides, the question of adaptability between battery capacity and charging power transfers a simple-unitary transaction for the automotive manufacturer (one car, one battery) into complicated and costly-shared infrastructure investment, since charging operators have to deploy various power chargers to fill the needs of all-sizes BEVs. Indeed, destination recharging comes with another purely technical dilemma: Battery size influences charging infrastructure since not all vehicles are adapted with all charging powers (Electric Vehicle Database, 2021). For instance, contrary to bigger-battery BEVs that could be charged using all-power chargers, small-battery ones are only compatible with slow charging power and rarely suitable with fast charging technology. Therefore, our question is highly correlated with the interactions of the BEV ecosystem stakeholders. Figure 1 presents the goals of the three main stakeholders: car manufacturers (OEMs), charging point operators (CPOs), and customers, each of which seeks to maximize their utility (Kley et al., 2011; Madina et al., 2016), and the scope of the study. OEMs' objective is to maximize their revenues, especially BEVs, while respecting car emissions regulations (Mock, 2019). The customer's dual goals are to minimize purchase and operating costs, the waiting time to access an on-street charger, and the time spent charging the vehicle. The CPO aims to deploy the optimal number of chargers and minimize investment and operating costs while considering various chargers of different powers that do not share the same investments, technical characteristics, and services (Madina et al., 2016). Since these members of the BEV ecosystem's goals are often antagonistic, it is crucial to determine which combination of battery capacity and recharging network investment is the most cost-efficient for each, the customer and the CPO, given that OEM sales will increase if no more barriers are facing the customers.

While determining the optimal battery size of BEVs and optimizing the charging network have received widespread attention in the literature, the implication that battery size influences - charging powers combinations has rarely been considered and reveals complexity. First, this question is highly individual and depends on the driver's needs and behaviour, which is strongly variant towards countries or within the same country based on the urbanization level.

Second, a solution to this question should ensure both the BEV customer and the charging point operator's profitability, considering their adversary interests.

To answer the battery sizes and charging power combinations question, this article will analyse and compare BEV owner purchasing and usage costs, considering French government subsidies and environmental taxes, on the one hand, and CPO investment and operational costs, taking into account French government subsidies and real-market charging tariffs, on the other hand. The cost and revenue models we computed are based on the Equivalent Annual Cost (EAC) method, i.e. the cost of owning, operating, and maintaining an asset over its entire lifetime (Funke et al., 2019). The EAC method is appropriate here since BEVs and charging infrastructure do not share identical lifetimes nor own, operate, and maintain costs, and which EAC calculations allow integration with one calculation. Besides, since the choice is highly individual, we applied this cost comparison methodology by considering cluster areas: we took two typical examples of urban -Paris- and rural -Ambérieu-en-Bugey- French areas, which differ in their socio-economic characteristics, such as population density.

To sum up, this article assesses the trade-off between bigger batteries and more chargers, with various relevant and novel contributions by:

i) Considering several input data for the costs models, namely:
   a. Spatial analysis in terms of French urban- and rural-mobility needs and availability of at-home chargers.
   b. Considering technical constraints, regarding the combinations of battery size and charger speed, based on their BEV-socket compatibility. We also address a sensitivity analysis of the mix of the BEV-charger compatibility.

ii) Concluding with several innovative deductions:
   a. Addressing the two main cost EAC models of the BEV ecosystem: BEV customer and charging point operator.
   b. Concluding about profitable, win-win solutions for both parties, based on the Pareto optimum.
   c. Discussing policy implications for the whole BEV ecosystem: the automotive industry, the charging operator, and the government.

Our results suggest that the optimal overall investment strategy seems to favour investment in charging infrastructure rather than bigger batteries, especially for 22 kW chargers (among 7 and 50 kW). Based on Pareto fronts, purchasing a 35-50 kWh BEV for an urban area *-versus 50 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 as well as charging operators.

Our paper is structured as follows: Section 2 presents the literature review. Section 3 discusses the methodology and, in Section 4, the data and the techno-economic parameters. The results of the study are presented in Section 5. The conclusion, discussion, and policy recommendations are drawn up in Section 6.

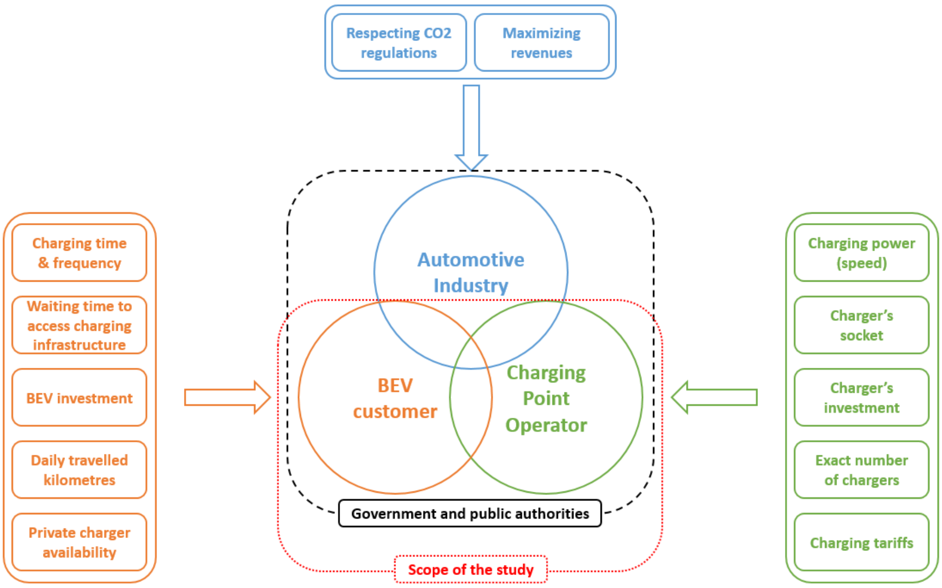

Figure 1 Battery Electric Vehicle Ecosystem

2. Literature Review

The current literature on electric vehicle recharging can be divided into four main streams. The first estimates the drivers' needed range. Secondly, the determination of the optimal battery capacity is elaborated. Thirdly, a group of publications investigates the deployment of charging infrastructure. Lastly, the fourth stream compares the investment in both technologies.

2.1. Estimating BEV Range

A first stream of the literature has focused on determining the appropriate battery capacity to satisfy customer transportation requirements. The question is challenging, as range requirements can move with social and driving behaviours changes, requiring a large dataset of trips for many drivers over a long period, such as surveys and questionnaires at a national scale, data on long-mileage trips, and GPS-based trips.

The first source uses large databases from data for daily trips using surveys and questionnaires, including national travel surveys. Zhang et al. (2013) used a dataset of 20,295 privately owned vehicles in California 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, using only at-home charging. Similarly, Zhou et al. (2020) conducted a stated preference survey in Beijing to estimate the different recharging behaviours of two clusters of BEV drivers in Beijing. They concluded that a 300-miles BEV could cover 90% of the drivers' travel demands, while a 100-mile BEV can satisfy 80% of the drivers.

The second group of articles is based on survey data of long-mileage trips. Since data on BEV trips are still rare, especially for long-distance trips, Weiss et al. (2014) used statistical mobility surveys: the German Mobility Panel study on individual car mileage and fuel consumption, and the long-distance travel survey INVERMO, from which they concluded that only 16% of private vehicle data exceeded the mileage of 100 km for 1-4 days a year, concluding with the unnecessity of a bigger range than 100 km.

The last group of publications used GPS-based data of trips. 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 to 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 that after analyzing the trips by 317 ICEVs over one year, 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 battery's optimal range would be 158 km, based on 412 cars and GPS data for 384,869 individual trips while maximizing GHG savings. Overall, this stream shows that range requirements are low for most of the population and uses (a 60-150 miles BEV could satisfy the needs of a large group of drivers), but that diversity exists depending on geographical origin and exceptional trips.

2.2. Determining The Optimal Battery Capacity

Determining the optimal battery[3] capacity for a BEV is subjected to technical (battery technology, charging power), economic (the price of the battery pack), and drivers' behaviour (needed range and at-home charger availability) factors (Mies et al., 2018). First, as technical factors, the battery is mainly dependent on two factors: the Voltage (V) and the current in Ampere (A), of the vehicle, the charging infrastructure, and the adaptability between the BEV and the charging socket, due to a variety of charging powers and sockets that are not compatible with all BEV types (Yong et al., 2015). Therefore, determining the optimal battery size rely on adequate charging power. Second, the battery size is linked to the BEV cost and could affect the driver's willingness-to-pay. The price of one battery pack is experiencing a downward trend: from 1037€/kWh in 2010 to 150€/kWh in 2020 (Groupe Renault, 2020). Thirdly, as elaborated in Section 2.1., sizing the battery capacity relies on the drivers' needed range and the availability of at-home charging, and the tolerated charging duration if using the public charging infrastructure. While bigger battery capacity will provide extended autonomy, it comes with a higher purchasing cost for the driver and long charging duration if using slow chargers.

Based on these factors, a driver, who has an at-home charger and drives for short distances, is more likely to purchase a small-battery BEV than a large one, limiting the purchasing price. Therefore, determining the optimal battery capacity is subjected to a trade-off between the BEV's purchasing cost, the charging duration, and the charging power.

2.3. Deployment of Charging Infrastructures

According to the international standard IEC-61851, different charging powers are available. The slowest charging speed is Mode 1, mainly installed at home, with a power of 3-7 kW using AC[4], and costs 2500€/charger. Mode 2 chargers, which power is 7-22kW at AC, found in public-parking spaces (such as parking lots or streets), costs 4000€/charger. The mode 3 charger, which is around 25000€, operates at up to 50kW in DC, is installed on public-parking spaces. Finally, ultra-fast chargers or Mode 4 operate at powers above 50kW using DC, and are generally installed on corridors (highways). Its price is around 40000€/charger. It should be

[3] We consider that the BEV battery is a lithium-ion one.
[4] 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.

noted that every charging power has its own charging tariffs and pricing method (circutor, 2020).

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 charging operator's costs (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). In determining the optimal location of recharging network locations, various optimization methods have also been considered (Pagany et al., 2019; Shareef et al., 2016; Shen et al., 2019).

While we have learned a great deal about optimal recharging network properties, these studies generally only focus on the charging infrastructure geo-localization while ignoring or holding constant data related to the BEVs, such as the battery capacity or autonomy. Since some BEVs are not compatible with fast charging technologies, battery capacities have a substantial impact on range requirements as well as charging speeds, our insight into the appropriate deployment of recharging infrastructure is likely to require a simultaneous consideration of both battery specifications and recharging network characteristics, which is the focus of the following stream of literature.

2.4. Comparison of Investments in Both Technologies

The comparison between deploying charging infrastructure and increasing battery capacity has only received scarce attention in the literature. Jabbari and Mackenzie (2017) examined the trade-off between DC fast-charging facilities, BEVs using a theoretical queuing model, and the cost of charging-infrastructure deployment. They concluded that high reliability of recharging-network access and a high utilization rate of charging stations could be achieved by installing many 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 deploying more fast-charging infrastructure. Indeed, analyzing the effects of these deployment scenarios would require a greater understanding of both the nature of driving and charging behaviours.

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-mileage 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 expanding the fast-charging infrastructure for doubled and tripled BEVs battery size. They concluded that the investments in only fast charging infrastructure (50 and 150 kW chargers) are low compared to larger batteries due to the high price of a 1 kWh battery pack (350€/kWh). While (Funke et al., 2019) made significant improvements in this field, questions remain regarding socio-techno-economic assumptions.

First, various 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 7-22 kW chargers due to their non-compatibility with fast charging technology, others can use all types of charging powers, mostly BEVs with battery capacity higher than 50 kWh. Furthermore, since the extended part of the BEV range is occasionally used (Funke et al., 2019), the question of the trade-off between battery capacity and charging infrastructure cost comparison for daily needs, such as home-work trips, has not elaborated in the literature. Also, none of the papers considered real charging tariffs from operators on the market. Lastly, the question of the optimum battery capacity or the optimum deployment of charging infrastructure was only studied with a focus on one single actor, either society as a whole, the charging operator, or the BEV customer, neglecting the fact that their interests may be antagonistic, and only a small number of solutions to this trade-off could be profitable for all actors in the BEV ecosystem using the Pareto optimum. This paper aims to close these research gaps and study the trade-off between bigger batteries and various power chargers' availability for drivers.

3. Methodology

This paper 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; Plötz et al., 2014)'s methodology.

As illustrated in Figure 3, we simulated 12 scenarios of 5,000-identical BEVs, taking into account their daily trips' needs to determine their energy demands (Section 3.1). We increased the battery capacity by 5 kWh from a scenario to another. Based on the BEVs' energy demands, 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 aimed to identify an optimal balance of costs, considering costs and benefits for the customer and the CPO. To find responses, we compared the BEV customer and the charging operator's cost models before concluding profitable solutions for both parties based on Pareto fronts (Section 3.3). In what follows, we offer a more detailed description of these methodological choices.

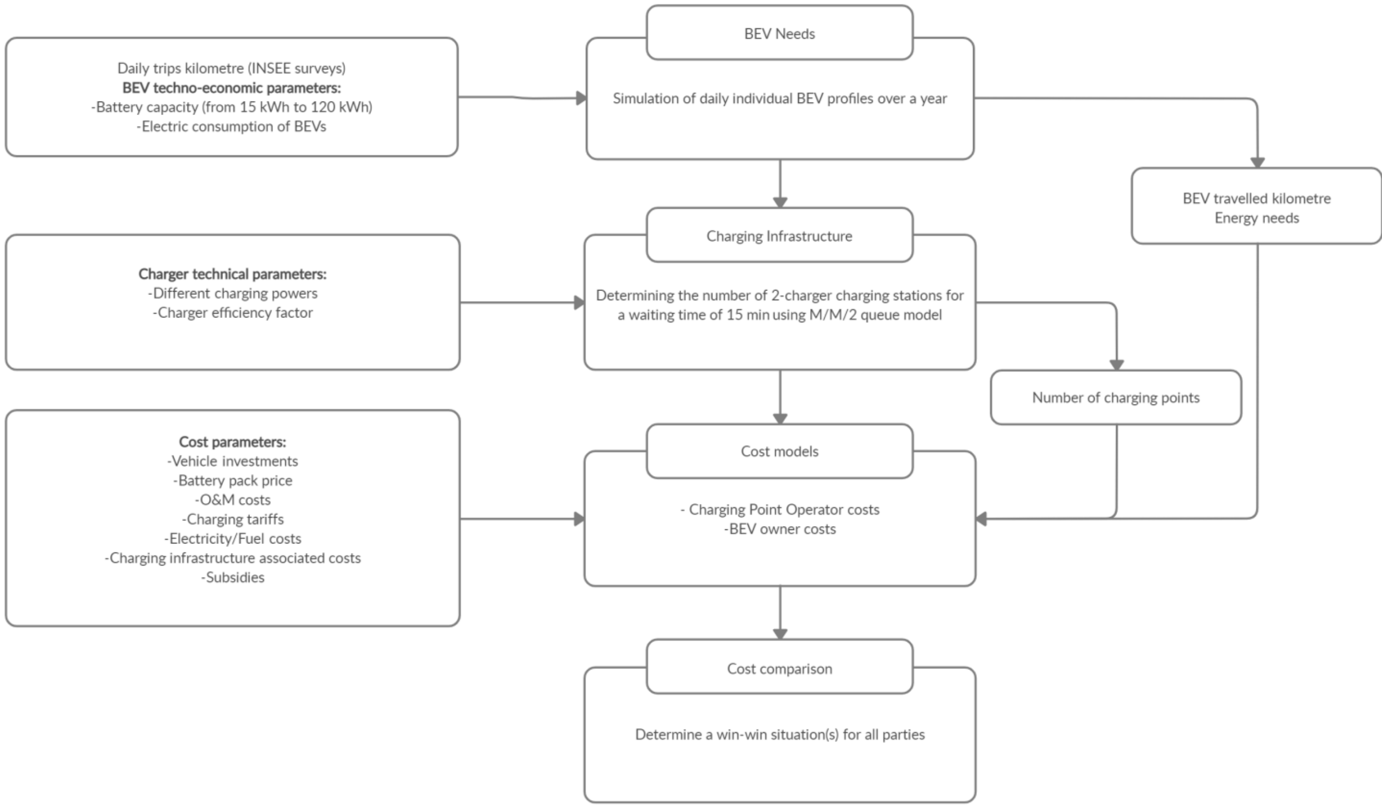

Figure 2 Model overview

3.1. Modelling the BEV Charging Needs

We used data from several sources to estimate the BEVs energy needs in urban and rural areas separately. Twelve scenarios of 5,000 individual-identical private BEV profiles each were simulated based on their daily trips travelled kilometres to determine the energy needs over one year. We then increased the battery capacity by 5 kWh from a scenario to another.

Note we focused on BEVs used for private transport and excluded BEVs used for professional transport such as taxis or delivery vans. To determine WLTP needs, a conversion factor from real to WLTP standards was used for daily home-work-home trips. This conversion factor, which will be elaborated in the data section, differs from the driving speed. For instance, driving on the highway requires a higher speed than in cities; thus, higher energy is needed for the same distance. Besides, a random initial State of Charge (SoC) is given to all BEVs. 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 of the battery should always stay between 20% and 80%, leading to a higher lifetime of the battery (Redondo-Iglesias et al., 2019). The SoC is then calculated, taking into account technical parameters such as energy consumption (c_i^e), the kilometres travelled of the next day (VKT), and a normal distribution variable (a) (Equation 1). After simulating all the BEV driving profiles and determining the number of charging stations that could fill the BEVs' energy needs, we determine the yearly charged energy for 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 the default 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 an at-home charger and then will not use public infrastructure. Since the accommodation type differs from the urbanity degree, we consider two values for drivers who will access the public charging infrastructure: one for each urban and rural areas. Therefore, fewer drivers will have access to the public charging infrastructure rather than in urban areas. And:

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

Where:

- $i = 1, \ldots, N$ is the driving profile
- j is the day
- c_i^e the energy consumption, c_i^{batt} the battery capacity of the BEV ‘i’

3.2. *Modelling the Charging Infrastructure Demand*

As mentioned in Section 2.3., different charging powers are available. In our study, we consider that every BEV size segment will charge at the maximum speed level. Therefore, a BEV with a battery capacity of less than 20 kWh will use a 7 kW charger; those between 20 kWh and 45 kWh will use a 22 kW charger non-compatibility with fast charging technology. With a battery capacity higher than 50 kWh, BEVs 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. Chargers with a power higher than 50 kW chargers could be found on highways and are mainly used for long-distance trips, i.e., vacation trips, to ensure the minimum charging time during the trips.

The need for charging infrastructure is deduced from the previous steps based on BEVs' daily energy. Then, we determine the number of charging stations to be installed to cover the demand based on a queuing model. On the one hand, users want to find a vacant CP 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 (Gnann et al., 2018).

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 realistically consider 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). Finally, we identified for every battery-capacity scenario a specific average arrival rate.

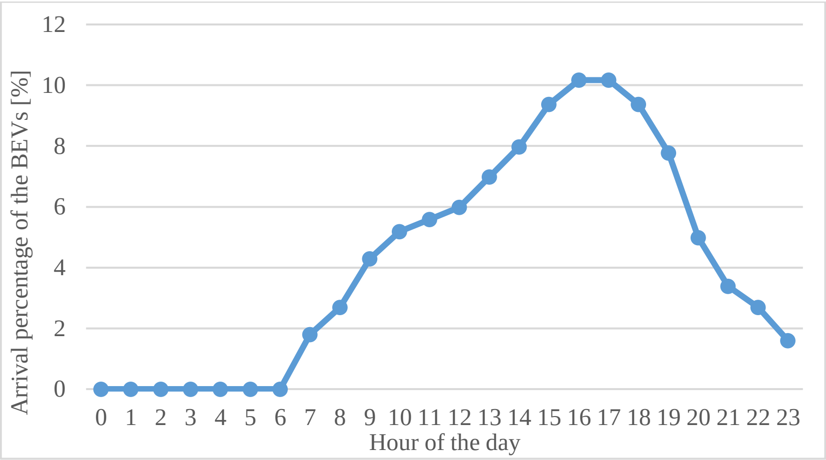

Figure 3 BEV arrival percentage

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 quality of service, we ensure that users' waiting time remains limited. Therefore, the average waiting time ($W_q^{M/M/2}$) of 15 minutes maximum was applied to determine the number of stations for every charging power. For more information on queuing models, 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 Equivalent Annual Cost (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 Cost Model of the BEV Customer

Regarding the cost 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).

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

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 (in the case of BEV), annual operating and maintenance costs that differ for every driving profile due to the individual $aVKT_i$, and charging or refuelling costs as noted in (Gnann, 2015; Plötz et al., 2014). While registration taxes for ICEVs are determined based on the vehicle's CO2 emissions, $LCA_{ICEV,z}$ in Equation 3, (French Property, 2020), BEVs are exempted from these taxes. Note there is no battery cost, subsidy, or subscription fee to access a conventional vehicle's charging infrastructure. Table 1 details the parameters of Equation 3, and all the values are presented in Appendix A.

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

Where:

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

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

Table 1 Techno-economic parameters of EAC_{VEH}

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

3.3.2. Charging Point Operator Business Model

Before detailing the business model, we assume 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, based on a benchmark of charging operators in Appendix A, that these firms use 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:

- $i = 1, \dots, N$ is the CP

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. Furthermore, operation and maintenance costs, electricity expenses (per kWh consumed), and communication costs are added to the business model. Regarding the revenues, we consider government subsidies the operator receives for installing new charging stations, as well as revenues from the BEV customer per charging event and a subscription fee. Table 2 details the parameters of Equation 5, and values are presented in Appendix A.

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

Where:

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

Table 2 Techno-economic parameters of EAC_{CPO}

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

4. Data and Techno-Economic Parameters

To determine travelled kilometres, we used data from surveys done by The French National Institute of Statistics and Economic Studies (INSEE, 2008), which provides the travelled kilometres during the weekends (e.g. 25 km for a Saturday, and 20 km for a Sunday). We used additional data on daily home-work trips were reported by (ENTD, 2019) for regular home-work trips per town. The vehicle-travelled kilometre per day is 32 km/day for urban areas compared to 135 km/day for rural areas. These "real" kilometres were converted into WLTP autonomy-scale by multiplying them using a factor: 0.75 for city trips, 1 for roads, and 2 for highways since higher energy is required for highway trips than for city trips. 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 (ENTD, 2019; INSEE, 2008). Figure 5 presents our two case studies.

Since a comparison between a BEV and an ICEV is made for the driver, we should compare the same vehicle type. Thus vehicles were divided into three sizes depending on their battery capacity, and detailed in Appendix A (Tables 4 and 5). These parameters include energy consumption (electricity for BEV and fuel for ICEV), vehicle cost (without the battery), operation and maintenance costs, and life cycle assessment. Our study assumed that vehicle ownership duration 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 (Groupe Renault, 2020), 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)[5].

The CPO's EAC 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 charger price, communication costs are 100€ per

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

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 infrastructure is 5%.

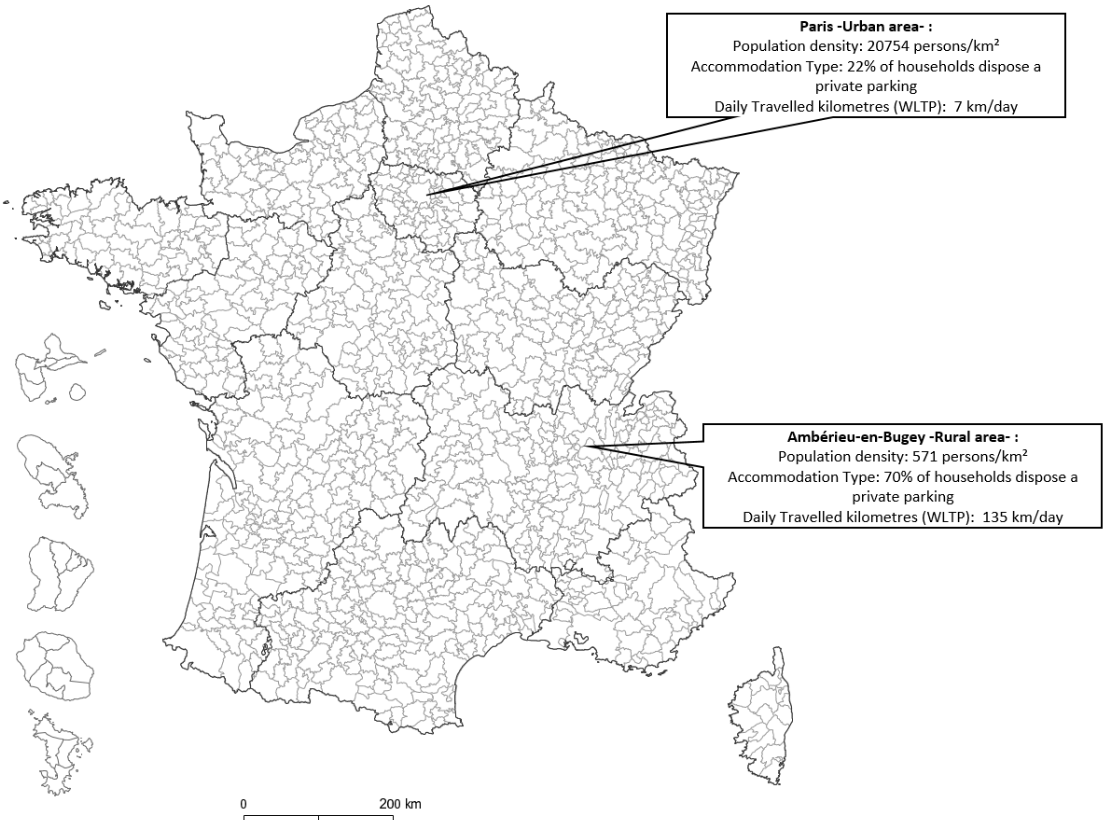

Figure 4 Urban and Rural case studies areas

5. Results

Results relating to identifying 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 5.1). Second, we quantify the number of charging stations (Section 5.2).

Third, results compare the investments in both technologies and detail the cost models of the various BEV market parties (Section 5.3).

5.1. Individual Driving Profiles

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: daily travelled kilometre (ENTD, 2019; 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 are on average 35 km/day for urban needs and 135 km/day for rural needs. The travelled kilometres during weekends fluctuate between 18 and 23 km for Saturdays, and between 26 and 33 km for Sundays. 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).

Also, to calculate each BEV's needs, we consider the driver will not charge her 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. Since rural drivers travel higher distances than urban drivers, BEVs with a battery capacity between 15 kWh and 35 kWh were excluded, for the rural case study, due to their limited autonomy.

5.2. Charging Infrastructure Demand

As mentioned earlier in this paper, some BEVs are not compatible with fast charging technology. For this reason, as mentioned in Section 3.2., we consider that every BEV size segment will charge at the maximum speed level. Figure 3 presents how many BEVs an available CP could serve: it shows that the more the charging power, the less the need for charging infrastructure. For the same charging power, increasing the battery capacity also increases the required number of chargers. Indeed, larger battery BEV will less frequently stop to charge. However, since the BEV will charge from 20% to 80% at one event, it will take more time than smaller battery capacity BEVs. In order to respect the 15 minutes maximum waiting time constraint, the number of chargers, having the same power, increases with bigger battery capacities.

Furthermore, since a higher percentage of drivers could install private chargers at home in rural areas than in urban areas, results show that one CP can serve more BEVs in urban areas than in rural ones; thus, fewer deploying charging needs infrastructure by comparing the two areas. Regarding the urban needs, on average, one 7 kW CP can serve up to 18 small-battery BEVs per day, one 22 kW CP up to 46 medium-battery BEVs per day, and one 50 kW CP up to 80 large-battery BEVs per day. In rural needs, one 22 kW CP can serve up to 8 medium-battery BEVs per day, and one 50 kW CP up to 26 large-battery BEVs per day.

Altogether, we concluded that having more BEVs with a bigger battery increases the need for charging infrastructure when holding charger speed constant. However, if we compare different charging powers' results, it is clear that the need for charging infrastructure becomes lower for a 50 kW charger than 22 kW and 7kW chargers. Currently, deploying charging infrastructure is based on technical factors and neglects some psychological factors such as range anxiety, due to the limited data. Indeed, range anxiety, which will lead to higher charging frequency towards the drivers, could conduct a higher number of CPs.

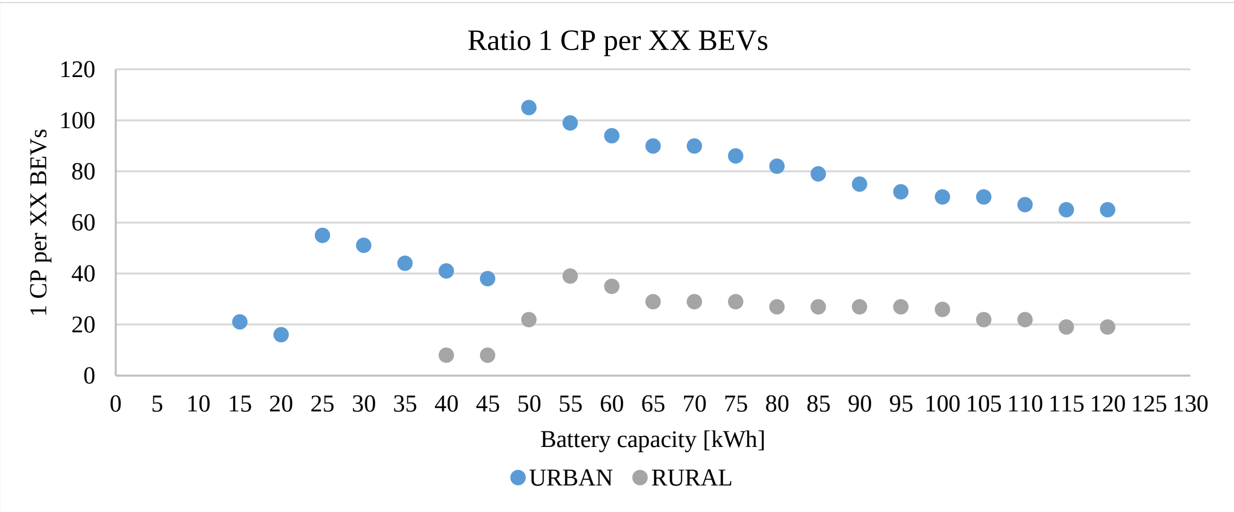

Figure 5 Number of BEV that use one CP as a function of battery capacity

5.3. Costs Models

In order to understand the cost implications of the trade-off between bigger batteries and charging stations, we compare their respective investments for the BEV customer on the one hand and the CPO on the other hand, and seek to determine the most cost-efficient solution for both parties using the Pareto optimum.

5.3.1. Investments Comparison of Bigger Batteries and Charging Infrastructure

We compared the investments of adding 50 and 100 km of autonomy (battery capacity), 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 higher battery capacities are higher than those in CPs 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.

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 small–battery BEVs' limited autonomy. 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 range 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 CPs, 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.

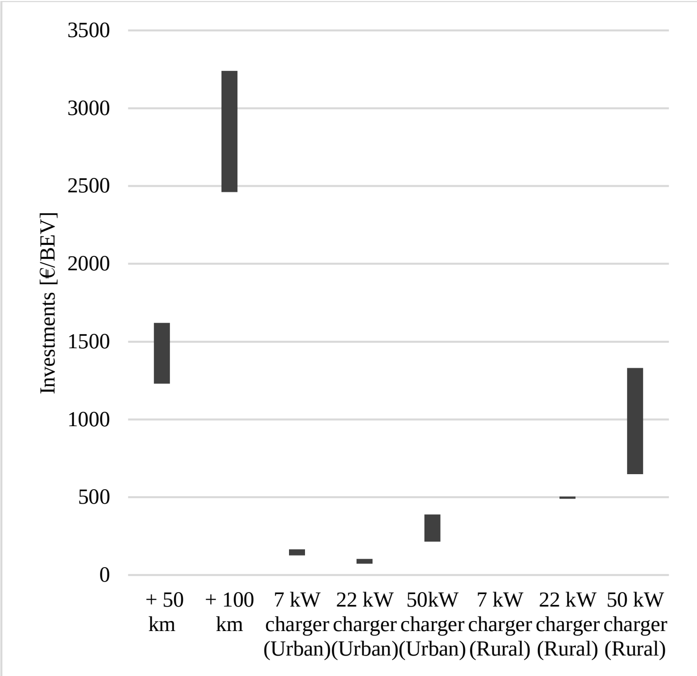

Figure 6 Range of investments for extending the range of BEVs vs. those in charging infrastructure

5.3.2. The Cost 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 a battery capacity of 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 40-50 kWh vehicle is cost-efficient for the driver since $\Delta EAC < 0$. The autonomy of 40 to 45 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, the solution is highly individual. Regarding the most cost-efficient solution, a 50 kWh BEV does not only come with the lowest costs (ΔEAC=-1,030 €/BEV/Year) but also with reasonable charging durations (12hours/month). A 55-65 kWh BEV would satisfy drivers' driving needs, willing to eliminate the risk of limited autonomy, and 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). On the contrary, several choices could be interesting for the driver for rural needs based on his/her daily trips. Yet, the less risky solution is 55-65 kWh BEV with the required autonomy and a minimum ΔEAC.

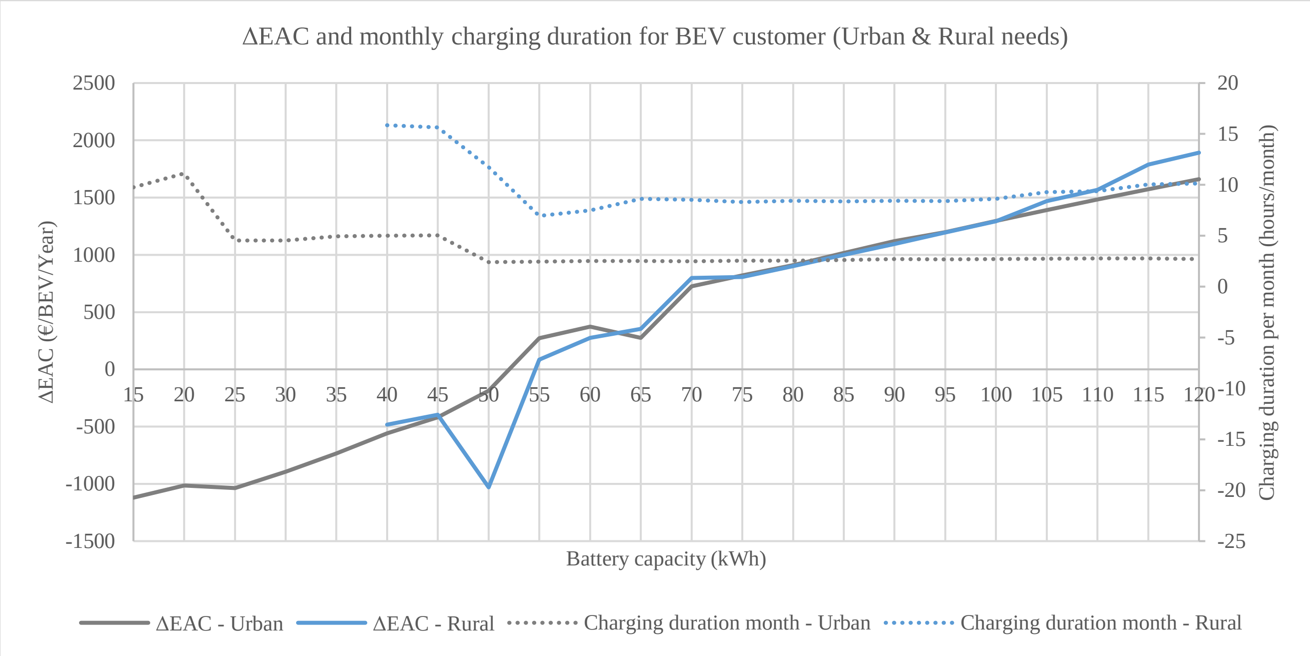

Figure 7 The cost model and the monthly charging duration for the BEV customer

5.3.3. The Business Model of the Charging Point Operator

We calculated the EAC of the whole infrastructure in both urban and rural areas regarding the CPO. Results are given in Figure 6. As a reminder, we consider that 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.

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 25 and 30 kWh battery capacity 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, charging durations exceeding 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 generates profits for the operator, especially for the 50 kWh case. These results underline 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 research should consider revising charging tariffs, especially for 7 kW and for the first hour of 22 kW chargers.

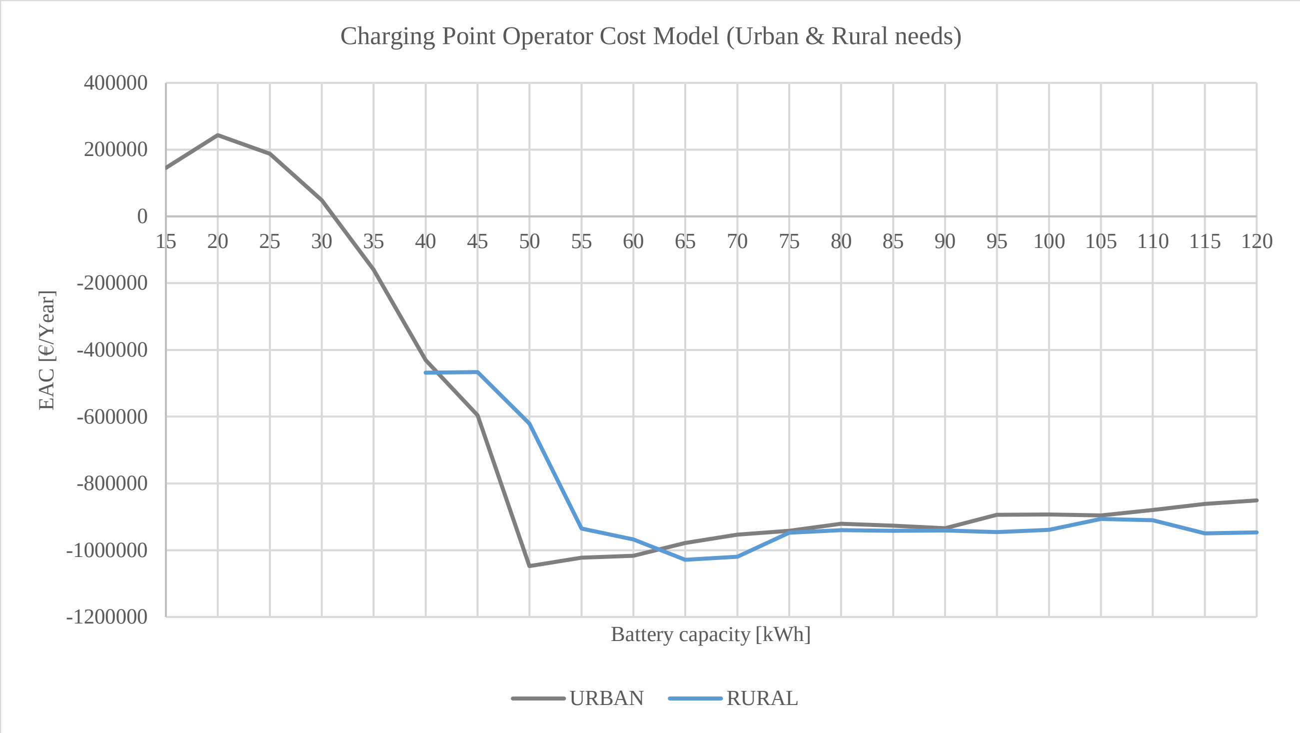

Figure 8 The cost model of the CPO

5.3.4. Win-Win Situations

After detailing the cost models of the driver and the charging pont operator, we will represent all the solutions found, based on the Pareto fronts solutions, where none of both parties realizes a loss, i.e. $\Delta EAC_{BEV\ customer} < 0$ and $EAC_{CPO} < 0$. Regarding the urban needs, a Pareto front is presented by different solutions: 35-45 kWh BEV and deploying 22 kW chargers; or 50 kWh BEV and deploying 50 kW chargers. Similarly, a Pareto optimum solution is found for the rural case study: a 50 kWh BEV and 50 kW chargers, which comes with the lowest costs for the driver and the charging operator's highest profits. A solution for drivers willing to eliminate range anxiety is a 55-65 kWh BEV and deploying 50 kW chargers. Yet, it does not present an optimum solution.

5.4. Sensitivity Tests

We apply three sensitivity tests to explore how charging behavior changes and charging pricing methods would affect our results. 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.

5.4.1. 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 chargers' usage with the battery sizes and disassociating battery size and charger power. 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 though some BEVs are not compatible with fast charging technology). Results show that the customer's benefits and those of the operator are antagonistic, but in line with our conclusions (Figures 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 50 kWh BEV presents the pareto optimum solution for the customer and the operator simultaneously. Yet, the battery size choice is highly individual and will depend on the driver's daily trips.

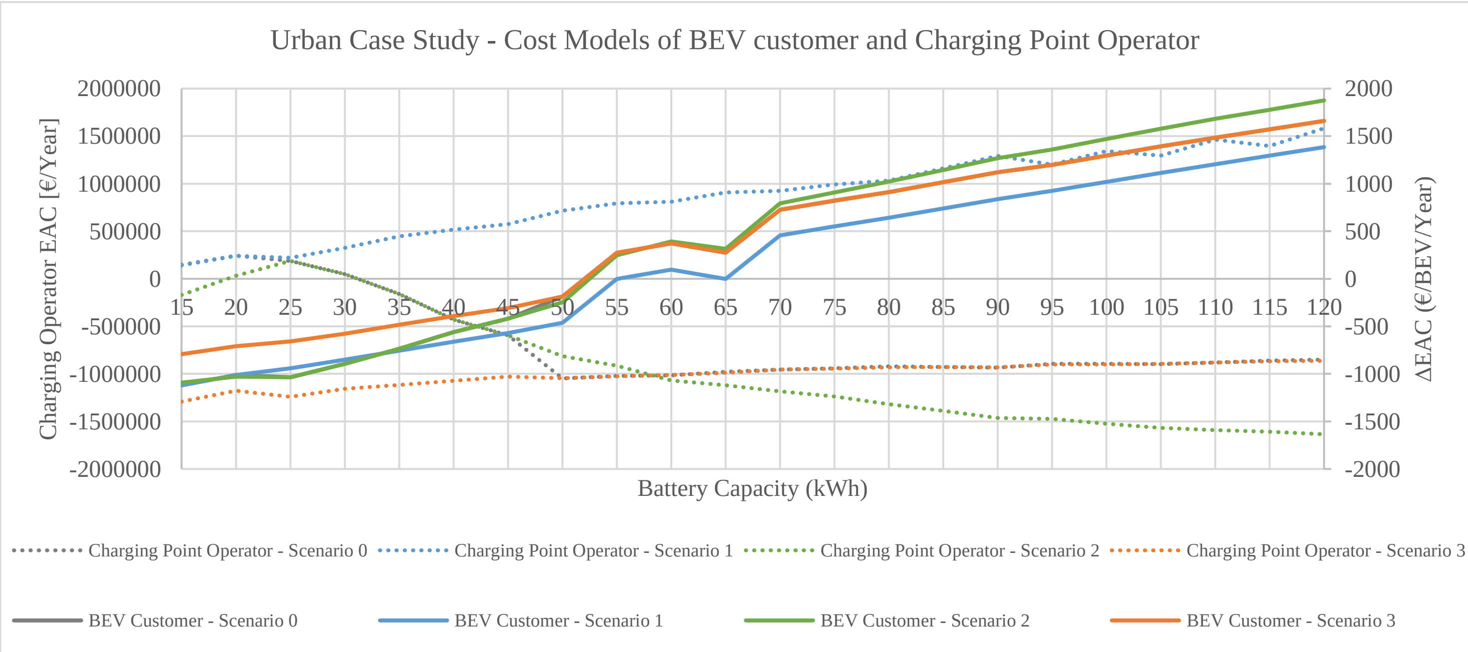

Figure 9 Sensitivity test 1 results on the urban case study

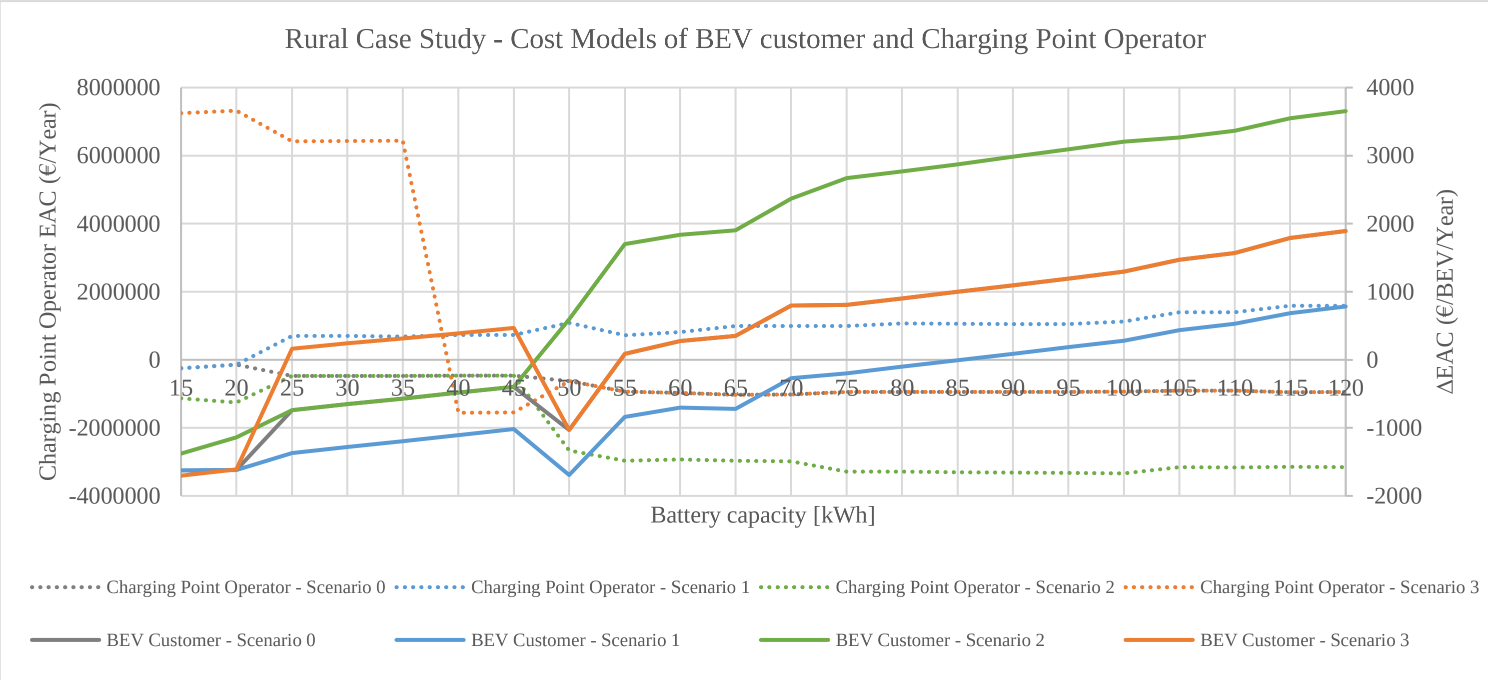

Figure 10 Sensitivity test 1 results on the rural case study

5.4.2. 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, represented in Figure 11, are in-line with our conclusions in terms of battery capacity and charging power combinasions. Besides, results show that Scenario 0 pricing method (Table 8) ensure profitability of the charging services: 22 kW chargers using "per exceeded minute" pricing method) and 50 kW chargers using "an access fee + per minute".

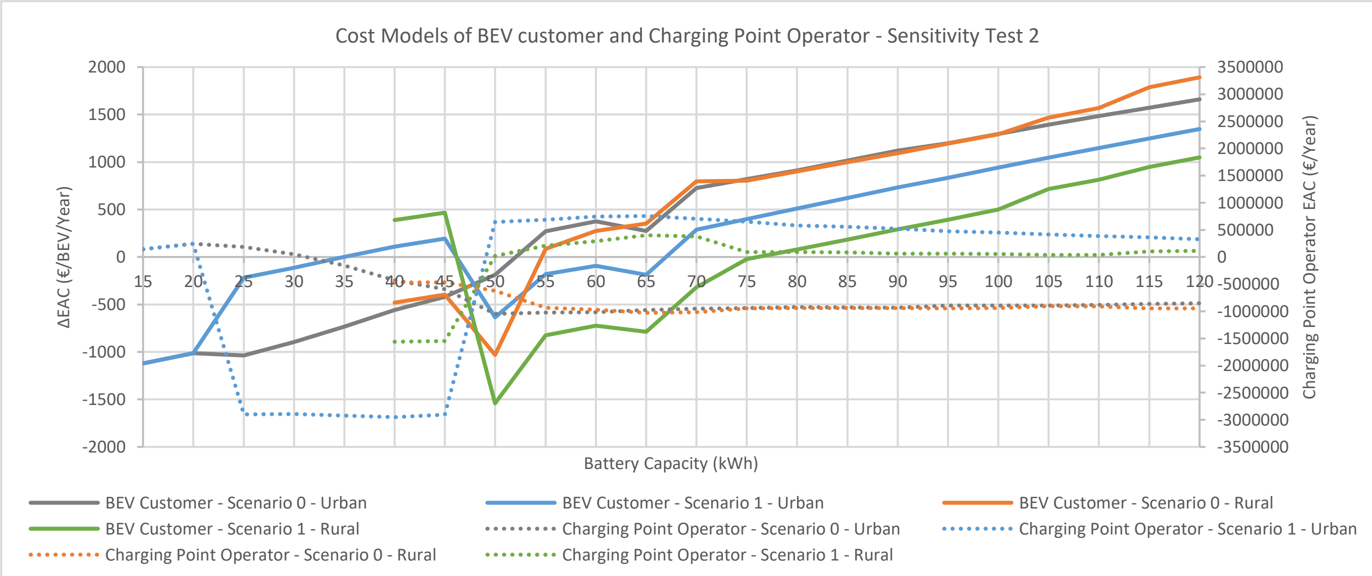

Figure 11 Sensitivity test 2 results

5.4.3. 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). The rural case study results show a 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 highly demand elastic, BEV customers could change their driving behaviour. It is then recommended that operators review the charging tariffs and consider the driver's point of view towards similar variations.

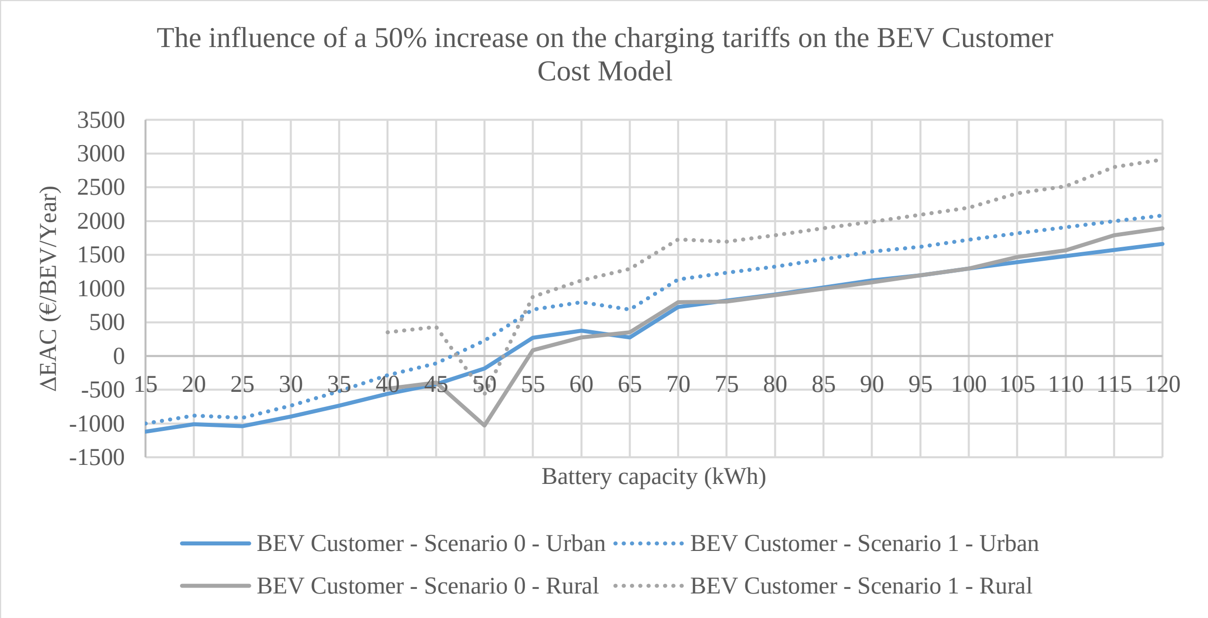

Figure 12 Sensitivity test 3 results on the BEV customer

6. Conclusion and Policy Recommendations

6.1. Conclusion

To reach global ambitions regarding GHG emissions, achieving growth in BEV market share is of paramount and necessary importance. Range anxiety, a primary barrier to BEV adoption, could be solved using two interdependent and complementary options: increasing the battery capacity and/or enlarging the charging network. This study presents a novel approach to answer the issue by calculating the EAC of different battery capacity and recharging infrastructure development scenarios. We modelled public infrastructure usage by simulating 5,000 privately purchased BEVs, taking into account their daily driving needs for urban and rural French areas scenarios and neglecting long-mileage trips (e.g. vacations), while limiting the BEV cost. 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 EVs using 22 kW chargers, and large-battery EVs 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 charger's power, and thus on the battery capacity. Our outcomes demonstrate that the battery capacity and CPs are correlated since the charger usage depends on the battery size.

After detailing and comparing the different cost models of the BEV ecosystem parties, the analyses for urban needs showed that 35 kWh to 50 kWh BEVs with 22 and 50 kW chargers are 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 50 kWh BEV use 50 kW chargers, which comes with a minimum positive ΔEAC, using a fixed pricing method: a fee for access tariff per minute charged.

Although our model's design 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. Therefore, we applied several sensitivity tests 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 sensitivity tests results 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, or other activity centres, malls, 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. When simulating BEV profiles, we neglected comfort parameters such as heating, cooling, lights, radio, and data that may increase BEVs' energy demand. 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. We did not consider external parameters such as the land price in the operator’s business model, due to the no-spatial model and the wide variety of these prices. Overall, it is vital to use real-world data that reflect BEV drivers' driving and charging behaviours, 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.

6.2. Policy Recommendations

Based on our analysis results, this paper provides policy recommendations for the BEV ecosystem members: the automotive industry, the charging operator, and government and public authorities.

First, car manufacturers should consider various models for different customer categories, especially those willing to limit their BEV investment. More 35-50 kWh BEVs should be advertised in urban areas, contrary to minimum 50 kWh BEVs in rural areas. These sizes present a dual solution for the drivers: limited cost and reasonable monthly charging durations.

Second, charging operators should consider deploying more 22 and 50 kW chargers. Besides, since each battery size is compatible with a specified charging power, results showed that profitability is correlated with the pricing method. Based on our sensitivity tests, we suggest to apply per exceeded minute pricing for 22 kW charging services, and access fee and per-minute pricing for 50 kWh charging services.

Finally, providing additional subsidies for 22 and 50 kW chargers could encourage charging operators to install more of these powers, especially that a 50 kW charger comes with a high cost.

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Appendix A: Techno-economic parameters of the cost 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		++	(chargemap, 2020)

			0,293 €/min after 1 hour			
Indigo		0,036 €/min	0,036 €/min		+	
Virta			0,218 €/min		-	
Freshmile		0,011 €/min (no access fee)	1.5€ for the 1st hour. 0,2 €/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	2 €/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**						

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		(Groupe Renault, 2020)
$\boldsymbol{aVKT_i}$	Annual Vehicle Km Travelled [km]		*Depends on every BEV profile*		(ENTD, 2019)
$\boldsymbol{c_{BEV,charging}}$	Charging fees [€/hour]	1€/hour	1.5€ for the 1st hour 0.2€/min	2€ for the 1st hour 0.247€/min	(chargemap, 2020)
$\boldsymbol{cons_i}$	Electricity consumption [kWh/km]	0.164 kWh/km	0.201 kWh/km	0.216 kWh/km	(Gnann, 2015)
$\boldsymbol{c_{BEV,O\&M}}$	Operation and Maintenance cost [€/km]	0.021€/km	0.040€/km	0.062€/km	(Gnann, 2015)
$\boldsymbol{c_{BEV,card}}$	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**
$\boldsymbol{r_{ICEV}}$	Interest rate [%]		5%		(Funke et al., 2019)
$\boldsymbol{T_{ICEV}}$	Lifetime [Years]		11		(Funke et al., 2019)
$\boldsymbol{I_{ICEV,veh}}$	Vehicle investment [€]	12600	19480	32980	(Gnann, 2015)
$\boldsymbol{aVKT_i}$	Annual Vehicle Km Travelled [km]		*Depends on every BEV profile*		INSEE surveys
$\boldsymbol{cons_i}$	Fuel consumption [L/km]	0.046 L/km	0.057 L/km	0.071 L/km	(Gnann, 2015)
$\boldsymbol{c_{fuel}}$	Fuel cost [€/L]		1.518 €/L		(Funke et al., 2019)
$\boldsymbol{c_{ICEV,O\&M}}$	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)