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Vehicle-to-grid systems for sustainable development: An integrated energy analysis

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Abstract

Vehicle-to-grid (V2G) systems represent a means by which power capacity in parked vehicles can be used to generate electricity for the grid. This paper describes the first detailed and global analysis of the potential of V2G technologies over the long-term (to 2100) using a comprehensive energy-systems model. In this analysis we explore the potential for V2G systems to supply a number of electricity submarkets and concomitantly accelerate the diffusion of advanced vehicle technologies, including hybrid-electric and fuel cell drivetrains. We also examine the potential impact of V2G on the global energy system, particularly in terms of investment in conventional capacity, and the possible role of V2G-enabled vehicles in increasing the market penetration of renewable electricity generation technologies. Importantly, however, V2G technologies represent a paradigm shift in how the energy and mobility markets are related, and a number of possible barriers to the widespread adoption of this technology are also discussed.

Keywords: Fuel cell vehicles; Hybrid vehicles; Ancillary services; Vehicle-to-grid power; Greenhouse gas emissions; Technological change; V2G

1. Introduction

New technologies represent an important means by which challenges facing the energy system can be overcome. Current global challenges include, among others, the need to reduce greenhouse

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gas emissions, manage energy security and reduce local and regional pollution, while providing access to cheap and safe energy needed for development [1,2]. These challenges are particularly pronounced in the transport sector, where the current dependence on internal combustion engine vehicles (ICEVs) fuelled with petroleum from politically volatile regions remains a major threat to energy security, climate change mitigation and urban air pollution. However, a number of alternative technologies exist that may ameliorate some of the risks emerging in the transport sector through their higher efficiencies and potential to utilize non-petroleum fuels [3]. These technologies include hybrid-electric vehicles (HEVs), fuel cell vehicles (FCVs) and battery electric vehicles (BEVs), although there exists some debate about the suitability of these different options [4–6]. Collectively, these options can be categorised as electric-drive vehicles (EDVs), because they all have the capability to produce motive power from electricity, rather than from the internal combustion engine.

However, these technologies currently suffer to different degrees from a lack of market experience and high costs. Moreover, even if and when these current barriers are overcome, the transition to EDV technologies may span long periods of time, due to the large inertia resulting from the current dominance of the ICEV and related technologies and social systems [4,7,8].

In this paper we explore whether vehicle-to-grid (V2G) technologies represent a potential opportunity to bring forward and accelerate a transition towards EDVs by improving the commercial viability of new vehicle technologies. The V2G concept involves using parked vehicles to supply generation services to the electricity grid [9–13]. In simple terms, vehicles are plugged in to the grid, and then feed in electricity generated from the vehicle engine (in the case of FCVs) or stored in an on-board battery system (HEVs and BEVs).[1]

However, V2G systems are only likely to change EDV deployment and diffusion patterns if there are benefits associated with providing energy from parked cars. One factor which suggests such benefits may exist relates to the fact that private vehicles are parked on average 93–96% of their lifetime, during which time each represents an idle asset [11,14]. Each parked vehicle contains underutilised energy conversion and fuel (or battery) storage capacity, and may actually create negative value due to parking costs. Accordingly, generating V2G power from parked vehicles can better utilise an expensive investment (particularly in the case of new and alternative vehicle technologies), thereby enabling cars to provide both mobility and energy services.

Nonetheless, the question remains as to whether vehicles, via V2G, can provide electricity services competitively compared to conventional electricity generation technologies. Electricity services can be characterized according to specific power markets, which differ in terms of control method, response time, duration of the power dispatch, contract terms and price. V2G power generation has already been analysed in several studies [14–16] which showed that although EDVs may be less suited to base-load electricity generation, they may be suitable for providing regulation services, spinning reserves and peak power demand. These services are described below:

- *Peak power* is required at times of day when high levels of demand are expected (e.g., hot summer afternoons when air conditioning demands are large). Typically, peak power is generated

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[1] Of course, electricity could be produced onboard HEVs by operating the internal combustion engine to run a generator, but this would merely provide an inefficient way of generating electricity from the vehicle's primary fuel—petroleum—contributing little to the main challenges outlined above.

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by power plants that can be switched on relatively quickly, such as gas turbines. However, because these plants are only utilised during the few hundred hours per year (i.e., less than 10% of the time) when demand is high, and are idle otherwise, they represent a relatively inefficient investment.

- *Spinning reserves* refers to generating capacity that is up and running, and synchronized with the electricity grid (but not contributing power). Spinning reserves generators contribute to grid stability, helping to arrest the decay of system frequency when there is a sudden breakdown or loss of another generator. Again, typically, power plants that can provide fast response to the calls of the grid operator are the most suitable, e.g. gas turbines. The capacity required to provide spinning reserves can also be seen as an underutilised investment, although essential for managing market risks.
- *Regulation services*, on the other hand, are used to continuously fine-tune the balance between power generation and demand, in terms of the voltage and the frequency of the grid. In many power markets, this function, called regulation or automatic generation control (AGC), is priced separately from power generation and procured as an ancillary service (another such service is spinning reserves). The grid operator needs to be able to ensure generators ramp output up *or* down in real time to meet customer reactive power needs, manage customer impact on system voltage, frequency and system losses and ensure that power-factor problems at one customer site do not affect power quality elsewhere in the system [17]. Again, providing regulation services requires electricity generation capacity in excess of demand.

V2G may provide a means by which to utilise the spare power capacity available in each parked vehicle and avoid the need to maintain the excess conventional electricity generation capacity currently required to provide regulation, spinning reserves and peak power.

The potential economic benefits of V2G systems employing different EDV technologies for providing both electricity and mobility services have been discussed in a related analysis in Moura and Turton [9]. The analysis in [9] represents an important improvement on earlier approaches 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 mobility services. However, despite the advantages of the approach employed by Moura and Turton [9], the analysis is essentially static and based on a single power market, although they examine the potential of possible future technology and energy system developments.

Accordingly, this paper builds and extends upon Moura and Turton [9], and is the first to examine V2G technologies in detail in a long-term, dynamic, bottom–up, global energy systems model which optimizes discounted energy system cost. This analysis framework facilitates the exploration of linkages and competing demands within the energy system, in addition to emulating some features of technological change, including learning-by-doing, that may accelerate the deployment or improve the competitiveness of new technologies.

In the remainder of this paper we first describe the energy-systems methodology applied to model and explore the possible future deployment of V2G systems (in Section 2), including details of how these technologies are represented. Section 3 then presents and discusses some of the main findings of the analysis. Other issues related to the diffusion of V2G technologies and important uncertainties are discussed in more detail in Section 4, and the main conclusions presented in Section 5. Readers should refer to [9], for a more detailed discussion of the V2G concept and results of a preliminary analysis.

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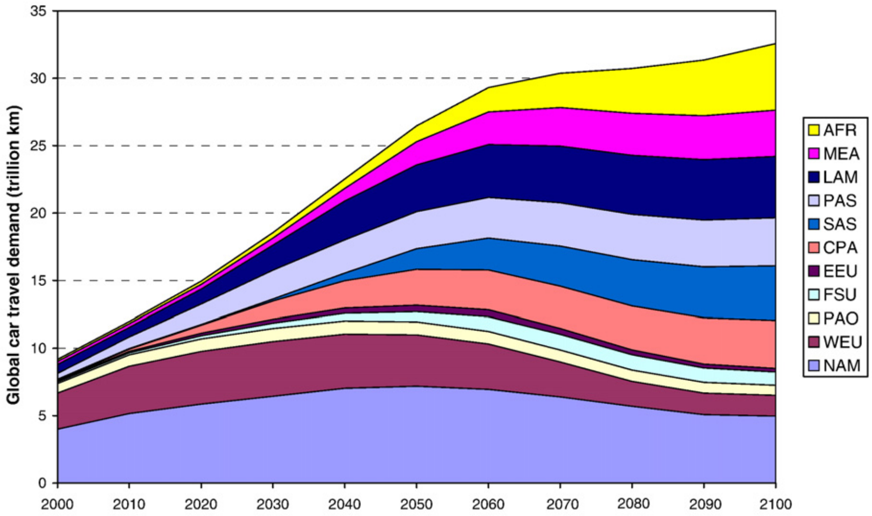
2. Methodology

2.1. Modelling and scenario framework

To study the potential long-term impact of V2G systems on the global energy market, we employed ERIS (*E*nergy *R*esearch and *I*nvestment *S*trategies), a "bottom–up" energy optimization model that includes a detailed representation of technologies and technology dynamics. ERIS is a global 11-region model that endogenizes technological learning curves [18–20]. It models energy demands and technologies in electric and non-electric sectors, covering transportation and thermal needs, in addition to fuel production technologies, specifically for hydrogen, alcohols and Fischer–Tropsch liquids production. For transportation, ERIS distinguishes seventeen distinct technology-fuel combinations, including ten technology-fuel combinations for the private automobile (see Turton and Barreto [4], also for information on cost assumptions for different vehicle technologies), making it well-suited to studying the potential impact of new transport technologies. For the analysis of V2G systems, an electric battery vehicle technology was also included in ERIS. ERIS also models other aspects of sustainable development, including resource availability (based on Rogner [21]) and GHG abatement options for several non-CO_2 greenhouse gases [22], as well as geological and forest sinks [23,24].

The ERIS model is calibrated to year 2000 energy and transport statistics [25,26] and to analyse future V2G and other technology deployment we applied an economic and demand growth trajectory from the B2 scenario from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios [27,28], although updated to account for recent economic developments and the latest United Nations long-term population projections (see Turton [29]). In addition, we have used the future automobile transport demand scenario presented in Fig. 1 [29], which shows total kilometers of travel in



NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific and Other Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

Fig. 1. Global automobile transport demand projection.

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different world regions. More information about this scenario is available in Turton and Barreto [4] and Turton [29].

2.2. V2G system technologies

Specific V2G system technologies were incorporated into the ERIS model to represent the V2G system infrastructure—including wiring, metering, communication to the grid manager, and safety systems. This is assumed to cost $400 for a basic V2G system with a capacity of 6.6 kW and an additional $1500 to upgrade this to 15 kW (based on Kempton and Tomić [11]). These costs are based on estimates for the US for residential buildings, and may be lower for large parking lots, but potentially higher for on-street parking [9]. The V2G wiring systems are assumed to have an average lifetime of 30 years. Costs for vehicle technologies were taken from Turton and Barreto [4], with average vehicle lifetime assumed to be 10 years.

For our analysis, vehicles used for V2G are assumed to be available to provide electricity services (i.e., plugged in and with enough fuel) for 50% of the time. This can be compared with the estimated 96% of the time that vehicles are parked on average in the USA [11], so our assumption may be conservative. In the case of HEVs it is assumed that, on average, on-board fuel (e.g., gasoline) is not used for providing V2G electricity services, and these are provided only from the battery.[2] Given that the battery storage capacity of HEVs is limited, the effective power capacity of these vehicles for V2G services—particularly in the case of peak power, is assumed to be well below maximum power output capacity. Accordingly, we have assumed that a HEV with a 10 kWh battery[3] can supply only 1.25 kW over an average period of peak demand (for example, 4 h—see [9]), which also accounts for limited vehicle availability and battery charge level. In comparison, FCVs are assumed to have a FC output capacity of 40 kW [3,18], so the limiting factor in the provision of peak power from these V2G-enabled vehicles is assumed to be the system wiring capacity, which is either 6.6 or 15 kW in this analysis.

2.3. Energy market services

As discussed, V2G technologies may have advantages for supplying specific electricity markets. To model these markets, we have assumed that in each world region the electricity system is required to maintain:

- a 5% spinning reserve margin;
- a 10% regulation up and down margin: and
- a 50% peaking margin.

To apply these requirements we have introduced two additional electricity submarkets into the ERIS model, covering regulation (up and down) and spinning reserves. Peak power was included earlier in the model's development [19]. In each of the electricity markets it is assumed that only a limited number of conventional technologies are suitable. For regulation services, only conventional gas turbine, gas

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[2] Moreover, we assume that the on-board fuel is not used indirectly for providing V2G services, such as via regenerative braking. That is, we assume that in net terms the amount electricity delivered by the HEV battery for V2G is equivalent to the amount of grid electricity used for recharging.

[3] Note, this is larger than many current HEVs, such as the Toyota Prius with a storage capacity of around 1.3 kWh [30].

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Table 1
Four scenarios analysed in this paper

		Baseline scenario	Climate policy scenario
V2G system technologies	Yes	BaseV	ClimateV
	No	BaseN	ClimateN

combined cycle, thermal oil, hydroelectric and stationary fuel cell generators are assumed to be suitable. On the other hand, for peaking and spinning reserves, all technologies except those that cannot be reliably dispatched are included. Those excluded comprise all solar technologies, wind turbines and some other renewables.

It should of course be stressed that the results presented in subsequent sections rely on the set of assumptions described above regarding the cost and characteristics of V2G infrastructure, vehicle drivetrain technologies (see Turton and Barreto [4]), and electricity markets. Some sensitivity analysis of the impact of alternative costs and related assumptions on the attractiveness of V2G are presented in Moura and Turton [9] and Moura [31].

2.4. Scenarios

The above framework is applied to study the potential impact of V2G technologies over the long-term on diffusion of alternative drivetrain systems and the development of the electricity system, using four main scenarios. These are summarized in the 2 × 2 matrix presented in Table 1, and comprise scenarios either including or excluding V2G system technologies. These scenarios are modeled otherwise identically, except that the systems which allow EDVs to supply services to the electricity grid are included in only one set of scenarios. The other division shown in Table 1 is between a simple baseline scenario in which economic energy system costs are minimized while ignoring external costs, and an alternative where a global climate policy is included, modeled simply as a tax on greenhouse gas emissions of $500 per tonne of carbon-equivalent. The climate policy scenarios are included so as to explore any possible role for V2G technologies in a future carbon-constrained world. Although we conducted similar analysis for each of the four scenarios, we focus primarily in the following section on results for the scenarios which include V2G technologies.

3. Results and discussion

3.1. Baseline scenario

3.1.1. Deployment of V2G infrastructure and V2G-capable vehicles

The benefits of V2G technologies can only be realized if a combination of infrastructure, including regulation, metering and wiring in buildings, electric-drive vehicles, and fuel production and distribution systems are all available. Under our no-climate-policy (BaseV) scenario, the main drivers of V2G deployment and diffusion relate entirely to the electricity system services these systems are able to provide: spinning reserves, regulation, peak power and, possibly, non-peak generation. Importantly, the modelling framework applied here may not be sufficiently detailed to identify all possible technology niches—such as capacity-constrained sub-regional markets. Nonetheless, each of the services markets is included in the ERIS model used for this analysis, as mentioned in Section 2.3.

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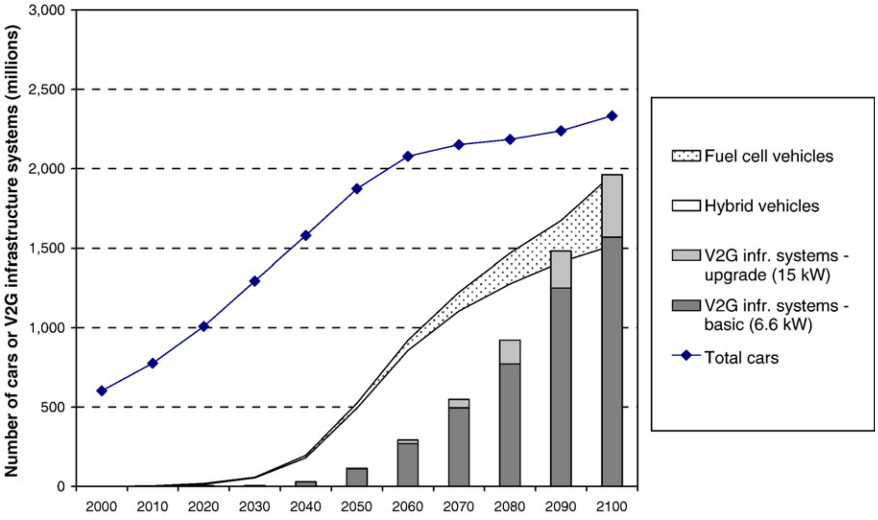

Fig. 2. Global deployment of V2G infrastructure and V2G-capable vehicles, BaseV scenario.

Fig. 2 presents the global deployment of V2G infrastructure—both basic (6.6kW) and upgraded (15kW) systems—and uptake of V2G-capable fuel cell and hybrid-electric vehicles under the BaseV scenario. The total number of cars is also indicated in Fig. 2. As shown in Fig. 2, under the assumptions applied in the ERIS model, V2G systems diffuse slowly early in the century in this scenario. In 2040 there is around 1 V2G system for every 50 vehicles (although already 1 for every 6.5 V2G-capable vehicles), but market penetration accelerates rapidly thereafter reaching a level of over 0.8 systems per vehicle in 2100. This result indicates that V2G technologies are potentially attractive and cost-effective over the long-term under the assumptions applied here, and hence warrant further investigation.[4]

Fig. 2 also indicates that the majority of the V2G systems are installed for connection with HEVs in the BaseV scenario. In some ways this merely reflects the greater competitiveness of HEVs over FCVs in the transport market, consistent with studies which do not include V2G systems (see [4,29]), rather than HEVs necessarily being the preferred solution for providing services to the electricity grid. The analysis in Moura and Turton [9] tends to support this conclusion, however it should be noted that slightly different assumptions regarding hybrid-electric vehicles are used in this paper. Specifically, a larger battery storage system of 10 kWh is assumed here, which would be consistent with consumer preferences for a longer range of electric-only operation, and the availability of plug-in recharge systems. As discussed in Moura and Turton [9], and mentioned above, such large batteries may be important for improving the suitability of HEVs for V2G.

3.2. Accelerated uptake of electric-drive vehicles

To examine in more detail the impact of the availability of V2G systems on the deployment of alternative vehicle technologies under the baseline scenario, we show in Fig. 3 the share of global travel

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[4] Refer to Moura [31] and Moura and Turton [9] for some analysis of the impact of alternative assumptions on the attractiveness of V2G technologies.

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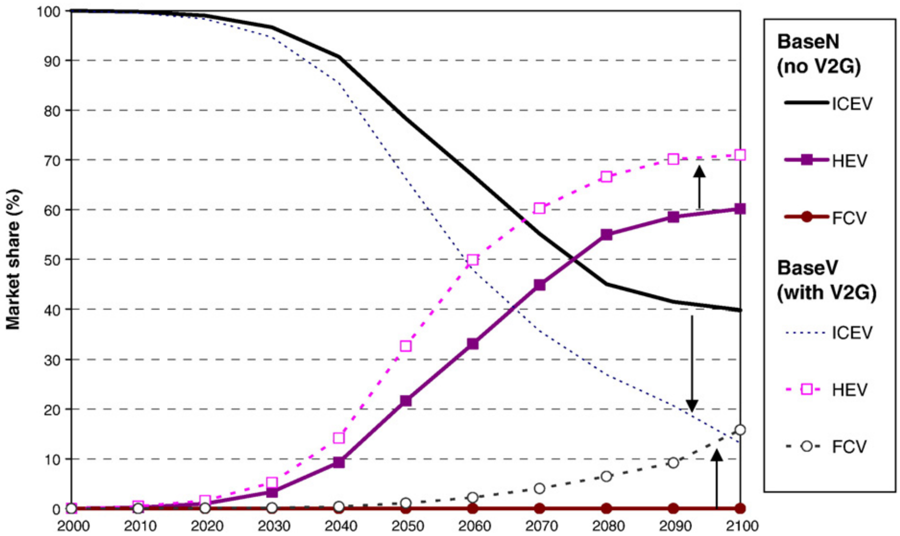

Abbreviations are as follows: ICEV – internal combustion engine vehicle; HEV – hybrid-electric vehicle; and. FCV – fuel cell vehicle.

Fig. 3. Impact of availability of V2G technologies on global car technology market share, baseline scenario.

by different vehicle technologies in the two baseline scenarios—with and without V2G system technologies (BaseV and BaseN, respectively). Fig. 3 shows that the availability of vehicle-to-grid technologies enables fuel cell and hybrid-electric vehicles to capture a significantly larger share (up to 25% more) of the car market by the end of the 21st century—that is, V2G systems promote a more rapid uptake of new vehicle technologies under the assumptions applied here. Again we see that HEVs account for a majority of the displaced ICEVs until the last decades of the century, but by 2100 fuel cell vehicles (FCVs) achieve market penetration of close to 16% of automobile travel. Compared to an earlier analysis in which FCVs were observed to be relatively unattractive in the absence of climate change policies [4], the results here show that the potentially large market niche provided by V2G may overcome a number of the barriers to FCV deployment, such as fuel cell cost, distribution infrastructure needs, on-board storage and the cost of hydrogen production [5]. Importantly, Fig. 3 does not indicate any adoption of battery electric vehicles because this technology is uncompetitive under both baseline scenarios, under the assumptions applied in this analysis.

3.2.1. Energy market services

Having established that V2G systems and EDV technologies are competitive under our baseline scenario, the next step in the analysis is to identify the specific power market services for which they are most suited over the long-term. This is explored in Fig. 4, which shows the global requirements for regulation, spinning reserves and peak power, and the availability of conventional capacities under this scenario. Fig. 4 shows that, for both regulation and spinning reserves (SR), capacity from conventional generators is sufficient to meet the requirements modeled here. In both cases, the requirements are presented as the total capacity necessary to: i) provide the average generation from power plants suited to regulation or spinning reserves; and ii) maintain a buffer above this amount of 10% in the case regulation,

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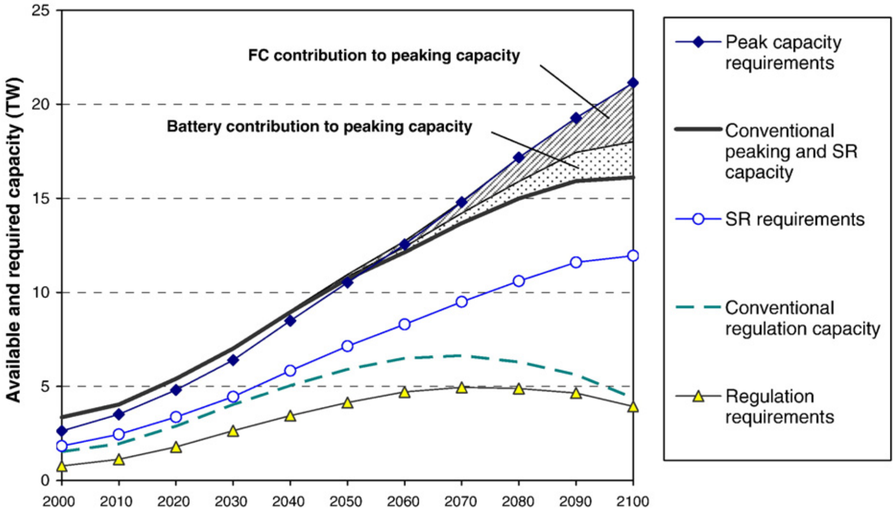

Fig. 4. Contribution of V2G to global energy market services (peak power, spinning reserves (SR) and regulation services), BaseV scenario.

and 5% in the case of spinning reserves. From Fig. 4, it appears that V2G systems are not required to supply these markets, at least at the average aggregated level explored with our methodology. However, in the case of regulation, it appears that perhaps a small change in our assumptions may create market conditions that may be more suited to V2G, although it could be argued that a 10% regulation buffer is already very conservative (i.e., high).

The other electricity service presented in Fig. 4—peak capacity—is where the services provided by V2G systems appear to be potentially most attractive. Under our baseline scenario, HEVs and FCVs are used to provide peak demand from around 2050 onwards, and by the end of the century the almost 2 billion V2G systems worldwide (Fig. 2) provide roughly 25% of peak electricity demand. This is a massive amount, equivalent to over 5 TW, or roughly 50% more than estimated global generation capacity in 2000. Accordingly, the availability of V2G systems avoids the need for a substantial amount of investment in conventional electricity capacity. Moreover, because they are able to store excess generation during off-peak times and dispatch it during peak periods, V2G systems effectively allow intermittent generation sources to play a larger role in the electricity system. Under this scenario, in the second half of the century generation from intermittent sources is between 30 and 75% greater than in our otherwise identical BaseN scenario in which V2G technologies are unavailable (not shown). We return to the implications of this later, given that intermittent sources are all renewable.

3.2.2. Energy technology deployment

The results presented above indicate that the availability of V2G systems may result in an accelerated and deeper penetration of advanced vehicle technologies into the passenger transport market, and decreased investment in conventional electricity generation technologies. To some extent these developments may be reinforcing, with earlier deployment of advanced vehicle technologies leading to earlier learning-by-doing, stimulating further cost reductions and hence additional uptake. A result

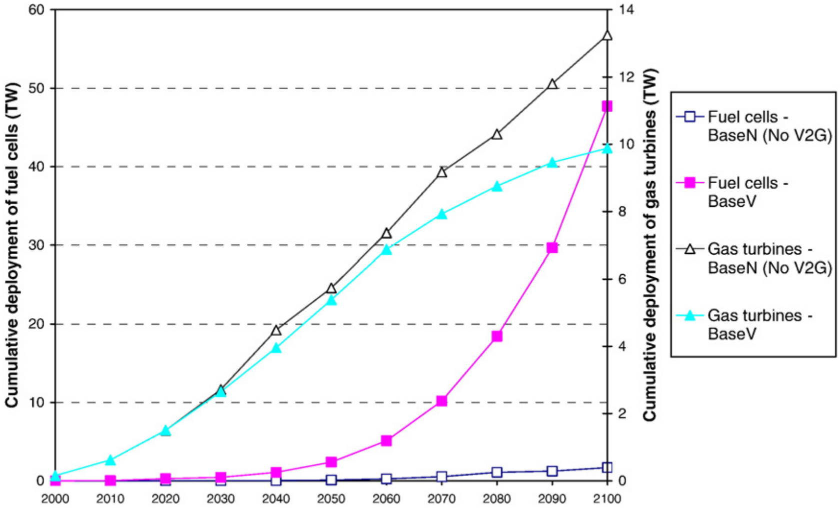

Fig. 5. Global diffusion of selected technologies, with and without V2G system availability (baseline scenario).

consistent with this effect is seen in Fig. 5 which shows the cumulative installations of two learning components—fuel cells and gas turbines—over the century in our BaseV and BaseN (no-V2G) scenarios. In the case of fuel cells, there is a dramatic difference between the two scenarios, with around 30 times the capacity of this component installed by 2100 as a result of the increased attractiveness of FCVs when they are also able to supply V2G electricity services. On the other hand, gas turbines experience a lower level of deployment, consistent with the fact that gas turbine generators are typically an attractive conventional peak-supply technology.

3.3. Climate change policy scenario

The analysis in the previous section has shown that V2G systems can accelerate the deployment of advanced and efficient transport technologies, substantially alter some features of the energy system over the long-term, and facilitate increased generation from intermittent, and renewable, energy sources. Given these changes, it would also appear that V2G systems have the potential to play an important role in greenhouse gas abatement. To explore this potential in more detail, this section examines the application of V2G technologies and EDVs under a scenario in which climate change mitigation policy is a critical element. Specifically, we examine a scenario where a tax of $500 per tonne of carbon-equivalent (i.e., around $135/t CO_2-e) is applied globally throughout the century. This policy assumption should be seen as illustrative only, but likely to be consistent with a relatively stringent global abatement regime. A stringent policy has been applied in order to explore a close-to-maximum deployment scenario of abatement technologies. A further reason specific to the study of V2G systems is that this level of stringency is already likely to support many of the advanced vehicle and renewable electricity generation technologies (see [4,29]), and it is interesting to see whether in this case the availability of V2G systems elicits any further transformations in the global energy and transport system.

Global greenhouse gas emissions under the baseline and climate policy scenarios are presented in Fig. 6, with and without the availability of V2G technologies. It is apparent that even under the baseline

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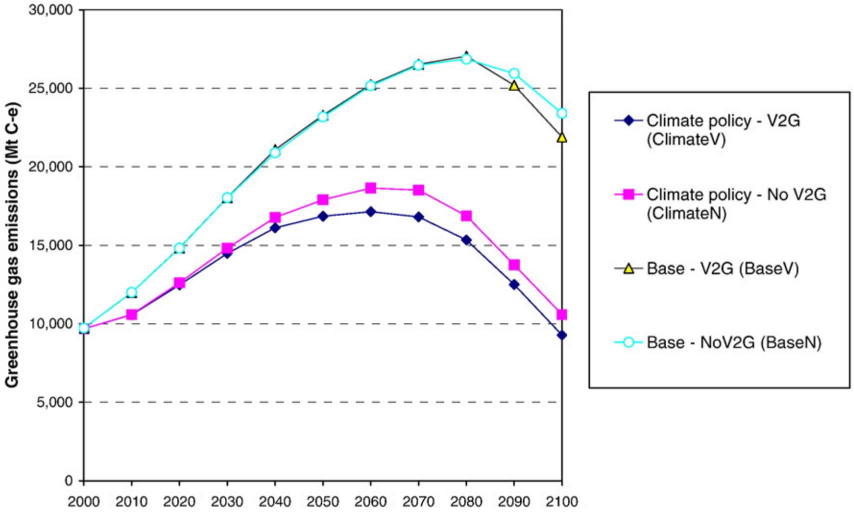
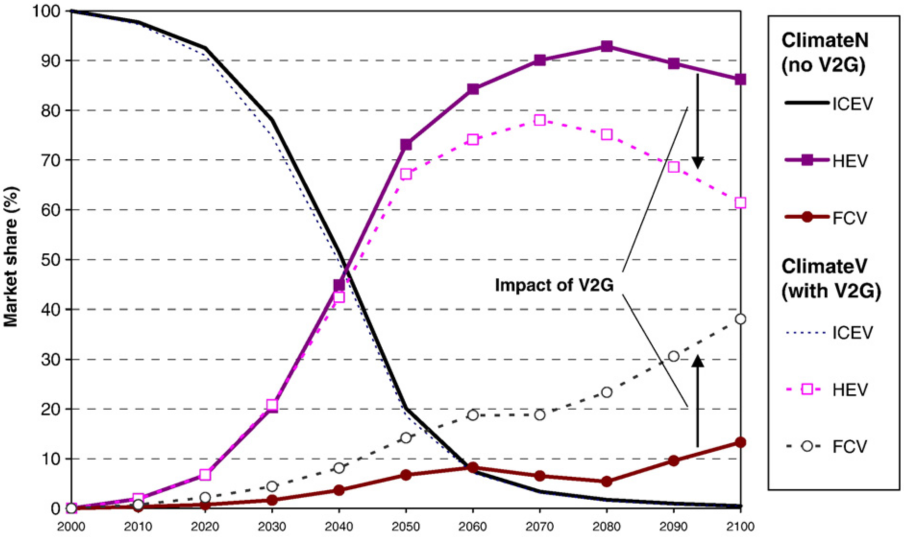


Fig. 6. Global greenhouse gas emissions ($CO_2+CH_4+N_2O$), with and without V2G technologies and climate policy.

scenario (Base) the availability of V2G technologies reduces emissions slightly—by around 6.5% at the end of the century. Fig. 6 also shows, as expected, that emissions are much lower under the climate policy scenarios, and the availability of V2G technologies results in still lower emissions. This indicates that the availability of V2G technologies provides a mechanism to achieve further reductions in emissions. This is explored in the following sections.



Abbreviations are as follows: ICEV – internal combustion engine vehicle; HEV – hybrid-electric vehicle; and. FCV – fuel cell vehicle.

Fig. 7. Impact of availability of V2G technologies on global car technology market share, climate policy scenario.

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3.3.1. Vehicle technology deployment

Similar to the results observed for the baseline scenario (see Section 3.2), the availability of V2G technologies also changes technology deployment patterns in passenger transport under the climate policy, as shown in Fig. 7. This is despite the fact that the climate policy already encourages a rapid transition to advanced vehicle technologies. However, unlike the results presented in Section 3.2, Fig. 7 shows that the availability of V2G technologies under a climate policy favours FCVs at the expense of HEVs. Most of the difference occurs later in the century, with only relatively small changes before 2050 (although the early introduction of FCVs in small niche markets may be very important for learning with this technology, and its future competitiveness). Accordingly, the effect of V2G technologies on vehicle technology diffusion depends critically on the broader policy environment, as evidenced by a comparison of Fig. 7 with Fig. 3, but generally favours more efficient technologies. Accordingly, support for V2G system technologies may represent a hedging strategy in response to uncertainty about future climate change mitigation targets. This is for two reasons: firstly because V2G systems help reduce emissions irrespective of the climate change policy regime; and secondly because the availability of V2G infrastructure appears to lower barriers to the future adoption of FCVs, which represent a further abatement option.

3.3.2. Electricity market impact

In the electricity sector, the climate change policy also brings forward the contribution of V2G systems in providing peak capacity compared to the baseline scenario, as shown in Fig. 8 (left-hand axis). However, the climate policy also results in much larger non-peak generation from V2G FCVs—as high as 19% of total generation, compared to a peak of around 3% under the BaseV scenario (right-hand axis of Fig. 8). That FCVs become competitive for providing what is effectively intermediate-load (or possibly base-load) generation may be a consequence of a range of factors, including the high efficiency of fuel cells compared to other forms of power generation, and their ability to use low-emission fuels. On the other hand, the decline in the contribution of V2G for base-load power generation from 2060 onwards

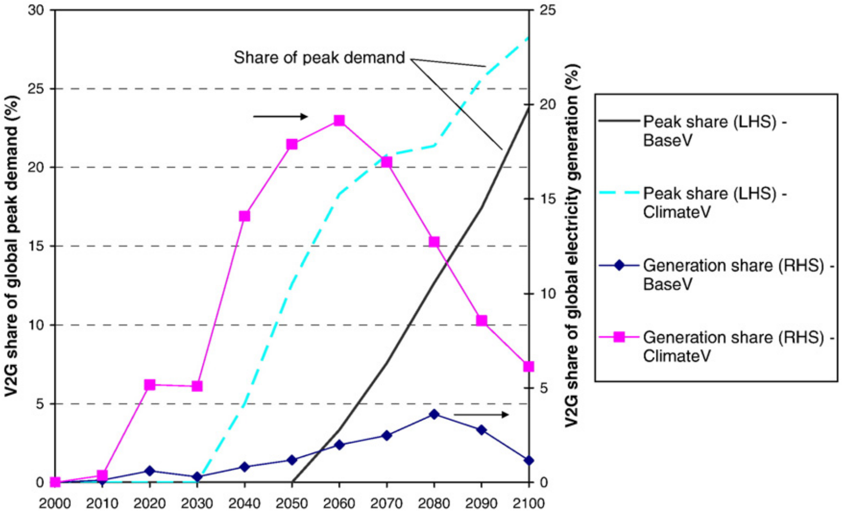

Fig. 8. Contribution of V2G systems to peak power and generation, with and without climate policy (ClimateV and BaseV).

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shown in Fig. 8 appears to be related to the improving cost-competitiveness of other low-emission technologies for electricity generation, notably renewables.

This finding that V2G FCVs may be suitable for larger-scale generation is contrary, however, to the results of previous studies which have suggested that V2G systems may be unsuitable for providing base-load generation services [9,11,13]. Although our baseline scenario results are more consistent with these earlier assessments, the results shown in Fig. 8 indicate that the imposition of a stringent greenhouse gas abatement policy may significantly increase the competitiveness of FCVs for additional power markets (such as providing intermediate- and some base-load electricity demand), consistent with the findings of other analyses of the impact of greenhouse policies on deployment of alternative transport technologies [4,32]. This result helps to illustrate the benefits of the analytical approach employed here, which can capture the impact of a range of factors, including: the simultaneous provision of multiple electricity services from V2G (peak, intermediate and possibly base-load); the climate policy; the higher efficiency of fuel cells compared to conventional thermal technologies; limits to the overall availability of low or zero-carbon technologies such as renewables and nuclear power; and, over the longer term the impact of depletion of cheap fossil fuel resources. Although the other studies mentioned above examined base-load generation, even with some sensitivity analysis in the case of [9,31], their analyses were unable to do more than speculate about the possible impact of some of the factors outlined above. Accordingly, the application of a detail energy-systems model to assess V2G technologies may provide a more complete picture of possible future deployment opportunities.

The specific FCV technologies which are attractive for large-scale generation under the stringent climate policy scenario are presented in Fig. 9, and discussed in more detail below. Fig. 9 shows that the three FCV V2G technologies initially displace mainly thermal fossil power plants. The main FCV V2G technology providing electricity early in the century is the petroleum-FC, which may have some advantages in early deployment because it relies on a conventional energy carrier for which fuel production and distribution infrastructure are already mature. Later in the century hydrogen FC V2G systems appear to dominate. However, late in the century generation from FCVs displaces a larger amount

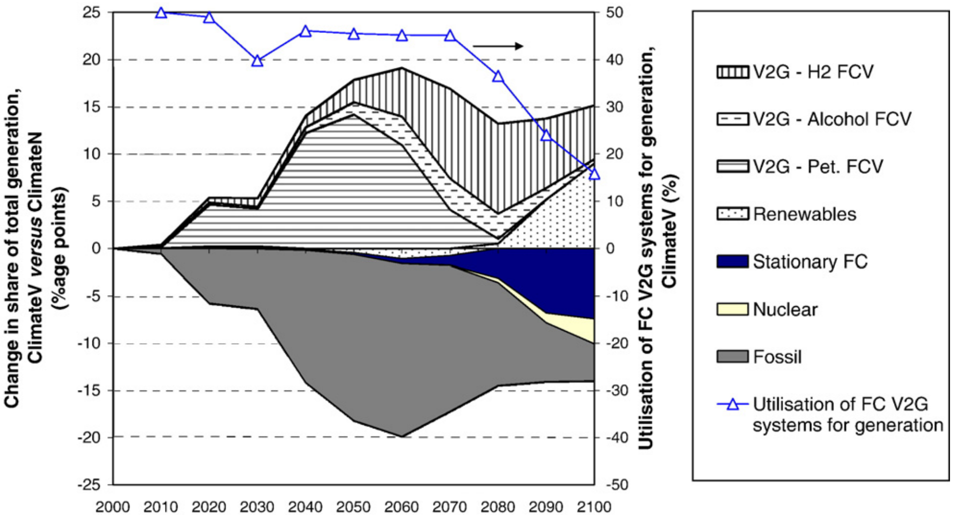

Fig. 9. Impact of V2G technologies on electricity generation, climate policy scenario.

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of stationary FC generation compared to our otherwise identical no-V2G (ClimateN) scenario. This highlights the potential benefits of V2G for providing two services—electricity and transport services—with the same piece of hardware instead of installing stationary generation for electricity services and investing in separate transport technology. We estimate that the overall reduction in investment in the stationary power sector resulting from the shift to generation from V2G-enabled vehicle drivetrains is around US(2000) $2.8 trillion between 2000 and 2050. Importantly, later in the century investment in the power sector increases again because, as also shown in Fig. 9, V2G systems support additional generation from what are relatively capital-intensive renewable technologies. As discussed in Section 3.2.1, the V2G battery systems help overcome one of the disadvantages of these intermittent generation technologies, indirectly enabling them to supply also peak power.

One further indicator shown in Fig. 9 is the level of utilization of FC V2G systems—that is, the average plant factor of FCVs with access to V2G infrastructure. Recall that this plant factor is capped at the level of availability (50%) assumed in Section 2.2. Accordingly, Fig. 9 shows that FCVs are used at close to V2G capacity until around 2070, at which time FCV becoming increasingly attractive in their own right as a transport-only technology, and other low-emission generation sources become more competitive. However, FCVs also remain important for peak power, as in the baseline scenario.

Importantly, however, when considering the result presented in Fig. 9 it should be mentioned that although the cost of fuel distribution is accounted for in this analysis, the convenience isn't. One of the main barriers to large-scale use of FCVs for electricity generation may be limited on-board fuel storage capacity, if this requires more frequent refueling (although H_2 FCVs could be connected simultaneously to the electricity grid and a H_2 reticulation system). Another important factor may be fuel cell degradation from more continuous use, although based on the lifetime and degradation rates estimated in Kempton and Tomić [11], the assumptions used in our analysis mean that this should not be significant. This is partly because the average generation load per FCV, after accounting for the assumed 50% availability, does not exceed 6 kW under the scenario presented in Fig. 9. This compares to the 40 kW assumed capacity of the FCV fuel cell system, implying only a small degradation effect.

4. Discussion and other issues

The results presented in the previous section indicate that vehicle-to-grid (V2G) technologies may have the potential to transform the energy and transport systems in a number of fundamental ways. These include: accelerating the uptake of new transport technologies; reducing the installation of conventional peak generation capacity; and supporting the installation of renewable electricity sources (by helping overcome problems of intermittency). The combination of these transformations helps to lower greenhouse gas emissions. Furthermore, this analysis identifies specific roles for V2G in both peak and non-peak (intermediate- and possibly base-load) power markets, with the latter significant under greenhouse gas constraints. This represents a new result that challenges previous findings that V2G is unsuitable for base-load markets [9,11,13].

Despite these findings in support of V2G, it is important to recognise that this analysis may be conservative in the representation of the niche markets in which V2G may be most competitive. This is because the methodology applied here uses a high level of geographical aggregation based on eleven world regions. This aggregation means that regulation, peak power and spinning reserves markets are modeled on a world-regional basis, whereas the most competitive applications of V2G are likely to arise from distribution infrastructure bottlenecks, generation capacity constraints and highly peaky electricity

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markets within subregions—often confined to small areas with a given country. Accordingly, the approach taken here may in some ways underestimate the competitiveness of V2G systems.

However, there are a number of key uncertainties related to the possible future role of V2G. In addition to uncertainties about the future costs of key technologies and systems, the technologies required for V2G systems have rarely been combined, even though HEVs, BEVs, distributed generation, and plug-in recharge systems all exist. Unforeseen technical difficulties may arise when these systems are applied together on a large scale, although there may also be unanticipated beneficial spillovers and synergies. Critical for the diffusion of V2G technologies is also likely to be the communication and grid regulation systems required to manage dispatch, recharge and regulation up and down. The grid operator (or perhaps a fleet aggregator) will need to communicate directly and instantly with specific plugged-in vehicles, although this should be manageable with current technologies. Nonetheless, the smaller scale of generation from each vehicle may lead to difficulties in compatibility with existing systems based around large generation units. For example, replacing a relatively small 100 MW peaking gas turbine unit would require approximately 30,000 vehicles supplying 6.6 kW with an assumed availability of 50%.

Consumer acceptance and enthusiasm is another uncertainty (and one which the methodology applied in this paper is unable to address), but a key requirement to maximise the availability of EDVs for providing power services. Achieving high levels of availability and customer engagement may initially require a closer relationship between electricity companies and the consumer. However, electricity companies themselves may see V2G as a potential competitor—as noted, there may be a large shift in investment away from stationary generation capacity if V2G is deployed on a large scale—and how the electricity industry responds may have a large bearing on the adoption of this technology. For instance, conventional generators perceiving V2G as a major threat may attempt to persuade network regulators to impose onerous requirements on distributed V2G generation (similar to the regulatory barriers confronting distributed generators in many US states—for example, see Ayres et al. [33]). On the other hand, electricity retailers and distributors may be supportive of V2G technologies, since they represent a cheaper way of providing electricity services and of diversifying financial and physical risks; one can envisage enterprising electricity businesses offering EDV lease arrangements that enable customers to upgrade to new vehicle technologies, whilst maximising V2G availability for electricity generation. Similarly, owners of large vehicle fleets, such as rental agencies and government departments, may be able to access a new source of revenue, which itself may further contribute to a more rapid diffusion of alternative vehicle ownership regimes, such as car sharing.

Importantly, like many new technologies that represent a substantial shift from dominant paradigm, V2G and EDVs may also require additional forms government support or intervention to realize their commercial potential. Such government intervention is required at a very minimum to eliminate regulatory barriers that unfairly discriminate against distributed energy resources, such as plug-in vehicles. Additional forms of support, such as procurement in government fleets, or establishing fiscal or tax incentives, may also be necessary for building public confidence in what represents a radical departure from conventional approaches to mobility and electricity production.

Two further and critical uncertainties relate to the possible emergence of alternative technologies for electricity generation that may be superior to V2G systems and whether automobiles will continue to play as large a role in the transport sector as they currently do. Regarding the first uncertainty, this analysis is limited in that only existing and some currently emerging technologies are represented in our modelling framework. On the second uncertainty, although there are no foreseeable alternatives able to provide the same range of services as the automobile, the possibility of technological breakthroughs cannot be ruled out.

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This raises a connected issue, which is whether V2G technologies may themselves further entrench the private motor vehicle as the dominant transport mode, and whether this would necessarily be a good development. In this analysis, we have simply assumed that automobiles continue to be important, and that they remain the only technology able to satisfy the future transport demand projection presented in Fig. 1, although we have allowed the deployment of alternative drivetrain technologies and fuels. However, even if threats to sustainable development posed by greenhouse gas emissions, local pollution and availability of secure energy supplies can be resolved, there may still be other reasons to avoid further entrenching private automobiles, associated with congestion, accidents, access and urban land management.

These uncertainties and limitations aside, it is interesting to consider the niche markets in which V2G could first emerge. These are likely to be generator-constrained electricity networks—particularly in areas with a large difference between average and peak load. Network-constrained areas may also be important targets for distributed generation, although V2G systems may only be able to provide benefits within the network-constrained area. Regions with abundant intermittent renewable generation but constrained interconnection capacity, perhaps because of remoteness, may also represent an early niche market for V2G. As illustrated in the results, applying V2G technologies to such a market could enable higher utilization of renewable energy whilst avoiding problems with dispatch. In addition, V2G may be adopted early at specific sites where power requirements are critical, and the impact of grid or generator failure high.

However, in all applications of V2G, economies of scale are likely to be important. Increases in scale are likely to reduce potential problems arising from limited availability—and the more diverse the EDV V2G owner base, the more likely that availability will always remain above critical thresholds. Moreover, the cost of the communication and management systems need to regulate and dispatch from V2G systems may also experience significant economies of scale.

5. Conclusions

This study represents the first time that a detailed energy system model has been used to model explicitly V2G technologies and their possible diffusion over long-term. The results indicate that V2G systems may have the potential to transform both energy and transport systems in profound ways, by promoting the deployment of alternative vehicle technologies; reducing inefficient investment in conventional generation; and supporting the installation of renewable electricity sources. On this basis, this technology warrants further analysis to identify how to support the possible diffusion of V2G technologies and, importantly, address some of the key technological and social uncertainties. This will require alternative methodological approaches, particularly since a proper analysis of some of the key social uncertainties—including issues related to consumer, electricity market, and regulatory acceptance—are beyond the scope of the analytical framework applied in this paper, but may well represent some of the most significant challenges to the possible emergence of V2G energy systems.

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