Resource and Energy Economics 69 (2022) 101310

Contents lists available at ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

An economic model of vehicle-to-grid: Impacts on the electricity market and consumer cost of electric vehicles

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ARTICLE INFO

Article history:
Received 8 June 2021
Received in revised form 12 April 2022
Accepted 16 April 2022
Available online 21 April 2022

JEL classification:
Q41
Q42
Q54
R42

Keywords:
Electric vehicles
Vehicle-to-grid
V2G
Electricity market

ABSTRACT

Higher battery storage capacity in electric vehicles (EV) implies less need for inconvenient recharging during long trips and increases the potential gains from vehicle-to-grid (V2G) electricity supply. We present an analytical model for the intertwinement of the consumers' choice of battery capacity and the electricity market. We show that V2G increases the consumers' choice of battery capacity, and it may reduce the cost of owning an EV vis-à-vis a traditional car. Furthermore, V2G alleviates the capacity pressure on peak hours, and thereby reduces the need for investment in generating capacity, saving social costs. Moreover, V2G may make the difference in electricity prices between peak and off-peak hours smaller, potentially increasing social surplus further. Based on a future scenario for the Belgian electricity market, we provide a numerical illustration indicating that the savings might be substantial.

1. Introduction

Electric vehicles (EVs) are dependent on electricity supply from the grid and will increase total electricity demand. On the other hand, since an EV with a large battery only needs charging for driving occasionally, the EV may also store electricity in order to smooth out daily variability in demand and supply of electricity. Moreover, the EV can also help to balance the grid by supplying quick power when there is a local imbalance. The present paper explores the EV owners' choice of battery size when there are possibilities for earning money on peak shaving, and the subsequent implications for the electricity market.

EVs come with a wide range of battery capacities. We build a simple analytical economic model to study the interlinkages between the consumers' choice of battery capacities and the power market, where the optimal battery capacities and power production capacities are endogenously determined.

The battery capacity serves two purposes. During days with long trips, the larger the capacity, the smaller the need for inconvenient recharging during long trips. But during days with short trips, the larger the storage capacity, the larger the potential gains from vehicle-to-grid (V2G) electricity sales during peak periods. We show that consumers' optimal choice of

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https://doi.org/10.1016/j.reseneeco.2022.101310

battery capacity increases with the availability of V2G as well as with the price difference between peak and off-peak electricity prices.

Although we derive these ideas from a simple economic model, the implications of the results are not a priori obvious. First, we show that V2G significantly lowers the cost of owning an EV, which, all other things equal, could increase the sales of EVs in general. Second, we find that the total available battery capacity in the EV fleet for supply of electricity in periods of shortages is larger if consumers plan for V2G when they choose their EV. Hence, public energy agencies should signal early if they plan to open up for V2G electricity supply. Third, as the benefit to the EV owner of the V2G option depends strongly on the peak and off-peak price differential, the desirability of V2G varies over countries.

Our main contribution in the paper is to integrate our model of EV users' choice of battery capacity with a simplified long run equilibrium model of the electricity market. From the model, we can illustrate how consumers' optimal battery capacity choices affect the optimal investments in conventional power plants and the equilibrium electricity prices during peak and off-peak hours. Moreover, we find that V2G may increase social surplus through several mechanisms; i) the cost of car ownership for EV owners declines, ii) the need for investment in conventional power capacity decreases and iii) low value electricity in off-peak periods may be exchanged with high value electricity in peak periods. Note however that iii) will only happen if the participation in V2G by EV owners reach a certain level. Then the extra charging demand in off-peak hours created by EV owners who intend to sell electricity in peak hours, will equate demand in off-peak and peak hours. Thus, conventional power plants run at full capacity in both periods, and due to the electricity supply from V2G, electricity prices in peak periods are lower than without V2G.

We demonstrate the three mechanisms in an illustrative numerical model of the future Belgian electricity market. With limited participation of V2G by the EV owners, electricity prices are not affected, and on average, each EV driver may earn around 700 € per year on V2G lowering their cost of EV ownership. In addition, there is a significant saving in investment costs for conventional power; an annuity of about 100 million €/year. With higher participation, the electricity price differential becomes smaller and average earnings per EV owner declines. On the other hand, the total increase in social surplus is much higher due to an increase in consumer surplus, and additional investment savings.

V2G also implies some caveats that are less well understood. First, as far as we understand from the engineering literature, daily charging and recharging of the EV battery must be tightly controlled in order not to accelerate the depreciation of the battery. Also, V2G will only succeed in realizing its social benefits as long as there is true peak load pricing in the electricity sector, and marginal cost pricing of fast charging along roads.

In the following, we first discuss some of the relevant literature (Section 2). Thereafter we derive the private demand function for battery capacities (Section 3). We find the consumers' optimal choice of capacity and show how the V2G technology decreases the consumer cost of EVs, and thereby may contribute to a larger rollout of EVs. In the next section, we introduce a simple model of the electricity market (Section 4), which we use to discuss the social value of V2G and how V2G affects the equilibrium prices depending on the characteristics of the electricity market. In the same section we show under what conditions the private and social optimum coincide. In Section 5, we present a simple numerical illustration of our model. And in a concluding section we discuss the policy implications and the caveats.

2. Literature review

Electrification of the car fleet contributes to reduced greenhouse gas emissions, as well as local pollution, and is promoted by a variety of policy instruments in several countries (IEA, 2020). In the present paper, we focus on the EV's capacities for storing electricity and the implications for the power market, and do not explicitly model the rollout of EVs. There are several studies pointing to the need for energy storage and flexible demand in a future energy system with a large share of intermittent energy sources, like wind and solar, see Newbery (2018). EV batteries, through V2G options, can thus play an important role in achieving a low-carbon electricity market. In the present paper, we focus on variations in electricity demand between peak and off-peak hours (see Williamson, 1966), once renewable production has been taken into account.

Thompson and Perez (2020) categorize the potential use of electricity supply from EVs when they are parked into i) vehicle-to-load (V2L), ii) vehicle-to-home (V2H), iii) vehicle-to-building (V2B) and iv) vehicle-to-grid (V2G). V2L refers to the use of EVs as a local back-up capacity in case of black-outs or other unexpected shortages. Furthermore, V2H and V2B imply use of EVs to balance the power input to residential or business uses. Among other, owners will be able to save on capacity charges and differences in electricity prices over the day. In this paper our focus is on V2G in which the supply of electricity from EVs is integrated into the grid. However, many of our results would also hold for V2H and V2B.

Bibak and Ekiner-Mogulkoç (2021) review the growing technical literature investigating the impact on the electricity system of the bidirectional power flows from EVs. EVs can contribute to the power market by supplying peak power as well as quick-response services required to maintain grid stability and security (ancillary services), like spinning reserves and regulation services.

In the technical literature there is a belief in the significant potential for financial return when the vehicle-to-grid (V2G) technology is used for frequency regulations, but less so for peak shavings (Freeman et al., 2017; White and Zhang, 2011). The latter opinion follows from discussions on the fear of battery degradation under frequent charging and discharging. Uddin et al. (2018) conclude that V2G can be economically viable, but demands a smart control algorithm, which takes into consideration the impact of V2G cycling on the battery life.

Although not yet commercially available to private households, Bibak and ekiner-Mogulkoç (2021) mention 67 V2G innovation and trial projects aimed at making V2G chargers commercially available. In terms of value contribution, the peak shaving function of V2G is probably an order of magnitude larger than the contribution to ancillary services as the value of ancillary services is small compared to the value of energy at the day ahead market (see Ortner and Totschnig, 2019 and Gillingham and Ovaere, 2019).[1] But this depends on the load profiles and the availability of hydro resources that are able to bridge the gap between peak and off-peak demand.

The success of V2G depends on EV owners willing to make their EVs available for electricity supply when parked. Geske and Schumann (2018) found in a survey of the German drivers that, 'range anxiety' and the 'minimum range' proved most important determinants of the willingness of vehicle users to participate in V2G. If these concerns are smoothed out by advanced systems for controlling the electricity supply from an EV, high participation rates might be achieved. Noel et al. (2019) found in a choice experiment for five Nordic countries that only consumers in Finland and Norway were willing to pay extra for V2G availability, while consumers in Sweden, Iceland and Denmark did not see V2G as an additional benefit. The study suggests that consumers with more experience with EVs (Norway) are more prone to also value V2G. Moreover, the study also indicates that consumers need to be educated in the benefits of V2G. Kester et al. (2018) used expert interviews to analyze the bottlenecks in the development of the V2G. As the potential depends on the specifics of the country's electricity production sector, they find that a restructuring of the electricity market institutions is needed for the proper development of V2G.

This empirical research shows that an economic model integrating consumers' choice and electricity production as well as the correct pricing of electricity is needed to fully understand the role of battery capacity and V2G.

3. Demand for EV battery capacity

In order to concentrate on the essentials, we opt for a simple model in which both the stock of EVs and the driving pattern of consumers are given. We assume that there is a peak and an off-peak period in the electricity market each day. Consumers can then earn money on V2G by buying electricity off-peak and selling it in the peak period.

There are N owners of EVs, and they are denoted by i = 1,…,N. Every day of the year, an EV owner makes either a short trip with electricity demand d_s or a long trip with electricity demand d_l. Furthermore, we let x_l represent the fraction of long trip days in a year, and, hence, x_s = 1- x_l, is the fraction of short trip days in a year. The owners are heterogenous with respect to the fraction of long trips they make every year. For each owner, we assume that the fraction of long trips is uniformly distributed on the interval $[\underline{x}, \bar{x}]$ with $\underline{x} < \bar{x}$ and $\underline{x}, \bar{x} \in \langle 0,1 \rangle$.

The EV batteries can be charged either at home, or at the destination of the trip, or en route during a long trip. We assume that, on short trip days, EV owners only charge their battery when the price of electricity is low typically. With a battery size B_i, $(B_i - d_s)$ is available to supply to the grid on short trip days, if the battery is fully charged.[2] We assume that all houses, offices and parking lots are already equipped to charge or discharge EVs during peak and off-peak hours, and we do not model the investment in such equipment.[3] Furthermore, we assume that consumers will never buy a battery that has a lower capacity than the energy demand from a short trip, and will never buy a battery larger than the energy demand on a long trip, e.g., $d_s < B_i < d_l$.[4] Hence, for the days when the consumer makes a long trip, all consumers have to fast charge en route. The EV owners do not prefer this kind of charging as fast charging is more costly due to the need for separate stations with high KW capacity. Moreover, fast charging takes time, which could have been spent driving.

Even if V2G is generally available, it is unlikely that all EV owners will participate in V2G. Hence, we assume that a fraction β of the N owners of EVs will participate.[5] To simplify matters, we assume that the decision to participate in V2G is uncorrelated with the fraction of long trips in a year. Each EV owner chooses a battery capacity, B_i, that minimizes her costs, given her fraction of long trips and the decision on participation in V2G.

For an EV owner who participates in V2G, and makes a fraction x_l^i of long trips per year, the daily cost of operating a vehicle equals:

$$
\begin{aligned}
&c(B_i) \\
&\quad = p_e^o B_i - p_e^p (B_i - d_s)(1 - x_l^i) + [p_{ch}(d_l - B_i) + v(d_l - B_i)^2] x_l^i + aB_i
\end{aligned}
\tag{1}
$$

The first term represents the cost of charging the battery fully in the off-peak period (at price p_e^o). The next term is the income from supplying the grid on all short trip days, that is, the EV owner will sell the surplus to the grid at peak price p_e^p.[6]

[1] Price differences across hours in the day ahead market in several European countries points to significant income potential from peak shaving, see https://www.nordpoolgroup.com/.

[2] Note that the electricity demand d_s could include both the electricity required for a short trip and a reserve for contingency events. We thank an anonymous referee for pointing this out.

[3] Alternatively, the cost could be included in the parameter a from the cost function as a larger battery will in general require a home charger with higher capacity.

[4] Note that a battery size larger than what is needed for a long trip is rather unlikely as its only purpose would be to store electricity. For this storage function, there likely exist cheaper stationary options. A battery size less than d_s is inconvenient as it implies charging also during short trips.

[5] This feature of the model represents both a behavior element and a physical constraint. The behavior element stands for possible neglect of small incentives. The physical constraint can stand for driving patterns that are not compatible with periods where V2G is most useful.

The third component is the cost associated to charging en route, which consists of a monetary part and a disutility part. The monetary part is the cost of buying the additional power en route $(d_l - B_i)$ at the price p_{ch}. The disutility part captures the inconvenience associated with charging en route (waiting time). We assume that the longer time you spend charging your vehicle; the larger is the marginal disutility of waiting. To simplify, we use a quadratic disutility function with a parameter v scaling the time cost.

The fourth component represents the daily cost of battery capacity. We use a cost that is proportional to the size of the battery, which is in line with current supply options offered for EVs.

For an EV owner who does not participate in V2G, and makes a fraction x_l^i of long trips per year, the daily cost of operating a vehicle equals:

$$c^0(B_i) = (1 - x_l^i)p_e^o d_s + [p_e^o B_i + p_{ch}(d_l - B_i) + v(d_l - B_i)^2]x_l^i + aB_i \tag{2}$$

,where the first term is the charging for the short trip days, the second term is the total cost of a long trip, and the third term is the battery related costs. For EV owners who do not participate in V2G, the consumer will only fully charge the vehicle if it is used for a long trip.

3.1. Choice of battery capacity by the EV owner

As already mentioned, for both with and without V2G participation, we assume $d_s < B_i < d_l$. When we rule out corner solutions, we can use the first order conditions to find the battery capacities that minimize (1) and (2), respectively:

$$B_i^* = d_l - \frac{a - (p_{ch} - p_e^o)x_l^i}{2vx_l^i} + \frac{(p_e^p - p_e^o)x_s^i}{2vx_l^i} \tag{3}$$

$$B_i^0 = d_l - \frac{a - (p_{ch} - p_e^o)x_l^i}{2vx_l^i} \tag{4}$$

It is easy to see that $B_i^* > B_i^0$. Thus, not surprisingly, independently of the fraction of long trips per year, the EV owners who participate in V2G will choose a higher battery capacity than those who do not participate, as it is profitable to use the storage capacity during days with short trips. Note that we must have $a - (p_{ch} - p_e^o)x_l^i - (p_e^p - p_e^o)x_s^i > 0, \forall x_i^l$ for $B_i < d_l$ to hold. Finally, due to the disutility from waiting while the car is charged on long trips, we find that both battery capacities are increasing in the fraction of long trips,:

$$\frac{\delta B_i^*}{\delta x_l^i} = \frac{a}{2v(x_l^i)^2} - \frac{p_e^p - p_e^o}{2v(x_l^i)^2} > 0 \tag{5}$$

$$\frac{\delta B_i^0}{\delta x_l^i} = \frac{av}{2(vx_l^i)^2} > 0 \tag{6}$$

From (5) and (6) we note that the difference in battery size between “no participation in V2G” and “participation in V2G” is smaller, the higher the fraction of long trips per year, e.g., $\frac{\delta B_i^*}{\delta x_l^i} < \frac{\delta B_i^0}{\delta x_l^i}$. Consumers with a low fraction of long trips per year have more to earn on V2G. Furthermore, consumers with a high fraction of long trips per year invest in battery capacity to save en route charging costs and on time spent charging en route independently of whether V2G is an option or not.

We also see that the larger price gap between peak and off-peak prices, the larger is the optimal battery size for consumers participating in V2G.

The expressions for the optimal battery sizes (3) and (4) can be inserted into the cost functions (1) and (2), respectively, to yield minimized EV costs with and without V2G participation. We have that the cost of an EV is always lower with V2G participation than without.[7].

$$c^0(B_i^0) - \quad c(B_i^*) = \left[\frac{B_i^* + B_i^0}{2} - d_s\right](p_p - p_o)(1 - x_l^i) > 0, \tag{7}$$

since we assume $B_i^* > B_i^0 > d_s$.

Assuming that consumers compare the cost of an EV with the cost of a gasoline car and will choose the car type with the lowest cost, we can conjecture that the option for V2G will lead to a higher number of EVs (for $\beta > 0$).

[6] We disregard any conversion loss in the paper as it has no decisive impact on our main results.
[7] See the Appendix A1 for the derivation.

3.2. Total battery capacity

In order to investigate how V2G may affect the electricity market, we need to derive the total battery capacity in the EV fleet. Total battery capacity is depending on the participation rate, β, and is given by:

$$\Gamma=\frac{\beta N}{\bar{x}-\underline{x}}\int_{\underline{x}}^{\bar{x}} B^{*}(s)ds+\frac{(1-\beta)N}{\bar{x}-\underline{x}}\int_{\underline{x}}^{\bar{x}} B^{0}(s)ds \tag{8}$$

Remember that consumers' preferences for long trips are uniformly distributed on $[\bar{x}-\underline{x}]$. The term outside the integral signs is thus the density of consumers at each point along this interval, while the integral adds the choice of each type of consumer. Inserting for B_i^* and B_i^0, e.g., the individually optimal battery capacities, from (3) and (4), and solving the integrals we obtain:

$$\Gamma^{*}=\beta N\left[d_l-\frac{a-(p_e^p-p_e^o)}{2v(\bar{x}-\underline{x})}ln\left(\frac{\bar{x}}{\underline{x}}\right)+\frac{p_{ch}-p_e^p}{2v}\right] \tag{9}$$

$$\Gamma^{0}=(1-\beta)N\left[d_l-\frac{a}{2v(\bar{x}-\underline{x})}ln\left(\frac{\bar{x}}{\underline{x}}\right)+\frac{p_{ch}-p_e^o}{2v}\right] \tag{10}$$

,where Γ^* is total available battery capacity for those who participate in V2G and Γ^0 is total available battery capacity for those who do not participate in V2G.

Hence, introducing V2G to EV owners increases total available battery capacity with:

$$\Delta\Gamma=\frac{\beta N(p_e^p-p_e^o)}{2v}\left[\frac{1}{(\bar{x}-\underline{x})}ln\left(\frac{\bar{x}}{\underline{x}}\right)-1\right]>0 \tag{11}$$

We note that total available EV battery capacity is increasing in the price difference between peak and off-peak periods, and it is decreasing in the level of disutility from en route charging. This also follows from our results about the individual choice of battery capacity.

The impact of V2G on total available battery capacity is also influenced by the limits of the uniform distribution $[\underline{x}, \bar{x}]$. The mean is given by $(\bar{x}+\underline{x})/2$ and the standard deviation by $(\bar{x}-\underline{x})/\sqrt{12}$. It is then easy to show that any increase in the mean will make $\Delta\Gamma$ smaller, while an increase in the standard deviation due to a lower $\underline{x}$, will make $\Delta\Gamma$ larger. Finally, an increase in the standard deviation due to a higher $\bar{x}$, will make $\Delta\Gamma$ smaller. This also follows from our results about the individual choice of battery capacity: When the average consumer is making more long trips, the difference in the choice of battery capacity between a person who participates in V2G and a person who does not, diminishes.

4. V2G and the electricity market

We assume that there are two demand periods within a day. Peak demand periods could be evening hours cooking, heating and washing at home, while off-peak hours would be the other hours. We distinguish between demand from all other use of electricity than EV charging in peak and off-peak, and net charging demand from the EVs. The net charging demand from EVs also differ between peak and off-peak, and whether V2G is utilized or not. If the car owner utilizes V2G, the EV's both demand and supply electricity, whereas without V2G, the EV's only demand electricity.

4.1. Electricity demand from EV owners

We denote the number of off-peak hours per day by h_o, and the number of peak hours per day by h_p. Finally, we let γ denote the probability that fast charging en route happens in the peak demand period.

For those who participate in V2G, the charging demand function (D_p) in a peak hour is given by:

$$D_p=\frac{\beta N}{(\bar{x}-\underline{x})h_p}\int_{\underline{x}}^{\bar{x}}[\gamma(d_l-B(s))s]ds \tag{12}$$

Consumers only charge during peak hours on long trip days by a fast charger, and the amount of electricity they demand depends on their battery size, as shown by the expression inside the integral. The integral must be multiplied by the factor $\frac{\beta N}{(\bar{x}-\underline{x})}$ to get the density of consumers along the interval $(\underline{x},\bar{x})$.

The charging demand function for those who participate in V2G in an off-peak hour (D_o) is given by:

$$D_o=\frac{\beta N}{(\bar{x}-\underline{x})h_o}\int_{\underline{x}}^{\bar{x}}[B(s)+(1-\gamma)(d_l-B(s))s]ds \tag{13}$$

Inside the integral is the charging demand from an arbitrary consumer. Every day during off-peak hours, the consumer charges her battery fully. In addition, there is need for charging when out driving on long trip days. Again, the integral must be multiplied by the density factor.

For those who do not participate in V2G, the charging demand function in a peak hour is given by:

$$D_p^0 = \frac{(1-\beta)N}{(\bar{x}-\underline{x})h_p}\int_{\underline{x}}^{\bar{x}} [\gamma(d_l - B(s))s]ds \tag{14}$$

Eq. (14) is identical to (12) with the only difference that the battery size is smaller in (14) than in (12). Consequently, peak hour demand from EVs will be higher without V2G than with V2G, that is, $D_p^0 > D_p$. The result follows from the fact that the need for en route charging is smaller due to the larger battery sizes with V2G participation.

The charging demand function without V2G participation in an off-peak hour is given by:

$$D_o^0 = \frac{(1-\beta)N}{(\bar{x}-\underline{x})h_o}\int_{\underline{x}}^{\bar{x}} [(1-s)d_s + (B(s) + (1-\gamma)(d_l - B(s)))s]ds \tag{15}$$

The EV charging demand in off-peak hours for those who do not participate in V2G differs from the corresponding expression for those who participate. First, without V2G, EV owners only charge d_s on short trip days. On long trip days, they charge their battery fully in the off-peak hours, and in addition, they charge en route in the off-peak hours with probability $(1-\gamma)$.

It is easy to show that $D_o^0 < D_o$.[8] The reason is that without V2G, the EV owners will only charge their battery fully before they are going on a long trip, while with V2G the EV owners charge it fully every day.

4.2. The EV's supply of electricity

Only EV owners participating in V2G will supply electricity, and electricity will only be supplied in peak hours. We denote this supply by X^{V2G}, given by:

$$X^{V2G} = \frac{\beta N}{(\bar{x}-\underline{x})h_p}\int_{\underline{x}}^{\bar{x}} [(B(s) - d_s)(1-s)]ds \tag{16}$$

By assumption, EV owners only supply electricity to the grid on short trip days.

It is easy to show that we have $X^{V2G} - D_p > 0$ when γ is small.[9] In the rest of the paper we assume that the option for V2G decreases net demand for electricity in peak hours. This turns out to always be the case in our numerical model even if the participation rate β is as low as 0.1 (Section 5).

4.3. Demand and supply from other sources

Electricity supply consists of renewables and conventional power like natural gas, nuclear and coal. As the output of renewable electricity is intermittent and as storage of electricity remains costly, there is a need for a capacity of controllable electricity production, see e.g. Ambec and Crampes (2012). To simplify our model, we assume a fixed level of intermittent renewable production capacity, with an expected output, which is always less than the demand. Hence, there is always some residual demand for conventional controllable power, both in peak and off-peak hours from other sources than EVs.

By subtracting expected renewable output from the demand from other sources than EVs, we can derive the expected residual demand functions for conventional power in peak and off-peak for a representative day (denoted $\bar{D}_p$ and $\bar{D}_o$, respectively).

We assume perfectly competitive producers of conventional electricity. The technology has operating cost c_0 per KkWh and a daily capacity cost Iper kW.

4.4. Electricity market equilibrium without the V2G option

Let K denote the amount of conventional power capacity in the market. Our point of departure is that conventional power supply only runs at full capacity K in peak hours. In the off-peak hours, there is spare capacity, but some of the capacity is still in use. Hence, the only equilibrium price in off-peak hours is:

$$p_e^o = c_0 \tag{17}$$

For the capacity investments to be profitable, we must then have for the peak price:

$$p_e^p = c_0 + \frac{I}{h_p}, \tag{18}$$

where I denotes the capacity investment cost (per day).

Below, in Fig. 1, we illustrate the electricity market equilibrium with and without EVs when V2G is *not* an option, which correspond to the outcome of $\beta = 0$. Prices are equal to the short run and long run marginal costs of the peak-load power

[8] See Appendix A2

[9] See Appendix A2

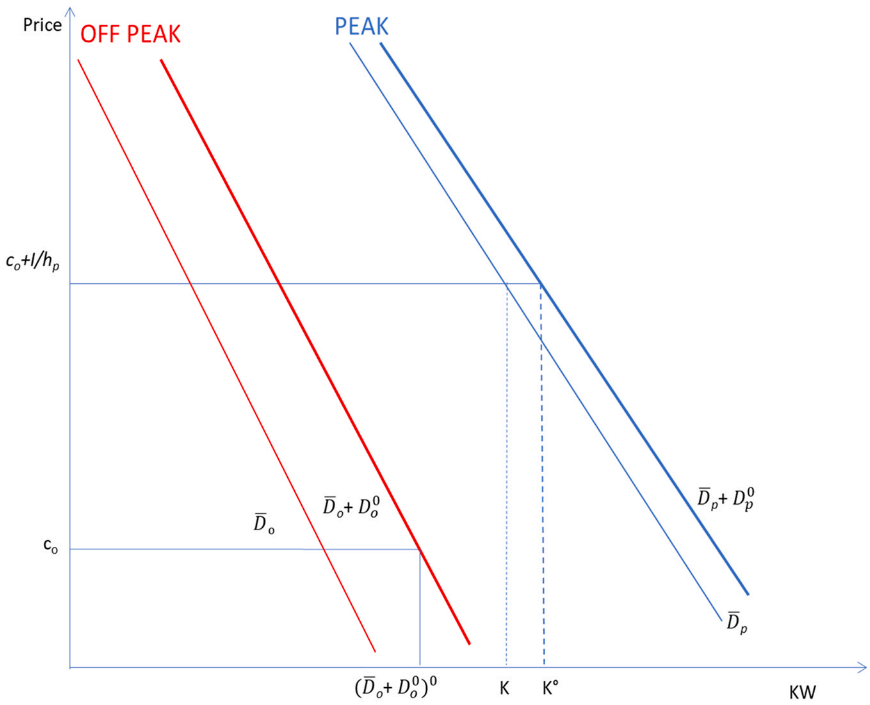

Fig. 1. The electricity market equilibrium without V2G.

technology given by (17) and (18). Moreover, we have included the expected residual demand functions; $\bar{D}_o$, $\bar{D}_p$, and the demand for EV charging in the absence of V2G; D_o^0, D_p^0, in the off-peak and peak periods, respectively.

The thin lines are electricity demand for conventional power in off-peak and peak periods without demand from EVs (the residual demand functions). Then, without V2G, the EV owners select a battery capacity that allows them to limit recharging en route during long trips. This gives the solid, bold demand functions in the off-peak ($\bar{D}_o + D_o^0$) and the peak period ($\bar{D}_p + D_p^0$). We note that demand increases in both periods, but more in the off-peak period, since EV owners do most of their charging off-peak when electricity prices are low. However, because there is always some en route charging, demand also increases in the peak period. The optimal level of generating capacity in this case equals K°, which is greater than K – the original level before EVs started to replace conventional cars.

4.5. Electricity market equilibrium with the V2G option

When we introduce the V2G option, EV owners start to sell electricity to the grid in the peak period on short trip days, which shifts the peak demand function to the left. To simplify, in Fig. 2, we have set $\beta = 1$, and hence, the stippled line denoted ($\bar{D}_p + D_p - X^{VTG}$) is the new net demand function in peak periods. Since we have $X^{VTG} - D_p > 0$, the power capacity can be reduced to $K^* < K^0$.

In the off-peak, power demand will shift further to the right, as EV owners always want to charge the battery fully in order to sell electricity to the grid at peak times. This is illustrated in Fig. 2 by the stippled line denoted ($\bar{D}_o + D_o$).

Note that V2G cannot influence electricity prices as long as net demand in the peak period is higher than total demand in off-peak periods, that is:

$$D_p(p_e^p, p_e^o) + \bar{D}_p(p_e^p) - X^{VTG}(p_e^p, p_e^o) > D_o(p_e^p, p_e^o) + \bar{D}_o(p_e^o) \tag{19}$$

,where p_e^p, p_e^o are given by (18) and (17) above. This is the case in Fig. 3 as off-peak equilibrium demand just falls short of peak demand K^*.

Because prices of electricity in peak and off-peak periods remain constant, the EV owner will receive all the benefits of the option to sell to the grid: a profit from the sales to the grid and the reduced disutility from a larger battery implying less recharging en route. Furthermore, V2G also increases social welfare through decreased need for conventional power capacity.

4.6. V2G and the price of electricity

Clearly, (19) may no longer hold if V2G is introduced. In this case it is optimal with full capacity utilization of peak load power also in off-peak periods. In this case, we must find prices (p_e^o, p_e^p) that equalize net demand in the two periods. Moreover,

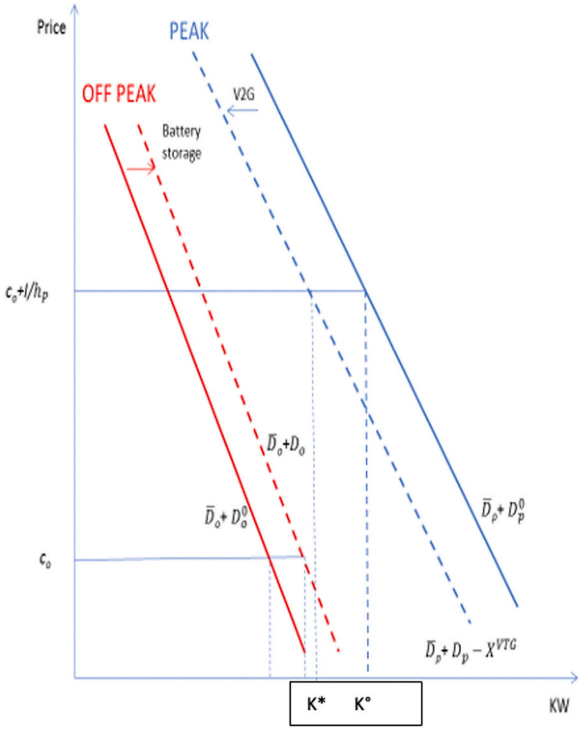

Fig. 2. The electricity market with fixed prices. The effects of V2G (for $\beta = 1$).

we must ensure that the average price over the peak and off-peak hours is equal to the long run marginal cost of conventional electricity. This implies solving the following two equations where p_e^o, p_e^p are the two unknowns.[10].

$$D_p(p_e^p, p_e^o) + \bar{D}_p(p_e^p) - X^{VTG}(p_e^p, p_e^o) = D_o(p_e^p, p_e^o) + \bar{D}_o(p_e^o) \tag{20}$$

$$\frac{h_o}{24}p_e^o + \frac{h_p}{24}p_e^p = c_0 + I \tag{21}$$

In Fig. 3 below, we illustrate the electricity market equilibrium effects of V2G, in the case with full utilization of the capacity at all times:

As above the solid, bold lines are electricity demand in peak and off-peak periods without V2G, and the stippled lines are demand functions in the off-peak and peak period with V2G. Note first that the prices given by (17) and (18) can no longer be an equilibrium: This would imply higher demand in off-peak periods than in peak periods. Consequently, there would be too little conventional capacity in off-peak periods.

Note second, the compression in the difference between the new equilibrium prices and the old equilibrium prices. Allowing EV owners to sell to the grid will still benefit them, but not as much as in the model with spare capacity in off-peak hours. All other electricity consumers may however benefit. Since lower valued KWh from reduced consumption in off-peak periods is exchanged with higher valued KWh for the peak period, gross consumer surplus increases. We illustrate this effect in our numerical model in the next section. Furthermore, there is even less need for conventional capacity to serve the market at peak hours with more EVs participating in V2G.

4.7. Social versus private optimum

The choice of battery capacity by car consumers, derived above, can be compared with the social optimum value of battery power. The social optimum is reached when the total electricity system costs plus the costs of EVs, the EV users' disutility of charging, and the charging services en route are minimized. Given optimal peak and off-peak pricing, and simplifying expressions using $\beta = 1$, the social cost can be written:

$$\Omega = [h_p p_e^p \quad (\bar{D}_p + D_p - X^{V2G}) + h_o \quad p_e^o(\bar{D}_o + D_o)]$$

[10] The solution must also satisfy $c_0 \le p_e^o < p_e^p$ in order for the peak load producer to supply electricity.

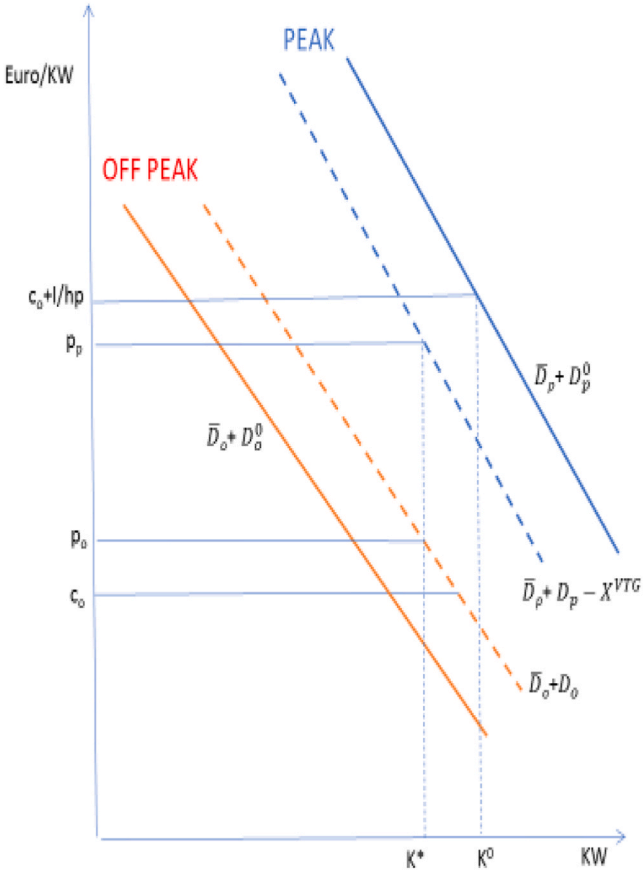

Fig. 3. The electricity market effects of V2G with endogenous prices.

$$+ \quad \frac{N}{(\bar{x}-\underline{x})}\int_{\underline{x}}^{\bar{x}} [[v(d_l - B(s))^2 s] + aB(s) + K(d_l - B(s))s \quad]ds \tag{22}$$

,where D_p, D_o, X^{V2G} are given by (12), (13) and (16), and $K(d_l - B(s))$ is the social cost of providing charging services (fast charging) en route (exclusive the cost of electricity).

By minimizing Ω with respect to $B(x^i)$ we find the following first order conditions for the social optimal battery choice (B_i^{**}) for the EV owner:

$$B_i^{**} = d_l - \frac{a - (K'^{**} + (\gamma p_e^p + (1-\gamma)p_e^o) - p_e^o)x_l^i}{2vx_l^i} + \frac{(p_e^p - p_e^o)x_s^i}{2vx_l^i} \tag{23}$$

,where K'^{**} is the social marginal cost of providing charging services en route ($\frac{\delta K}{\delta B(x^i)}$).

By comparing (3) with (23), we see that if the driver pays the full social marginal cost of charging (charging services plus electricity cost; $p_{ch} = K'^{**} + (\gamma p_e^p + (1-\gamma)p_e^o)$, the private optimal battery capacity equals the social optimal capacity. Hence, a sufficient condition to decentralize the social optimum is to have peak load pricing in the electricity sector, and marginal cost pricing of fast charging along roads.

5. Numerical illustration

5.1. Calibration

Our point of departure will be the Belgian electricity market in 2040. The Belgian network operator ELIA (ELIA, 2017) has made a scenario study for Belgium in 2040, and ELIA projects 2 million EVs in Belgium in 2040 (40% of total car stock). We use Elia (2017) to build a simple model of the Belgian electricity market in 2040.[11]

We assume that gas power is still in use as a marginal source electricity. Consequently, in our baseline scenario gas power only runs with full capacity in peak hours, while there is spare capacity in off-peak hours. [12]

Assuming 2 million EVs, but no V2G, we calibrate the following demand functions to fit with prices and quantities given by ELIA (2017):

$$\bar{D}_j - \bar{S} = M_j (p_e^j)^{-\epsilon} \tag{24}$$

,where $j = o,p$, $\bar{S}$ is the expected supply of renewables, M_j is a market size parameter and ϵ the elasticity of demand in the two periods, which we have set to − 0.8.[13]

In the numerical simulations, we assume that renewable production is uncorrelated with peak and off-peak demand. Hence, we can simply subtract expected renewable production from the electricity demand functions for the peak and off-peak periods.

5.2. Scenarios

There are four scenarios: A baseline scenario without EVs, a no-V2G scenario with 2 mill. EVs, and two scenarios with 10 per cent and 20 per cent EV owner participation in V2G, respectively. For comparison, we have normalized the off-peak electricity price to 1, the off-peak hourly residual demand to 100 and the traditional power investment to 100; all in the scenario without EVs.

As can be seen from Table 1, in the three first scenarios (Column 2–4), neither electricity prices nor residual electricity demand is affected by V2G as long as the participation rate does not exceed 10 per cent. Hence, electricity prices are the same as in the baseline scenario. Still EV charging makes up a considerable bulk of residual electricity demand in off-peak hours, that is, between 40 and 60 per cent of residual demand (Row 7). Note, however, that residual electricity demand is demand after renewable production has been subtracted.

In peak hours matters are different; without V2G, EV charging makes up only 2% of residual electricity demand, while with V2G, the net supply from EVs make up 12% of residual demand (Columns 3, Row 8). This is the reason for the negative sign. In the bottom row we note that this leads to a saving of peak load capacity investments by 14 per cent when we compare with the scenario with 2 million EVs, but no V2G.

We note from comparing the second and the third column in Row 7, that demand in off-peak hours increases due to the introduction of V2G. However, even if those who participate in V2G, increase their charging in off-peak hours by a lot, the participation rate is low such that the total increase in off-peak EV charging is not overwhelming when we introduce V2G.

Finally, if we increase EV owner participation to 20%, the electricity market no longer runs with spare capacity in the off-peak hours. This is due to the increased demand from EV owners wanting to charge their batteries in order to sell electricity in peak hours. Note that EV charging makes up more than 60 per cent of residual demand in off-peak hours with 20 per cent participation rate. Consequently, peak, and off-peak prices change and move closer to each other. Due to the high EV electricity supply in peak hours, capacity investment is further reduced to 84% of the baseline.

In Table 2 we show the welfare effects of introducing V2G for the scenarios with 10% participation and 20% participation. All numbers are relative to the case of 2 million EVs, but no V2G option.

Observe first that the average income from V2G decreases as more owners of EVs start to sell electricity from their car. Eventually, this will likely discourage new EV owners to adopt V2G. Note next for the scenario with 20% participation that the total increase in net consumer surplus is positive. The reason is, as mentioned, that lower valued KWh are exchanged by higher valued KWh, when the price difference between peak and off-peak periods becomes smaller (bottom row, Column 3&4). Finally, note that the saving in capacity investments has increased simply because more EV owners participate in V2G.

5.3. Sensitivity

We have run our numerical illustration with lower elasticities of demand and with more off-peak hours per day. This did not affect our result in any significant way.

6. Discussion and concluding remarks

We have used a highly stylized model to analyze the impact of V2G on the consumers' choice of battery capacities and the impact on the electricity market. From the model, we find that, compared to no V2G charging technology, V2G:

[11] Elia projects yearly electricity demand to be 97,6 TWh including 2 million Evs. We divide each day in 18 off-peak hours and 6 peak hours. The peak and off-peak charge then becomes 14 GW and 10.2 GW, respectively.

[12] In baseline, the price of electricity in off-peak hours is equal to the marginal cost of gas power, which is set to € 50/MWh for natural gas + € 45.2 for EU ETS emission permits. In the peak hours, the electricity price is € 146,9/MWh where € 51,7/MWh is the capital charge.

[13] Csereklyei (2020) estimates the EU long-run price elasticity of residential electricity consumption to be between 0.53 and 0.56 and for industrial electricity use, price elasticities between 0.75 and 1.01. Giving an equal weight to both uses we obtain a value of 0.78, that we round off to 0.8. We have run sensitivity tests for this number down to 0.3 and found that results were little affected.

Table 1
Numerical illustration results.

Number of EVs	Zero	2 mill.	2 mill.	2 mill.
V2G participation (β)	0	0	10%	20%
Off-peak el price €/MWh	1	1	1	1.06
Peak el price €/MWh	1.54	1.54	1.54	1.36
Off-peak residual demand MWh	100	100	100	95
Peak residual demand MWh	183	183	183	202
EV charge off-peak/residual demand	0	41%	50%	61%
Net EV charge peak/residual demand	0	2%	-12%	-24%
Traditional power investment MW	100	102	88	84

Table 2
Welfare effects of V2G (compared to no V2G).

	Income from electricity sales, average per EV owner (€/year)	Change in net consumer surplus off-peak period (mill €/year)	Change in net consumer surplus peak period (mill €/year)	Reduced capacity costs in peak capacity (mill €/year)
2 mill. EVs, V2G available (10%)	688	0.0	0.0	138
2 mill. EVs, V2G available (20%)	380	-136	266	173

- Increases the EV owners' preferred size of battery capacity
- Decreases the cost to the consumer of having an EV
- Reduces the need for investment in power capacity
- Increases social welfare.

Obviously, a stylized model cannot capture all characteristics of the electricity market, consumers' charging and driving behavior, and technological development. However, it is reasonable to expect that the electricity market will face periods with higher net demand (peak hours) and periods with lower net demand (off-peak hours). It is thus a robust result that V2G offers opportunities for peak shaving in countries where hydro capacity is insufficient to bridge the gap between peak and off-peak demand. In addition, V2G can also have a more limited role in balancing.[14] Our numerical illustration of the Belgian electricity market in 2040 indicates that V2G can significantly reduce the need for power production capacity, even if only a small fraction of the EV owners sell electricity to the grid.

6.1. Some caveats

A simplifying assumption in our analytical model is that number and timing of short trip and long trip days are given, although differentiated across EV owners. A justification for assuming exogenous number and timing of short trip days is that short trips and long trips meet very different needs. A short trip typically meets the need for transportation to the office, daily shopping or driving the kids to school, whereas a long trip meets the need for weekend-excursions, visiting friends and relatives, or out of office business trips. Hence, the number of long trips cannot easily be replaced by short trips without losses in welfare.

We presented the electricity market analytically with one conventional generating technology and V2G as the only peak shaving technology. Of course, the electricity supply and demand is more complex with many types of plants and with different centralized and decentralized storage options. The presence of cheap electricity supply together with ample centralized storage (hydro, pumped storage) guarantee that peak and off-peak prices cannot be very different. This is the case in a country like Norway, in which a large hydro-capacity makes electricity production cheap and easy to accommodate to demand fluctuations. In such countries, V2G will only be of secondary importance, while V2H and V2B may still make sense to save electricity grid capacity investments (see Thompson and Perez, 2020, and our literature review in Section 2). When, on the contrary, there is only intermittent renewable combined with traditional fossil fuel plants, prices may fluctuate much more. Other types of storage will then compete with V2G, but we conjecture that V2G anyhow could be an important ingredient of the electricity market since the battery of the EV fulfills a dual role. Furthermore, as we pointed out in Section 3, an increase in the price difference between peak and off-peak prices makes it more profitable for an EV owner involved in V2G to choose a large battery, and thus contribute more to peak shaving.

[14] The model presented in Section 4 can be tailored to analyze the balancing function by adding probabilities for a normal day and a problem day and foresee that EV's that plan a short trip are available for balancing services. This is an additional incentive to increase the battery size.

Another policy implication of our result is that an optimal planning of investments in power plants must consider not only the number of electric cars in the market, but also the development of V2G, the consumers' participation in V2G and their choice of battery capacities.

Realizing this potential faces several barriers. There are the technical problems as regards the proper use of the battery to allow a large number of cycles of charging and recharging. If V2G leads to lower battery performance, the gains from peak shaving and frequency regulations will decrease (or be negative). Furthermore, car companies may decide that participation in V2G supply voids battery warranty. However, current strategies point in the other direction and this problem is being solved.

More important are the proper functioning of the electricity markets and the attention to the specific consumer concerns. We showed in our model that the private optimal battery capacity equals the social optimal capacity if we have peak load pricing in the electricity sector and marginal cost pricing of fast charging along roads. Correct electricity pricing will give car users the incentives to participate in options for smart charging and for V2G. These incentives may also be integrated in the EV packages offered by car manufacturers that may act as aggregators for EV power supply and load shedding. In our model, we assumed that the agents faced the socially optimal electricity prices. There are, however, many distortionary taxes in the electricity market. For instance, the electricity bills for consumers in Europe typically contain renewable energy levies, fees, surcharges etc. (Grave et al., 2016). High consumer taxes on electricity make the income from peak shaving small, and even negative. Such taxes will therefore lead to insufficient investment in batteries, compared to the social optimum. Note, however, that the disincentives following from the price difference between consumer and producer prices can be avoided if the EV owners use the EV battery capacity to meet their own residential demand during peak hours, so called V2H or V2B (see Thompson and Perez, 2020). We also need marginal cost pricing of fast charging along roads. However, competition between fast charging stations will typically be monopolistic, due to the variety of geographical locations. We should then expect en route charging prices that exceed the marginal cost (socially optimal charging cost). We see from (3) and (4) that when the price of charging en route is higher than the socially optimal price, the battery capacities will exceed the socially optimal capacity.

Another potential source for inefficiency is subsidies on battery capacity. EVs are heavily subsidized in many countries (Kemfert, 2016). Due to network externalities, subsidizing EVs to increase the stock can be a socially optimal policy (Greaker and Midttømme, 2016). In our model, the number of EVs are given, but the model can point to situations where subsidizing EVs can lead to inefficiencies. In our model, the cost of purchasing the EV is increasing in the battery size, which is a typical characteristic of the market prices of EVs (see aB_i in Eq. 1.). If subsidies are linked to the price of the car (as for instance purchase subsidies), the consumers will buy a larger battery (more expensive car) than without the subsidies, and the total battery capacities will exceed the socially optimal level.

A policy recommendation from our analysis is that regulators planning to support the introduction of V2G should signal that early, in order to ensure that EV owners can adjust their choice of optimal battery capacity accordingly. According to Thompson and Perez, there is an urgent need to adapt the regulatory framework to V2G. Starting that process now will send a clear signal to EV buyers that they should take V2G (and V2H/V2B) into account when buying an EV.

Finally specific consumer concerns require attention. First, as V2G is an extra feature of the new technology (EV), one needs research to overcome the consumer hurdles that are specific for the adoption of new technologies (Sovacool et al., 2017). One specific concern is range anxiety, EV drivers prefer to avoid en route charging and this requires that their battery always allows a capacity for a short trip. This needs to be integrated in smart V2G software.

Acknowledgements and Conflicts of Interest

We thank associate-editor Antweiler and anonymous referees as well as Rolf Golombek and Terje Skjerpen for their helpful suggestions. We are also grateful for financial support by the Norwegian Research Council (NRC) for the two projects 209698 and 255077, and the Industry Partners Co-Financing the project 255077 (Energy Norway, Norwegian Water Resources and Energy Directorate, Ringeriks-Kraft AS, Norwegian Public Roads Administration and Statkraft Energi AS). The authors have no conflict of interest .

Appendix

A1 The derivation of Eq. (7)

By rearranging the expressions for the EV costs and using the first order condition for the optimal battery size, we obtain:

$$c(B_i^*) = v((d_l)^2 - (B_i^*)^2)x_l^i + p_e^p d_s x_s^i + p_{ch} d_l x_l^i$$

$$c(B_i^0) = v((d_l)^2 - (B_i^0)^2)x_l^i + p_e^o d_s x_s^i + p_{ch} d_l x_l^i$$

By inserting for the optimal battery size in the two cases and subtracting $c(B_i^*)$ from $c(B_i^0)$ we obtain (7).

A2 Proofs of $D_o^0 < D_o$, and that $(X^{V2G} - D_{p)})$ can be positive

By rearranging the integrals, it is easy to see that $D_o^0 < D_o$:

$$D_o = \frac{N}{(\bar{x} - \underline{x})h_o} \int_{\underline{x}}^{\bar{x}} [(1-s)B^*(s) + (1-\gamma)d_l s + \gamma B^*(s)s]ds$$

$$D_o^0 = \frac{N}{(\bar{x} - \underline{x})h_o} \int_{\underline{x}}^{\bar{x}} [(1-s)d_s + (1-\gamma)d_l s + \gamma B^0(s)s]ds$$

since $B^*(s) > B^0(s) > d_s$.

For the net supply from EVs with V2G in peak hours, we have:

$$X^{V2G} - D_p = \frac{N}{(\bar{x} - \underline{x})h_o} \int_{\underline{x}}^{\bar{x}} [(B^*(s) - d_s) + ((1-\gamma)B^*(s) + \gamma d_l - d_s)s]ds$$

This is clearly positive for $\gamma = 0$. By continuity it will be positive for $\gamma > 0$.

A3 Variations in intermittent energy supply

In Section 4, we looked at a long run equilibrium in which investments in conventional capacity were based on the expected demand for conventional electricity production, given the expected renewable energy production in peak and off-peak. Since electricity produced from wind and solar are intermittent, it will typically vary across days and seasons. In our model, a day with lower renewable production than expected implies a positive shift in the residual demand function. The car owners have the same charge and discharge behavior, such that the net demand function will have a correspondingly positive shift. If we are in a situation where there is still excess off-peak capacity, the impact under both V2G and without V2G will be higher prices in the peak time to clear the market, and no impact on the off-peak price. For linear residual demand functions, as in our figures, the price increase in peak will be identical under V2G and without V2G. Due to larger differences between peak and off-peak prices, the EV owner will earn more money on peak shaving by V2G that day. For days with renewable production higher than expected, the impact will be reversed. Price in peak will fall, and the EV owner will earn less money on peak shaving by V2G that day. On average, however, the income will be the same.

However, we saw from Fig. 2 that V2G leads to lower production capacity than without V2G ($K^* < K^0$). Furthermore, the net demand in off-peak is higher under V2G than without. Both effects lead to an off-peak demand closer to the full capacity under V2G than without V2G. Hence, a normal day may have spare capacity in off-peak, but days with low renewable production may lead to full capacity production in off-peak under V2G, but not without V2G. We illustrate this effect in Figs. 4 and 5.

Fig. 4 presents the possible outcome without V2G, whereas Fig. 5 presents the possible outcome with V2G. The thin lines in both figures are residual demand functions in the off-peak and peak period with expected production of renewable production (denoted with superscripts "E"). These outcomes correspond to the situation described in Fig. 2. The bold lines are residual demand functions in a day with low renewable supply, and hence high residual demand for conventional power (denoted with superscript "H"). With V2G, the shift in demand is sufficiently large to induce full utilization of the capacity also in the off-peak period (Fig. 5). Due to the larger spare capacity without V2G, a similar shift in demand would not influence the off-peak price in the absence of V2G (Fig. 4). Thus, V2G implies a lower residual consumption in off-peak compared to no V2G in days with sufficiently low renewable energy production. The peak price will increase under both V2G and without.

The impact of days with higher versus lower renewable production than average is not symmetric, as the consumer price in off-peak cannot fall below the operating cost (c_0). Hence, we can conclude that although V2G saves capacity investments, this comes with a cost. Variations in renewable energy production may have a larger negative impact on the consumer surplus under V2G compared to no V2G.

A4 The numerical model

According to ELIA (2017), yearly total demand for electricity in 2040 amounts to 97.6 TWh including 2 million EVs (40% of Belgian car stock). According to our model 2 million EVs will need a yearly charging of 12 TWh without V2G. On a yearly basis, we assume 2200 peak hours and 6560 off-peak hours, and hence, we have $h_p = 6$ and $h_o = 18$. Again according to Elia (2017) the peak hour load is expected to be 14 GW, assuming that nearly all charging takes place in off-peak hours, we calculate the off-peak hour load to be 8,4 GW.

The variable fuel cost of gas power is €50 per MWh. Adding the cost of ETS permits, we get to €95.2 per MWh which we assume is the price in off-peak hours. Assuming an investment cost of €850,000 per MW, a 20 year lifespan, and a real interest rate of 12%, we obtain for the capital cost per year €113,797. In order to cover this in 6 peak hours per day, the capital cost charge must be €52 per MWh. Thus, our peak hour price of electricity is €147.2 per MWh.

Moreover, we assume that the expected production from renewables is 4.9 GW per hour. This implies an average renewable share of residual demand of 50%. Moreover, we set the number of EVs to 2 million (ELIA, 2017), and assume that only a fraction of the EV owners will use their EV for V2G. We also introduce a conversion factor (η), that is, we assume that only 90% of the available battery capacity can be sold to the grid. Furthermore, the KWh use for a long trip is 60; for a short trip it is set to 10. The number of long trips per year varies between 10 and 100, which we think encompasses the bulk of the real distribution.

In order to simulate the numerical model, we solve the integrals (12) - (16):

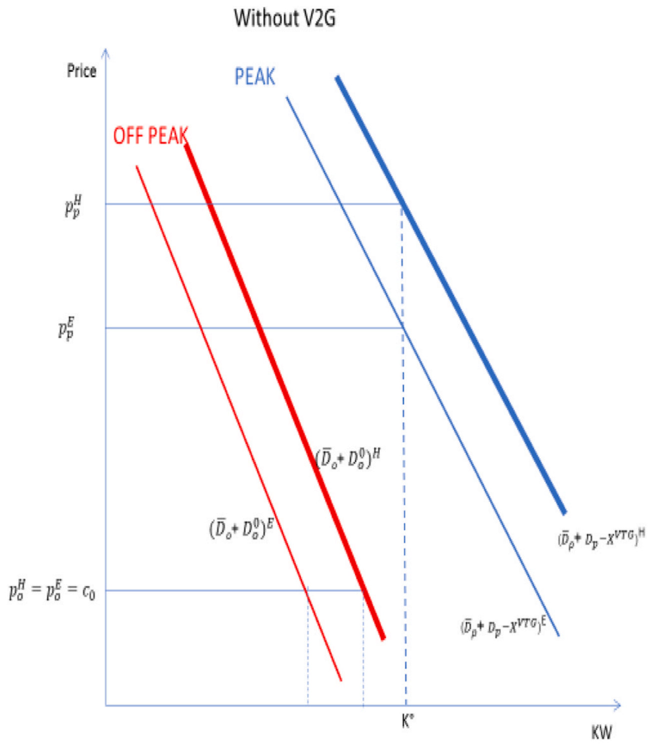

Fig. 4. Electricity market on a day with high residual demand without V2G.

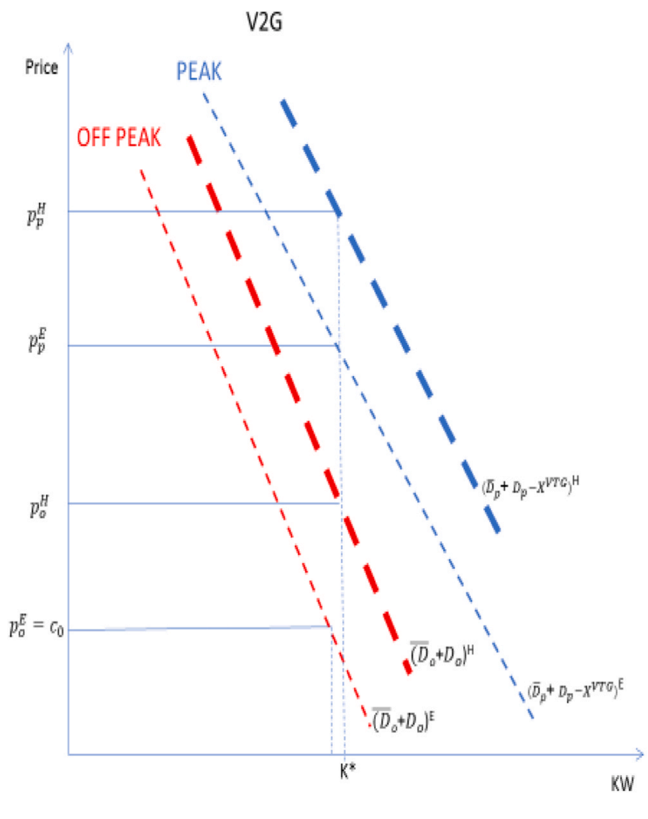

Fig. 5. Electricity market on a day with high residual demand with V2G.

$$D_p = \frac{\gamma N}{365h_p}\left[\frac{a - 365(\eta p_e^p - p_e^o)}{2v} - \frac{p_{ch} - \eta p_e^p}{4v}(\bar{x} + \underline{x})\right]$$

$$D_o = \frac{\Gamma^*}{h_o} + \frac{(1-\gamma)N}{365h_o}\left[\frac{a - 365(\eta p_e^p - p_e^o)}{2v} - \frac{p_{ch} - \eta p_e^p}{4v}(\bar{x} + \underline{x})\right]$$

$$D_p^0 = \frac{\gamma N}{365h_p}\left[\frac{a}{2v} - \frac{p_{ch} - p_e^o}{4v}(\bar{x} + \underline{x})\right]$$

$$D_o^0 = \frac{Nd_s}{h_o} + \frac{N}{365h_o}\left[\frac{2v(d_l - d_s) + (p_{ch} - p_e^o)\gamma}{2v}\frac{(\bar{x} + \underline{x})}{2} - \frac{\gamma a}{2v}\right]$$

$$X^{V2G} = \frac{\eta(\Gamma - Nd_s)}{h_p} + \frac{\eta N}{365h_p}\left[\frac{a - 365(\eta p_e^p - p_e^o) - v(d_l - d_s)(\bar{x} + \underline{x}) - (p_{ch} - \eta p_e^p)\frac{(\bar{x} + \underline{x})}{2}}{2v}\right]$$

Finally, we have for the change in gross consumer surplus:

$$\Delta CS = \frac{(M^j)^{\frac{1}{\epsilon}}}{\frac{1}{\epsilon} - 1}\left[(d_j^0)^{-(\frac{1}{\epsilon}-1)} - (d_j)^{-(\frac{1}{\epsilon}-1)}\right]$$

Where (d_j^0) is demand without V2G in period j (off-peak or peak) and (d_j) is demand with V2G in period j (off-peak or peak). The model is programmed in Excel Solver.

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