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

4 Bassem Haidar^{1,2,*}, Pascal da Costa², Jan Lepoutre³, Fabrice Vidal¹

5 ¹Groupe PSA, Route de Gisy, Vélizy-Villacoublay, 78140, France

6 ²Université Paris-Saclay, CentraleSupélec, Laboratoire Genie Industriel, 3 rue Joliot-Curie
7 91190 Gif-sur-Yvette, France

8 ³ESSEC Business School, 3 Avenue Bernard Hirsch, 95021 Cergy-Pontoise, France

9 ^{*}Corresponding author

10 **Abstract**

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

30
31 **Keywords: Battery range, Charging infrastructure, Electric vehicles, Innovative business model,**
32 **Techno-economic scenarios**

1 **Highlights**

- 2 1. Each battery size is compatible with a dedicated charging power speed. And bigger battery
3 capacity will always require more charging stations compatible.
- 4 2. We show benefits of the BEV customer and those of charging operator are antagonists.
- 5 3. 35-50 kWh BEV and deploying 22-50 kW chargers is the cost-efficient solution for urban
6 needs.
- 7 4. 65 kWh BEV and deploying 50 kW chargers is the cost-efficient solution for rural needs.
- 8 5. Future reviews of charging tariffs and pricing method is recommended.

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1 **1. Introduction**

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

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

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

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

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

16 Results show cheaper investments in charging infrastructure, especially 22 kW chargers,
17 rather than in bigger batteries. For urban (*for rural*) areas, purchasing a 35 to 50 kWh BEV
18 (*65 kWh BEV for rural*), and deploying 22 and 50 kW chargers (*50 kW for rural*), prove the
19 most cost-efficient and profitable solutions for both BEV owners and charging operators.

20 The paper is structured as follow: Section 2 presents the literature review. Section 3 discusses
21 the methodology, the data, and the techno-economic parameters. The results of the study are
22 presented in Section 4. The conclusion, discussion and future works are drawn up in Section
23 5.

24 **2. Literature Review**

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

29 2.1. Optimal Battery Capacity for a BEV

30 Determining the exact need for autonomy requires a large dataset of trips, for a large number
31 of drivers, over a long period of study. This is because the travelled kilometres could change
32 with social and driving behaviours changes. The publications used three primary sources as

1 input data: surveys, data on long-mileage trips, and GPS-based trips. The first source uses
2 large databases from surveys and questionnaires at a national scale. (Zhang et al., 2013) used
3 the Californian dataset of 20,295 privately owned vehicles travelling 83,005 single daily trips
4 or 7.85 trips each, from the 2009 National Household Travel Survey (NHTS). They found that
5 88% of the trips could be operated using a BEV with a 60-mile range (approx. 97 km), taking
6 into account only at-home charging. Similarly, (Zhou et al., 2020) conducted a stated
7 preference survey, and analyzed its data using the Latent Class model to predict the different
8 recharging behaviours of two clusters of BEV drivers in Beijing. They concluded that a range
9 of 300 miles (approx. 483 km) is needed to cover the travel demands of 90% of the drivers,
10 while a 100-mile (approx. 161 km) range battery is able to satisfy the need of 80% of the
11 drivers.

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

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

30 2.2. Deployment of Charging Infrastructures

31 The question of charging station locations has been extensively studied in the literature.
32 Research has focused on optimizing the locations of charging infrastructure based on various

1 objectives: minimizing the cost (Yang et al., 2017), minimizing the travelled distance
2 (Sathaye and Kelley, 2013), maximizing the coverage (Wang and Wang, 2010), minimizing
3 failed trips (Alhazmi et al., 2017), minimizing the distance between demand and charging
4 sites (Sathaye and Kelley, 2013). Various optimization methods are elaborated in the state-of-
5 the-arts that reviewed spatial localization methodologies for the electric vehicle charging
6 infrastructure (Pagany et al., 2019; Shareef et al., 2016; Shen et al., 2019).

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

11 2.3. Comparison of Investments in Both Technologies.

12 The comparison between deploying charging infrastructure and increasing battery capacity is
13 rarely studied in the literature. (Jabbari and Mackenzie, 2017) examined the trade-off between
14 DC fast charging¹ facilities and BEVs, using a theoretical queuing model, and cost of
15 deployment. They concluded that high reliability of access and high utilization rate of
16 charging stations could be achieved by installing a large number of chargers. (Wood et al.,
17 2015) studied various fast-charging infrastructure deployment scenarios and found that it is
18 more costly to add 100 km to the BEV autonomy than to deploying more fast-charging
19 infrastructure. Indeed, analyzing the effects of these deployment scenarios would require a
20 greater understanding of both the nature of individual trips and charging behaviour.

21 The originality of (Funke et al., 2019)'s study is to combine all the three streams presented
22 above: identification of BEV needs for German long-milage trips, determining the number of
23 needed fast chargers, and comparing both of them, using a techno-economic approach, in
24 order to address this trade-off. They compared the EAC of owning a BEV, and of expanding
25 the fast-charging infrastructure, for doubled and tripled battery size of BEVs. They concluded
26 that the investments in only fast charging infrastructure (50 and 150 kW chargers) are low
27 compared to the investments in larger batteries, due to the high price of 1 kWh battery pack
28 (350€/kWh). While (Funke et al., 2019) made significant improvements in this field,
29 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.

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

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

14 **3. Methodology and Data**

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

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

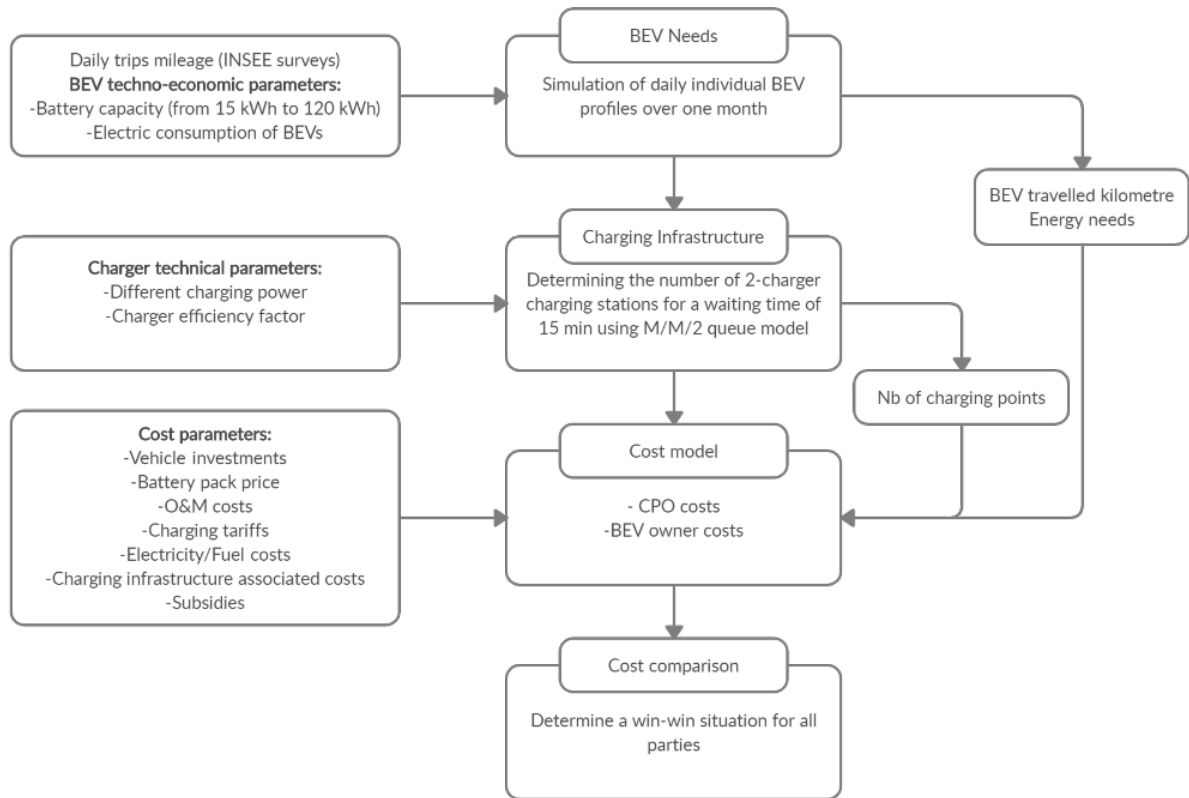


Figure 1 Model overview

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

1 calculated, taking into account technical parameters such as energy consumption (c_i^e), the
 2 kilometres travelled (VKT), and a random variable (a) (Equation 1). After simulating all the
 3 BEV driving profiles, we determine the yearly charged energy every BEV profile for the
 4 twelve scenarios.

5 The present work is focused on the usage of the public charging infrastructure, even though
 6 we cannot neglect private chargers, which are a popular option (according to surveys and
 7 questionnaires, 90% to 95% of BEVs drivers use home charging to fill their battery - TOI,
 8 2018). For our study, we do not consider household having one or more private parking places
 9 for vehicles who installed at home charger and then will not use public infrastructure. Since
 10 the type of accommodation differs with the urbanity degree, we consider two values for
 11 drivers who will access the public charging infrastructure: one for each urban and rural areas.

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

12 Where:

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

15

16 3.2. *Modelling the Charging Infrastructure Demand*

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

24 According to the international standard IEC 61851, the slowest is Mode 1, usually installed in
 25 private homes, which has a power of 3 kW using AC we do not consider in this study. The
 26 power of Mode 2 chargers is between 3 and 22 kW at AC, and they are generally found in
 27 either private homes or private or public parking spaces (such as parking lots). A Mode 3
 28 charger operates up to 50 kW, using DC, and is generally not found in private homes.
 29 Preferably, these charging points are installed in public spaces and parking lots. Finally, ultra-

1 fast Mode 4 chargers operate at powers above 50 kW using DC and are generally installed on
2 inter-city corridors (highways) (Circutor, 2020).

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

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

19 The critical input parameters of a queue are the arrival rate and the service rate. The BEVs
20 arrival rate, λ [#BEVs/hour], is deduced from the number of BEVs that cannot charge at
21 home, and are obliged to use the charging stations. We consider that the BEVs arrival rate is
22 equal on all charging stations, and the stations have two identical chargers ($s=2$). We also
23 consider, just like in reality, that there is no arrival for BEVs to charging stations 00:00 to
24 06:00 am. 62% of the BEVs arrive from 02:00 pm to 7:00 pm, known as peak hours, Figure 2
25 (Groupe Alpha et al., 2018). Besides, we identified for every battery-capacity scenario a
26 specific average arrival rate.

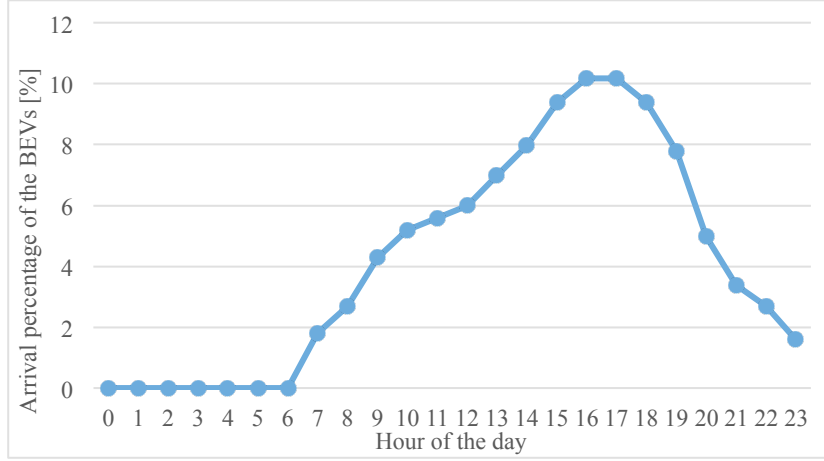


Figure 2 BEV arrival percentage

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 $\eta_{\text{charger}}=85\%$ 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).

$$\Delta EAC_i = EAC_{BEV,i} - EAC_{ICEV,i} \quad (2)$$

1 Equation 3 applies to all types of vehicles, electric or conventional. As shown, it is composed
2 of the sum of amortized investments of the car body and the battery capacity, annual
3 operating and maintenance costs that differ for every driving profile due to the individual
4 $aVKT_i$, charging or refuelling costs and the CO2 emissions cost for ICEVs, as noted in
5 (Gnann, 2015; Plötz et al., 2014). Note there are no battery costs, subsidies, nor subscription
6 fees to access the charging infrastructure for a conventional vehicle. Table 1 details the
7 techno-economic parameters of Equation 3, and all the values are presented in Appendix A.

$$EAC_{VEH,i} = \frac{(1 + r_{VEH})^{T_{VEH}} * r_{VEH}}{(1 + r_{VEH})^{T_{VEH}} - 1} (I_{VEH,z} + c_{batt,i} * p_{1kWh} - c_{BEV,subsidies}) + aVKT_i \quad (3)$$

$$* (c_{VEH,O\&M,z} + c_{VEH,charging}) + c_{BEV,card} + LCA_{ICEV,z} * p_{CO2}$$

8 Where:

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

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

10 - $z = \begin{cases} \text{Small}; & \text{if } c_{batt} \leq 20 \text{ kWh} \\ \text{Medium}; & \text{if } 20 \text{ kWh} < c_{batt} < 50 \text{ kWh} \\ \text{Large}; & \text{if } c_{batt} \geq 50 \text{ kWh} \end{cases}$

11 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]

12

13

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.

$$EAC_{CPO} = \sum_{i=1}^N EAC_{CPO,i} \quad (4)$$

Where:

- $i = 1, \dots, N$ 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.

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

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

1 *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]

2

3 *3.4. Data and Techno-Economic Parameters*

4 To determine the travelled kilometres, we used data from surveys done by The French
5 National Institute of Statistics and Economic Studies (INSEE, 2008), which provides the
6 travelled mileage during the weekends (e.g. 25 km for a Saturday, and 20 km for a Sunday).
7 We used additional metadata on daily home-work trips was reported by (ENTD, 2020) for
8 regular home-work trips per town. The vehicle-travelled kilometre per day is on average 32
9 km/day for urban areas compared to 135 km/day for rural areas. These “real” mileages were
10 converted into WLTP autonomy-scale by multiplying them using a factor: 0.75 for city trips,
11 1 for roads, and 2 for highways (source: Groupe PSA). Generally, the individual-annual
12 kilometre travelled for regular daily trips varies between 7,000 km/year and 12,000 km/year
13 for urban areas and between 12,000 km/year and 42,500 km/year for rural areas.

14 Regarding techno-economic-environmental parameters, vehicles were reported into three
15 sizes depending on their battery capacity. Since a comparison between a BEV and an ICEV is
16 made for the driver, we should compare the same type of vehicle. Therefore, all the
17 parameters of both electric and conventional vehicles are divided into three types and detailed
18 in Appendix A (Tables 4 and 5). These parameters include energy consumption: electricity for
19 BEV and fuel for ICEV, investments (without the battery), operation and maintenance costs,
20 and life cycle assessment. We assumed in our study that the duration of vehicle ownership is
21 9.5 years for both BEV and ICEV (ACEA, 2019). We consider the price of one kWh pack of

1 battery capacity as 150 €/kWh, and the price of 1 tonne of CO₂ as 100€ (Fox et al., 2017;
2 Quinet et al., 2009). A 6,000€ governmental subsidy in France is offered to the BEV customer
3 if the battery capacity is less than 50 kWh. This amount decreases to 3,000 € if the battery
4 capacity is between 50 kWh and 70 kWh, and is cancelled for large BEVs with 70 kWh and
5 more (French Government, 2020)².

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

16 The charging/refuelling tariffs are fixed based on the French market. The fuel cost is fixed as
17 1.518€/l (French Ministry of Economy and Finance, 2020), and the charging pass costs
18 5€/BEV/month. Charging tariffs are set as follow: 1€/hour using a 7 kW charger, 1.5€ for the
19 first hour and 0.2€/minute after the first hour for a 22 kW charger, and 2€ for the access to a
20 50 kW charger, plus a cost of 0.247€/min (Chargemap, 2020). The industrial electricity
21 bought by the charging operator is 0.18€/kWh (Eurostat, 2020). A maximal interest rate for
22 purchasing a BEV or ICEV is 3%, for the charging points is 5%.

23 **4. Results**

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

29 **4.1. Individual Driving Profiles**

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

1 In order to quantify the electric needs of the BEVs, we simulated 12 scenarios of 5,000
2 identical BEVs per scenario, separately for urban and rural case studies. We increased the
3 battery capacity from 15 kWh to 120 kWh from a scenario to another. We modelled the
4 individual driving profiles taking into account socio-technical parameters, namely daily
5 travelled kilometre (ENTD, 2020; INSEE, 2008), and electricity consumption (Gnann, 2015)
6 that vary with the size of the vehicle. The daily travelled kilometres for “home-work-home”
7 trips on weekdays is on average 35 km/day for urban needs and 135 km/day for rural needs.
8 Besides, the travelled kilometres during weekends fluctuate between 18 and 23 km for
9 Saturdays, and between 26 and 33 km for Sundays. Generally, the annual vehicle kilometres
10 travelled for daily purposes vary between 7,000 and 12,000 km for urban needs, and between
11 12,600 and 42,400 km for rural needs. Real travelled kilometres are then converted to electric
12 needs (WLTP) using a factor.

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

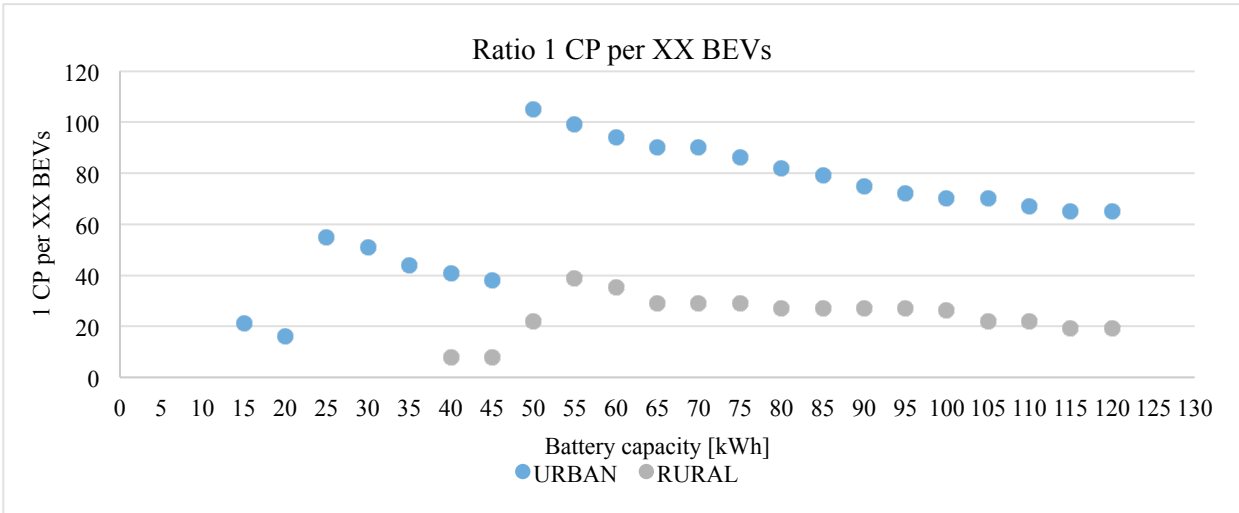
19 4.2. Charging Infrastructure Demand

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

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

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

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



11
 12 *Figure 3 Number of BEV that use one charging point as function of battery capacity*

13 **4.3. Costs Models**

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

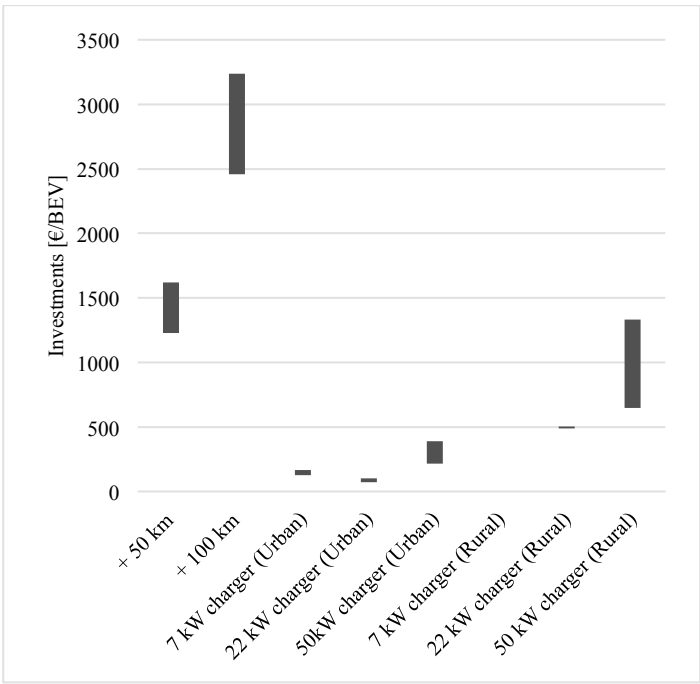
19 **4.3.1. Investments Comparison of Bigger Batteries and Charging Infrastructure**

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

1 At today's battery capacity prices, the cost of adding 50 km of autonomy can vary between
 2 1200€/BEV and 1600€/BEV. Similarly, for a range extension of 100 km, the investments add
 3 up to several thousands of euros (from 2400 €/BEV to 3200€/BEV). The investments in
 4 added autonomy vary between two values given that the electricity consumption of BEVs
 5 increases with bigger battery capacity. The price of one pack of 1 kWh is fixed at 150 €/kWh.

6 Regarding charging infrastructure, associated investments are considered to be equally
 7 distributed across all BEVs. The required investments of 7 kW chargers vary from 125€/BEV
 8 to 165€/BEV for urban needs and do not exist in rural needs, due to the limited autonomy of
 9 small-battery BEVs. Also, the investments of 22 kW chargers vary from 70€/BEV to
 10 105€/BEV for urban needs and between 490€/BEV to 505€/BEV for rural needs. Similarly,
 11 those of 50 kW chargers alter from 240€/BEV to 390€/BEV for urban areas and between
 12 645€/BEV to 1330€/BEV. These investments range between two values given that an optimal
 13 number of charging stations is identified for every battery capacity.

14 Generally, it is cheaper to deploy more charging points, of different powers, than to extend
 15 the BEV range; except for rural needs because adding 5 km to the battery range comes with a
 16 lower cost than deploying 50 kW chargers. Among the three charging powers, lower costs for
 17 22 kW chargers are the cheapest thanks to both limited investments and the number of BEVs
 18 that use one charger.



19
 20 *Figure 4 Range of investments for extending the range of BEVs vs. those in charging infrastructure*
 21

1 4.3.2. The Business Model of the BEV Customer

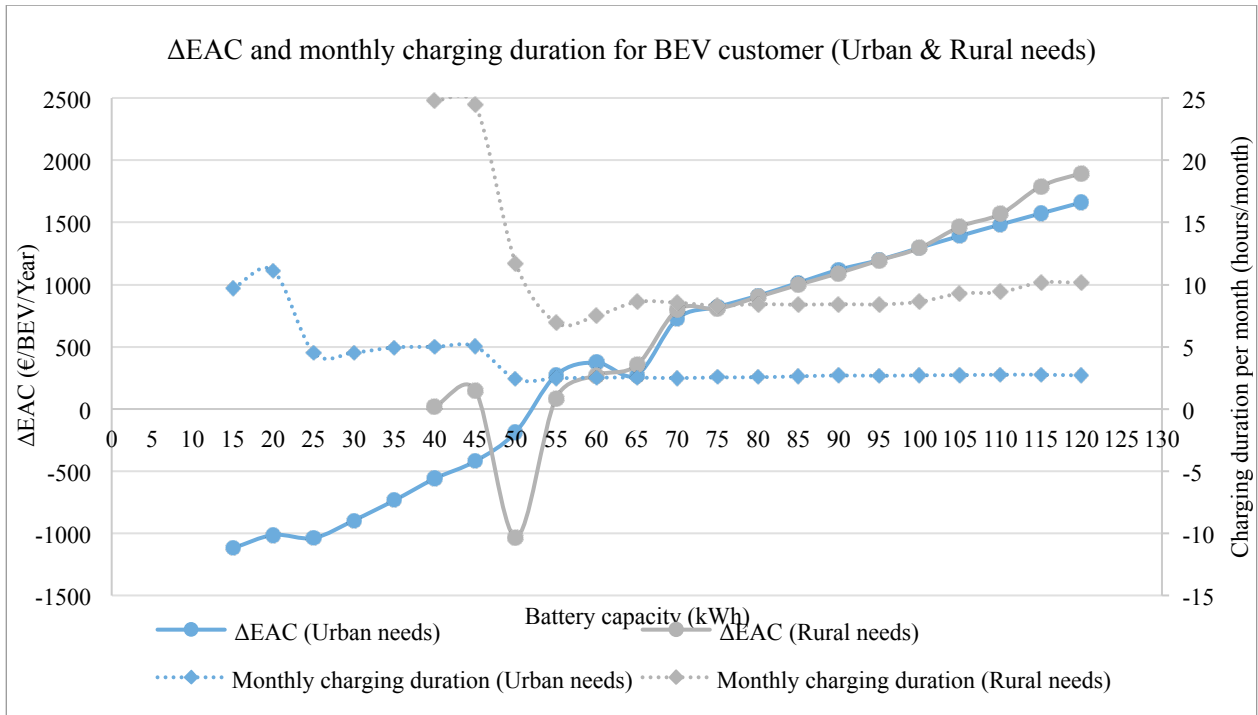
2 From the BEV customer's perspective, we first analyze the difference between the EAC of
3 purchasing a BEV and an ICEV for the customer, hereafter noted as ΔEAC . A positive ΔEAC
4 indicates that a BEV comes with higher costs than an ICEV. Figure 5 indicates the average
5 ΔEAC and the monthly charging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

7 Regarding the urban needs (Figure 5), results show that negative ΔEAC is guaranteed for
8 purchasing a BEV with a battery capacity between 15 kWh and 50 kWh. Indeed, purchasing a
9 15 kWh BEV is the most cost-efficient for the customer (with the lowest ΔEAC : -
10 1120€/BEV/Year). Nevertheless, the driver will spend around 10 hours/month to charge his
11 vehicle. For medium-battery BEV, ΔEAC has a negative value between 35 kWh and 45 kWh
12 while the charging duration fluctuates around 5 hours/month. For large-battery BEV, a 50
13 kWh vehicle comes with a dual-advantage: lower cost than an ICEV (ΔEAC = -
14 105€/BEV/Year) and low charging duration (3 hours/month). BEV with battery capacity more
15 than 55 kWh are not economical for the client (positive ΔEAC), even so the charging duration
16 does not exceed 3 hours/month.

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

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

1 daily trips. Yet, the less risky solution is 55-65 kWh BEV with the required autonomy and a
 2 minimum ΔEAC .



3
4 *Figure 5 The business model and the monthly charging duration for the BEV customer*

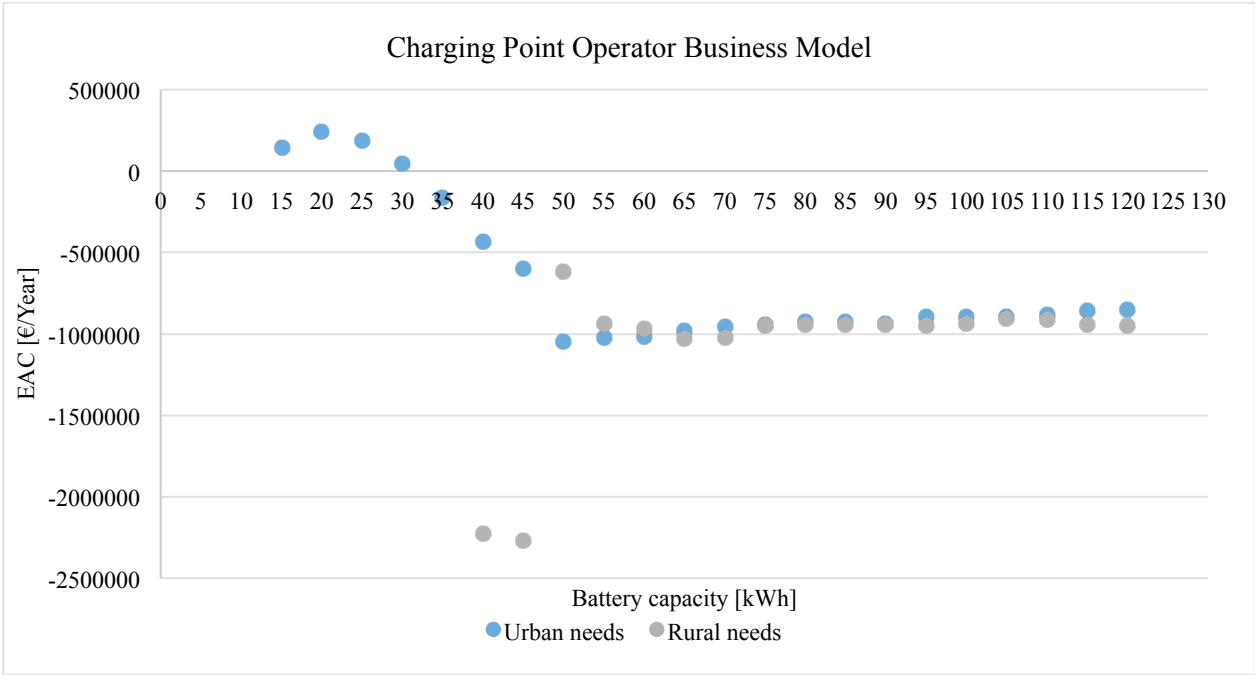
5 **4.3.3. The Business Model of the Charging Point Operator**

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

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

1 Regarding the fast charging infrastructure, the operator generates profits by deploying 50 kW
 2 chargers and based on the used tariffs. It is essential to stress on the fact that the profits
 3 slightly decrease with broader autonomy. Overall, the operator receives profits for a fleet of
 4 35 to 120 kWh BEVs, with a maximum at 50 kWh, because of two main reasons: the 2-hour
 5 charging duration per vehicle and the “per exceeded minute” pricing method. Urban and rural
 6 share the same results.

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



13
 14 *Figure 6 The business model of the Charging Point Operator*

15 **4.3.4. Win-Win Situations**

16 Regarding the urban needs, two solutions could be profitable for the ecosystem: 35-45 kWh
 17 BEV and deploying 22 kW chargers; or 50 kWh BEV and deploying 50 kW chargers.
 18 Similarly, for rural needs, we conclude with two solutions based on the driver’s daily
 19 travelled kilometres. The first one is a 50 kWh BEV and deploying 22 kW chargers, that does
 20 not only come with the lowest costs for the driver but also with the highest profits for the

1 charging operator. This choice could be risky for some drivers due to limited autonomy.
2 Therefore, the second safe choice is a 55-65 kWh BEV and deploying 50 kW chargers.

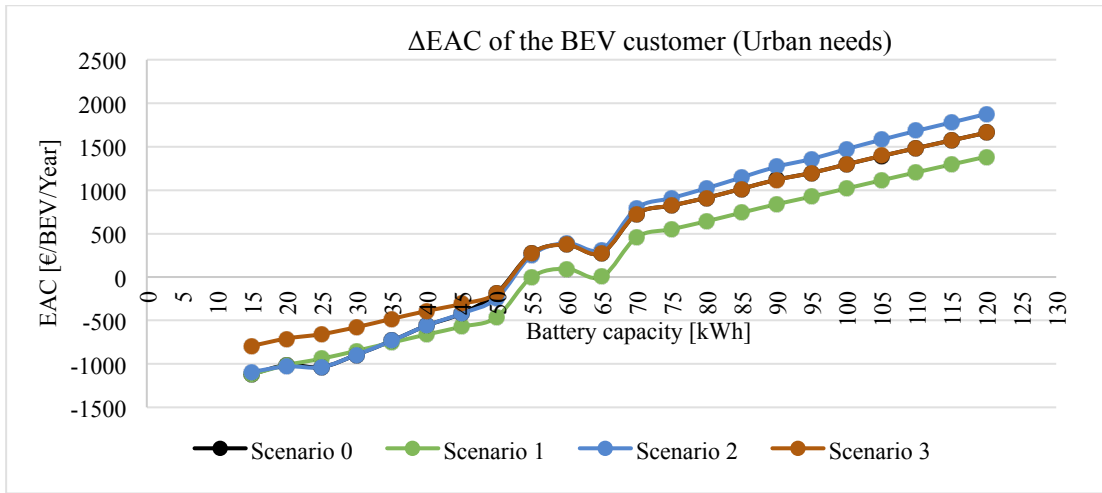
3 4.4. Sensitivity tests

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

9 4.4.1. Mixing the charging powers and the BEV battery size

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

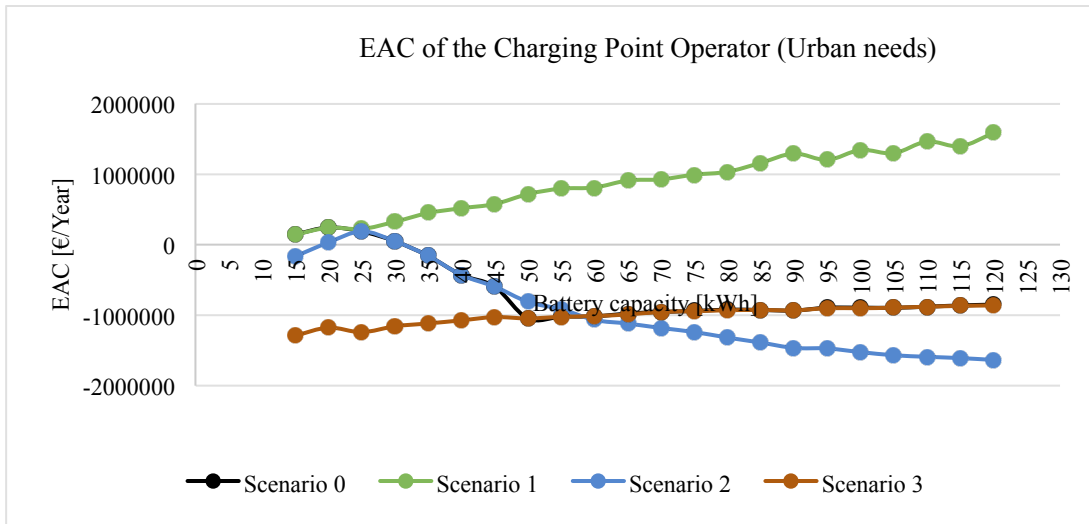
20 Regarding the rural needs, a 40-65 kWh BEV presents a win-win solution for the customer
21 and the operator at the same time. The choice of the battery size will depend on the driver's
22 daily trips.



1

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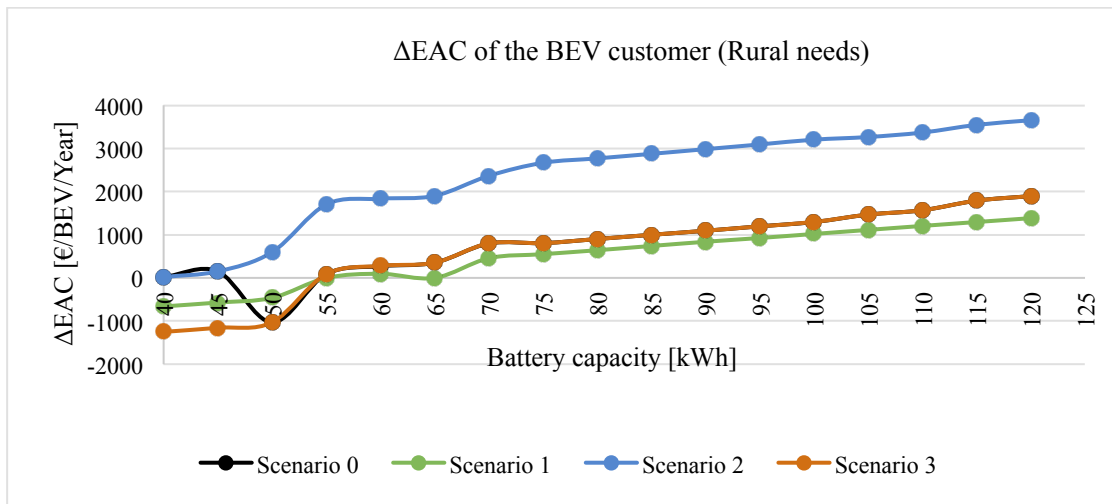
Figure 7 Sensitivity test 1 results on the BEV customer for urban needs



3

4

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



5

6

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

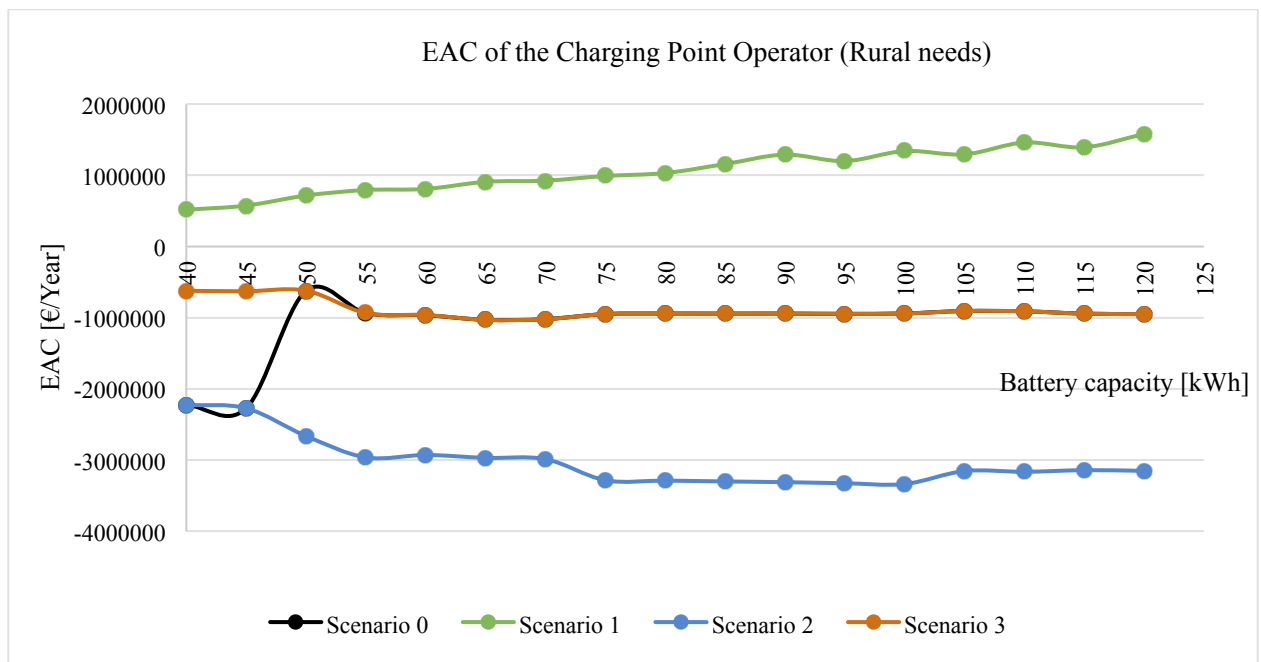


Figure 10 Sensitivity test 1 results on the charging point operator for rural needs

4.4.2. Changing the Pricing Methods

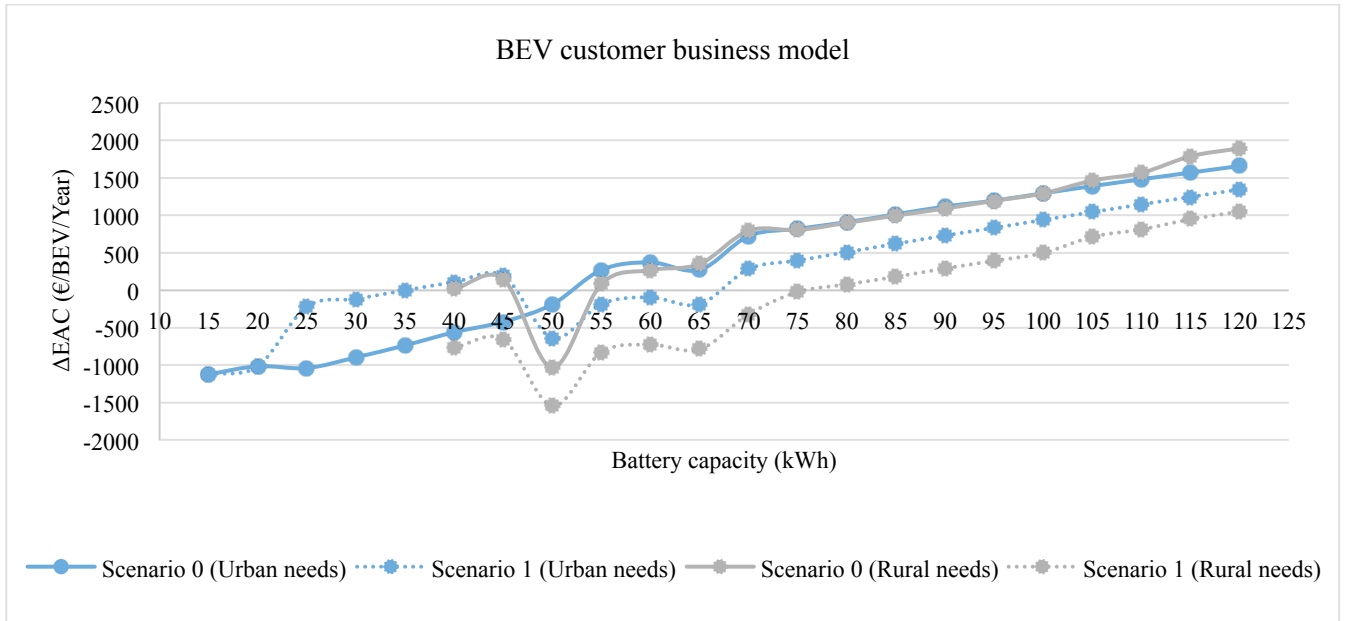
Different pricing methods are available on the market: a tariff per hour, a fixed tariff for the first hour and every exceeded minute, and an access fee to the charging station and per minute (Appendix A Table 1). For robustness, we changed the pricing method for medium and large-battery BEVs. The scenarios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

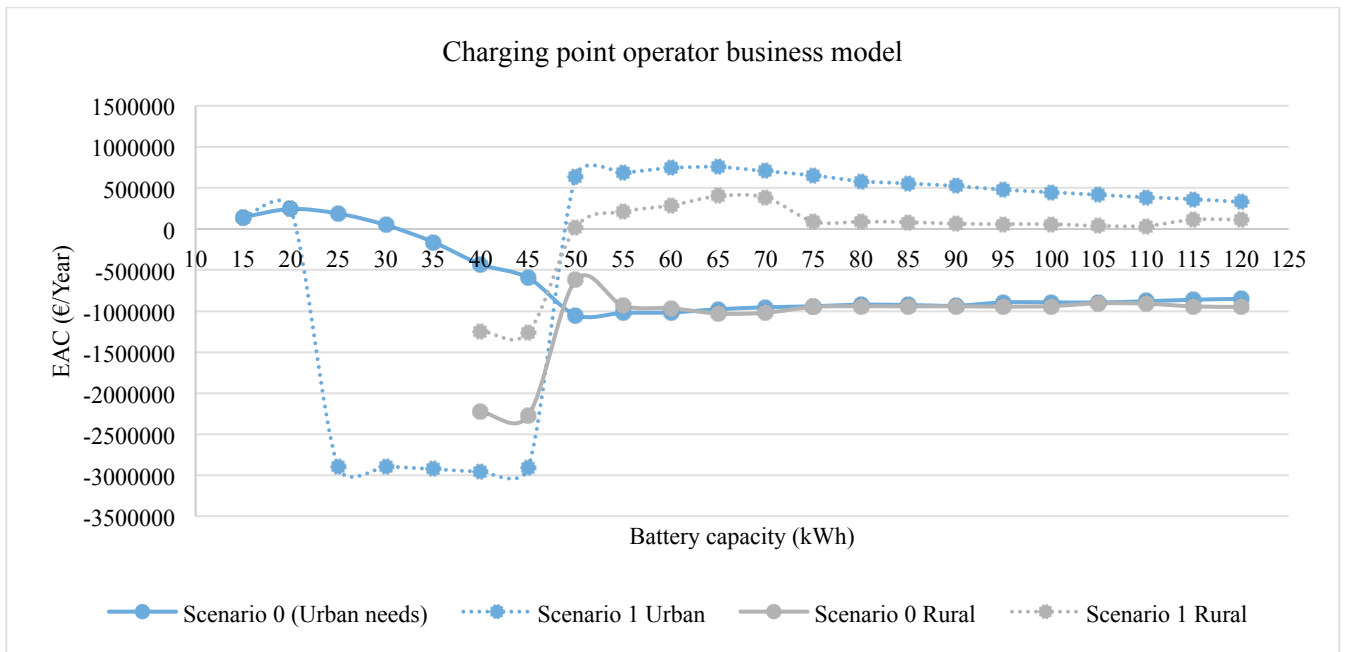
- 1 For rural needs, no conclusion could be drawn, since no win-win situation is detected.
- 2 Therefore, we share the same solution as elaborate in Section 4.3.3. We recommend as future
- 3 studies, to investigate about a profitable solution for both BEV customer and charging
- 4 operator for the rural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



5

6

Figure 11 Sensitivity test 2 results on the BEV customer



7

8

Figure 12 Sensitivity test 2 results on the charging point operator

9

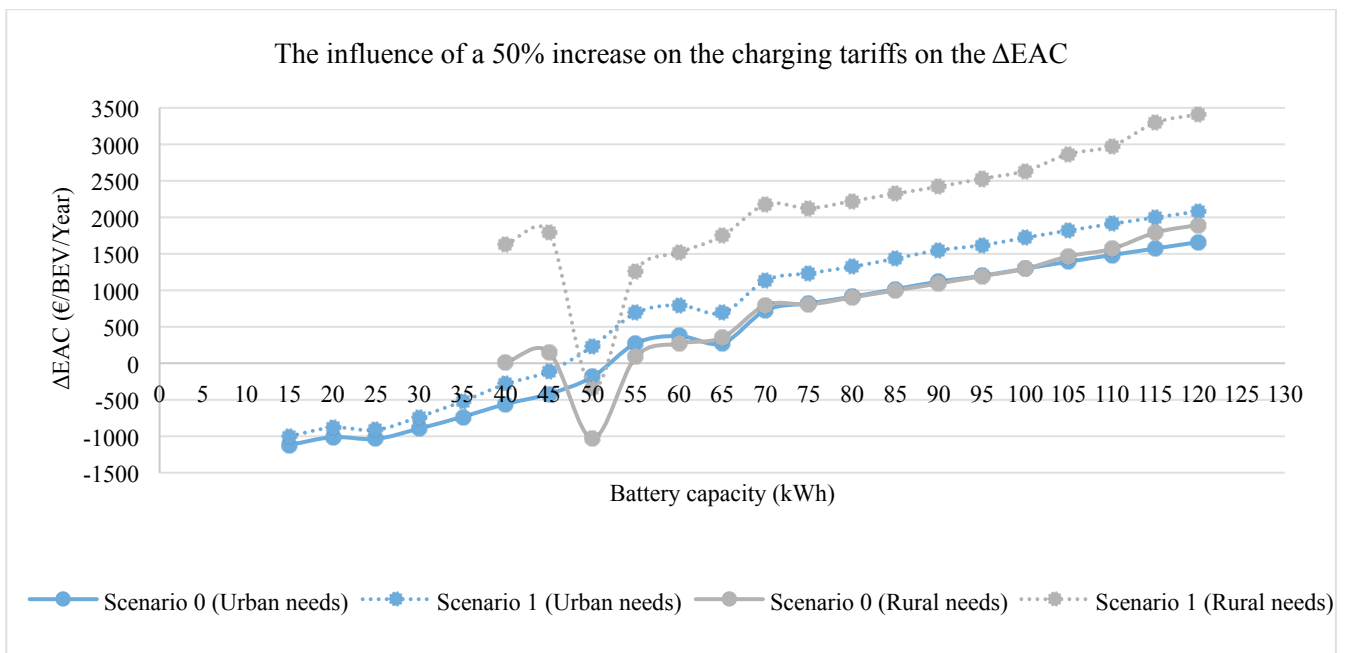
10

11

1 4.4.3. Increasing the Charging Tariffs

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

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



10
11 *Figure 13 Sensitivity test 3 results on the BEV customer*

12 **5. Conclusion and Discussion**

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

1 BEVs using 22 kW chargers, and large-battery BEVs that can connect to 50 kW fast-chargers.
2 The model could be applied to different territories by changing the values of these parameters.
3 However, it does not deliver a geo-spatial allocation of charging infrastructure..
4 Our analyses showed that the specific investments [€/BEV] in the deployment of charging
5 infrastructure, especially for 22 kW chargers, is lower than that of expanding the BEV range
6 by 50 km and 100 km. We found that bigger batteries do not pay off, since additional
7 investments will apply. In our study, the operator uses the third type of discrimination while
8 fixing its charging tariffs, because the pricing depends on the power of the charger, and thus
9 on the battery capacity. Our outcomes demonstrate the fact that the battery capacity and
10 charging points are correlated since the charger usage depends on the battery size.
11 After detailing and comparing the different business models of the parties of the BEV
12 ecosystem, the analyses for urban needs showed that 35 kWh to 50 kWh BEVs with the
13 deployment of 22 and 50 kW chargers is cost-efficient. The used pricing method is a variable
14 one, taxed by exceed minute after one hour of charging. In contrary, for rural needs, the
15 results showed two solutions depending on the driver's trips: a 50 kWh BEV with 22 kW
16 chargers that comes with the lowest cost for the customer but could not be the right choice for
17 some drivers due to the limited autonomy. A second solution is a 55-65 kWh BEV use 50 kW
18 chargers, which comes with a minimum positive ΔEAC but a more significant autonomy,
19 using a fixed pricing method: a fee for the access added to a tariff per minute of charging.
20 Although the design of our model presents a dual analysis for both parties (i.e. BEV driver
21 and the charging infrastructure operator), it has some limitations due to several assumptions
22 related to driving and charging behaviours, due to the lack of data and parameter calibration
23 choices. We, therefore, applied several sensitivity tests, in order to measure the effect of
24 different scenarios variations on the results, by i) mixing the charging powers and the BEV
25 size, by ii) changing the pricing method, and by iii) increasing the charging tariffs. The results
26 of the sensitivity tests were in line with our general conclusions for both urban and rural areas.
27 In future work, the assumption of driving and charging behaviour should be considered,
28 because the driver could change their attitudes in terms of additional trips, such as home-
29 school travels, other activity centres, malls, etc. where semi-public charging stations could be
30 available. For this reason, the arrival rate to the charging stations may change, causing a
31 different number of chargers. Also, when simulating BEV profiles, we neglected comfort
32 parameters such as heating, cooling, lights, and radio, that may increase the energy demand of
33 BEVs. Besides driving behaviour, some hypotheses about installation and techno-economic

1 grid parameters are not considered. The question related to grid expansion is under discussion
2 because specific technical problems could be resolved by smart charging such as peak
3 demands, especially for fast charging infrastructure. Also, we did not consider external
4 parameters such as the land price in the operator's business model, due to no-spatial model
5 and the high variety of these prices. Overall, it is vital to use real-world data that reflect the
6 driving and charging behaviours of BEV drivers, such as trip mileage, arrival rates, and actual
7 charging durations. Finally, based on these real-data, charging tariffs and the pricing methods
8 should be revised, taking into account an oligopolistic market where competition between
9 charging operators stakes.

10

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16 writing of the manuscript; and in the decision to publish the results.

17

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13 Appendix A: Techno-economic parameters of the business models

14 *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

15

16 *Table 5 BEV techno-economic parameters*

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

1

2 *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)
αVKT_i	Annual Vehicle Km Travelled [km]	<i>Depends on every BEV profile</i>			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 [tCO ₂ /ICEV]	21.15	32.1	44.8	(Carbone4, 2018, p. 4)
p_{CO2}	CO2 price [€/tCO ₂]		100 €/tCO ₂		(Quinet et al., 2009)

3

4 *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]	<i>Depends on every BEV profile</i>			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)

