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Towards an electric revolution: a review on vehicle-to-grid, smart charging and user behaviour

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Abstract: According to the Intergovernmental Panel on Climate Change in their Special Report on Global warming, it is clear that there is a need of a rapid change in all aspects of society to achieve limiting global warming to 1.5°C. The transport sector alone is currently responsible for 20.5% of the global emissions. Therefore, the transport sector is exploring new technologies and business models to make a transition to electric vehicles. This paper presents a review of the last decade on vehicle-to-grid (V2G), the advantages and barriers of this technology and the support V2G can give for the transition to electric mobility. The future scenarios for vehicle-to-grid are discussed, including the application of user behaviour analyses, data management and real-world demonstrators such as EV-elocity. This paper highlights the relevance of adopting V2G to integrate different vectors of the transport system and the energy infrastructure to generate environmental, social and economic benefits.

Keywords: electric vehicles; smart charging; vehicle-to-grid; renewable energy; clean transport; human behaviour

1. INTRODUCTION

Climate change is one of the biggest concerns of humanity as forecasts are currently showing risk of irreversible damages to the planet and human health. The Intergovernmental Panel on Climate Change in their Special Report on Global warming stated that a rapid change in all aspects of society is necessary in order to achieve limiting global warming to 1.5°C (Allen et al., 2018). The transport sector alone is currently responsible for 20.5% of the global emissions (The World Bank, 2019) and the adoption of clean transport technologies had become a steadfast alternative to reduce those emissions (Li et al., 2018). However, the problem has more factors to be considered as the mass production and large adoption of electric vehicles (EVs) will bring new challenges, such as the coordination of vehicles and the energy infrastructure (Letendre and Kempton, 2002), the integration of renewable sources to energy storage on EVs, the democratisation of the energy transactions and the prevention of energy shortage (Sortomme and El-Sharkawi, 2011).

In 2002, Letendre and Kempton pinpointed the relevance of looking at two different but compatible energy conversion systems: vehicles and the energy grid. According to the authors' forecasts, in 2050 electric vehicles could provide 20% of the energy required by the energy grid. The integration of these two systems occur with the 'Vehicle-to-Grid' or V2G, which refers to the capability of an electric vehicle to feed into the electric grid (Letendre and Kempton, 2002). The bidirectional characteristic of V2G allows the reversal of electric energy stored in EVs batteries. This two-way communication system works by charging and discharging the energy according to the demand (Zheng, 2019). Therefore, V2G can provide several ancillary services such as extra power for peak load demand, spinning reserves and regulation of the system (Lopes et al., 2011), as well as storage of renewables, which can be erratic, unpredictable and geographically determined (Yaqoot et al., 2016).

According to the Department for Business, Energy & Industrial Strategy (2018), renewable energy generated from photovoltaics and wind in the UK increased from 5,288 GWh in 2007 to 61,529 GWh in 2017. However, these sources are intermittent and dependant on weather variations, and this aspect has been reported as an important obstacle for its inclusion in the energy systems (Yaqoot et al., 2016). Therefore, energy storage systems are required as they can compensate the system by storing the renewables and sending it to the grid on demand, whilst providing flexibility, reliability and stability to the system (Parra et al., 2017; Sardi et al., 2017).

Ofgem (2019) stated that the rapid fall in the cost of EV batteries *"means that EVs may soon be as cheap to consume as conventional vehicles"* (p. 2) which will increase their use, and in consequence will bring implications to the energy system. Therefore, integrating electric mobility with the energy grid has become crucial to unlock storage capacity of renewable energy and the future demand that vehicles will bring to the grid. It is however observed that the academic production and studies regarding vehicle-to-grid have been conducted mainly during the last decade and it would be of interest to determine what are the main drivers that impulse research in this field. Therefore, this paper presents an overview on the last decade of vehicle-to-grid developments, the advantages and barriers to integrate this system reported by other authors, and future scenarios integrating behavioural analysis in real-world demonstrators.

2. LITERATURE REVIEW OF THE LAST DECADE OF V2G

A literature search of articles was conducted in the databases ScienceDirect and Scopus using common terms referring to vehicle-to-grid: "vehicle to grid", "vehicle-to-grid" and "V2G". The search was limited to publications in the last decade 2009-2019 which included the referred terms in the title, abstract or author-specified keywords. The number of papers published by year are presented in Figure 1.

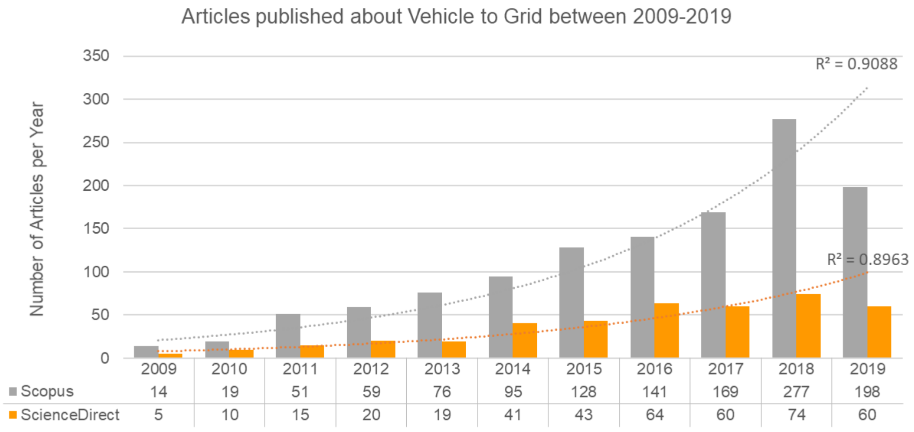

Figure 1 - Number of articles published in Scopus and ScienceDirect between 2009 and 2019 about V2G

The number of publications about V2G presented a growth over the last decade. Taking into account the number of publications made until July 2019, the trend line is projecting that the number of papers will continue to increase as it has done during the past 10 years, achieving nearly 300 publication in Scopus and 50 publications in ScienceDirect by the end of 2019 (Scopus R^2=.91 and ScienceDirect R^2=.90). It is interesting to observe that in 2009, only 14 papers were published about V2G in Scopus and 5 papers in ScienceDirect, as the earliest publications on V2G date from 2002.

According to H. Sekyung et al. (2010) the first publications on V2G were mainly focused on how to connect the batteries to the grid (this refers to the earliest publication in the field conducted by Kempton et al., 2001 and Tomić and Kempton, 2007) and the fundamentals of load leveling, regulation and reserve (Pang et al., 2012). Later on, in 2010, other aspects such as the characteristics of the aggregator performance and the algorithms to control energy exchanges started to be developed using simulated scenarios (H. Sekyung et al., 2010; Lopes et al., 2011). By this time, the unpredictability brought by the users' behaviour was identified, as this prevented the business models to be successfully developed. One of the authors addressed this concern and proposed a possible solution by stating that: *"It is mandatory that drivers actively notify the expected departure time upon plugging in. A driver would sign on a contract that he or she would keep the vehicle connected to the grid for certain amount of time in return of incentives such as a life time battery warranty"* (H. Sekyung et al., 2010, p. 66), nevertheless, restricting the flexible use of the vehicles could affect the adoption of the technology.

Other challenges were also highlighted regarding the creation of a communication infrastructure to allow: i) the integration between the aggregator and the grid, and ii) the data management as this system required high frequency of data exchange due to its fluctuation (Guille and Gross, 2009).

A study conducted by Saber and Venayagamoorthy (2011) demonstrated the importance of integrating renewable sources of energy to the vehicle to grid system. In this study, the authors compared two simulated scenarios: the first one consisted in a conventional generation of energy where the EVs were charged using load-leveling optimisation, and the second one consisted in a smart grid model where the EVs were charged from renewable energy sources. The authors reported that the model integrating renewables presented significantly better performance in the reduction of greenhouse emissions. However, this model required a higher initial investment in the infrastructure to generate renewable energy.

One of the main strengths of vehicle to grid is the expansion on the energy storage capacity to integrate renewable sources. This is achieved by storing the surplus of energy generated by renewables and selling it on demand to the energy grid. However, this bidirectional charging and discharging of the battery have been generating concerns over the battery degradation and performance (Taiebat and Xu, 2019; Zheng et al., 2019). A study conducted by Peterson et al. (2010) regarding the degradation of lithium-ion battery concluded that several thousand driving days charging and discharging (driving/V2G) cause less than 10% of capacity loss regardless of the amount of V2G support used; however, intermittent modes of V2G could lead to rapid capacity fade.

3. ADOPTION OF VEHICLE-TO-GRID TECHNOLOGIES

Despite the relevance of integrating V2G to the energy infrastructure envisaged by several authors in the early 2000s (Brooks, 2002; Kempton et al., 2001; Kempton and Tomić, 2005a, 2005b), its application did not become a popular topic until more recent years. Some of the main barriers to adopt V2G, reported from 2010, were: i) the costs of the infrastructure to produce renewables (Saber and Venayagamoorthy, 2011), ii) the high costs of the EVs (Sortomme and El-Sharkawi, 2011), and iii) the technology development required (Guille and Gross, 2009; Sortomme and El-Sharkawi, 2011). In order to understand the evolution of the different systems involved in vehicle to grid, here is presented a comparison between the energy generated from renewables in the UK and the number of ultra-low emission vehicles licensed in the UK in the last years. Figure 2 presents the data regarding the renewable resources used to generate electricity and heat in the UK from 2007 to 2017 (BEIS, 2018). The data was filtered to include only the contribution made by solar photovoltaics and wind sources. A growth on the renewables since 2007 is observed. The contribution from wind sources increased from nearly 5,000 GWh in 2007 to 50,000 GWh in 2017 and the contribution of solar sources have been increasing since 2012.

Similarly, Figure 3 presents the data of ultra-low emission vehicles registered in the UK between 2010 and 2019. An important growth is observed in the acquisition of electric vehicles over the last decade, with and important acceleration between 2015 and 2019. This results show a similar pattern to the trends presented on Figure 1 and Figure 2, where the publications regarding V2G and the energy generated by renewable sources also presented a continuous increase over the last 10 years.

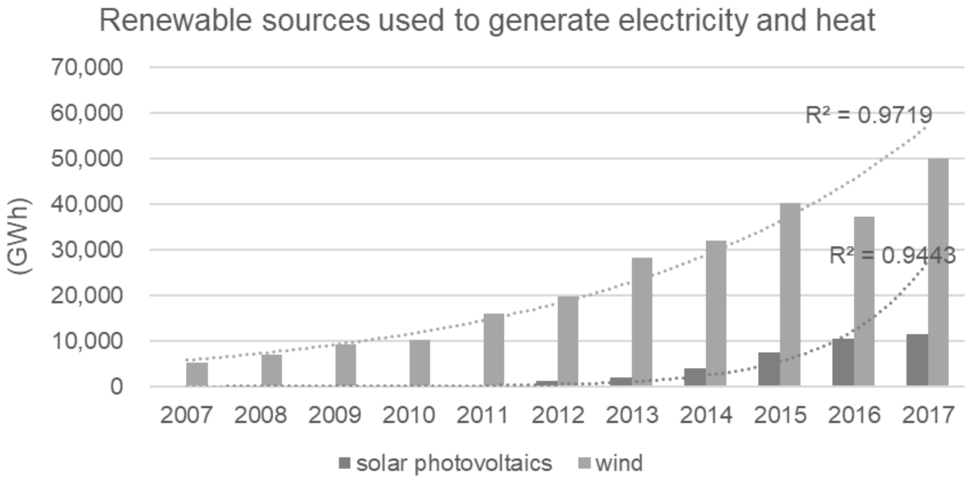

Figure 2 - Electricity and heat generated by renewable sources 2007 – 2017. Data source: BEIS, 2017

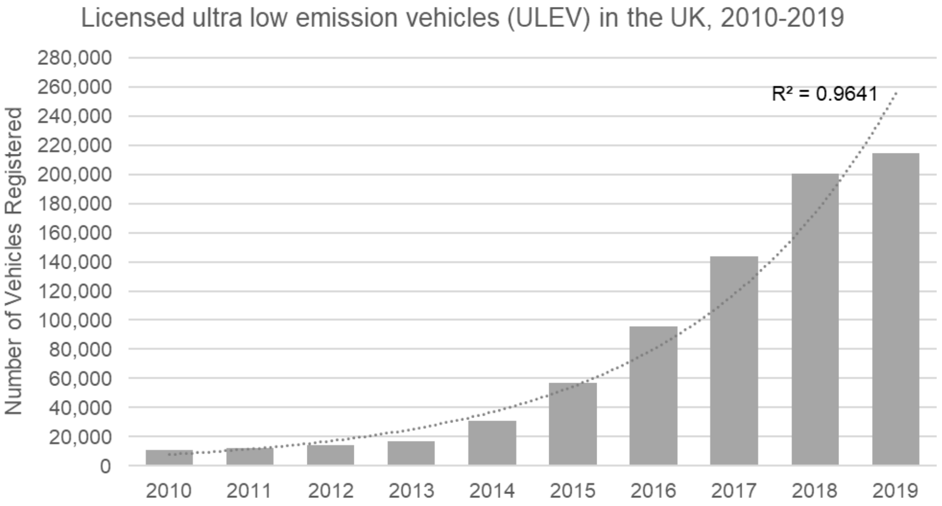

Figure 3 – Ultra-low Emission Vehicles registered in the UK between 2010 and 2019

According to Küfeoğlu et al. (2019), there are three trends that are currently enabling the bi-directional power flow to occur: i) the increasing uptake of electric vehicles, ii) the increased development and performance of vehicle batteries, and iii) the shift towards renewable energy. This combined development of EVs, energy storage and renewable energy can provide a revolution of the way we generate, store, manage and consume energy.

4. ADVANTAGES, BARRIERS AND CHALLENGES OF V2G

As mentioned in the introduction, one of the main benefits of V2G is that it can support the energy grid by regulating the peak demand, load shifting at distribution level and regulation of the system (Guille and Gross, 2009; Lopes et al., 2011). The bidirectional charging and discharging allows providing spinning reserve, frequency regulation, prevent overloading of lines and transformers, decrease the energy costs and charging costs, and also provides other ancillary services for power grid (Taiebat and Xu, 2019; Zheng et al., 2019).

From the user perspective, the benefits of V2G are related to economic incentives generated by selling the energy to the grid. This could represent a reduction of the life cycle cost of the vehicle by providing revenue (Taiebat and Xu, 2019). It also produces an optimisation on the price of electricity, as the price-based charge can achieve reductions up to 10% of the charging costs and possibilities of achieving more saving with dynamic prices, which could be available in different business models (Iacobucci et al., 2019; Taiebat and Xu, 2019). Some authors reported different types of incentives, such as life time battery warranty (H. Sekyung et al., 2010, p. 66) or commodities, services, information or money (Guille and Gross, 2009).

Vehicle-to-grid can also provide a better management of electricity resources (Taiebat and Xu, 2019). It offers the possibility to absorb the surplus energy valley before the EVs batteries are charged (Zheng et al., 2019) and it could reduce the system costs in V2G optimised transport networks (Iacobucci et al., 2018; Taiebat and Xu, 2019). Moreover, V2G and smart charging solutions are key to integrate variable renewable sources, such as wind and solar by coordinated charging strategies (Lopes et al., 2011; Zheng et al., 2019). According to Pfeifer et al (2019), renewable energy sources are frequently generating excess of power that requires to be stored. To address this issue, V2G can provide fast response storage with minimal impact on infrastructure costs when the vehicles are stationary. As a result of the capability to store renewables, V2G has the potential to make a significant contribution on the reduction of greenhouse emissions (Saber and Venayagamoorthy, 2011).

On the other hand, some of the barriers reported are: the anxiety among the challenges presented by implementing the V2G technology, concerns over battery performance and degradation (Taiebat and Xu, 2019; Zheng et al., 2019), lack of scientific consensus and uncertainties (Taiebat and Xu, 2019) and the fact that cost/benefit of combined models such as wireless charging, shared electric vehicles and V2G is still unknown (Taiebat and Xu, 2019). According to Zheng et al. (2019), uncoordinated charging modes of electric vehicles can increase power loss, elevate load peaks, affect the grid frequency, overload the lines and transformers, increase electricity costs for power companies and increase charging costs for EV users.

The reported uncertainties are the main challenges V2G projects will be facing over the coming years. As reported by Lopes et al. (2011), a new infrastructure will be required including charging stations, fast charging opportunities, battery swapping stations, domestic and public individual charging points and life cycle analysis of vehicle batteries. Moreover, an adequate market operation considering the patterns of the grid is also needed (Lopes et al., 2011).

5. HUMAN BEHAVIOUR AND DATA MANAGMENT

It is clear from the breadth of study in this field that V2G applications have a range of challenges to meet before wide-scale application is possible. However, many V2G studies focus only on the technical side of these challenges. Only 2.1% of papers published in the field sampled by Sovacool et al. (2018) addressed user behaviours and routines, with 1.1% addressing range anxiety adoption issues. Despite a relative lack of attention, user behaviours and routines remain a key component in whether V2G will be viable in application.

User-centred challenges in V2G applications can include the social (attitudes towards the technology, socioeconomic factors in technology adoption) and the practical (vehicle availability for V2G events, user predictability, behavioural incentives). In particular, analysis of user routines and vehicle use patterns can provide key evidence for V2G application. For example, in the simulation of vehicle battery availability for V2G, behavioural patterns can be used to assess the economic feasibility of V2G over the longer term (Gough et al., 2017). In the work of Metz and Doetsch (2012), it was found that domestic vehicles were spending a combined 81% of time on average available for grid support if able to charge at both home and work locations. It has been shown that the patterns of vehicle use, state of charge on arrival and desired state of charge on departure can significantly affect the impact that V2G services could have on load management in different building types (Kuang et al., 2017). Usage patterns can also inform the planning of public charging infrastructure (Morrissey et al., 2016).

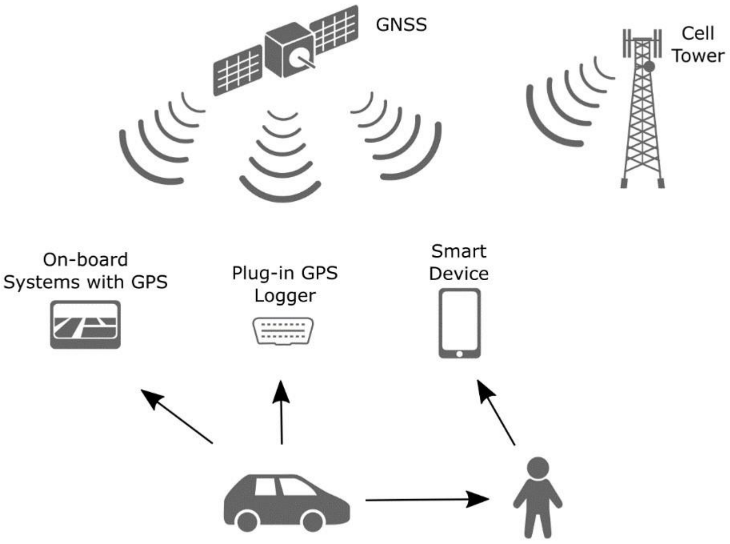

Figure 4 - Vehicle tracking data collection

While it is clear that user behaviours can have a significant impact on V2G application, solutions that seek to track user behaviours and routines encounter additional challenges around data collection. Vehicle mobility data requires some knowledge of location, traditionally from standalone GPS receivers that can be installed in vehicles. Increasingly, alternative data sources are becoming available, including on-board vehicle navigation/tracking systems and personal smart devices as shown in Figure 4. Mobility data can also be extracted without explicit knowledge of GPS co-ordinates as discussed in (Naylor et al., 2019). This is particularly useful to minimise risks related to data protection and privacy.

6. FUTURE SCENARIOS FOR V2G

Other authors referred several possibilities to connect electric vehicles to provide power services, such as: vehicle to home (V2H), vehicle to vehicle (V2V), vehicle to load (V2L) or vehicle to everything (V2X) which refers to the vehicle acting as independent clusters of generation (Rodríguez-Licea et al., 2019). According to Pang et al. (2012), vehicle-to-grid can take a long penetration time into the market as it is reported to produce significant revenue mainly in large-scale scenarios. Therefore, vehicle to building (V2B) was also identified as an option to attract early adopters of electric vehicles to “export electrical power from a vehicle battery into a building connected to the distribution system to support loads” (Pang et al., 2012, p. 474).

Several deployment scenarios will need to be studied taking into account multiple variables like the type of vehicles (fleet or individual), the technology used (electric, hybrid, or fuel cell), the owners’ behaviour, the traffic patterns, the places where cars are parked and connected to the grid, the type of connection between the EV and the network, as well as the grid control architecture (Lopes et al., 2011).

Real-world Demonstrator: EV-elocity

One of the challenges of vehicle-to-grid is the lack of real-world scenarios to gather data and test the viability of the technology and the business models. The literature review conducted showed that the benefits of V2G have been widely explored using modelling techniques and forecasting different scenarios. However, the deployment of vehicle-to-grid infrastructure has only occurred recently. As suggested by Taiebat and Xu (2019), there is lack of scientific consensus regarding the benefits of EVs adoption, particularly in determining the environmental benefits that this technology can generate. Currently, the attention has been focused in the operation and optimisation of the EV system, so there has not been quantitative analysis using real-world travel demand data, and this extends also to the V2G systems (Taiebat and Xu, 2019).

As part of the funding call “Innovation in vehicle-to-grid (V2G) systems: real-world demonstrators” (Innovation Funding Services, 2017), EV-elocity is a research and development project conducting real-world demonstrators that will support the uptake of electric vehicles through helping consumers to monetise their investment using vehicle-to-grid innovation (EV-elocity, 2018). This project is exploring new technologies, encouraging behaviour change and developing business models that will enable the sharing of the value V2G can bring to the grid, local and regional business and the consumer.

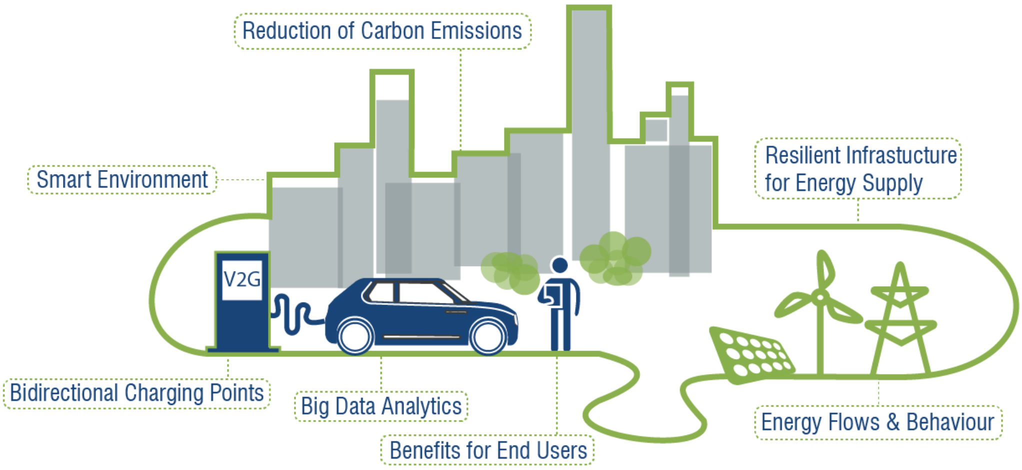

Figure 5 – Benefits of vehicle-to-grid and smart charging

In alignment with the advantages of V2G reported by other authors in Section 4, EV-elocity proposal will impact fundamental features of the vehicle-to-grid technology on various aspects: 1) Economic: by enhancing the business model to uptake electric vehicles through the provision of a new revenue source for the owners and helping to reduce the cost of energy, 2) Social: by increasing infrastructure resilience and security of the energy supply, increasing a wider participation by proposing sustainable life-styles and encouraging behaviour change by raising awareness of energy related issues, and 3) Environmental: by reducing carbon emissions from transport through increasing electric vehicle usage, optimising the energy system by providing energy on demand from the bi-directional charging, and increasing the energy storage capacity to integrate renewable sources to the energy grid (EV-elocity, 2018).

7. CONCLUSIONS

According to the review of the last decade of V2G, the importance of supporting the transition to electric mobility has been highlighted by various authors, as the transport sector is currently responsible for 20.5% of the global carbon emissions. This complex transition will need to consider the coordination of the transport and energy infrastructure. One of the risks envisaged by other authors regarding the transition to electric mobility is the overload of the energy system due to the simultaneous charge of electric vehicles. Therefore, a dynamic system where the EVs are contributing to the grid by storing renewable energy is required.

Early studies on V2G from 2002 pint-pointed the possibilities that electric vehicles could bring to the energy system. Nevertheless, the relevance of deploying this technology started to appear from 2012, when the market of renewables and electric vehicle batteries started to accelerate.

A similar increasing trend has been reported over the last decade between: i) the articles published about V2G, ii) the market of low emission vehicles, and iii) the production of energy from renewables. This correlation suggests a maturity of the transport system and the energy infrastructure to integrate V2G.

Several studies reported the advantages of V2G and smart charging technologies in terms of economic, social and environmental benefits. Moreover, V2G can support the energy grid by regulating the peak demand and offering ancillary services. From the user perspective, V2G can provide different incentives that can promote the switch from internal combustion engine (ICE) to electric vehicles (e.g. economic and environmental). With regards the energy grid, V2G can help to increase the storage capacity of the energy system allowing the generation and use of intermittent renewable sources and with low impact in infrastructure costs.

In order to implement vehicle-to-grid and smart charging successfully, some challenges which have been identified must be overcome. Amongst these are: the anxiety caused by the implementation taking into account concerns over the economic and environmental incentives of electric vehicles and vehicle-to-grid. There are also challenges in integrating algorithms based on user behaviour analysis to create a flexible and resilient charging infrastructure.

In the future scenarios of V2G and smart charging, real-world demonstrator projects such as EV-elocity are required to provide further real-world data regarding the economic, social and environmental benefits. This type of research and development projects will support the transition to electric mobility by developing products, services and knowledge of future V2G infrastructure.

8. ACKNOWLEDGMENTS

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