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Driving energy system transformation with "vehicle-to-grid" power

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Abstract

Today's electricity and transport systems face a number of challenges related to reliability, security and environmental sustainability. New technologies may provide a means by which to overcome some of these challenges, yet many such technologies are confronted with substantial technical or commercial hurdles. This report explores one promising technology, "Vehicle-to-Grid" (V2G) power generation, whereby parked Electric-Drive Vehicles (EDVs) are used to provide electricity to the grid. EDVs comprise battery-electric (BEV), hybrid-electric (HEV) and fuel cell-electric (FCEV) vehicles. V2G power generation may be attractive because, on one hand, vehicles are parked on average 96% of their lifetime (and thus available for other uses) and, on the other, the power capacity of the global automobile fleet greatly exceeds installed conventional electricity generation capacity.

We examine the potential of V2G power generation, firstly, from the EDV's owner perspective and, secondly, in the energy market place. Our results confirm that EDVs have some potential market value, considering our assumptions that are based on the CAISO Californian power market. To complement and extend the previous analysis, we compared the full economic costs of EDVs providing V2G power generation and mobility services with conventional solutions: power generated by gas turbine or coal-fired power plants; and mobility provided by conventional gasoline internal combustion engine vehicles (ICEVs). Our analysis indicates that although conventional systems generally remain competitive under today's market conditions, the complementary use of EDVs for energy and mobility may be competitive in specific power markets and under certain conditions. We explore the conditions under which V2G systems could be more competitive with a sensitivity analysis of the potential impact of technology and resource costs and infrastructure requirements. In addition, we analyse the impact of a climate policy on the competitiveness of alternatives. These results suggest that only carbon taxes up to $650/tonne of Carbon would have significant impacts on the ranking position of V2G technologies, although we explored only a limited set of scenarios and thus results should be envisaged with caution.

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About the Author

Filipe graduated in 1996 in Environmental Engineering in the Faculty of Sciences and Technology of the New University of Lisbon and completed his M.Sc. in Transportation in 2001 at the Instituto Superior Técnico of the Universidade Técnica de Lisboa. Since he finished is M.Sc., he has worked on transport, energy and environmental policy research analysis. In particular, he has conducted research on the impact of transport activity on the emissions of greenhouse gases and atmospheric pollutants (such as NO_x, SO_2, CO and PM) when he participated in the development of the background studies for the Portuguese National Program for Climate Change and the National Emissions Ceilings for Acidifying substances and Ozone precursors.

The main focus of his research thus far has been on the role of non-technological solutions to mitigate atmospheric emissions. His Ph.D. research now turns to looking at the technological issues of the transport system. He is currently a third-year Ph.D. student at the Instituto Superior Técnico and the title of his thesis is "Car fleet renewal as a key factor for the reduction of atmospheric emissions". For three months during the summer of 2005, he was a participant of the Young Scientists Summer Program, during which he researched the role of “Vehicle-to-Grid” (V2G) systems in a sustainable energy system and whether a possible implementation of this emerging new feature of Electric Drive Vehicles could accelerate the transition to more efficient and less polluting vehicles.

1 Introduction

In industrialised societies, virtually every aspect of modern existence is dependent on fossil fuels (such as coal, natural gas, oil, etc.). Fossil fuels have supported, and continue to be essential to economic development in the modern era. This is especially so in the case of modern transport systems which account for around 30% of global energy consumption and around 60% of global oil consumption (International Energy Agency, 2004a). Additionally, transport energy demand is forecast to grow rapidly—by 2.5% per year over the medium term (Energy Information Administration, 2002). Within the transport sector in industrialised countries, a large proportion of passenger and freight traffic is transported by road vehicles, with private automobiles accounting for nearly 80% of OECD passenger transportation (International Energy Agency, 2004a, International Energy Agency, 2004b). Moreover, road transportation relies almost entirely on oil-based fuels.

This dependence on oil poses challenges to the long-term sustainability and security of transport systems, particularly in light of concerns about how long conventional oil reserves will last and risks to disruption of the oil supply arising from geopolitical instability, hostilities or terrorist activity. In addition, transport has long been associated with environmental and other problems related to safety, air, water and noise pollution, and competition for urban space. Given these linkages between transport and energy security and environmental impacts, longer-term projection trends give rise to serious concerns about the future economic and environmental sustainability of current transport systems. As a means to address these concerns, a number of new vehicle technologies based around electric-drive systems are emerging.

While the availability of cheap oil has underpinned the development of the current transport system, other fossil fuels have been essential for supplying other energy needs, including in the production of electricity—a vital energy carrier in today's world. It is expected that electricity will become increasingly important in the future, given that it is a clean, convenient and flexible energy carrier (Nakićenović, 2000), which can be produced from a wide range of feedstock. Such an increase in the importance of electricity in the future means that the quality and reliability of the electricity system will become increasingly critical to economic and social activities (Gellings, 2003). This reliability and quality depend on a number of separate systems: before we can use electricity in any application, power has to be generated, transmitted, and distributed.

To ensure reliability and power quality, the elements of the electricity supply chain need to be able to withstand failures and disturbances of the network. These disturbances can last from few minutes to several days and can impose severe economic and social costs, both during and after disruptions. Although life-critical systems are generally required to have emergency backup power systems, a moment's disruption can have devastating effects on power sensitive customers such as internet service providers, data centres, and other users (Casazza and Delea, 2003). A 2001 report from the Electric Power Research Institute estimates that power outages and problems with power quality cost the U.S. over $119 billion per year (EPRI, 2001).

In the power market, it is currently accepted that centralized electric power plants will remain the major source of electric power supply. However, Distributed Energy Resources (DER)—usually small generators located at end-use sites—can complement centralised power production by providing incremental capacity to the electricity grid or end users. DER provides an alternative means to address the needs of customers, meet load growth without the need for costly network upgrades, and help to fill the reliability gaps through ancillary services to the grid (EPRI, 2001, Lasseter et al., 2002).

One currently unexploited source of DER is emerging in the form of Electric-Drive Vehicles (EDVs), which may have the potential to both address some of the challenges in the transport sector discussed above and ameliorate some of the electricity system reliability risks in specific power markets. EDVs powered by batteries (i.e., battery electric vehicles, or BEVs), hybrid engines (HEVs), or fuel cells (FCEVs), are beginning to play an increasingly important role in transport. EDV-DER is based on the concept of "vehicle-to-grid" (V2G) power generation whereby power is dispatched to the grid from the vehicle's engine, in the case of FCEVs, or from the vehicle's electricity storage, in the case of BEVs and HEVs, while these vehicles are parked and connected to an electric interface in residential garages or public and private parking lots (Kempton and Tomić, 2005a). As mentioned, V2G technology represents a potential opportunity to address important needs in transport and electricity supply.

However, despite this possible role of EDV-DER, EDVs still face a number of commercial and technical barriers (e.g., limited storage in BEV batteries and FCEV hydrogen tanks) and any transition to new vehicle technologies is likely to span long periods of time, due to the large inertia and lock-in of current technological systems designed around petroleum and internal combustion engine vehicles (ICEVs) (Turton and Barreto, 2004a). Nonetheless, V2G brings a new source of value to EDVs by using their power capacity and stored energy to provide electricity to the grid, and may support the deployment of EDVs, and thereby the shift away from petroleum-based technologies.

Many studies have contributed to the evaluation of the potential of V2G power generation (Arthur D. Little, 2002, Brooks, 2002, Kempton and Letendre, 1997, Kempton et al., 2001, among others). These previous studies have generally focused on the market potential of providing V2G power, on the basis of the costs and revenues associated with providing energy services only, whilst excluding the costs of purchasing and running the vehicles for mobility purposes. Critically, these costs are not insignificant, and by excluding them these earlier studies may have under- or overestimated the suitability of V2G.

To address this issue, our study examines the potential economic benefits of V2G employing different EDV technologies to provide both electricity and mobility services. The main goal is to examine the competitiveness of EDV-DER compared with conventional technologies used for power generation and mobility to explore the potential role of V2G in future energy systems. To reiterate, this approach represents an important improvement over those of the earlier studies referred to above, which examined only the incremental costs or benefits of using EDVs for electricity services—that is, without taking into account the costs associated with using EDVs for the provision of mobility services.

In the following sections, we first review the concept of V2G and relevant technical issues and assumptions used in our analysis (**Section 2**). Costs and revenues for EDV owners when providing V2G power are analysed in **Section 3**, where we review the calculation method proposed by Kempton and others (Kempton et al., 2001, Kempton and Tomić, 2005a) and discuss the results based on the sensitivity analysis performed to some variables considered in that method. After presenting the methodology used to assess the economic performance of each technology, results for a “Base Case” analysis are presented and discussed in **Section 4**. Here, the costs of using EDVs for electricity and mobility services are compared with alternative “conventional” technologies. We also explore the conditions under which V2G systems could be more competitive with a sensitivity analysis of the potential impact of technology and resource costs, infrastructure requirements and a climate policy. Finally, **Section 5** presents the discussion of final conclusions, overviews the limitations of the present analysis, and suggests further research to complement the results obtained.

2 Concept: Vehicle-to-Grid (V2G) power

2.1 The V2G concept, electric-drive vehicles (EDVs), interface and infrastructure

The logic behind the concept of V2G is that vehicles are parked, on average, 93-96% of their lifetime and thus available for alternative uses. While parked, vehicles represent an idle asset—in terms of both energy storage (in the fuel tank or battery) and energy conversion capacity—and can create negative value due to parking costs. V2G provides a means by which to exploit parked EDVs to generate electricity for the grid, creating additional value. That is, V2G enables EDVs to both act as DERs and provide mobility services, bringing the transportation and the electricity systems together.

Figure 1 schematically illustrates how V2G power generation works. It shows conventional electricity generation from primary energy sources (left hand side of the diagram), and the transmission and distribution systems leading to the retail power market and end-use consumers, i.e. houses, buildings, commercial areas, parking lots, etc… The doubled-arrows represent potential two-way flows to and from EDVs. Electricity flows one-way from conventional electricity generators through the grid to electricity users, including EDVs charging their batteries. Electricity flows back to the grid from EDVs (including FCEVs). Such a system must be controlled by the grid operator who monitors the flows from and to the vehicles by some remote control system. There are virtually no limits to where and when V2G power could be generated, providing that there is an outlet and the proper infrastructure and connection system. For example, V2G power could be generated during the night at home, when the vehicle is parked in the garage or in parking lots at the office, during the working hours.

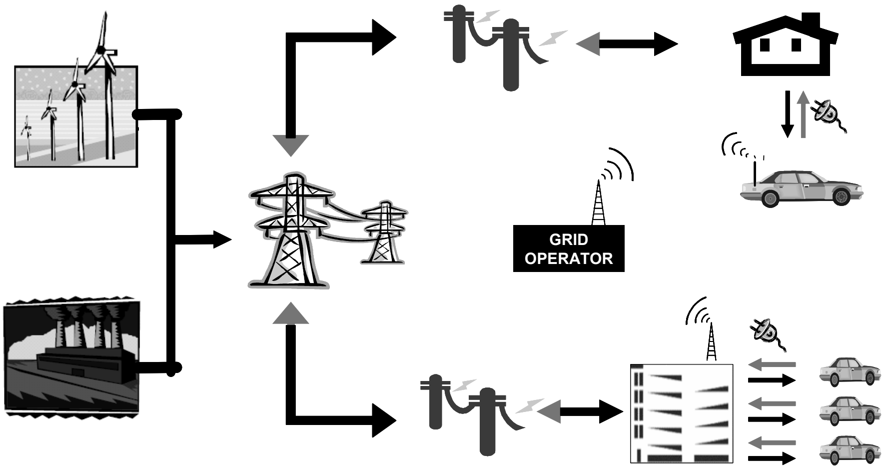

Figure 1: Illustrative diagram of the proposed V2G power generation system (Kempton and Tomić, 2005a)

As mentioned in Section 1, three main types of EDVs may be suitable for generating V2G power: BEVs, HEVs and FCEVs. Today's BEVs rely on large battery systems and are routinely connected to the electricity grid for recharging (with regenerative braking providing additional recharging), and thus may be well suited to providing power back to the grid during times when additional power is needed. On the other hand, today's HEVs can not be plugged into the grid to be recharged, even though they have similar (albeit smaller) electric propulsion and battery systems to BEVs, in addition to a more conventional internal combustion engine (ICE). However, the next generation of HEVs is expected to have larger batteries (up to 9 kWh unlike today's 1-2 kWh storage capacity), and be able to be recharged by plugging into a standard household outlet (EnergyCS, 2005, EPRI, 2001, Sanna, 2005). The third type of EDV examined here is the FCEV, which also relies entirely on electric motors for propulsion, but generates electricity onboard directly from liquid or gaseous fuel, typically, by feeding molecular hydrogen (H_2) into a fuel cell. In other words, FCEVs represent a potential source of V2G power that does not rely on battery storage, but rather the fuel stored in the onboard tank. Moreover, in the future it may be possible to connect FCEVs to gaseous or liquid fuel (e.g., H_2) distribution systems at many of the places where vehicles are parked (i.e., commercial or residential buildings). Such a fuel connection would allow power production of essentially unlimited duration. However, FCEVs currently face a number of commercial and technical barriers related to cost, distribution infrastructure requirements, on board storage of H_2, and conversion losses, meaning that these vehicles are unlikely to be practical and cost-effective, at least in the shorter term (Keith and Farrell, 2003). However, over the longer term significant cost reductions and improvements in competitiveness are possible. The main technical and economic characteristics of the EDVs discussed above assumed in the present study are presented in the next table.

Table 1: Technical parameters of the vehicles, base case

Vehicle type	Drivetrain cost[a] ($/vehicle)	Fuel efficiency for mobility (km/kWh)	Fuel type and cost		η electricity[b]	Energy storage capacity[c] (kWh)	Lifetime of battery or FC[d] (hours)
ICEV	$2,425	1.66	Gasoline	$5.00/GJ	na	na	na
BEV	$9,613	4.00	Electricity	$15.95/GJ	0.73	27.4	2,000
HEV	$3,528	2.13	Gasoline	$5.00/GJ	na	na	
			Electricity	$15.95/GJ	0.73	2	1,500
FCEV	$4,538	4.58	Hydrogen	$14.31/GJ	0.65	116.5	30,000

a. Manufacturing costs (Arthur D. Little, 2002).
b. Conversion efficiency, accounting for losses in grid-to-battery-to-grid conversion for BEVs and HEVs, and conversion from H_2 to DC electricity to AC electricity by FCVs.
c. Excluding gasoline tank in ICEV and HEV. Based on the NiMh battery of the Toyota RAV4 EV (BEV), a NiMh battery of 2kWh of a Toyota Prius (HEV), and 3.5 kg of H2 (rather than the 2kg from Prodigy2000) (Kempton and Tomić, 2005a).
d. Measured in cycles of charge and discharge for energy throughput and the fuel-cell system. We considered an 80 percent depth-of-discharge (DoD) for BEVs providing V2G services, and a deeper 20 percent DoD for HEVs, to account for the smaller size of the battery in the latter.

In terms of the connection to the electric grid, for BEVs and HEVs with on board conductive charging, virtually all the physical connections already exist. Conductive charging allows V2G flow with little or no modification to the charging station and no modification to the cables or connectors assuming on-board power electronics are designed for this purpose. However, in addition to the physical connection, the interface between the vehicle and the grid operator has to be considered (Figure 2). The basic concept assumed here is that the vehicle providing grid power is draining a battery (in the case of BEVs and HEVs) or emptying an on-board liquid or gaseous fuel tank (in the case of FCEVs). In such situations, the driver has to limit the drawdown so the next trip is not affected by a shortage of fuel. As proposed by Kempton and Letendre {, 1997 #233}, working within the constraints of the driver's settings, the grid operator (or the power buyer in general terms) must limit the degree of battery discharge or fuel tank rundown. Figure 2 shows a suggested design of vehicle dashboard control, allowing driver to limit loss of range of vehicle and monitor power transactions.

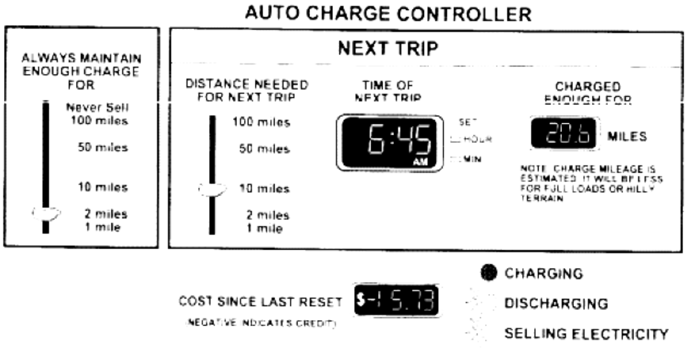

Figure 2: Suggested design of vehicle dashboard control, allowing driver to limit loss of range of vehicle and monitor power transactions (Kempton and Letendre, 1997).

Based on the settings provided by the dashboard, the vehicle communicates with the power buyer. Refer to Kempton and Tomic (2005b, Appendix A3) for details on the possible communication systems for concentrated or dispersed V2G sources. In the first case, an example is a parking lot of a car rental company that also provides power to the grid and for which communication requirements are simplified. In the second, an example can be low density rural areas where the communication system is more complex but could be managed with mobile phone text messages, wireless connections or Internet.

2.2 V2G power capacity and targeted power markets

There are four independent factors limiting V2G power capacity that EDVs can supply, including: the carrying capacity of wires in buildings and other circuits connecting the vehicle to the grid; the maximum power of the vehicle's power electronics (up to 100 kW); and the number of vehicles plugged and with available stored electricity to dispatch to the grid (refer to Kempton and Tomić (2005b) and Kempton *et al.* (2001), for further details). The fourth limiting factor is the stored energy in the vehicle which, together with the time the vehicle is used for providing V2G power, constrains the maximum power capacity—the longer the duration of dispatch, the lower the maximum power capacity. We discuss each of these in more detail below.

Wiring capacity – The electrical wiring in houses varies from country to country. For instance, in the United States, household electricity is supplied at 110 or 120 volts and 60 Hz whereas European electricity is generally supplied at 220 volts and 50 Hz. Considering electric wiring at 110V AC, a major appliance (e.g., an electric range) can draw a power capacity of 5.5 kW at a current of 50A (Power = Voltage x Amperage), from the 6.6 kW standard US circuits of residential buildings. For commercial buildings or larger residential buildings, the limit could be 25-50 kW. On the vehicle side, the wiring capacity of the EDV can be charged with a more than the standard 6.6 kW circuit. AC Propulsion (Brooks, 2002) designed a V2G-compatible EDV able to charge and supply at 80A, equivalent to 18 kW (if the voltage at the outlet is 220V AC). Although the standard wiring capacity of US residential buildings is 6.6kW, in this study, we assumed an upper limit of 15 kW, so that higher power capacity could be provided by EDVs. Additional costs of wiring up buildings are included (refer to footnote 2, p.13).

Stored energy in the vehicle – The power capacity of V2G is also capped by the maximum amount of energy available in the on-board storage system, and can be estimated by Eq. 1, as proposed by Kempton *et al.* (2001).

$$P_{Vehicle} = \frac{\left(E_s - \frac{d_d + d_{rb}}{\eta_{veh}}\right)\eta_{inv}}{t_{disp}} \qquad \text{Eq. 1}$$

Where, $P_{Vehicle}$ is the maximum power from V2G in kW, E_S is the stored energy (kWh DC) available to the inverter, η_{inv} is electrical conversion efficiency of the DC to AC inverter (we assumed 0.93), d_d is the distance driven in km since the energy storage was fully charged (we assumed 20 km), d_{rb} is the distance in km of the range buffer required by the driver (we assumed 10 km), η_{veh} is the vehicle fuel economy in (km/kWh), and t_{disp} is the time the vehicle's stored energy is to be dispatched in hours.

In the case of HEVs, the driver doesn't need to have any buffer range (d_{rb}) from the batteries, because we assume that there is enough petrol in the tank for the next trip on full ICE mode. Thus, the available electric energy capacity of the HEV depends on the driving behaviour and decisions of the EDV owner over the last trip. On this basis, we conservatively assume that, on average, 50 percent of the energy storage capacity in the battery is available for V2G services. Thus Eq. 1 is transformed into Eq. 2.

$$P_{Vehicle} = \frac{0{,}5 \times E_s \times \eta_{inv}}{t_{disp}} \qquad \text{Eq. 2}$$

By analysing Eq. 1 and Eq. 2, it is clear that the larger the energy storage, the higher is the V2G power capacity of an EDV, up to limits imposed by vehicle wiring capacity. However, the V2G power capacity also depends on driver requirements and behaviour: the longer the daily travelling distance, the larger the buffer range required.

The time of dispatch (t_{disp}) in Eq. 1 and 2 above is dependent on the type of power market (Table 2). By time of dispatch we refer to the time during which the vehicle is providing electricity to the grid. The longer is the time of dispatch the lower will be the V2G power capacity.

Availability of resources – V2G power is limited also by the total number of EDVs in the fleet, whether these are plugged-in and if the vehicle owner makes available a sufficient share of on-board stored energy for provision of electricity services. For the last two factors, we conservatively assumed in our calculations that there is 50% chance that some part of a vehicle's energy storage is available (not including the average daily distance energy consumption or assumed buffer range for the following trip). In comparison, Kempton *et al* (2001) estimate that between 92% and 95% of vehicles are available for V2G power, even during the afternoon rush hour. The other limiting factor is the number of EDVs, which is currently small but growing rapidly. For example, the California Air Resources Board (CARB) mandates increasing percentages of each manufacturer's new vehicles sold in the state to be zero-emission vehicles (ZEV) or partial (P)ZEV (CARB, 2000). The power capacity from EDVs in this market was estimated to be 424 MW in 2004, and is expected to increase to 2,279 MW by 2008. For comparison, 2,279 MW would be a quantity similar to two large nuclear power plants or 4% of the California state-wide generating capacity of 54,000 MW.

Accordingly, V2G power capacity is limited by several factors, both internal and external to the EDV's systems. However, it is expected that if EDVs become widely diffused, some of the limitations will be less relevant as the total number of EDVs plugged to the grid and ready for energy dispatching increases.

Depending on the power market, the V2G power capacity can greatly vary. In this study, we distinguish between four main power sub-markets. Among these, base load power represents the largest in terms of volume of electricity because it covers "*round-the-clock*" generation. V2G power generation was analysed in several studies showing that EDVs are unlikely to be competitive for base load electricity generation, but may be suitable for ancillary services (regulation services and spinning reserves) and peak power demand (Kempton and Kubo, 2000, Kempton and Letendre, 1997, Kempton et al., 2001). These electric power submarkets, which we discuss below, differ in terms of control method, response time, dispatch duration, contract terms and price. Key assumptions concerning power market technical characteristics are presented in the next table.

Table 2: Technical and economical assumptions of the power markets, base case

Parameters	Power markets[*]				Comments and references
	RUD	RU	SR	PP	
Standard residential line capacity (kW)	6.6				Assumed basic wiring capacity in residential buildings. Commercial sites or buildings this could go up to 25 kW or higher.
Upgraded line capacity (kW).	15				The upgrade is assumed to cost $1,500 in our baseline scenario.
Vehicle upgrading ($)	400				Cost of additional systems required to connect vehicles for V2G power generation (e.g., communication, wiring, safety systems, etc.)
$R_{d\text{-}c}$	10	n.a.	n.a.	n.a.	Ratio (%) of dispatched energy to contracted capacity (CAISO, 2004).
Time of Dispatch (hours)	0.33	1.40	1.00	4.00	Assumed duration of dispatching energy (Kempton and Tomić, 2005a).
Nº Calls (per day[†]; per year[‡])	400[†]	200[†]	20[‡]	50[‡]	Number of call during one year (Brooks, 2002, Kempton and Tomić, 2005a).

[*] RUD-Regulation Services Up and Down; RU-Regulation Services Up; SP-Spinning Reserves; PP-Peak Power; n.a.-not applicable.

Regulation services are necessary to meet customer reactive-power needs and control the impact of each customer on system voltage, frequency and losses, thereby ensuring that power-factor problems at one customer site do not affect power quality elsewhere on the system. Depending on system needs, providers of regulation services may need to increase ("Regulation Up") or reduce ("Regulation Down") their output. In many power markets, regulation services are priced separately from power generation, based on availability (hereon referred to contracted capacity) and dispatch (Hirst and Kirby, 1998, Kirby and Hirst, 1996). Of the three EDV types discussed previously, BEVs and HEVs are suitable for both regulation up (RU) and regulation down (RD), since they are assumed to have relatively large battery systems. FCEVs, on the other hand, are assumed in this study to be suitable for RU only due to their smaller battery capacity.

Spinning reserves represent generating capacity that is up and running, and synchronized with the electricity grid. Generators of spinning reserves contribute to grid stability, helping to arrest the decay of system frequency when there is a sudden loss of another generator. Providers of spinning reserves need to be able to ramp up output rapidly—for example, within 10 minutes in the California energy market—so only some conventional generators, such as gas turbines, are suited to providing this service. Again, spinning reserves are unbundled and priced as a separate service—for example; a generator with spare capacity may market this to the grid operator as spinning reserves.

Peak power is generated when electricity demand is high (e.g., hot summer afternoons when air conditioning demand peaks). Typically, peak power is generated by power plants that can be switched on relatively quickly, such as gas turbines. In deregulated electricity markets, suppliers of peak power are generally paid according to the amount of energy they dispatch, and the peak electricity price (which can greatly exceed the average electricity price). Power providers are not paid for contracted capacity as in previous markets.

These power markets can represent a significant share of the energy marketplace. For instance, in the California market operated by CAISO the peak power capacity demand is now more than 60 percent above average demand. These levels of annual peak load are very demanding and require significant increases in resources from the grid operator (CAISO, 2004).

As discussed, the aim of this study is to evaluate the potential of V2G power from EDVs in supplying the above mentioned markets. We estimate the market potential of V2G power and increased revenues for EDV owners (Section 3). Unlike earlier analyses (Kempton and Tomić, 2005a, Kempton et al., 2001), we extend our analysis by comparing the economic costs associated with providing electricity services with V2G compared to conventional power generation technologies, including also the costs of providing mobility with EDVs, compared to conventional ICE vehicles (Section 4).

3 Markets for V2G: preliminary analysis

3.1 Analysing the market potential of V2G power

This section presents a preliminary analysis of market potential for V2G power generation, and extends substantially on research work by Kempton and others (Kempton and Tomić, 2005a, Kempton et al., 2001). The analysis presented here explores the potential of V2G from the perspective of consumers, accounting mainly for capital and energy costs. It is important to reiterate that this analysis excludes the costs of purchasing and running the vehicles. As referred by Kemtpon *et al.* (2001), these costs are assumed to be allocated to mobility services and are not accounted in their analysis. Moreover, this analysis presents simple accounting costs, which differ from economic opportunity costs corresponding to the value of the best alternative. A more comprehensive economic analysis is presented in Section 4, where we compare the costs of V2G power generation with generation from conventional power plants and where mobility costs (the primary functionality of EDVs) are also included.

The methodology of Kempton *et al.* (2001) develops equations to calculate the capacity for providing power to the grid from the three types of EDVs mentioned in earlier sections. These equations are applied to estimate costs and revenues for three power markets: regulation services, spinning reserves and peak power. Appendix A1 presents the full set of equations used to obtain the results while Table 1 and Table 2 present the key assumptions of our study.

After characterizing the power markets to which EDVs can potentially provide electricity, the V2G power capacity and energy dispatched for each power market is estimated. Providers of regulation services and spinning reserves are assumed to be paid for both the power capacity they make available (contracted capacity) and for the total amount of energy dispatched. These contract arrangements are favourable for EDVs and V2G power generation, since owners are paid for having their vehicles plugged in, while generating power for only relatively short periods. Typical times of dispatch vary depending on the power market (this issue is briefly discussed in Section 3.2). In the case of peak power, it is assumed that EDV owners are only paid for the energy they provide and not for contracting capacity (as mentioned in Section 2.2).

After determining the duration of contracted capacity and V2G power for each type of vehicle and for each type of power market, revenues and costs can be calculated, based also on the total amount of energy dispatched to the grid. These vary significantly according to the power market. Net revenues are calculated by subtracting costs to revenues. Total net revenues are analysed on an annual basis, i.e. costs and revenues are calculated based on the total amount of energy produced and total time the vehicles are plugged to the grid and available for energy dispatching. Here again, it should be remembered that this method ignores vehicle costs, either purchasing or running costs, so that net revenues represent the benefit that existing owners of EDVs could obtain from V2G .

3.2 Results for the base case

The results presented here differ from those estimated by Kempton and Tomić (2005a) since our assumptions on the vehicles are different. We assumed the technical characteristics similar to those of the Toyota Prius with energy storage of 2kWh, instead of the DaimlerChrysler Sprinter van with 14.4 kWh assumed by Kempton and Tomić (2005a). We adopted the Toyota Prius because the Sprinter is a van and the remaining EDVs considered in the present study are light vehicles, reducing the comparability of the results across the three types of EDV. Based on our assumptions, the maximum power capacity of EDVs is presented in Table 3, for the selected power markets.

Table 3: Power capacity of V2G for selected power markets (kW)

	Regulation Up/Down	**Regulation Up**	**Spinning**	**Peak Power**
Time of dispatch (hours)	(0.33)	(1.4)	(1)	(4)
BEV	20.98	5.00	6.99	1.75
HEV	2.79	0.66	0.93	0.23
FCEV	-	41.94	58.72	14.68

The time of dispatch (in brackets) for each power market was based on Kempton and Tomić (2005a) assumptions. Briefly, 4h for peak power seems reasonable attending to the typical time of the calls referred in Table 2. Although the typical dispatches for spinning reserves are of 10 minutes, 1h was considered in order to ensure that the minimum 1 hour requirement of contract arrangements is met. For regulation services, power can flow in and out of the battery with typical durations of 1-4 min. However, we used time of dispatch of 20 min to allow for the possibility of a long or repeated regulation up sequence (where the storage requirements are more exigent). Finally, for regulation up only, assuming that EDVs are plugged during 18h and its effective availability is of 14 h, the total time of dispatch is 1.4 h (t_{plug} x R_{d-c} = 14 x 0.1—refer to Appendix 1 for further details on the "Dispatch to contract" ratio, R_{d-c}). The power capacity of V2G is determined by the lower of the building wiring capacity and the maximum power of the EDV for each power market. With a power line capacity of 15 kW, the higher power output of FCEVs allows them to fully exploit this capacity, as do BEVs used for Regulation Services. On the other hand, the limited battery storage of HEVs' caps their maximum V2G generation output in all markets. These results suggest that FCEVs may represent the highest potential for generating V2G power.

The results presented in Table 4 include the partial costs and revenues referred in the methodology we described in Appendix 1. Generally, costs derive mainly from capital costs (i.e., wiring up the buildings and adapting the vehicles for V2G power generation—w_{up}; Degradation costs of the vehicles—c_d) and energy costs (cost of one unit of energy—c_{en}) represent a small fraction, except for regulation services, where energy costs are higher due to the significantly higher amount of energy dispatched by EDVs (and more noticeably for BEVs and FCEVs).

Table 4: Costs, revenues and net revenues from V2G power generation for three EDVs and three power markets ($/vehicle/year)

Power Market		**BEV**	**HEV**	**FCEV**[1]
Regulation Services	w_{up}	*-309*	*-309*	*-399*
	c_d	*-741*	*-19*	*-25*
	c_{en}	*-1,350*	*-251*	*-1,803*
	Total Costs	-2,400	-579	-2,227
	r_{cap}	*3,942*	*733*	*1,971*
	r_{disp}	*986*	*183*	*986*
	Total Revenues	4,928	917	2,957
	Net Revenues	**2,527**	**338**	**730**
Spinning Reserves	w_{up}	*-309*	*-309*	*-399*
	c_d	*-11*	*0*	*-1*
	c_{en}	*-19*	*-3*	*-55*
	Total Costs	-339	-312	-454
	r_{cap}	*322*	*43*	*690*
	r_{disp}	*4*	*1*	*9*
	Total Revenues	326	43	699
	Net Revenues	**-13**	**-269**	**244**
Peak Power	w_{up}	*-309*	*-309*	*-399*
	c_d	*-26*	*0*	*-7*
	c_{en}	*-48*	*-6*	*-537*
	Total Costs	-383	-316	-943
	r_{cap}	-	-	-
	r_{disp}	*175*	*23*	*1,468*
	Total Revenues	175	23	1,468
	Net Revenues	**-209**	**-293**	**525**

The revenues presented in Table 4 include income from contracted capacity (r_{cap}) and energy dispatch (r_{disp}). The majority of revenues accrue from payments for contracted capacity, rather than from the energy dispatched, except for V2G provided to peak power markets as we explained before (see Section 2.2). This is the reason why V2G power generation represents a high value market. It constitutes an opportunity for owners of EDVs to increase their return on investment (in their EDV) without increasing significantly the degradation costs of the energy storage system. Figure 3 illustrates the results obtained and clearly shows that V2G power generation is potentially attractive for EDV owners under certain market and technology combinations.

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[1] We assume that FCEVs can only provide Regulation Up Services due to the smaller battery of the model considered.

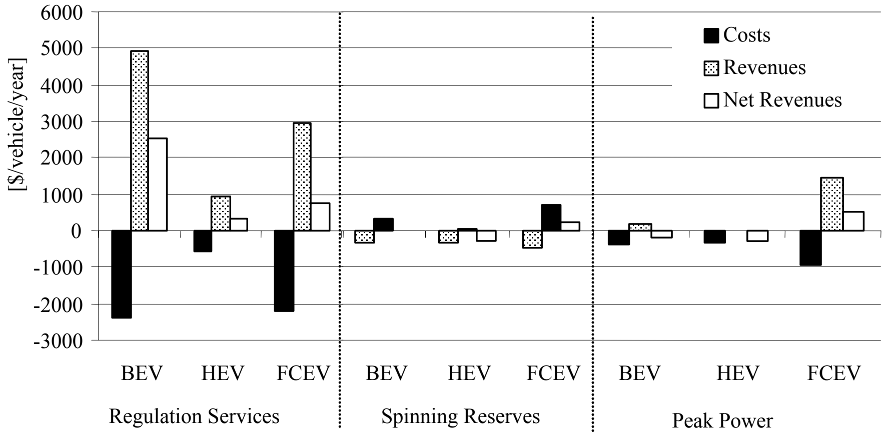

Figure 3: Costs, revenues and net revenues from V2G power generation for three EDVs and three power markets

Some competitive combinations include the provision by BEVs of regulation services and provision by FCEVs of regulation up and peak power. HEVs and FCEVs can potentially be interesting for regulation services and spinning reserves, respectively. We should mention that, although slightly different, our conclusions are consistent with the estimates of Kempton and Tomić (2005a).

3.3 Sensitivity analysis

In order to gain insights into the relative influence of different variables on costs and revenues, this section presents a sensitivity analysis for the scenarios examined above (with other assumptions and parameters held constant). Each graph presented in this section illustrates the sensitivity for the three technologies considered for EDVs. Results are shown for costs, revenues and net revenues. A selection of the most interesting results was made, but the complete set of analysis is presented in Appendix 3.

3.3.1 Wiring costs of buildings and upgrading of vehicles

We saw that wiring costs are a large share of the total cost of providing V2G power, especially in the cases where only a small amount of energy is dispatched (e.g., V2G generated by HEVs to spinning reserves). Figure 4 presents the estimated V2G power generation net revenues as a function of the wiring costs for spinning reserves, for the three EDVs (results for the remaining power markets are illustrated in Appendices). We assumed an upgraded power line capacity of 15 kW for the base case, compared to the standard residential capacity of 6.6 kW.

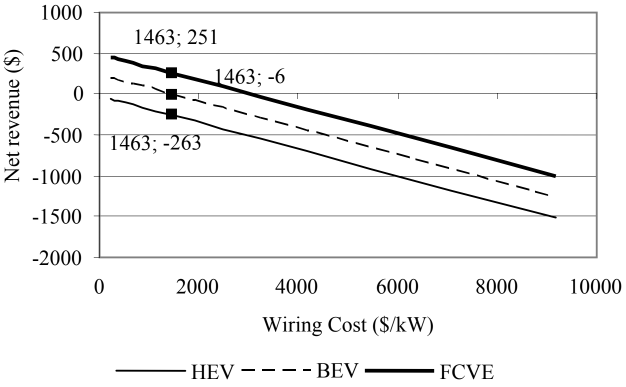

Figure 4: Estimated V2G power generation net revenue as a function of the wiring costs, for spinning reserves. *Black squares* [■] *refer to the Base Case situation for each technology.*

The results in Figure 4 show that net revenues change linearly with respect to wiring costs. Further, the results show that HEVs are unlikely to become profitable in spinning reserves (the same for peak power), even if wiring costs decrease significantly. If wiring costs decrease 10%, BEVs are potentially profitable for spinning reserves. For peak power markets (not shown), wiring costs would need to be lowered more than 80% in order to be meet positive net revenues. By contrast, FCEVs can still be profitable if wiring costs increase comparatively to our base case assumptions (refer to Figure A1 in Appendix 3). This is despite our assumptions that contract arrangements for peak power markets that do not include revenues from contracted capacity. However, for the other technologies (BEVs and HEVs) wiring costs have an important impact on revenues and thus caution should be taken when concluding on the profitability of these V2G options.

In any of the cases, net revenues could potentially increase if the wiring and upgrading costs decline. Economies of scale could contribute to a widespread diffusion of this new source of distributed generation. As referred by Kempton and Tomić (2005a), wiring upgrades to a series of plugs in a parking infrastructure or fleet would be far less costly. In addition, installation costs in new residences would also be significantly lower, since the design of the electrical infrastructure of the buildings could incorporate the necessary equipment for V2G power generation.

3.3.2 Wiring capacity

Building wiring capacity is one factor capping the potential of V2G power generation. Here we analyse the impact of changing the wiring capacity on final net revenues received by EDV owners. Wiring costs vary according to the power line capacity. We estimated a logarithmic function to relate the wiring costs with capacity[2], based on Kemtpon and Tomić's (2005a) assumptions. Figure 5 presents the estimated V2G power generation revenues as a function of the wiring capacity and concomitantly of the wiring costs.

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[2] We assumed a logarithmic function to estimate the variation of wiring costs (w_{up}): $w_{up} = 1{,}826 \times ln(P_{line}) - 3{,}481.7$, where P_{line} is the wiring power capacity.

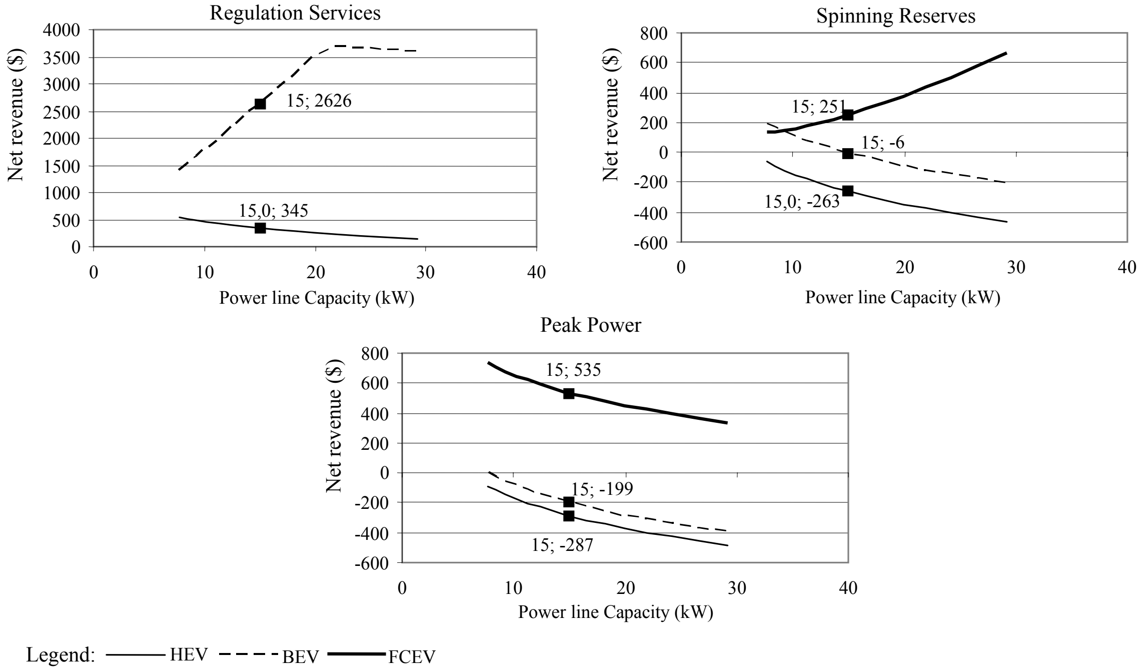


Figure 5: Estimated V2G power generation net revenues as a function of the power line capacity. *Black squares* [■] *refer to the Base Case situation for each technology.*

The impact of wiring capacity on costs and revenues are twofold: (1) wires limit the V2G power capacity; and (2) costs vary according to the wiring capacity of buildings. We recall that for Regulation Services and Spinning Reserves, revenues from contracted capacity represent a major share of total revenues (see Table 4). Hence, wiring capacity has a major influence on total revenues from V2G power generation. In comparison, in the case of peak power vehicle characteristics already limit the power available for dispatch (Table 3) so increasing the wiring capacity provides no benefit. On the other hand, it is interesting to analyse the cases of BEVs and FCEVs in regulation services and spinning reserves, respectively. In both cases, the revenues increase with the increase of wiring capacity. Here, the V2G power capacity is capped by the wires and not by vehicle characteristics. However, when the wiring capacity reaches roughly 20 kW, V2G revenues from BEVs start declining because the maximum capacity of the vehicle is met and hence revenues are capped. In the case of FCEVs, the wiring capacity could increase up to 75 kW, before revenues start to decline, under our assumptions. However, it should be noted that the storage capacity also plays an important role here, and although the power capacity of V2G would increase, the duration of dispatches would decrease inversely if the energy storage were to remain constant.

3.3.3 Energy storage of EDVs

Figure 6 illustrates the effect of varying the on-board energy storage capacity of vehicles on the net revenues from V2G power generated for regulation services and spinning reserves (Figure A1 in the appendix also illustrates the case for peak power). It is interesting to note that by increasing the storage of HEVs to 9 kWh, net revenues would reach the maximum achieved with BEVs (with no changes on the wiring capacity and thus dispatchable power capacity). This could represent an opportunity to increase the marketability and diffusion of HEVs, which are still in the stage of early diffusion with the non-pluggable version. However, carmakers are already announcing that the plug-in version of HEVs with an energy storage capacity of around 9 kWh will be soon available, motivated by the goal of providing a longer driving range on electric-only mode (Sanna, 2005).

Still, HEVs still appear to be unattractive for spinning reserves and peak power. On the other hand, there are some gains from increasing storage capacity of BEVs in most power markets, except for regulation services where the V2G power is capped by the wiring capacity. Similarly, FCEVs haven't much to gain from increased storage capacity due to capping from the wiring capacity.

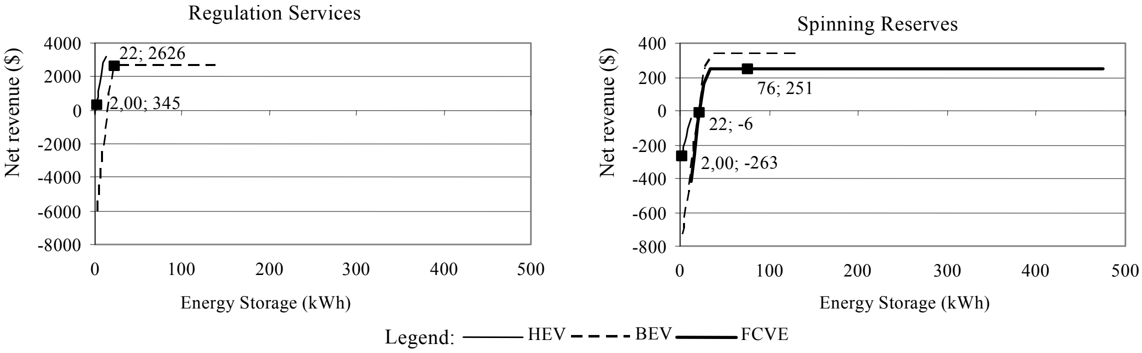


Figure 6: Estimated V2G power generation net revenues as a function of the energy storage capacity. *Black squares* [■] *refer to the Base Case situation for each technology.*

3.4 Discussion of results

We analysed the market potential of V2G power generation by three different types of EDVs for three selected power markets. Based on our assumptions, V2G represents a source of net revenue for BEVs and FCEVs providing regulation services, and for FCEVs for peak power. HEVs are also interesting for regulation services and FCEVs for spinning reserves, although to a lesser extent.

From our sensitivity analysis, we also conclude that net revenues can potentially increase for HEVs providing V2G for regulation services, if the energy storage is enlarged to 9 kWh from the currently available 1-2 kWh. Accordingly, HEVs would become more attractive and V2G can potentially contribute to the acceleration of diffusion rates of this technology. Additionally, BEVs can possibly increase their profitability when providing spinning reserves if wiring costs can be decreased by around 10%. Still, FCEVs are generically more interesting than the other EDV technologies for all power markets considered.

Increasing the wiring capacity of the connection between vehicles and the grid is potentially worthwhile when the dispatchable power capacity of vehicles exceeds standard wiring power capacity. This occurs when BEVs provide V2G power to regulation services and FCEVs to spinning reserves. In both cases, revenues could increase significantly. However, these results should be viewed with caution since the V2G power capacity is also dependent on the storage and power capacity of the EDV. Capital costs of EDV powertrains are a small part of V2G power generation costs that are dominated by the upgrading costs of wiring connections between buildings and vehicles and thus changes in capital costs of powertrains has little influence on the final results, except for BEVs where some impact is still noticeable (see Figure A 4 in Appendix 3).

As referred in the introduction of this section, the analysis was performed from the consumer's perspective, based on a particular case (the CAISO power market). Different power markets with different contract arrangements, retail prices, taxes, etc., could potentially lead to different conclusions on the market value of V2G power. On the other hand, accounting *costs* do not include the costs of opportunities forgone or the cost of mobility, which is the primary functionality of EDVs. Section 4 will now address this analysis by approaching the assessment of V2G power potential from an economic perspective, including the costs of buyng and running EDVs for mobility purposes.

4 Comparative assessment of economic performance of V2G

In Section 3, we established that V2G power represents a considerable value market for the owners of EDVs when it is generated either by BEVs and HEVs for regulation services or by FCEVs for spinning reserves and peak load. Importantly, however, this analysis was based on a simplified representation of electricity costs. To analyze the competitiveness of V2G technologies in the electricity marketplace, the costs of providing V2G power using EDVs should be compared with the costs of providing the same services with existing electricity generation technologies. In addition, the V2G concept is based on the dual use of EDVs for both mobility and electricity services. Accordingly, the assessment of economic costs of V2G power generation must also account for the *opportunity costs* of selecting EDVs instead of alternatives (at the present moment, ICEVs being the more realistic alternative). After considering all economic costs, we can explore some possible favourable conditions under which V2G power could represent a competitive source of generation in the overall energy system.

In this section, we present a comparative assessment of economic performance of providing power generation and mobility with V2G vehicles relative to providing the same services with conventional electricity generation technologies (gas turbine (GT) and conventional coal steam turbine (CC) power plants) and ICE vehicles. After presenting the methodology used to assess the economic performance of each technology (Section 4.1), results for base case are presented and discussed in Section 4.2. In Section 4.3, we present the results of a sensitivity analysis were we vary some of the key uncertain assumptions.

4.1 Methodology

The present comparative assessment considers the costs of technology usage for power generation and mobility services, using either "conventional" technologies or EDVs. Alternative "conventional" technologies were selected on the basis of cost-competitiveness, maturity (i.e., no major changes in capital costs are expected in the future), and compatibility with ancillary services and peak power markets (where V2G can potentially be cost-effective). Accordingly, the gasoline-fuelled ICEV was selected for mobility services (refer to Table 1, p. 5), and GT and CC power plants were chosen for electricity generation. For the sake of comparability with V2G generation, we assume that marginal capacity in these power plants is used to provide ancillary services only and is unused the rest of the time.

If we consider the power markets discussed in Section 2.2, of the two conventional electricity generation technologies mentioned above, the GT is technically more suitable for fast response and short periods of peak and ancillary power generation, while CC may be technically more suited to providing spinning reserves, base load generation and for peak shaving. Nonetheless, we compare all technologies in all of the power markets. Table 5 presents the assumptions for technical and economic specifications of these power plants. Throughout this analysis we apply a discount rate of 10 percent, and assume an average vehicle lifetime of 10 years.

Table 5: Technical assumptions of power plants

Parameters	**Power plant**	
	GT	**CC**
Capital cost ($/kW)	300	1,3
Fixed cost ($/kW/year)	52	74
Lifetime (years)	30	30
Assumed plant factor (%)*	100	100
Input fuel cost ($/GJ)	2.66	1.66
Conversion efficiency (%)	40	38

* For the limited sub-markets of interest (peak power, regulation and spinning reserves) the plant factor considered is 100 percent.

The comparative assessment of V2G power generation was performed by analysing five combinations of technologies, as presented in Table 6: "conventional" technologies only (C1 and C2), combining "conventional" technologies with EDVs for mobility services only (C3 and C4); and using EDVs for V2G and mobility services together (C5). As mentioned earlier, all of the previous analyses of V2G systems (Arthur D. Little, 2002, Brooks, 2002, Kempton and Letendre, 1997, Kempton et al., 2001, Letendre et al., 1999) effectively compared only C3/4 with C5, ignoring the mobility costs associated with using EDVs.

Table 6: Combinations of technologies for mobility and energy services

	Services for		**Description**
	Mobility	Energy	
C1	ICEV	GT	ICEV is used for mobility and GT produce the equivalent amount of energy services provided by V2G in C5.
C2	ICEV	CC	Same as previous but using CC for electricity production.
C3	EDV	GT	EDV is used for mobility only and GT produce the equivalent amount of energy services provided by V2G in C5.
C4	EDV	CC	Same as previous but using CC for electricity production.
C5	EDV	EDV	EDV is used for mobility and provides V2G power.

Figure 7 presents a simplified diagram of an illustrative energy system (Turton and Barreto, 2004b), which is structured in 3 major groups according to the stage of the energy's lifecycle: *primary energy source*, conversion to *secondary energy* (energy carriers) and *energy end-use* (final demand sectors). The boxes represent primary fuels, groups of technologies and demand sectors. Arrows are used to illustrate the flows of energy between primary energy sources, technologies and demand activities. The three competing technologies to be assessed in this section are highlighted in this diagram and it is possible to track the energy flow from its primary source until its end-use (dashed lines in arrows and boxes in bold).

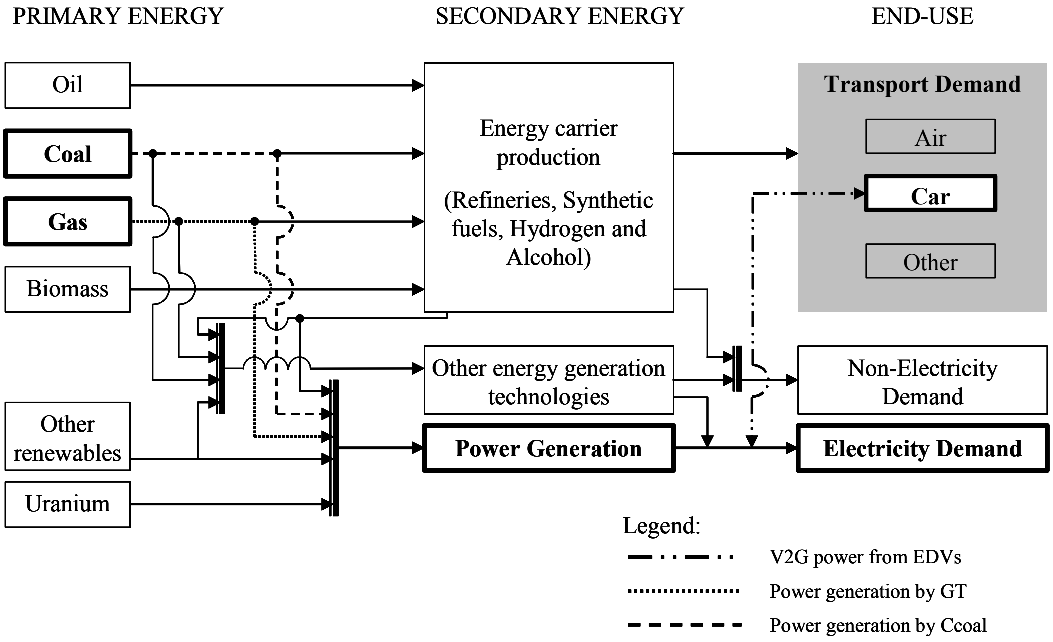


Figure 7: Competing technologies in the energy system assessed in the present study (adapted from Turton and Barreto, 2004b)

The dual use of EDVs for both mobility and energy services is also illustrated in this figure through the double-arrowed connection between Cars (in the Transport Demand Box) and Electricity Demand suggesting that electricity flows in both directions.

The economic costs considered for the comparative assessment include:

- Annualized capital costs and fixed operating costs, due to the use of technology for electricity and mobility services;
- Electricity production costs, which, in the case of V2G power generation, includes the increased wear of batteries and fuel cell engines due to the additional production of electricity;
- Costs of wiring up the buildings to higher power-line capacity, where EDVs will be plugged (from 6.6 kW, the base-case power line capacity considered here, to 15 kW);
- Costs of upgrading EDVs for V2G operation (computer and communication requirements);
- Mobility costs, which include manufacturing costs of the non-battery components of the drivetrain (annualized capital costs of fuel storage, transmission, motor and controls), fuel consumption cost (related with travel) and non-fuel operation and maintenance costs. The degradation costs of the battery or fuel cell engines due to mobility use are also accounted here.

The detailed methodology used to estimate the economic costs for each technology is described in Appendix 2. The following mobility assumptions were considered for the analysis:

- The average annual distance of vehicles is 15,000 km; and

- We recall that we assumed a minimum range required by the driver for the next trip after being parked is 10 km, which is not considered for hybrids, assuming that they have fuel left to run on ICE only.

In the following sections we first present results for the base case, based on the assumptions presented in Tables 1, 2 and 5.

4.2 Results for the Base Case

Results presented in the following sections are calculated based on the total amount of electricity that each type of EDV can dispatch over one year, considering the power capacity and energy storage of the vehicle and the maximum capacity of the electric wiring at the connection point. The figures we present below show the costs of electricity (left-hand side of graph of the following graphs) and mobility (right-hand side) services for each power market. We now discuss each power market in turn.

Regulation Up & Down – Among all technologies considered for this market, gas turbine power plants (GT) and EDVs are more competitive than coal power plants (CC), as shown in Figure 8. The technical profile of CC is more compatible with base load power generation because of its high capital costs and lower operation costs. Accordingly, in many situations GT represent a cheaper source of energy compared to CC, which is in some cases more costly than V2G power. In addition, CC power plants have longer start up periods before they can dispatch electricity (several hours). For this reason, we focus on the other technology combinations for the remainder of this section.

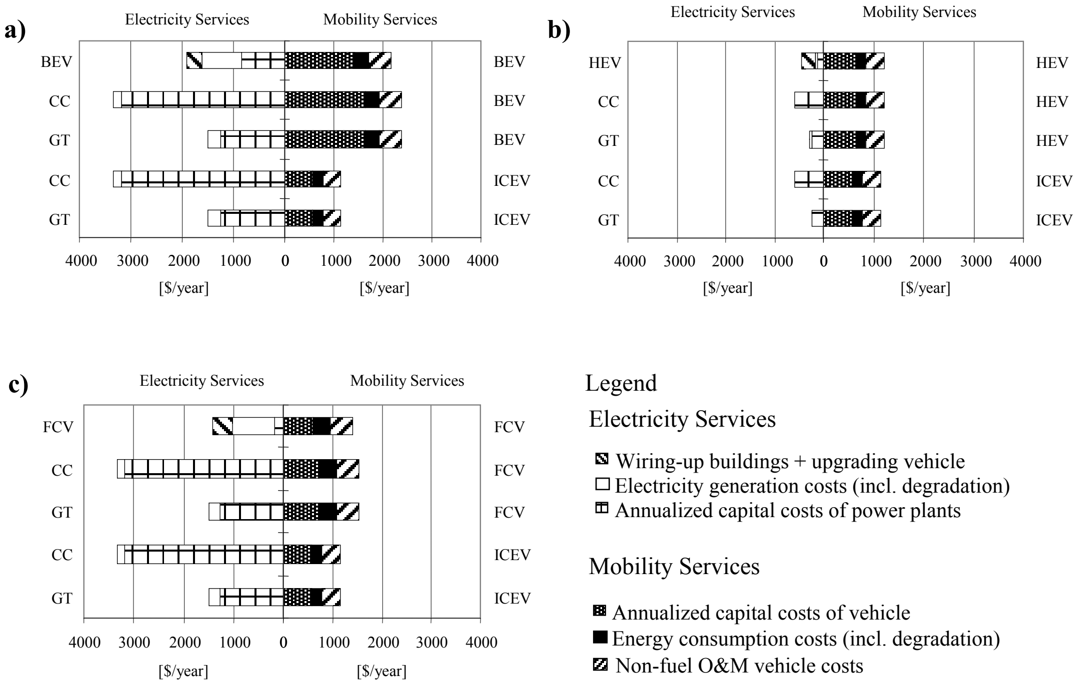


Figure 8: Economic costs of providing mobility and energy services for Regulation with (a) BEVs, (b) HEVs and (c) FCEVs

Figure 8a shows that GTs are more attractive than BEVs for supplying electricity for regulation services. Based on the assumptions of this study, the costs of dispatching 10 MWh over one year amount to approximately $1,500.year-1 for GT (horizontal bar in the bottom left hand side of Figure 8a) but over $1,900 for BEVs (top left hand side of the same figure). Similarly, the costs of generating electricity with GT ($280/year) are lower than with HEVs ($500/year) (see Figure 8b). It should be noticed that the overall costs are much lower with HEVs, compared to BEVs, because HEVs can only dispatch 2 MWh over the same period due to the lower power capacity and energy storage of their smaller battery.

Looking at the cost structure of the electricity services, power generated by BEVs and HEVs is more expensive due to the costs of wiring up the buildings and upgrading vehicles for V2G power generation, despite these technologies having lower annualized capital costs than GT. In addition to these capital costs, the cost of input energy is much higher in the case of V2G power ($0.06/kWh of electricity) than for GT (roughly $0.01/kWh of natural gas), under the assumptions considered here.

If we now consider also mobility services, the cost-competitiveness of BEVs (and HEVs) for dual services declines significantly. Mobility costs of an ICEV (bar in the bottom right hand side of the graph) are much lower than BEVs (top right-hand side): $1,150/year for ICEVs, compared to $2,400/year for BEVs, based on our assumptions. The main difference is that the annualized capital costs of BEVs ($1,600/year) is roughly 3 times higher than that of ICEVs ($600/year), due to the higher costs of the electric drivetrain compared with the ICE. In the case of HEVs, the total costs of annual mobility are quite close to those of ICEVs, under our assumptions. Annualized capital costs of hybrid power trains are much lower than BEVs and only slightly higher than ICE.

As mentioned previously, FCVs are assumed to be suitable for providing regulation up only, due to their smaller battery. However, the total costs of providing regulation-up services with FCVs is higher than with BEVs and HEVs (Figure 8c) because FCVs are able to provide a larger service due to their higher energy storage (75 kWh) and power capacity available for this market (42 kW) than BEVs (22 kWh; 5 kW) or HEVs (2 kWh; 3 kW). The amount of energy FCVs are able to dispatch is therefore 3 times greater than BEVs and roughly 20 times higher than HEVs, so both costs and output are higher. Figure 8c illustrates that many of the technological combinations for providing electricity and mobility services are similar in cost (with the exception of CC). Although close to the most competitive alternative (i.e., ICEVs combined with GT), using FCVs for mobility and V2G power generation is slightly more expensive. This is because both electricity generation costs by FCVs (using H2) and mobility costs (both capital and energy) are higher than the costs of providing the same services from GTs and ICEVs, respectively.

Spinning Reserves – Compared to regulation services, where EDVs are assumed to be plugged and available for regulation services during 6570 hours/year and to dispatch energy for 10 percent of this time, the duration of dispatch for spinning reserves (20 hours/year) is 97 percent smaller. Therefore, the annual energy generation for spinning reserves is much smaller than for regulation services. Based on the 20 hours/year of service for Spinning Reserves, the estimated energy dispatched by BEVs, HEVs and FCVs, for spinning reserves, is 140 kWh/year, 19 kWh/year and 300 kWh/year, respectively.

Figure 9a shows that providing spinning reserves and mobility services with BEVs is around twice as costly as using the GT ICEV combination. Although capital costs of BEVs are nearly half of GT, here again, the wiring costs of buildings and upgrading vehicles must be accounted for, levelling up the power generation costs between these two technologies. Secondly, the capital costs of batteries and the electric drivetrain for mobility purposes are twice those of the ICEV drivetrain. It is thus very unlikely that the relative cost competitiveness of the dual use of BEVs could be improved, although we explore this issue in more detail in subsequent sections. Similarly, HEVs (Figure 9b) do not appear to be attractive for spinning reserves because the fixed costs of wiring up buildings and upgrading vehicles are relatively high.

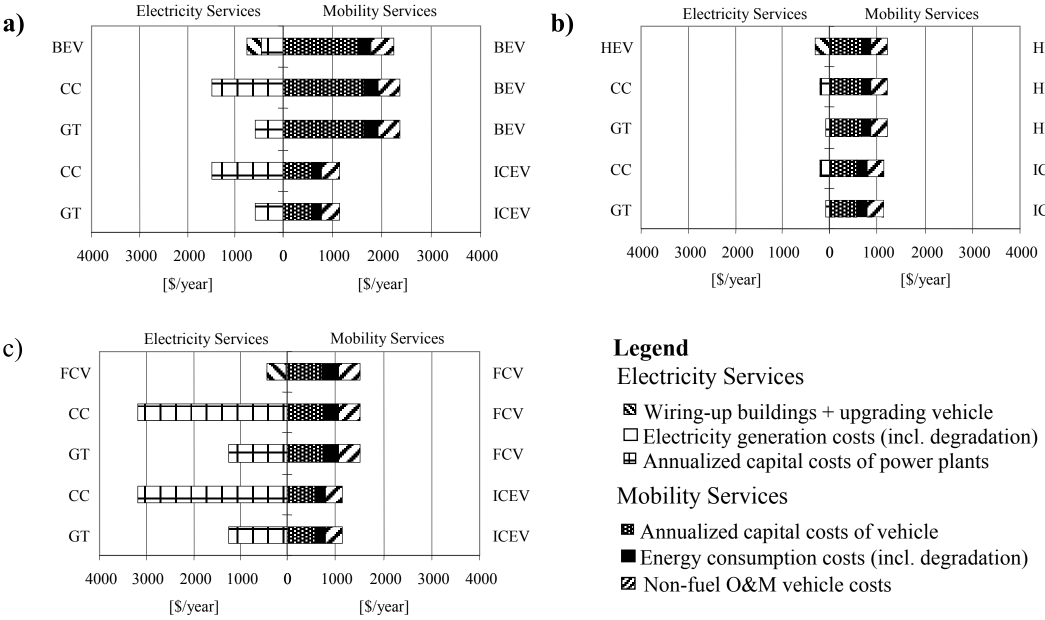


Figure 9: Economic costs of providing mobility and energy services for Spinning Reserves with (a) BEVs, (b) HEVs and (c) FCVs

Turning to FCVs, we can see that this EDV is a very attractive option for providing spinning reserves power generation and mobility services (Figure 9c). This option is around 20 percent less expensive than the second best option (GT combined with ICEVs) shown in Figure 9c. However, it should be remembered that capital costs of FCVs and energy costs used for these calculations are based on favourable assumptions. The manufacturing costs of fuel cell system were assumed to be $2,180, which corresponds roughly to $30/kW, an estimate based on a scenario where fuel cells could be competitive with ICEVs (Ogden et al., 2004). In addition, the thermodynamic efficiency of the drivetrain was assumed to be around 65%, significantly higher than the 44% assumed by Kempton et al. (2001). This difference has a significant impact on the cost of electricity generated by FCVs. With our assumptions, FCVs are able to generate electricity at a cost of around $0.08/kWh, compared with almost $0.12/kWh under the assumptions of Kempton and Tomić (2005a).The sensitivity of the results to these assumptions is analysed and discussed in Section 4.3.

Peak Demand – Peak Power is generated during times of high electricity demand. Generally, the total energy dispatched during one year for peak power is lower than the amount of energy dispatched for regulation services but considerably higher than for spinning reserves. Under our assumptions there are also significant differences between the quantities of power dispatched by each type of EDV for Peak Power, with BEVs providing 350 kWh/year, HEVs 50 kWh/year, and FCEVs able to provide more than 2900 kWh/year because of their larger energy storage. *A priori*, FCEVs seem more interesting for this power market, as they can generate much more energy than the other EDVs.

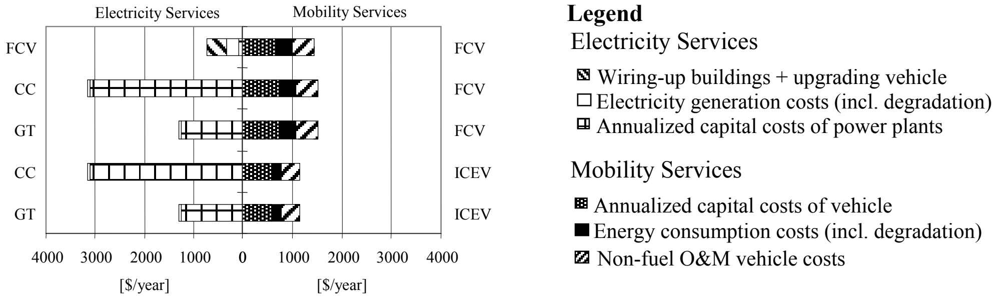
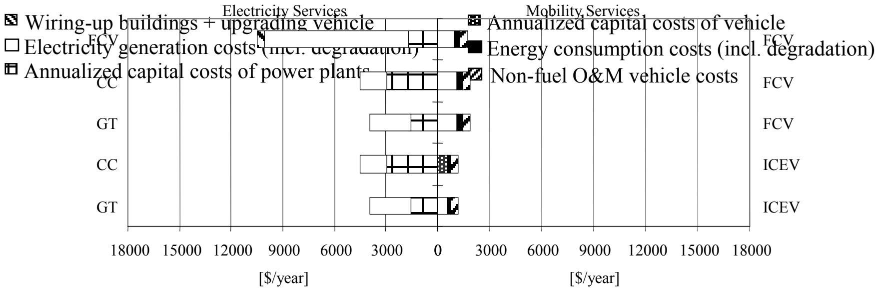


Figure 10: Economic costs of providing mobility and energy services for Peak Demand with FCEVs

Accordingly, we present only the results for FCEVs in Figure 10, which shows that this technology is very attractive for providing electricity for peak demand when compared to the GT ICEV combination. Although mobility costs of FCVs are significantly higher than the costs of ICEVs, the costs of V2G power generation are sufficiently below the generation costs using GT to more than offset this difference. In comparison, BEVs and HEVs (not shown here, but refer to the Appendices for full length results) are not competitive under the base case assumptions. To summarise, the costs of providing power for peak demand and mobility services from BEVs are 122% higher than the costs of providing the same services from GT and ICEVs. HEVs are 30% more expensive than GT combined with ICEVs. Hence, unlike FCEVs, BEVs and HEVs are not attractive for peak power generation under our assumptions.

Base Load – For completeness, we also examined V2G for base load generation—i.e., "round-the-clock" generation—despite earlier studies suggesting this may not be a competitive application (Kempton and Kubo, 2000, Kempton and Letendre, 1997, Kempton et al., 2001). These earlier analyses showed that BEVs and HEVs do not have enough power capacity or sufficient energy storage to satisfy the requirements of this market, and made a similar argument for FCEVs. However, if we consider a scenario where the vehicle would be connected to a hydrogen distribution or production system (such as a natural gas reformer) installed at the plug-in site and operated continuously, FCEVs could overcome storage capacity limitations on V2G generation. With this in mind, a FCEV could effectively supply continuous output capped only by engine size and on-site wiring capacity—assumed to be 15 kW. Nevertheless, Figure 11 confirms that FCEVs are far from being an alternative in the base load power market, under our assumptions.



Legend

Electricity Services

Mobility Services

Figure 11: Economic costs of providing mobility and energy services for Base Load with FCEVs

The overall conclusions from the analysis in this section are that FCEVs are cost competitive for spinning reserves and peak power submarkets, while also providing mobility services. However, we recall that our assumptions are generous regarding the production costs of H2 and capital costs of fuel cell systems. In the case of regulation services, FCEVs might be cost competitive with different assumptions on the vehicles' technical aspects and the economic conditions of the energy marketplace. The same applies for BEVs and HEVs for regulation services, considering that the costs of providing electricity and mobility services with HEVs (or with BEVs) are 17 percent (and 54 percent) higher than the costs of providing these services with GT and ICEVs. These issues are discussed in the following subsection.

4.3 Sensitivity analysis

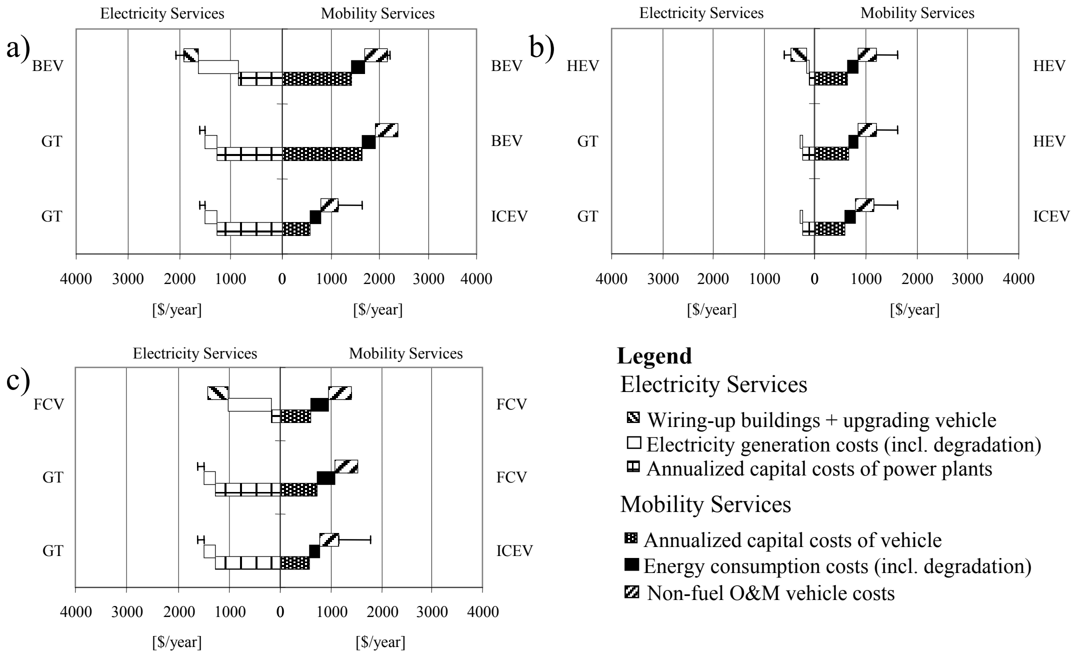
This section explores the sensitivity of the results obtained for the base case and presented in the previous section to alternative assumptions regarding the costs of primary energy production (Section 4.3.1), the manufacturing costs of vehicle technologies (Sections 4.3.2 and 4.3.4), and the technical characteristics of the grid (Section 4.3.3). We also analyse how greenhouse gas (GHG) abatement policies affect the economic performance of competing technologies by way of imposing various levels of carbon-equivalent (C-e) taxation (Section 4.3.5).

This sensitivity analysis is motivated by some of the limitations of the analysis presented in Section 4.2. These include, for example, the fact that it is based on a single energy market (CAISO), which is not fully representative of other electricity markets. In addition, the future values of many of the variables upon which the results presented depend are highly uncertain, so a single snapshot can provide only a very limited assessment of the possible future role of V2G technologies. Importantly, however, although we explore some of the key variables below, the large number of interactions within the future energy system precludes a comprehensive sensitivity analysis. We seek to begin to address this limitation in a forthcoming complementary analysis, which will apply a detailed energy-system model to account for the impact of competing demands, limited resources, and long-term dynamics.

4.3.1 Primary energy production costs

The production cost of the primary fuel or energy carrier used as an input for mobility (oil, electricity or H2) and for energy generation (natural gas and coal) is a key determinant of the overall cost of each energy and transport alternative examined in Section 4.2. Hence, under different assumptions of primary energy production costs, the costs of providing electricity and mobility services will vary and, possibly, the relative competitiveness of competing technologies will change. Accordingly, in this first sensitivity analysis we investigate the impact of higher oil, natural gas and coal costs, perhaps as a consequence of cheaper resources being exhausted over the longer term (Rogner, 1997). To explore the potential consequences, we analysed the impact of increasing the price of oil from \$5/GJ to \$15/GJ. In addition, we assumed an increase in the cost of natural gas and coal of 50 percent.

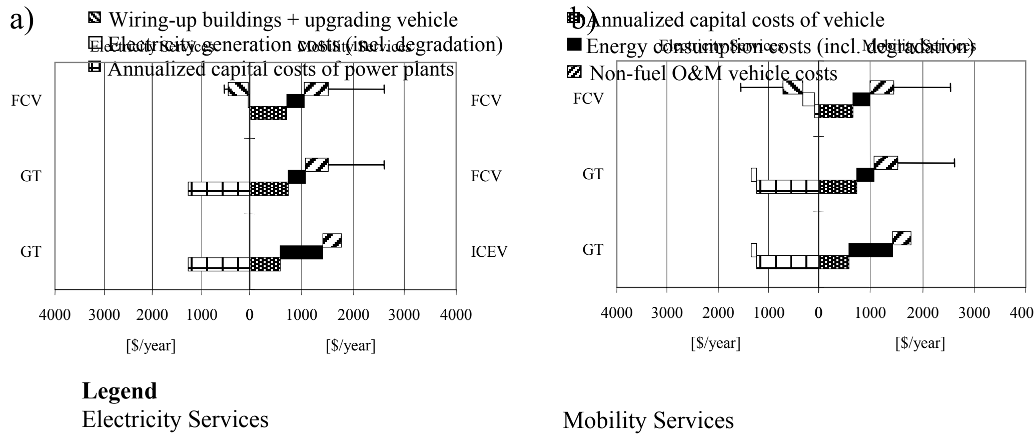
Figure 12 shows that for regulation services the relative competitiveness of BEVs and HEVs remains unchanged. Electricity generation by GT combined with gasoline ICEVs is still the most cost competitive alternative to provide both energy and mobility services, although overall costs are of course higher. FCEVs become more attractive under these new assumptions, which so far assume no increase in hydrogen costs. In fact, an increase of 80 percent in oil production costs and 50 percent increase in natural gas and coal costs would make FCEVs a competitive alternative in the regulation services electricity market, under our assumptions.



Note: The error bars in these graphs correspond to the increase (*outer limit of the error bar*) or decrease (*inner limit of the error bar*) of costs for each combination of technologies.

Figure 12: Effect of higher costs of oil (200 percent increase), natural gas and coal (50 percent) on the competitiveness of (a) BEVs, (b) HEVs and (c) FCVs for providing Regulation Services

However, if we also assume that H2 production costs increase up to the upper limit of the range of costs described in Kempton *et al.* (2001)—that is, from \$1.7/kgH_2 to \$5.6/kg, or, from around \$14 to \$47/GJ —FCEVs become less attractive for providing electricity for Spinning Reserves (a) and Peak Power (b) combined with mobility, as shown in Figure 13. Nevertheless, in the Spinning Reserves market, FCEVs still remain the most competitive alternative under the assumptions of this study. In the case of Peak Power, FCEVs fall behind the GT combined with ICEVs under our higher hydrogen cost assumptions. The loss of competitiveness due to the more than threefold increase in the cost of H_2 is not compensated by the increase of production costs of oil, natural gas and coal, partly because fuel accounts for a larger proportion of total costs for FCEVs in the base case, compared to the other technologies.



Note: Impact of increased oil and natural gas production costs (see Figure 6) is included. The error bars reflect the increased costs of hydrogen.

Figure 13: Effect of higher hydrogen costs (increasing from $1.7/kg to $5.6/kg) on the competitiveness of FCEVs in the (a) Spinning Reserves and (b) Peak Power markets

4.3.2 Capital costs of EDVs

One of the key uncertainties in this analysis relates to the future costs of the advanced technologies examined here, particularly FCEVs. Among all technologies in this study, the ICE is a very mature technology and no significant changes in cost are expected. Each of the other technologies is examined in turn below.

BEVs – The total capital costs of BEVs were estimated on the basis of manufacturing costs of the drive train components, which were obtained from Ogden *et al.* (2004) and are consistent with other sources (Arthur D. Little, 2002, Delucchi and Lipman, 2001, Wilkinson, 1997). In this sensitivity analysis, we examine the impact of varying the cost of the peak battery (keeping non-battery costs constant). Figure 14 below shows the impact of a ±50 percent variation of the capital costs of the battery on the economic performance of BEVs, in the three power markets considered. Battery costs need to fall by 60 percent before BEVs become competitive with the GT-ICEV combination in regulation services and spinning reserves. In the case of peak demand, the capital costs would need to decrease 85 percent compared to Base Case.

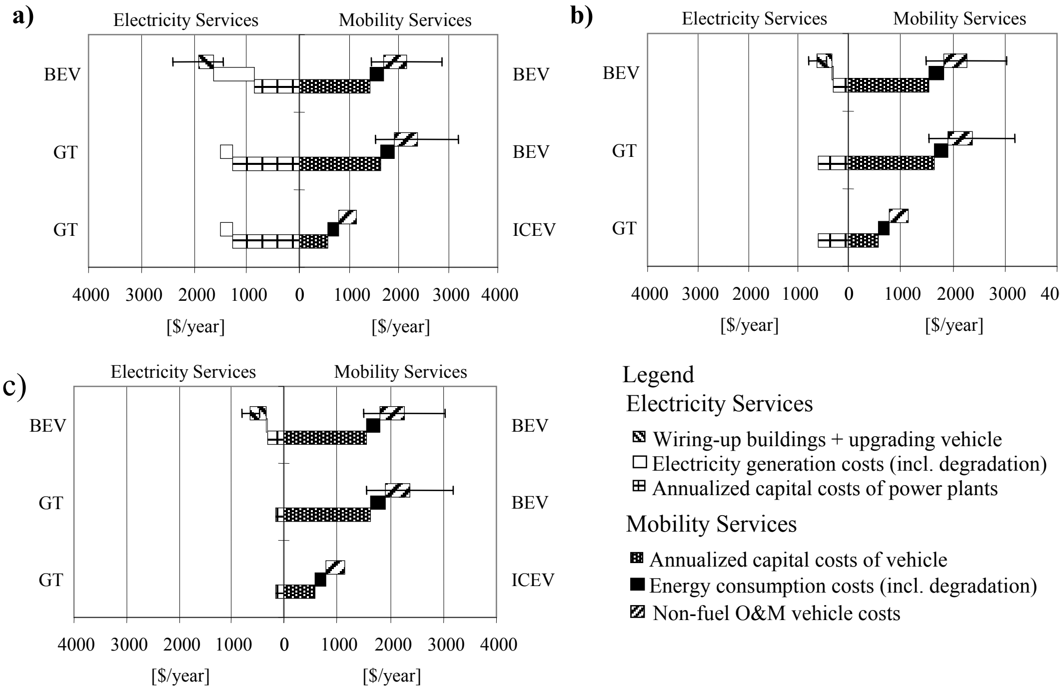


Figure 14: Impact of a ±50 percent variation in battery capital cost on the economic performance of BEVs in (a) Regulation Services, (b) Spinning Reserves and (c) Peak Load

The results indicate that BEVs could become cost competitive for electricity and mobility services if the manufacturing cost of batteries falls to $\$40.kW^{-1}$ (compared to $100/kW in the base case). However, $100/kW is the target of battery manufacturers for the longer term and there is some scepticism on the feasibility of this target (Wilkinson, 1997). Therefore, we argue that BEVs are unlikely to become cost-competitive without major technological breakthroughs.

HEVs – HEVs could be cost competitive for providing regulation and mobility services if battery production costs decline by around 20 percent. The impact of this reduction on the cost-competitiveness of HEVs, compared to ICEVs, is larger than the impact of a higher gasoline price (see Section 4.3.1). The reason is that both technologies depend on the consumption of gasoline for mechanical power, although HEVs to a lesser extent. In fact, an increase of 200 percent in gasoline costs has a small impact (4 percent) on the difference in the total costs for mobility and energy services between the HEV and ICEV-GT combination. As mentioned in Section 4.2, HEVs are not competitive in spinning reserves and peak power markets, and changes to vehicle capital costs do not change this previous conclusion (refer to the Appendices for complete results supporting this analysis).

FCEVs – Throughout this analysis we have used estimates of fuel cell production costs ($30/kW) based on an optimistic scenario of future manufacturing costs from Ogden *et al.* (2004). However, FCEVs are still an immature and expensive technology, and the costs of fuel cell systems range between $3,000/kW and 5,000/kW (for example, refer to Simbolotti, 2004). In this section, we analyse the implications of a scenario were the deployment and diffusion of fuel cells fails to lead to the reduction in manufacturing costs envisaged by Ogden *et al.* (2004), and production costs decline to $75/kW only. The total capital costs of FCEVs include in addition the costs of the transmission, motor/controller, controls and fuel storage (Ogden et al., 2004). As already mentioned, several studies analysed the potential of FCEVs to provide electricity to buildings and commercial sites, but assumed that the vehicles were purchased for automotive use and thus ignored a large proportion of the overall capital costs (for example, refer to Lipman et al., 2004). Figure 15 illustrates the variation of cost competitiveness of FCEVs with the increase of the unit cost of the fuel cell system, starting from $2,180 (equivalent to $30/kW, for a 72kW power train) to $5,450 (equivalent to $75/kW).

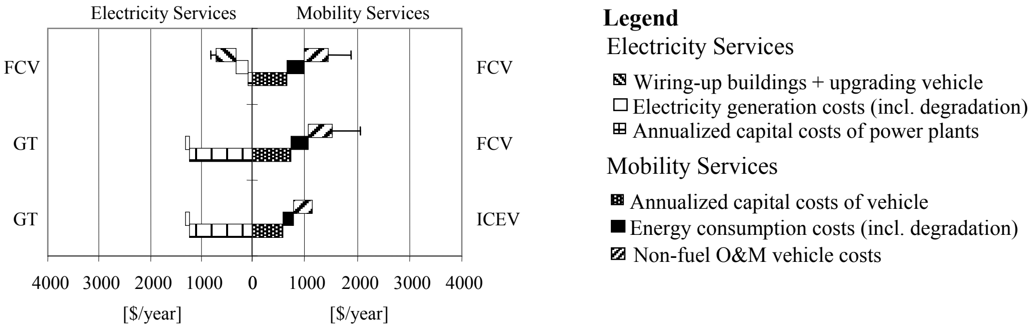


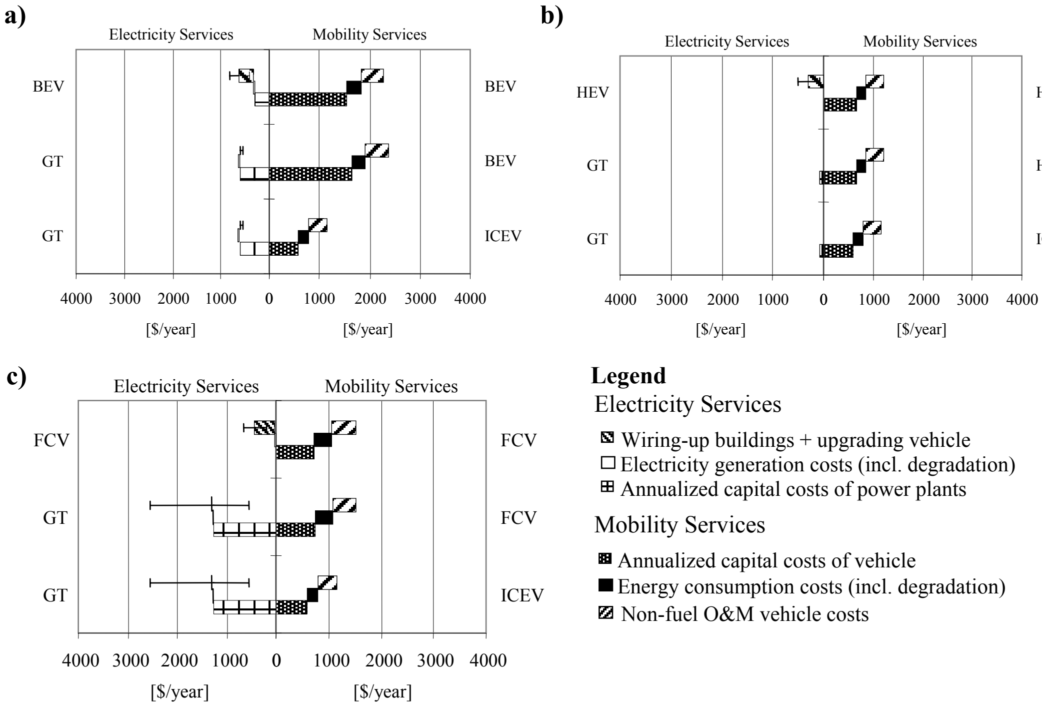
Figure 15: Impact of higher fuel cell capital costs on the competitiveness of FCVs in the Peak Power market

If the costs of fuel cell systems increase to $75/kW, then FCEVs are still an attractive alternative to generate V2G power for spinning reserves (approximately the same cost than the GT-ICEVs alternative, under our assumptions). In the case of peak demand, shown in Figure 15, FCEVs are less cost competitive than the GT-ICEV alternative when fuel cell systems costs remain above $55/kW (refer to the Appendices for complete results, including remaining power markets under considerations).

4.3.3 Changing the wiring capacity and respective costs

The standard electrical wiring capacity for US houses is 6.6 kW. To take full advantage of V2G, we have assumed that this can be increased to 15 kW with an upgrade costing $1,500 per installation (Kempton and Tomić, 2005a). Wiring upgrades in commercial or fleet car parks would probably cost far less, as would installation in new residences.

Here, we analyse the impact of not upgrading the wires of buildings, and thus consider a power line of 6.6 kW. The first obvious consequence is that the wiring costs decrease, although it also decreases the maximum power EDVs can deliver for electricity services. We also analysed the impact on the competitiveness of EDVs when doubling the wiring capacity up to 30 kW. We have assumed that wiring costs for a 6.6 kW system are $100, and for a 30 kW system almost $3,000. Figure 16 shows the impact on the costs of electricity and mobility services of both analyses for the spinning reserves power market.



Note: The error bars in these graphs show the impact of a 30 kW (*outer limit of the error bar*) or a 6.6 kW (*inner limit of the error bar*) system.

Figure 16: Impact of varying the wiring capacity on the competitiveness of EDVs in the Spinning Reserves market

The "no-upgrading" scenario brings down the wiring costs in general terms, and reduces the power capacity of V2G. However, in the case of BEVs and HEVs, vehicle characteristics already limit the maximum capacity for spinning reserves to below 6.6 kW. Partly for this reason, there are no significant changes in the cost competitiveness of BEVs and HEVs, across all power markets. The slight decrease in wiring costs is not sufficient to offset the considerably higher mobility costs faced by BEVs and HEVs relative to ICEVs In the case of FCEVs, however, the decrease in wiring capacity reduces power output from 15 to 6.6 kW, rendering this technology slightly less competitive, although still the most attractive option.

As mentioned previously, the increase in wiring capacity results in higher wiring costs. However, the BEVs and HEVs considered here are unable to exploit this increased capacity because the output of these EDVs is already limited below 6.6 kW. By contrast, V2G power generation by FCEVs increases with wiring capacity because their maximum power capacity for spinning reserves is 72 kW. However, the costs of providing an equivalent higher service from the GT alternative increases at a faster rate because the additional capital costs of GT generation are higher than the capital costs of additional wiring by around an order of magnitude. In other words, upgrading the wiring capacity significantly increases the competitiveness of FCVs for V2G, and may be an important requirement for successful deployment.

4.3.4 Changing the energy storage of hybrid-electric vehicles (HEVs)

In this section, we test the impact of increasing the assumed energy storage capacity of HEVs' batteries to 9 kW, on the competitiveness of this technology for providing V2G power and mobility. Based on the assumptions applied here, Figure 17 shows that such increased energy storage would result in HEVs becoming the most attractive technology for regulation services, when compared to GT combined with ICEVs or HEVs (for mobility only).

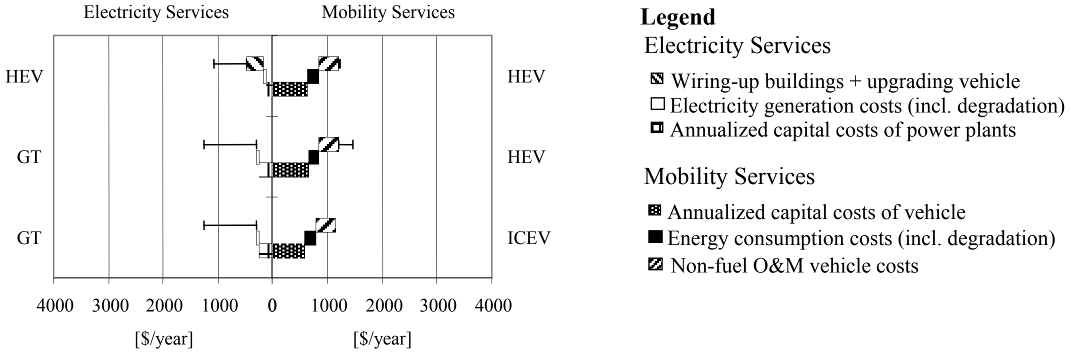


Figure 17: Impact of varying battery storage capacity on HEV competitiveness in the Regulation Services market

This may illustrate one possible way of improving the diffusion of HEVs, which are currently being commercialised with batteries with much lower storage (nearly 2 kWh). It is expected that "plug-in" versions of existing HEVs, such as the Toyota Prius, may soon be produced commercially with improved battery storage capacity (Sanna, 2005). This may further increase the existing enthusiasm for HEVs seen in a number of markets, thereby accelerating the uptake of this technology leading to a shift to a less polluting transportation system.

4.3.5 Climate policy

One further factor potentially affecting the uptake of EDVs and V2G technologies is the impact of climate change policy. In the sensitivity analysis presented below we examine how greenhouse gas (GHG) abatement policies can affect the economic performance of competing technologies by way of imposing various levels of carbon (C) taxation. The underlying assumption is that the use of a carbon tax (C.tax) could make EDVs more competitive in both electricity and mobility services compared with fossil-fuel-based technologies, such as GTs and gasoline-fuelled ICEVs. Costs of H_2 produced from fossil fuels would also be affected by a climate policy, since GHG are produced from the processes used today (e.g., H_2 steam reformed from methane). Although, the cost competitiveness of FCVs would also be affected by a climate policy, this technology is not analysed here due our exercise limitations.

Based on our assumptions, Figure 18 illustrates the impact of a range of emissions taxes (no C.tax—[I]; $150/tC—[II]; and $650/tC—[III]) on the relative cost competitiveness of BEVs and HEVs generating V2G power for regulation services while providing mobility services.

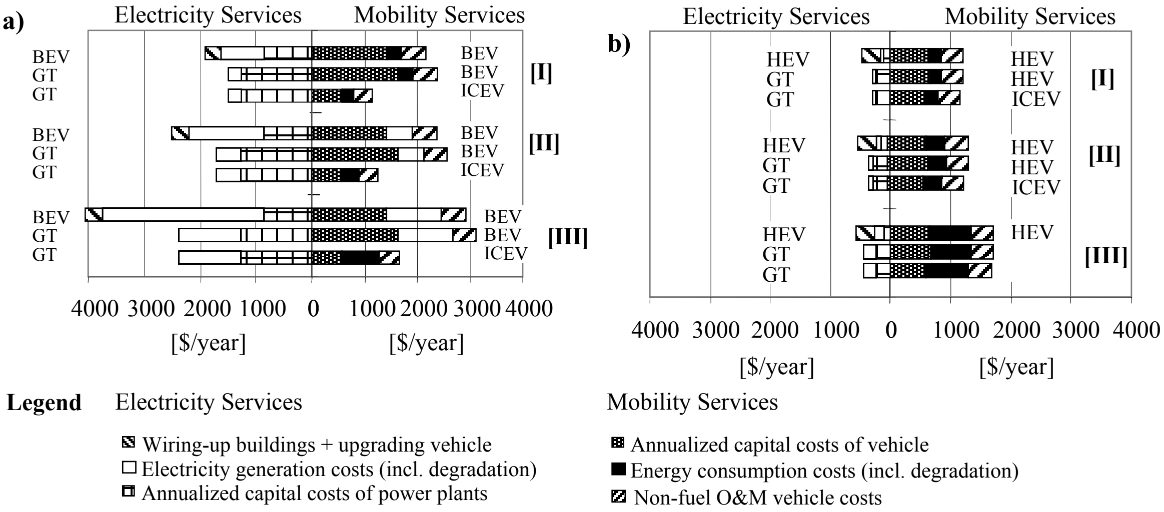


Figure 18: Impact of three different scenarios of a carbon tax (C.tax—[I]; \$150/tC—[II]; and \$650/tC—[III]) on the cost competitiveness of (a) BEVs and (b) HEVs in Regulation Services power market where electricity is produced from fossil fuels.

Figure 18a suggests that a climate change policy wouldn't be beneficial to BEVs for generating V2G power (while providing mobility services to), since power generation and mobility costs increase with the carbon tax. In this scenario, electricity is based on the production costs of natural gas and coal, which are affected by the carbon tax. However, if we assume that electricity used for V2G power would be based on renewable energies only that would not be affected by the C.tax increase, then the V2G-BEV solution might become increasingly more attractive than alternatives as the carbon tax increases. One possible niche market for BEVs may be the storage of intermittent renewable energy generation (such as from wind turbines and solar photovoltaics). Eventually, energy from renewables could also be used to produce H_2 with electrolysis in FCEVs (Kempton and Tomić, 2005b, Turton and Moura, 2006).

By contrast, providing V2G power and mobility with HEVs becomes more attractive as the carbon tax is increased, in any scenario considered (Figure 18b). This is due to the relative increase of the natural gas costs, which has a direct impact on the cost of energy services from GTs. Likewise, the impact on the cost of oil has a direct impact on the costs of mobility provided with ICEVs. However, the share of mobility in the total costs is three times higher than for electricity generation (due to the low power and energy storage capacities of HEVs). Thus, the impact of the increase of oil production costs is bigger than the impact of the increase of costs of natural gas production. The implications of a climate policy on the competitiveness of V2G power is explored by Turton and Moura (Turton and Moura, 2006).

5 Discussion of results and conclusions

We have presented an overview and extensive analysis of the potential of the "Vehicle-to-Grid" (V2G) concept. Technical details on the technology and associated infrastructure requirements were also described. V2G power generation was analysed from two different perspectives: first, the potential value of V2G power generation in different power markets and then its cost-competitiveness in the energy market place, by comparing it with two conventional technologies (gas turbine and conventional coal-fired power plants). Although there is still a rather small research community working on this concept (mainly concentrated in California, USA), the potential is starting to be recognized also in the automotive industry, and some V2G projects and vehicles are now under development. Here are some examples (Clayton, 2004):

- In Toronto, a V2G fuel-cell bus is to be in service in March.
- DaimlerChrysler has reported it is working on a version of its popular pickup truck with V2G capability for supplying power at a work site.
- AC Propulsion has plans to make as many as 1,000 V2G electric-drive vehicles starting as soon as next year.
- A major Florida city is on the verge of buying more than 50 battery-powered buses, including several that are V2G capable.

Earlier studies have demonstrated the potential value of V2G for owners of electric-drive vehicles (EDVs) wishing to sell electricity back to the grid (Brooks, 2002, Brooks and Gage, 2001, Kempton and Kubo, 2000, Kempton and Letendre, 1997, Kempton and Tomić, 2005a). From our analysis in Section 3, we confirmed that V2G power generation is potentially attractive for vehicle owners in the case of regulation services (with any type of EDV), and for spinning reserves and peak power markets (FCEVs only). Unlike these earlier studies, we extended our analysis by considering the role of EDVs in V2G power generation and mobility services, accounting for all costs and attending to the fact that EDVs are competing with existing technological alternatives (Moura and Turton, 2006). As a consequence, our analysis shows that V2G power generation may be less attractive than indicated by earlier analyses.

Our analysis shows that battery-electric and hybrid-electric vehicles (BEVs and HEVs) are unable to provide power to the grid at costs below those of conventional gas turbine generators. Adding mobility costs to this analysis, the competitiveness of these EDVs declines further, mainly due to capital costs of this technology compared to conventional internal combustion engine (ICE) vehicles. These capital costs include the costs of adapting vehicles for V2G power generation (costs for wiring up buildings and upgrading vehicles) and, particularly in the case of BEVs, the costs of batteries. Moreover, it is unlikely that the cost of batteries will decrease sufficiently, at least in the medium term, for BEVs to become competitive for providing mobility and electricity services. On the other hand, HEVs look more promising despite the fact that our analysis shows they are less attractive than using gas turbine generation and ICE vehicles for providing electricity and mobility. HEVs appear more likely to become an attractive alternative because only a small (20 percent) reduction in the production cost of the batteries could compensate for differences in competitiveness. Moreover, if the HEV battery capacity is increased to around 9 kW, HEVs may be able to compete successfully in the provision of regulation services. Nevertheless, today's HEVs still rely on petroleum fuels, so this technology option represents only a partial solution to some of the challenges confronting the global transport system, namely atmospheric emissions and maintaining energy security. Despite the potential of this technology option, it is important to reiterate that the results obtained here only partially corroborate the optimistic findings of previous analyses, considering the current energy market conditions and costs of technology. When analysing the impact of a climate policy on the relative competitiveness of selected technologies, HEVs can potentially benefit from a carbon tax, but remain less attractive than the "conventional" combination. By contrast, there is a decline of the competitiveness of BEVs when generating V2G power and mobility services. This is because electricity cost is assumed to be affected by the increase in costs of natural gas and coal, which, in turn, are affected by the carbon tax.

Turning to fuel cell-electric vehicles (FCEVs), our analysis indicates that this EDV option is potentially very attractive for providing spinning reserves and peak power; also when considering mobility costs. In this case, our results concur with the results from the previous analysis (and referred authors) that FCEVs are potentially the only competitive technology for V2G under a fairly wide range of conditions, although this is sensitive to the cost of hydrogen and fuel cell systems, particularly for peak power markets. In the case of regulation services, FCEVs can be cost competitive if the production costs of fossil fuels increase or if the wiring capacity of buildings is increased (which also reinforces the competitive position of FCEVs in other power markets). In any case, however, it is important to stress that FCEVs are perhaps a longer-term option since fuel cell systems and hydrogen are yet to become commercially competitive in any significant energy market. This implies that many of the potential benefits of V2G may also only emerge in the medium to longer term.

Despite these drawbacks, one important implication of the analysis presented in this study is that the potential for EDVs to provide V2G power to the grid at competitive costs, while providing mobility services also, may accelerate the deployment of these vehicles, particularly where they are not competitive for mobility services alone. One critical question that this study has not addressed directly, however, is how this could be organised and managed, considering that grid operators would need to contract services with vehicle owners. One possibility is that energy aggregators would act as intermediaries since, under current rules in many parts of the world, grid operators generally contract with large generators to provide spinning reserves or regulation services, typically with a minimum quantity of 1 MW (Kempton and Tomić, 2005b). If one EDV can provide 15 kW of power capacity, a 1 MW contract would require 67 EDVs. Kempton *et al.* (2005b) suggest using a rough multiplier of 1.5 as a buffer to accommodate eventually unavailable or discharged EDVs. Thus, fleets with 100 vehicles may be able to supply 1 MW contracts during non-driving hours. There are some existing examples of potential aggregators that could be interested in supplying these services. Further, car sharing businesses and car pooling communities could include in the management of their fleets periods for charging and providing regulation services or spinning reserves, especially during the night when most of the fleet is not being used. This business model could be extended to car rental companies. In addition, battery manufacturers or distributors could provide a "free battery replacement" for BEVs in exchange for reaping most or all of the profit of V2G. However, there are many other factors to consider when envisaging how the large-scale deployment of V2G technologies could be realised, and some additional social uncertainties and technical or regulatory barriers are discussed in the accompanying paper by Turton and Moura (2006).

As mentioned before, V2G power generation is one currently unexploited source of Distributed-Energy-Resource (DER) which could emerge in the form of Electric-Drive Vehicles (EDVs) and may have the potential to both address some of the challenges in the transport sector discussed above and ameliorate some of the electricity system reliability risks in specific power markets. One technologically optimistic outcome of "*turning the Car into a power plant*" is envisioned by Rifkin (2002), who prophesises that "*the distributed-generation revolution is likely to take off in the next few years, with the introduction of automobiles, trucks, and buses operated by fuel cells*". As analysed in the study presented here, the remaining EDVs could also have a role to play depending on the future conditions of the energy marketplace, such as the shortage of dominant fossil fuel primary energy sources.

In this context it is also important to mention some of the issues we have not addressed in our analysis. One potentially significant factor is that we did not include the possibility of EDVs becoming commercially viable in one power market as a consequence of being competitive in another. For example, if FCEVs are competitive for spinning reserves (i.e., all the costs are covered, including mobility), they might be competitive for providing other services (regulation in this case) since the wiring and mobility are already paid for by one market. Evaluating the potential to provide a combination of electricity services with a single EDV requires further research, particularly in terms of any possible technical limitations. We also imposed other boundaries on our analysis, such excluding other linkages and competing demands within the energy system. Additionally, we did not consider a number of uncertain variables in the future energy system, for the sake of avoiding excessive complexity in the analysis. To address these and other limitations, and the likelihood that V2G power generation may have some potential to influence the energy mix in the longer term, further research should be conducted in addition to the present study.

Appendices

Appendix 1: Methodology for the calculation of accounting costs to generate V2G power with EDVs (based on Kempton *et al.*, 2001)

The methodology by Kemtpon *et al.* (2001) develops equations to calculate the capacity for providing power to the grid from three types of EDVs. These equations are applied to estimate costs and revenues for three power markets: regulation services, spinning reserves and peak power. We now present the set of equations used to obtain the results.

The power capacity of V2G can be estimated by Eq. 3.

$$P_{Vehicle} = \frac{\left(E_s - \frac{d_d + d_{rb}}{\eta_{veh}} \right) \eta_{inv}}{t_{disp}} \qquad \text{Eq. 3}$$

Where, $P_{Vehicle}$ is the maximum power from V2G in kW, E_S is the stored energy available as DC kWh to the inverter, η_{inv} is electrical conversion efficiency of the DC to AC inverter (we assumed 0.93), d_d is distance driven in km since the energy storage was full (we assumed 20 km), d_{rb} is the distance in km of the range buffer required by the driver (we assumed 10 km), η_{veh} is the vehicle fuel economy in km/kWh, and t_{disp} is the time the vehicle's stored energy is to be dispatched in hours.

As referred in Section 2.2, in the case of HEVs, we assumed that the driver doesn't need to have any buffer range (d_{rb}), because we assume that there is enough petrol in the tank for the next trip on full ICE mode. In addition, we also considered that the energy stored in the battery only depends on the driving pattern of the previous trip, and how much the battery is full. In this sense, we assumed that, on average, there is 50 percent of the energy stored in the battery for V2G services. Thus Eq. 3 becomes Eq. 4.

$$P_{Vehicle} = \frac{0{,}5 \times E_s \times \eta_{inv}}{t_{disp}} \qquad \text{Eq. 4}$$

The energy dispatched by EDVs for regulation services (calculated with Eq. 5) is a fraction of the total power available and contracted by the electricity operator to the EDV owner and is calculated using Eq. 6.

$$E_{disp} = R_{d-c} P_{disp} t_{disp} \qquad \text{Eq. 5}$$

where R_{d-c} is the "dispatch to contract" ratio, P_{disp} is maximum power from EDV [*kW*] and t_{disp} is the duration of energy dispatch [*hours*].

$$R_{d-c} = \frac{E_{disp}}{P_{contr} t_{contr}} \qquad \text{Eq. 6}$$

where P_{contr} the contracted capacity [*MW*], and t_{contr} is the duration of the contract [*hours*]. $R_{d\text{-}c}$ was assumed to be 0.1 (Kempton and Tomić, 2005a, p.271), with the contract potentially covering 6570 hours (18 hours x 365 days).

The energy dispatched by EDVs for spinning reserves and peak power is calculated with Eq. 7.

$$E_{disp} = \sum_{i=1}^{N_{disp}} P_{disp} t_{disp} \qquad \text{Eq. 7}$$

where N_{disp} is number of dispatches during the contracted period of time.

After determining the duration of contracted capacity and V2G power for each type of vehicle and for each type of power market, energy dispatch can be estimated and thereafter, revenues and costs can be calculated. Revenues are calculated in Eq. 8 and costs in Eq. 9.

$$r = \left(p_{cap} P t_{plug}\right) + \left(p_{el} E_{disp}\right), \text{ for regulation services and spinning reserves}$$

$$r = p_{el} E_{disp} = p_{el} P_{disp} t_{disp}, \text{ for peak power.} \qquad \text{Eq. 8}$$

where r are the total revenues in any national currency, p_{cap} is the capacity price [*$/kW-h*], P is the contracted capacity available (the lower between the capacity of power line or the capacity of the vehicle)[*kW*], t_{plug} is the time in hours the vehicle is plugged, p_{el} is the market rate of electricity [*$/kWh*], E_{disp} is the energy dispatched [*kWh*], P_{disp} is the power dispatched [*kW*], and t_{disp} is the total time the power is dispatched [*hours*].

$$c = c_{en} E_{disp} + c_{ac} \qquad \text{Eq. 9}$$

where c are the total cost [*$*], c_{en} is the unit cost of energy produced [*$/kW*], and c_{ac} is the annualized capital cost of technology [*$/year*]. For c_{en} and c_{ac} specifications, refer to Appendix 2.

Finally, net revenues are calculated by subtracting costs to revenues. Total net revenues are analysed on an annual basis, i.e. costs and revenues are calculated based on the total amount of energy produced and total time the vehicles are plugged to the grid and available for energy dispatching.

Appendix 2: Methodology for the calculation of economic costs to provide electricity and mobility services with both "conventional" technologies and EDVs

Costs of providing electricity service from conventional power plants

The set of equations used to estimate the total production costs of electricity with conventional power plants are now described. Eq. 10 presents the general structure of costs considered.

$$C_{ENERG} = C_c + C_{E_{disp}} \qquad \text{Eq. 10}$$

where C_c is the total capital and fixed operating costs of the power plant, and C_{Edisp} is the cost of producing (*dispatching*) electricity (E_{disp}) (all measured in *\$/year*).

Eq. 11 calculates the total capital and fixed costs of the power plant, where c_{ac} is the annualized capital cost, c_{fix} are the fixed costs, pf is the power plant factor, c_{tech} are the total capital costs of the technology, d is the discount rate and n is the expected lifetime of the power plant. These are all measured in *\$/year*, except for n that is expressed in *years* and for pf and d, which are dimensionless.

$$C_c = \frac{c_{ac} + c_{fix}}{pf} = \left(c_{tech} \times \frac{d}{1-(1+d)^{-n}} + c_{fix} \right) \times \frac{1}{pf} \qquad \text{Eq. 11}$$

The total costs of providing electricity are estimated in Eq. 12, where E_{disp} is the total amount of energy dispatched during a year by the power plant [*kWh*], c_{en} is the cost of producing on unit of electricity output [*\$/kWh*], c_{pe} is the *per* unit cost of primary energy [*\$/kWh*] and η_{PP} is the efficiency of the power plant (dimensionless).

$$C_{E_{disp}} = E_{disp} \times c_{en} = E_{disp} \times \frac{c_{pe}}{\eta_{PP}} \qquad \text{Eq. 12}$$

Costs of V2G power generation using EDVs

The following economic costs of V2G power are calculated using "out-of-the-factory" costs of technology or energy sources and, therefore, do not include any margins or taxes. The unit cost of purchased electricity by BEVs and PHEVs were based on the minimum cost of electricity produced either by GT or CC power plants, as presented in Eq. 13. This approach was followed in order to incorporate the impact of changing the energy marketplace conditions (e.g., increased costs of natural gas or coal) in the calculation of the cost of electricity production.

$$c_{elec} = MIN\left(\frac{C_{E_{disp}GT}}{E_{dispGT}} ; \frac{C_{E_{disp}Ccoal}}{E_{dispCcoal}} \right) \qquad \text{Eq. 13}$$

where C_{Edisp} is the production cost of electricity (GT or CC), E_{disp} is the total amount of energy dispatched, over a year (GT and CC) [*\$/year*], and c_{elec} is the unit cost of purchased electricity by BEVs and PHEVs [*\$/kWh*].

In addition, the assessment of the degradation costs of batteries or fuel cell engines (which correspond to the annualized capital costs, c_{ac}) were split into energy costs and mobility costs, as referred before. We assumed that the allocation of degradation costs to both uses of the battery, or fuel cell engine, can be based on the energy throughput for each service and are calculated in Eq. 14.

$$c_{ac} = c_{dE_{disp}} + c_{dMob} = c_{du} \times w_{disp} \times E_{disp} + c_{du} \times E_{mob} \qquad \text{Eq. 14}$$

where c_{ac} is the annualized capital cost of the battery or fuel cell engine (or total degradation costs) [*$/year*], c_{dEdisp} and c_{dMob} are the degradation costs of equipment due to energy services and to mobility services, respectively [*$/year*], c_{du} is the degradation cost of the battery or fuel cell engine *per* unit of electricity produced [*$/kWh*], E_{disp} and E_{mob} are the electricity used for energy and mobility services, respectively [*kWh/year*], and w_{disp} represents a weighting factor to account for difference in battery or FC wear from providing V2G power relative to mobility (this is discussed more below).

The unit degradation cost (c_{du}) of the equipment is calculated in Eq. 15, by dividing the annualized cost of the equipment (c_{ac}) [*$/year*] with the estimated total annual energy throughput (E_{annual}) of the equipment for mobility and electricity services together [*kWh/year*].

$$c_{du} = \frac{c_{ac}}{E_{annual}}, \text{ where } E_{annual} = w_{disp} \times E_{disp} + E_{mob} \qquad \text{Eq. 15}$$

c_{ac} is calculated in Eq. 16, where c_c is the investment cost of the technology [*$*] and *Lt* is the lifetime of the equipment (measured in years).

$$c_{ac} = c_c \times \frac{d}{1-(1+d)^{-Lt}} \qquad \text{Eq. 16}$$

However, the lifetime of the equipment depends on its annual use, which can be measured in terms of energy throughput or in terms of hours in operation. For instance, if the annual use of the equipment increases, its lifetime (in terms of years) decreases. The latter is estimated in Eq. 17, in the case of BEV.

$$Lt = \frac{LET}{E_{annual}} = \frac{LET}{w_{disp} \times E_{disp} + \frac{T_{year}}{\eta_{veh}}} \qquad \text{Eq. 17}$$

where *LET* is the maximum energy throughput of the battery. LET was considered to be 43840 kWh (Kempton and Tomić, 2005a). However, this lifetime depends on the depth-of-discharge (DoD) of the battery. Under the assumptions of Kempton and Tomić's (2005a), the DoD of battery is kept at a low level (above 20%) for V2G purposes. Under these operating conditions, the equivalent wear on the battery is assumed to decrease by two-thirds (w_{disp} = 0.33). However, we assumed that, for mobility purposes, the battery will be discharged at its maximum possible DoD (i.e., 80% that is considered to be the threshold to avoid quick degradation of the battery).

Furthermore, the total annual energy throughput (E_{annual}) depends on E_{disp}, which is the total energy dispatched for V2G power generation during one year by one vehicle [*kWh/year*], T_{year}, which corresponds to the average annual mileage of the EDVs [*km/year*] and η_{veh}, the fuel economy of the EDV [*km/kWh*].

In the case of FCVs, the lifetime of the fuel cell is calculated in Eq. 18.

$$Lt = \frac{LH}{L_{annual}} \qquad \text{Eq. 18}$$

where LH is the maximum lifetime which the fuel cell engine is designed for [*hours*] and L_{annual} is the average annual operating time [*hours/year*]. LH was assumed to be 10,000 hours[3].

L_{annual} is estimated using the following equations. Eq. 19 is used in the case of Regulation Services and Eq. 20 is used for Spinning Reserves or Peak Power markets.

$$L_{annual} = t_{plug} \times R_{d-c} + \frac{T_{year}}{s} \quad \text{Eq. 19} \quad \text{or} \quad L_{annual} = N_{disp} \times t_{disp} + \frac{T_{year}}{s} \quad \text{Eq. 20}$$

where t_{plug} is the time the vehicle is plugged to some outlet and available to provide or intake electricity [*hours*], $R_{d\text{-}c}$ is the ratio between the time during which the regulation services were provided and the total time of contracted capacity (equal to t_{plug}), N_{disp} is the total of dispatches of energy for spinning reserves or peak load, t_{disp} is the average duration of each dispatch [*hours*] and s is the average circulation speed of EDVs (which we considered to be 30 km/h).

Eq.21 presents the general structure of costs for V2G power production. Here, fixed costs are already included in the cost of dispatch (C_{Edisp}) and the costs of wiring up (c_{wup}) the buildings and upgrading the vehicles are added [*$*].

$$C_{V2G} = C_{E_{disp}} + C_{dE_{disp}} + c_{wup} \qquad \text{Eq.21}$$

Estimation of mobility costs

The following equations were used to calculate the costs of mobility, C_{MOB} [*$/year*]. The costs considered for this comparative analysis are, in general terms, manufacturing costs (annualized machine capital costs), fuel consumption costs (related with travel), non-fuel operation and maintenance costs, and part of the degradation costs of the battery, or fuel cell engine. Eq.22 shows the general structure of costs.

$$C_{MOB} = c_{anonbat} + c_{fuel} + c_{non-fuel} + c_{dMob} \qquad \text{Eq.22}$$

where $c_{anonbat}$ are the annualized costs of non-battery components of the drive train (i.e., fuel storage, transmission, motor and controls), c_{fuel} are the annual fuel consumption costs, $c_{non\text{-}fuel}$ are the non-fuel operation and maintenance costs, and c_{dMob} are the degradation costs of the battery or the fuel cell engine due to mobility services. All are measured in [*$/year*].

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[3] If a FCV annual distance is 15,000km and the average circulation speed is considered to be 30 km/h, then the annual operating hours of the fuel cell engine is approximately 500 hours. In addition, the average lifetime of a vehicle is approximately 10 years. Thus, the total annual circulation hours of a fuel cell engine would be approximately 5,000 hours. We assumed 10,000 hours for the lifetime of the fuel cell, which corresponds to doubling the previous estimation.

$$c_{anonbat} = c_{c-nonbat} \times \frac{d}{1-(1+d)^{-n}} \qquad \text{Eq. 23}$$

where $c_{c\text{-}nonbat}$ are the total investment costs of the non-battery components of the drive train [*$*], d is the discount rate, and n is the expected lifetime of a vehicle, which was assumed to be 10 years.

Fuel consumption costs are accounted for a year period time, assuming that a car is driven 15,000 km/year. Delivered fuel costs do not include taxes and margins, and final results are expressed in [*$/veh/year*].

$$c_{fuelt} = \frac{T_y}{\eta_{veh}} \times c_{pe} \qquad \text{Eq. 24}$$

where T_y is the total annual mileage [*km*], η_{veh} is the vehicle's fuel economy [*km/kWh*], and c_{pe} is the *per* unit cost of energy [*$/kWh*].

Non-fuel operations and maintenance expenses include oil, tires and other costs related with travel [*$/year*]. These are assumed to be a fixed percentage of the vehicle's first cost, so that bigger and/or more expensive cars induce more expensive non-fuel operation and maintenance costs.

$$c_{non-fuelt} = c_{c-veh} \times (1 - r_{O\&M}) \qquad \text{Eq. 25}$$

where $r_{O\&M}$ is the a fixed percentage of vehicle first cost ($c_{c\text{-}veh}$, [*$*]).

Appendix 3: Sensitivity analysis to selected variables and parameters of the equations for calculation of market costs and revenues of V2G power generations

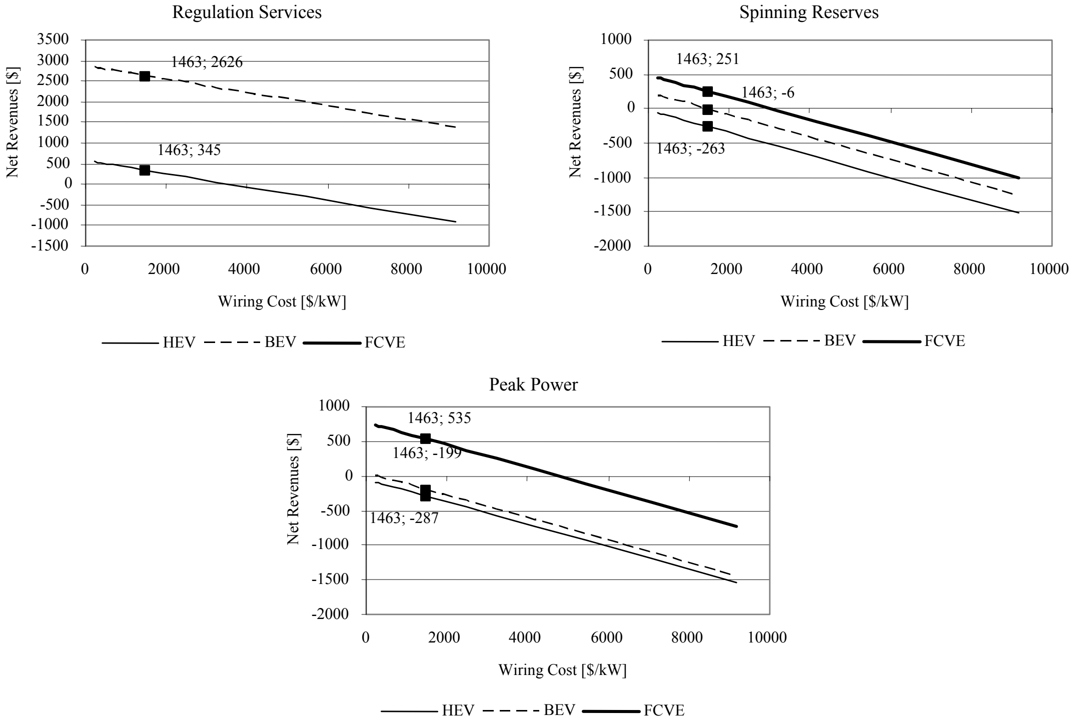

Figure A 1: Estimated V2G power generation net revenues as a function of the wiring costs.

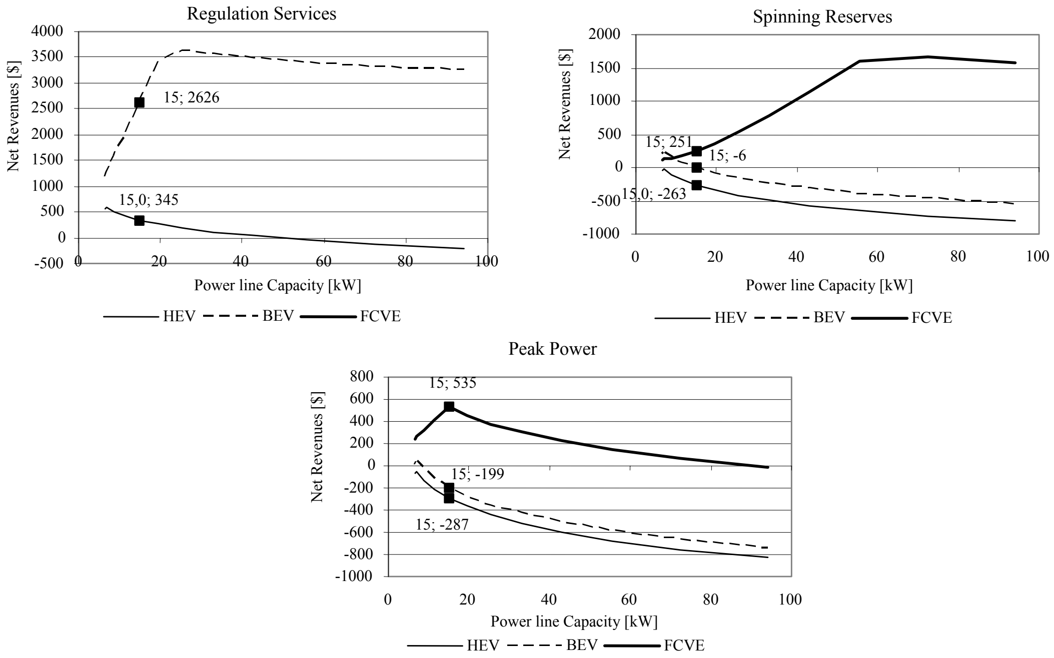

Figure A 2: Estimated V2G power generation net revenues as a function of the power line capacity.

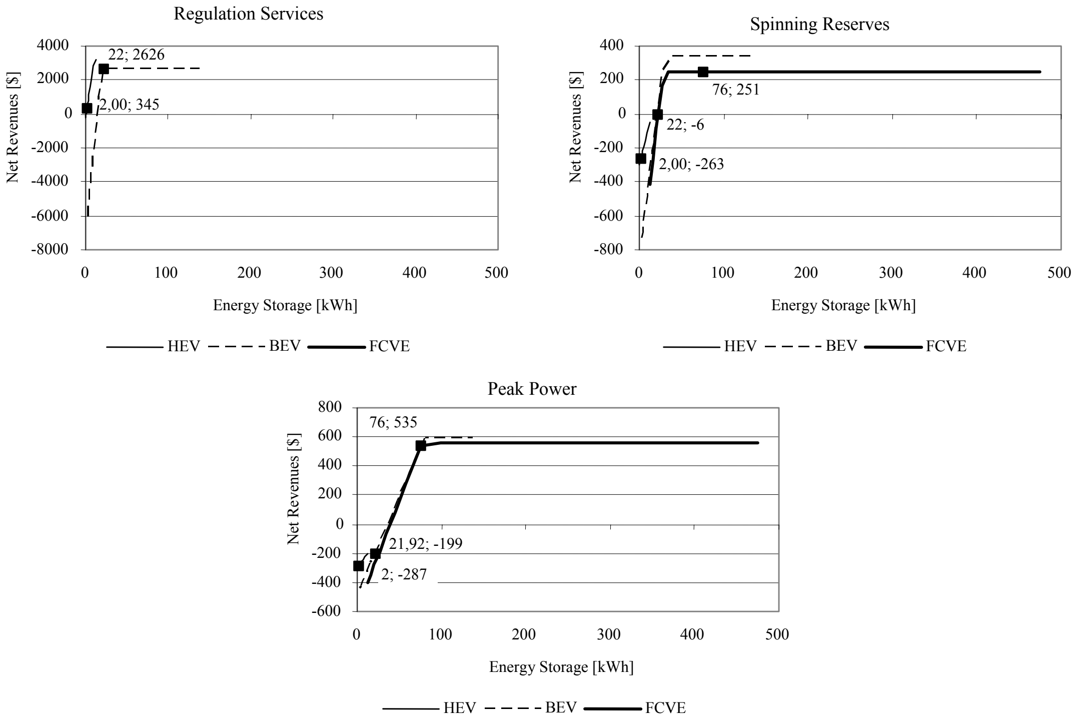

Figure A 3: Estimated V2G power generation revenues as a function of the energy storage capacity.

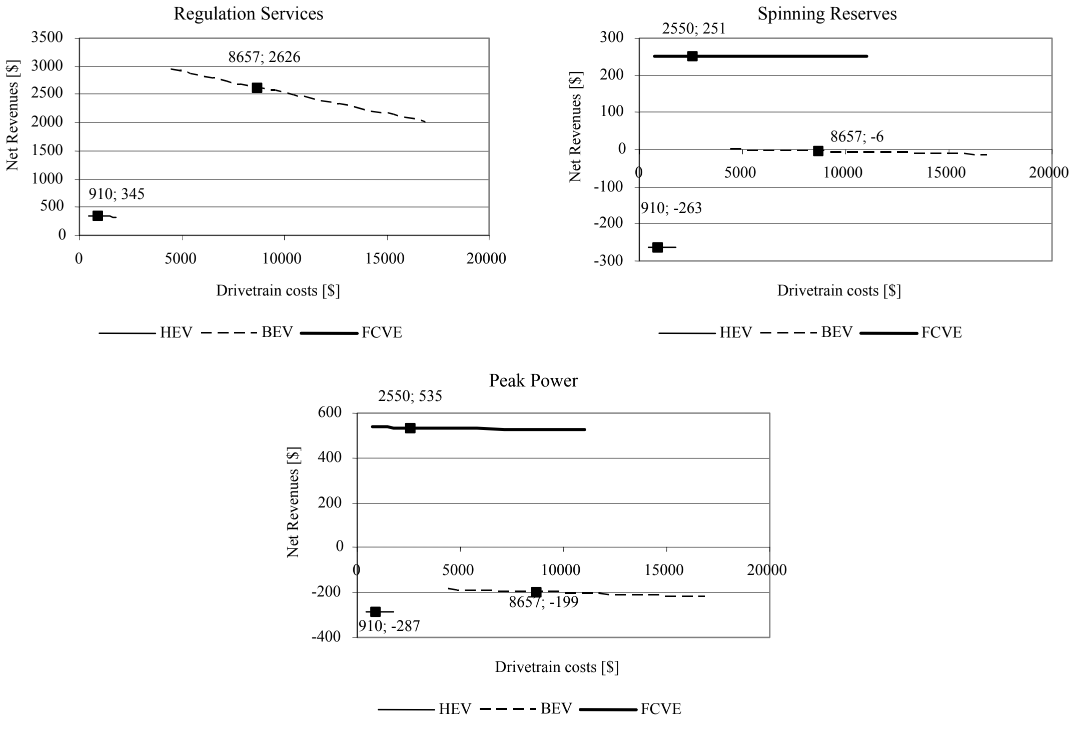

Figure A 4: Estimated V2G power generation net revenues as a function of the capital costs of the drive train.

Appendix 4: Results from the comparative assessment of the economic performance of alternative combinations of technologies to provide electricity and mobility services

Table A.1: Costs of mobility and electricity generation for Regulation Up & Down services ($/year)

		C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
		ICEV	**ICEV**	**BEV**	**BEV**	**BEV**	**ICEV**	**ICEV**	**HEV**	**HEV**	**HEV**
Costs for mobility	Ann. Cap. Costs of the vehicle	581	581	1642	1642	1434	581	581	667	667	655
	Energy Consumption by vehicles	208	208	276	276	276	208	208	193	193	193
	Non-fuel O&M costs of vehicles	364	364	453	453	453	364	364	364	364	364
	Total	1,153	1,153	2,371	2,371	2,162	1,153	1,153	1,224	1,224	1,211
		GT	**CC**	**GT**	**CC**	**BEV**	**GT**	**CC**	**GT**	**CC**	**HEV**
Costs for Electricity	Annualized capital costs	1,257	3,179	1,257	3,179	841	234	591	234	591	110
	Energy supply costs	236	155	236	155	775	44	29	44	29	45
	Cost of wiring-up Buildings and vehicles					303					303
	Total	1,493	3,333	1,493	3,333	1,920	278	620	278	620	458
Cost of Mobility and Electricity		**2,646**	**4,487**	**3,864**	**5,704**	**4,082**	**1,431**	**1,773**	**1,502**	**1,844**	**1,669**

Table A. 2: Costs of mobility and electricity generation for Regulation Up services ($/year)

		C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
		ICEV	**ICEV**	**BEV**	**BEV**	**BEV**	**ICEV**	**ICEV**	**HEV**	**HEV**	**HEV**	**ICEV**	**ICEV**	**FCEV**	**FCEV**	**FCEV**
Costs for mobility	Ann. Cap. Costs of the vehicle	581	581	1642	1642	1545	581	581	667	667	663	581	581	738	738	614
	Energy Consumption by vehicles	208	208	276	276	276	208	208	193	193	193	208	208	491	491	491
	Non-fuel O&M costs of vehicles	364	364	453	453	453	364	364	364	364	364	364	364	453	453	453
	Total	1,153	1,153	2,371	2,371	2,273	1,153	1,153	1,224	1,224	1,220	1,153	1,153	1,682	1,682	1558
		GT	**CC**	**GT**	**CC**	**BEV**	**GT**	**CC**	**GT**	**CC**	**HEV**	**GT**	**CC**	**GT**	**CC**	**FCEV**
Costs for Electricity	Annualized capital costs	419	1,059	419	1,059	305	56	141	56	141	41	1,257	3,179	1,257	3,179	180
	Energy supply costs	79	52	79	52	258	10	7	10	7	11	236	155	236	155	1,241
	Cost of wiring-up Buildings and vehicles					303					303					393
	Total	497	1,110	497	1,110	867	66	148	66	148	355	1,493	3,333	1,493	3,333	1,814
Cost of Mobility and Electricity		**1,651**	**2,263**	**2,868**	**3,481**	**3,140**	**1,219**	**1,301**	**1,290**	**1,371**	**1,574**	**2,646**	**4,487**	**3,176**	**5,016**	**3,371**

Table A. 3: Costs of mobility and electricity generation for Spinning Reserves ($/year)

		C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
		ICEV	**ICEV**	**BEV**	**BEV**	**BEV**	**ICEV**	**ICEV**	**HEV**	**HEV**	**HEV**	**ICEV**	**ICEV**	**FCEV**	**FCEV**	**FCEV**
Costs for mobility	Ann. Cap. Costs of the vehicle	581	581	1,642	1,642	1,545	581	581	668	668	668	581	581	738	738	730
	Energy Consumption by vehicles	208	208	276	276	276	208	208	193	193	193	208	208	491	491	491
	Non-fuel O&M costs of vehicles	364	364	453	453	453	364	364	364	364	364	364	364	453	453	453
	Total	1,153	1,153	2,371	2,371	2,273	1,153	1,153	1,225	1,225	1,224	1,153	1,153	1,682	1,682	1,674
		GT	**CC**	**GT**	**CC**	**BEV**	**GT**	**CC**	**GT**	**CC**	**HEV**	**GT**	**CC**	**GT**	**CC**	**FCEV**
Costs for Electricity	Annualized capital costs	586	1,482	586	1,482	305	78	197	78	197	1	1,257	3,179	1,257	3,179	8
	Energy supply costs	3	2	3	2	11	0	0	0	0	0	7	5	7	5	38
	Cost of wiring-up Buildings and vehicles					303					303					393
	Total	590	1,484	590	1,484	620	78	197	78	197	305	1,265	3,183	1,265	3,183	439
Cost of Mobility and Electricity		**1,743**	**2,637**	**2,960**	**3,855**	**2,893**	**1,232**	**1,351**	**1,303**	**1,422**	**1,529**	**2,418**	**4,337**	**2,947**	**4,866**	**2,113**

Table A. 4: Costs of mobility and electricity generation for Peak Power ($/year)

		C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
		ICEV	**ICEV**	**BEV**	**BEV**	**BEV**	**ICEV**	**ICEV**	**HEV**	**HEV**	**HEV**	**ICEV**	**ICEV**	**FCEV**	**FCEV**	**FCEV**
Costs for mobility	Ann. Cap. Costs of the vehicle	581	581	1,642	1,642	1,545	581	581	668	668	667	581	581	738	738	694
	Energy Consumption by vehicles	208	208	276	276	276	208	208	193	193	193	208	208	491	491	491
	Non-fuel O&M costs of vehicles	364	364	453	453	453	364	364	364	364	364	364	364	453	453	453
	Total	1,153	1,153	2,371	2,371	2,273	1,153	1,153	1,225	1,225	1,224	1,153	1,153	1,682	1,682	1,638
		GT	**CC**	**GT**	**CC**	**BEV**	**GT**	**CC**	**GT**	**CC**	**HEV**	**GT**	**CC**	**GT**	**CC**	**FCEV**
Costs for Electricity	Annualized capital costs	147	370	147	370	305	19	49	19	49	3	754	1905	754	1,905	44
	Energy supply costs	8	5	8	5	28	1	1	1	1	1	43	28	43	28	226
	Cost of wiring-up Buildings and vehicles					303					303					393
	Total	155	376	155	376	636	21	50	21	50	307	797	1,934	797	1,934	663
Cost of Mobility and Electricity		**1,308**	**1,529**	**2,525**	**2,747**	**2,909**	**1,174**	**1,203**	**1,245**	**1,275**	**1,531**	**1,950**	**3,087**	**2,479**	**3,616**	**2,302**

Table A. 5: Costs of mobility and electricity generation for base load ($/year)

		C1	**C2**	**C3**	**C4**	**C5**
		ICEV	**ICEV**	**FCEV**	**FCEV**	**FCEV**
Costs for mobility	Ann. Cap. Costs of the vehicle	581	581	1,118	1,118	952
	Energy Consumption by vehicles	208	208	491	491	491
	Non-fuel O&M costs of vehicles	364	364	454	454	454
	Total	1,153	1,153	2,063	2,063	1,897
		GT	**CC**	**GT**	**CC**	**FCEV**
Costs for Electricity	Annualized capital costs	1,572	2,980	1,572	2,980	1,656
	Energy supply costs	2,358	1,548	2,358	1,548	12,407
	Cost of wiring-up Buildings and vehicles					393
	Total	3,929	4,528	3,929	4,528	14,455
Cost of Mobility and Electricity		**5,083**	**5,682**	**5,992**	**6,591**	**16,352**

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