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Benefits of different electric vehicle smart charging strategies in a large-scale EV integration scenario for France

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Summary

Smart EV charging and vehicle-to-grid are likely to be important sources of flexibility for the electricity system in the future, facilitating the integration of intermittent renewable energy sources and reducing the needs for peak load power plants. In this paper, we examine the implications of e-mobility development on the security of electricity supply and the potential economic and environmental benefits associated with different types of smart charging in France in a welfare analysis framework. The analyses are carried out using a large-scale model of the European electricity system in a long-term scenario with a high share of renewable electricity generation.

Keywords: electricity security, smart charging, V2G (vehicle to grid), economics, power system

1 Introduction

In the context of generalized efforts towards greener uses of energy, massive transport electrification is an important driver of both greenhouse gas emissions and air pollution reduction, and several countries are taking steps in that direction. For example, Canada, India and Japan have all set ambitious targets for EV shares in the sale of passenger cars, while China requires OEMs to produce a minimum share of new energy vehicles and the European Union has set restrictive CO_2 emissions requirements for manufacturers [1]. France has recently put into the legislation a ban on sales of ICE vehicles using fossil fuels by 2040 [2]. While the impact of EV charging on peak electricity demand needs to be carefully analyzed, the flexibility of EV charging patterns can provide demand-side response opportunities to facilitate the penetration of intermittent renewable energy sources, reducing the needs for peak load power plants [3-5].

In this study, we quantify the potential effects of different scenarios for e-mobility development on the security of electricity supply, as well as their economic and environmental implications. The scenarios reflect a variety of combinations of key parameters that characterize the integration of electric vehicles into the power system, with a particular focus on EV load management strategies. The analyses focus on a long-term time horizon (2035) for France, with a high share of renewable electricity generation (48%) and a significant development of e-mobility (up to 15.6 million vehicles).

2 Modelling approach and scenario assumptions

The methodology used to assess the benefits of smart charging and V2G relies on the combination of two models: a model describing the driving patterns and uncontrolled charging demand of EVs and a power system simulator, both applied to a 2035 time horizon.

Simulation of EV behavior is based on data from the latest French national travel survey (Enquête Nationale Transports et Déplacements [6]) and on future travel demand projections. The travel survey data provides information about distances travelled, departure and arrival times and purpose of each trip, as well as information about the driver. Some interesting features of mobility in France emerge from the analysis. Firstly, on working days, only 30% of vehicles are used for commuting and 7% of vehicles are used for business-related travel. A large share of vehicles (28%) are not used at all on an average working day. Secondly, among the vehicles used for commuting, a significant number (15%) are driven home at lunchtime then back to the workplace. Finally, only 25% of distances travelled annually by light-duty vehicles correspond to "long-distance" journeys (Fig. 1). These are defined in the survey as travel to a main destination located at least 80 km from home as the crow flies. The average daily distance driven for local mobility on a working day is around 35 km.

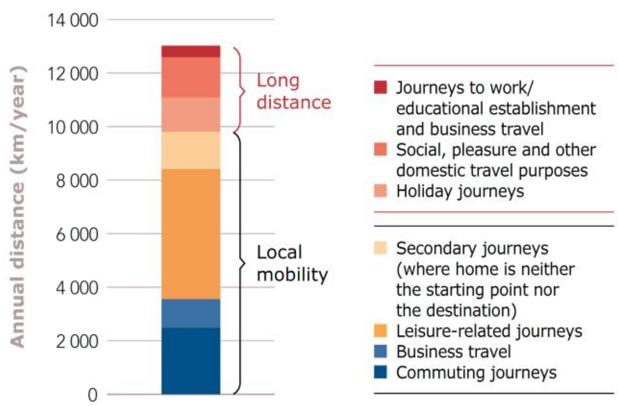

Figure1: Average annual mileage of light-duty vehicles in France, by purpose

Different user profiles are identified, based on the way light-duty vehicles are used over a whole day: commuting, leisure users, commuting/leisure combination, business trips, long-distance journeys. The behavior of EV users is then simulated throughout every day of the year based on this data, for three types of days (working days form Monday to Friday, Saturday, and Sunday). The distribution of profiles is different from the distribution observed in the survey, to reflect a non-homogeneous penetration of electric mobility throughout the French population in the coming years: we consider an uptake by affluent workers living in urban or suburban areas twice as high as that of the rest of the population. Long-distance journeys are not evenly distributed throughout the year: the number of holiday and leisure-related journeys increases over the summer months, when fewer business trips take place. This variability is taken into account using data from a national tourism survey [7].

Three scenarios (Table 1), with variants considering different numbers of EVs, are analyzed to represent different combinations of hypotheses concerning travel demand, share of PHEVs, battery capacities, power of charging points, number and location of charging points, charging patterns (frequency of charge and adoption of smart charging). For each scenario, the EV model provides the users' travel patterns, plug-in periods, plug-in power and uncontrolled charging demand (Fig. 2), taking into account the dependence of energy consumption on temperature and travel speed.

The share of plug-in hybrid vehicles influences particularly the aggregated charging behavior for long-distance journeys: we suppose that PHEVs use their internal combustion engine when the battery is discharged, plugging in only after having reached their destination, if a charging point is available. For local mobility, the share of

PHEVs has a very limited influence on uncontrolled charging behavior, but PHEVs have less flexibility compared to BEVs when considering smart-charging or V2G. Annual vehicle-kilometers travelled are supposed to be slightly higher on average for electric vehicles than for internal combustion engine (ICE) vehicles today, as the current cost structure of electric vehicles (higher purchase costs but lower operating cost compared to an ICE vehicle) is particularly interesting for high-mileage users. The breakdown between long-distance journeys and local mobility is also supposed to be different from the average breakdown today, as part of long-distance journeys might be realized using other modes of transport (e.g. train or internal combustion rental cars). Thus, the share of long-distance journeys in annual distances travelled by electric vehicles is 14% in Crescendo and Opera scenarios and 21% in Forte scenarios (compared to 25% for light-duty ICE vehicles today).

Table 1: Main parameters of e-mobility scenarios for France (2035)

	Number of ligh-duty EVs (millions)	Share of plug-in hybrid EVs (%)	Avg. battery capacity (kWh)	Car travel demand (km/ year)	Share of EV users that have access to away-from-home charging stations (%)	Avg. power of home EV charger (kW)	Share of smart charging (static/dynamic/ dynamic+V2G) (%)
Forte uncontrolled intermediate	11.7	40	89	15 300 (21% long-distance)	16	6.5	0 / 0 / 0
Forte uncontrolled high	15.6	22	89	15 300 (21% long-distance)	16	6.5	0 / 0 / 0
Forte intermediate	11.7	40	89	15 300 (21% long-distance)	16	6.5	35 / 5 / 0
Forte high	15.6	22	89	15 300 (21% long-distance)	16	6.5	35 / 5 / 0
Crescendo intermediate	11.7	40	73	14 000 (14% long-distance)	28	5.9	37 / 20 / 3
Crescendo high	15.6	22	73	14 000 (14% long-distance)	28	5.9	37 / 20 / 3
Opera intermediate	11.7	40	73	14 000 (14% long-distance)	45	6.5	30 / 30 / 20
Opera high	15.6	22	73	14 000 (14% long-distance)	45	6.5	30 / 30 / 20

Access to away-from-home charging stations, located at workplaces or on public roads, contributes to smoothing EV power demand during the day, shifting part of charging from the evening peak to other times. This can be observed in uncontrolled power demand curves (Fig. 2): the morning peak is highest for Opera scenario, in which 45% of EV users have regularly access to charging points away from home, and lowest for Forte scenario, where only 16% of EV users have access to them. The situation is reversed for the evening peak, as users who lack opportunities to charge elsewhere connect their EVs when returning home. High availability of charging stations away from home also increases the potential for flexibility in the case of controlled charging, as it allows charging to take place in the middle of the day, when PV power production is at its highest. The average power of chargers has a limited effect on the shape of uncontrolled charging power demand, but – as for access to charging points away from home – a higher power is associated with increased value for flexibility, as charging can be concentrated in the most optimal periods of time.

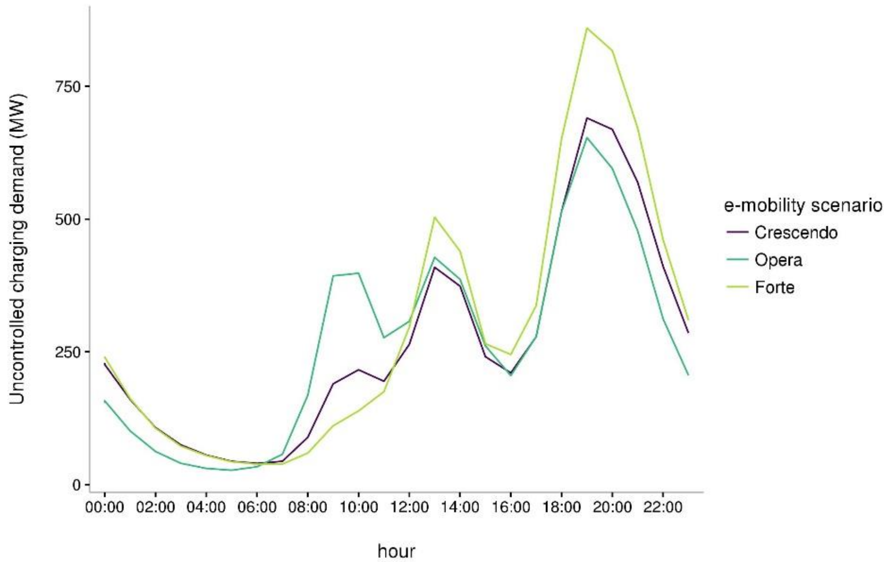

Figure2: Uncontrolled charging demand for a weekday, for one million EVs in different scenarios

The share of electric vehicles participating in smart charging and V2G is the most influential parameter in terms of security of electricity supply and economic and environmental benefits. Combinations of three types of smart-charging (uni- or bidirectional) are considered: static price signals (unidirectional), dynamic price signals (unidirectional) and dynamic price signals combined with V2G functionality (bidirectional).

Hourly power demand for these vehicles is the result of the optimization of the power system, carried out with the Antares power system simulator. The software represents the whole transmission-generation system for interconnected power grids at an hourly resolution, minimizing the expected operating costs. It relies on a Monte-Carlo approach, using a large number of wind, solar PV and hydro-electricity generation time-series, as well as time-series for load and conventional plant availability. A detailed presentation of the model can be found in reference [8]. For this study, the power system of 18 countries in Western Europe is represented, together with interconnections between countries. For France, the electricity generation fleet in 2035 is supposed to be coherent with government objectives (Multiannual Energy Plan [9] and the National Low Carbon Strategy [10]). For other countries, electricity generation fleets and load are based on the "Sustainable Transition" scenario from the TYNDP 2018 [11]. A detailed representation of EV behaviour is implemented in the simulation in order to estimate the flexibility of EV charging while ensuring the satisfaction of the users' mobility requirements (plus a 30% margin, meaning that the battery state of charge can never be lower than 30% when the vehicle arrives at the next charging point). The model provides hourly smart-charging demand of EVs, V2G injection volumes, electricity prices, CO_2 emissions and electricity generation costs.

The scenarios capture a wide range of possible futures, from an utilization of EVs that is close to the one of fossil-fuelled vehicles today with a relatively limited use of smart charging (Forte scenario with 40% unidirectional smart-charging), to a situation where travel demand is lower and the participation in demand-response reaches ambitious levels (Opera scenario, with 20% V2G and 60% unidirectional smart-charging).

3 Benefits of flexible EV charging for the security of electricity supply

The electrification of light-duty vehicles in France will result in a level of electricity consumption between 25 and 40 TWh in 2035. Although this corresponds to a significant rise in consumption, it only represents between 5% and 8% of total electricity consumption expected for France in 2035. For comparison, total consumption for heating in the residential sector is currently 44 TWh, and electricity consumption increased by 55 TWh between 2000 and 2010, which means that 40 TWh in 15 years would not represent an unprecedented rate of growth. Hence, the challenge in terms of e-mobility integration into the power system does not concern the capacity to meet total EV energy demand, but rather the capacity to meet power demand at any one moment in time.

As outlined in section 2, long-distance journeys occur in highly concentrated periods throughout the year, mostly at weekends and during school holidays (especially in the main July-August holiday period). However, although power demands associated with long-distance travel can be high (up to 8 GW in the busiest travel days in the Forte scenario, which has the highest long-range mileage), they do not present any cause for concern in terms of security of electricity supply. Peak load for EV charging will typically happen when the electricity system already has considerable margins, such as in the summer months and at weekends. Besides, considering the assumed battery capacities and the distribution of typical long-range travel distances in France, only 30 to 40% of charging (in terms of energy) would take place at on-road charging stations. The rest can occur either before departure or on arrival at the destination, and can therefore be controlled, allowing for additional flexibility.

Power demand for daily local mobility, on the other hand, present the biggest challenge for the power system, if charging is uncontrolled or only very partially controlled. In all scenarios, peak demand for uncontrolled charging (Fig. 2) falls between 7 p.m. and 9 p.m., that is during periods of peak electricity demand related to other uses (heating, lighting, etc.) and low or absent photovoltaic electricity generation. Two other, smaller peaks are likely to occur in the morning, when commuters arrive at their workplace, and at lunchtime. These peak demands are concentrated at times when the capacity margins of the electricity system are the lowest. Besides, they are temperature-sensitive: during a cold snap, EV power demand during the evening peak could be as much as 3 GW higher than in average weather conditions, for scenarios with 15.6 million vehicles.

The Forte scenario represents a deliberately challenging configuration in terms of security of supply, as in this scenario users have limited access to charging stations away from home, which concentrates uncontrolled demand in the evening hours and limits the options for EV load management. In its 100% uncontrolled charging variant, both with an intermediate and a high development of e-mobility, the official reliability standard for electricity security of supply would not be met by the electricity generation fleet considered (Fig. 3). However, with the introduction of simple static price signal charging for 40% of electric vehicles, the Forte intermediate scenario with 11.2 million electric vehicles would meet the reliability standard. A slight deficit in capacity is still present in the Forte high scenario (15.6 million EVs), but limited additional participation in simple smart-charging solutions (55% instead of 40%) would allow even this scenario to respect security of supply criteria. Thus, if government objectives concerning the future generation fleet (particularly the trajectories for renewables) and energy efficiency are met, a generalized development of EV smart charging would not be a technical prerequisite for an extensive electrification of vehicles. A minimum level of smart charging would be sufficient to ensure that the reliability standard is respected. With a high level of dynamic smart-charging and V2G injection (Opera scenarios), the capacity margins with a large development of e-mobility could even be higher than in an equivalent scenario without electric vehicles (Fig. 3).

4 Economic benefits of flexible EV charging

Even though a minimum level of smart charging is sufficient for ensuring security of electricity supply, developing smart charging strategies further represents a very interesting opportunity to reduce the costs of electricity generation and its environmental impacts. Smart charging can be used to modulate the load curve to adapt it to renewable energy production. This reduces daily and weekly variations in residual demand (i.e. the total national electricity consumption minus non-dispatchable renewable power production) which has to be met by dispatchable generation (nuclear, fossil fuel and hydropower plants). Reshaping the load curve lowers the need for curtailment of solar and wind generation for lack of outlets, optimizes the operation of the nuclear fleet by limiting variations in power production, and reduces the amount of electricity generated using fossil fuel plants.

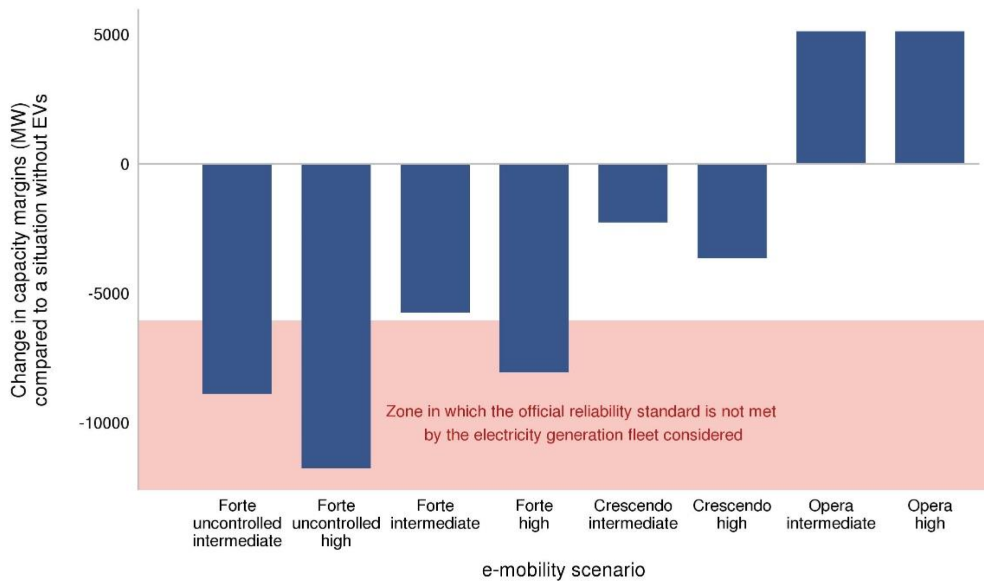

Figure3: Capacity margins in 2035 for different e-mobility scenarios, compared to a 2035 scenario without development of e-mobility

Based on the results of the power system simulation, it is possible to estimate the cost associated with the electrification of the vehicle fleet, in terms of electricity generation, by comparing e-mobility scenarios with a counterfactual 2035 scenario in which there is no development of e-mobility. Estimated costs include the difference in operating costs of the interconnected power system as well as investment in additional power generation facilities that may be needed because of the introduction of electric vehicles in France, compared to a scenario without electric vehicles in France. In scenarios with a high level of flexibility, investment costs might be negative, as the charging flexibility of EVs allows to increase the capacity margins of the system despite the increased total energy consumption: thus, fewer peak load power plants (e.g. gas turbines) would be needed.

For an equivalent level of transport electrification, the cost of electricity generation for charging electric vehicles varies considerably according to the e-mobility scenario, depending foremost on the type of smart charging and its diffusion (Fig. 4). For example, in the Forte high scenario, with 40% of electric vehicles charging based on static price signals, the cost of electricity generation associated with electric light-duty vehicles is 0.6 billion euros/year lower than in the uncontrolled Forte high scenario. The widespread deployment of even simple smart charging appears therefore to be a “no regret” option, leading to significant collective savings with little costs. Sophisticated smart charging, based on dynamic price signals combined with V2G injection and high access to charging stations away-from-home, leads to substantial additional savings: the cost of electricity generation for EVs is 1.1 billion euros/year lower in Opera high scenario than in Forte high, while the cost of an intermediate scenario in terms of flexibility options (Opera high) falls between the two. Similar conclusions apply to the intermediate scenarios (11.6 million electric vehicles in 2035).

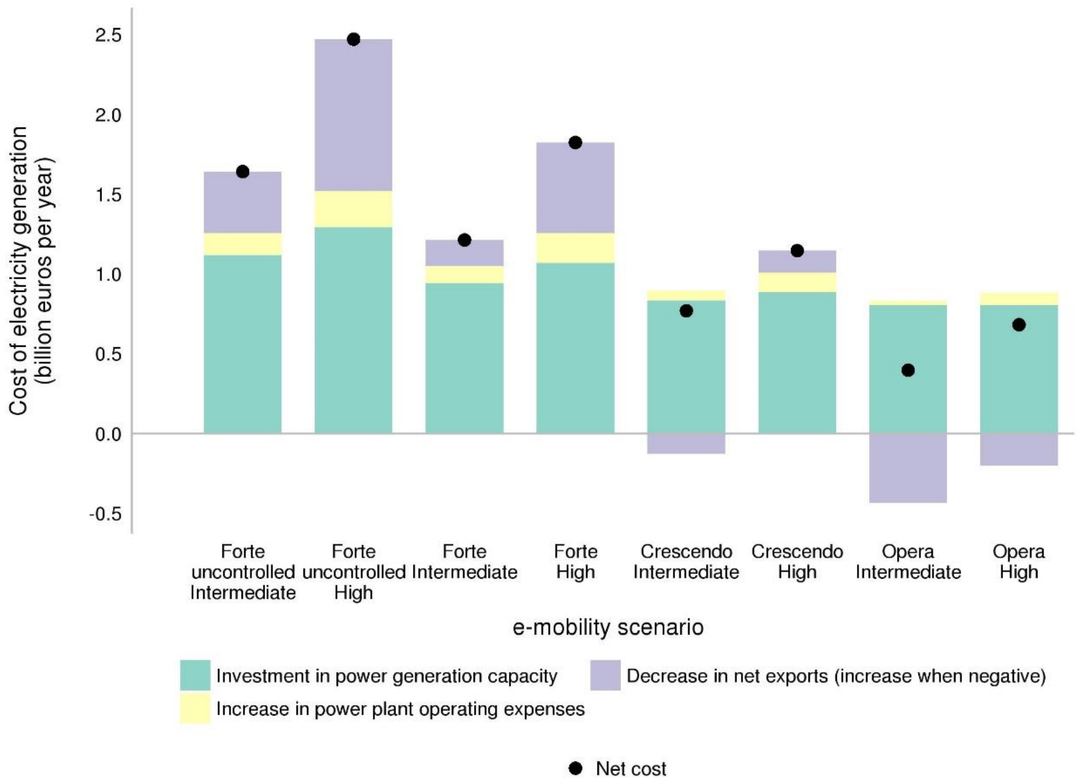

Figure4: Cost of electricity generation in different e-mobility scenarios, compared to a 2035 scenario without development of e-mobility

Investment in power generation capacity is the largest cost item in all scenarios, compared to a scenario without electric vehicles. However, the trajectory for the electricity fleet considered in government objectives is coherent with an ambitious development of e-mobility, so this cost should not be interpreted as an additional cost compared to existing public scenarios. Another important cost item for Forte scenarios is the decrease in the value of net exports, consequence of the increased electricity consumption in France. Yet, in other scenarios (Crescendo intermediate, Opera intermediate, Opera high), the value of net export increases compared to a situation without electric vehicles (therefore, the change is represented in Fig. 4 as a negative cost). This is due to the increased flexibility of the power system associated with smart charging of electric vehicles, which allows to maximize charging during high renewable production periods and free capacity at other times for export. A high penetration of smart charging is also associated with lower operating expenses, mainly attributable to fossil fuels used in power plants, thanks to the optimization of the generation mix.

Electric vehicles could also be involved in frequency regulation, contributing to balancing the electricity system in real time. These services (called “ancillary services”) are technically demanding, with reaction times of a few seconds (frequency containment reserve or FCR) or a few minutes (automatic frequency restoration reserve or aFRR). The participation of electric vehicles in these markets could create additional value for the electricity system, but given the current market size, a few hundred thousand vehicles would be sufficient to provide all the ancillary services required. Besides, revenues per vehicle are dependent on the development of competing flexibilities (e.g. storage batteries), and they decrease quickly according to the number of vehicles participating. Therefore, a large participation of EVs in frequency regulation, while ensuring sufficient profits for the users, seems unlikely.

5 Environmental benefits of flexible EV charging

Smart charging of electric vehicles improves the environmental performances of electricity generation as well. The volume of greenhouse gas emissions associated with EV charging is estimated by comparing direct greenhouse gas emissions due electricity generation for e-mobility scenarios with greenhouse gas emissions due to electricity generation in a counterfactual 2035 scenario without electric vehicles. The generation mix in e-mobility scenarios, and in particular the installed capacity of solar PV and wind power, is supposed to be coherent with the increased energy use due to EVs compared to the counterfactual scenario, following the same methodology used for cost estimation.

For all scenarios, direct greenhouse gas emissions due to electricity generation for charging electric vehicles (Fig. 5) are much lower than greenhouse gas emissions associated with fuel combustion for the same number of ICE vehicles and the same annual mileage. For example, for gasoline cars with a 4.5 l/100km fuel consumption (taking into account fuel efficiency improvements by 2035, coherent with the Multiannual Energy Plan), greenhouse gas emissions would range from 16.4 to 23.8 MtCO_2eq/year depending on the scenario (Fig. 6), considering an emission factor of 2.22 kgCO_2/l. Greenhouse gas emissions due to electricity generation for charging electric vehicles are particularly low for scenarios with a high level of smart charging and V2G (Crescendo and especially Opera). For some scenarios, total direct emissions associated with electric vehicles are even negative (Fig. 5), meaning that the optimization of electricity generation thanks to the flexibility introduced by smart charging and V2G allows for a reduction of total greenhouse gas emissions of electricity generation compared to a scenario without electric vehicles, despite the increase in total generation.

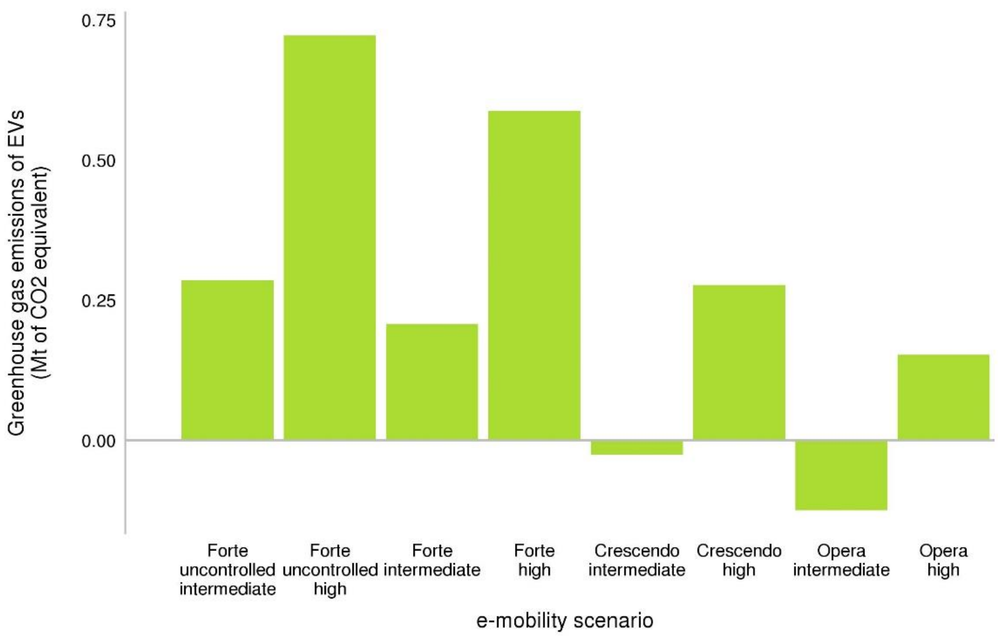

Figure5: Direct greenhouse gas emissions from electricity generation due to EV charging, in different smart-charging scenarios (compared to a scenario without electric vehicles)

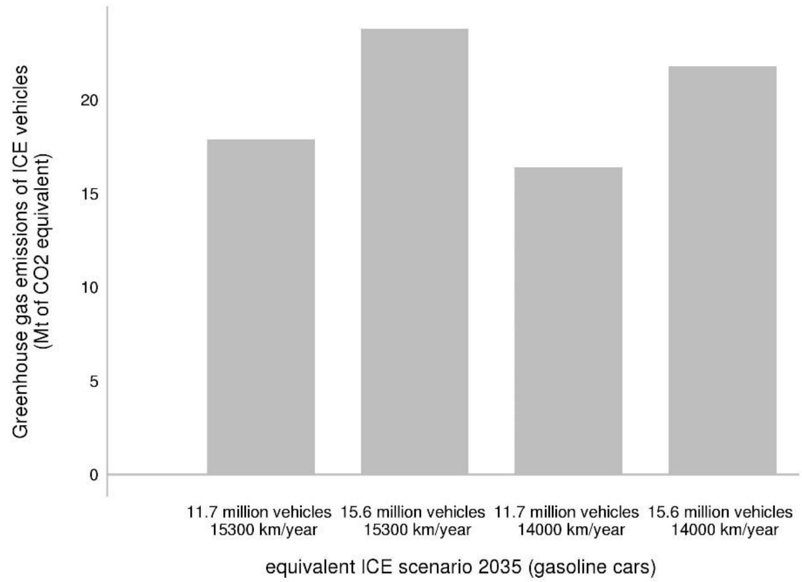

Figure6: Direct greenhouse gas emissions from fuel combustion in ICE vehicles (gasoline), for the same number of vehicles and mileage as in e-mobility scenarios

6 Conclusions

With an expected evolution of the power system towards a high share of renewables in the generation mix in France by 2035, the development of e-mobility, associated with the development of smart charging, can be an asset for the optimisation of electricity generation. The associated economic benefits can be seen at various levels. More stable electricity prices and fewer situations where there are low or negative prices thanks to smart charging benefit producers as well as public finances, reducing the needs for subsidies for the development of renewable electricity generation. Consumers also benefit from smart charging by charging at times when the electricity prices are the lowest, saving on their annual electricity bill.

Moreover, smart charging presents substantial benefits in terms of greenhouse gas emissions reduction. In France, using an electric vehicle results in very low greenhouse-gas emissions, due to the predominantly low-carbon electricity mix: in 2035, they are 30 times lower than the emissions of an ICE vehicle. Smart charging can reduce emissions due to electricity generation for charging electric vehicles still further, even reducing total greenhouse gas emissions associated with electricity generation compared to a scenario without electric vehicles, despite the increase in demand.

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