EVALUATING THE TRANSITION FROM V2G TO AV2G

The autonomous battery electric vehicle as decentralised bidirectional storage system

Master's Thesis

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Evaluating the transition from V2G to AV2G

The autonomous battery electric vehicle as decentralised bidirectional electricity storage system

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Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy and Management

by

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To be defended in public on March 29th, 2019

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Acknowledgements

This research report marks the end of my journey pursuing the MSc programme Complex Systems Engineering and Management at the Delft University of Technology. I am proud to present a report that contributes to the energy transition by evaluating a potential future integration of vehicle-to-grid and autonomous vehicles.

I would first like to thank my first supervisor Daniel Scholten for his excellent guidance and his flexibility to provide feedback on short notice when it was needed most. Second, I would like to thank Zofia Lukszo and Jan Anne Annema for their valuable advice.

I would also like to thank my family for showing their interest in a, to them, completely new topic. It feels good to know that the people you care about are proud of you.

Furthermore, I would like to thank my friends for distracting me when it was necessary. A special thanks to Sam. It was nice to have someone that went through the same process at the same time.

Finally, I would like to thank Rayana for her continuous support throughout the master's programme. You never made me doubt my decision to quit my job and go for a master's degree. Obrigado por tudo.

Daan Hammer
Amsterdam, March 2019

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Executive Summary

Introduction

The electricity grid has to be upgraded to a smart grid with a decentralised storage functionality to deal with the expected pressure from the increasing amount of renewable energy on the stability of the grid. Vehicle-to-grid (V2G) is considered to be a key technology to realise such a decentralised storage functionality. However, barriers, such as the accelerated battery degradation and high investment cost, hamper the performance of V2G. A dramatic shift towards autonomous vehicles (AVs) in the future transport system drastically changes the conditions for a potential transition to V2G, potentially resulting in a more flexible V2G system that efficiently deals with bidirectional flows between AVs and the electricity grid and the transport of passengers. Despite the beneficial effects AVs might have on a V2G transition, there is a lack of scientific research into the joint development of these technologies. This research bridges this knowledge gap by exploring the potential effects of autonomous battery electric vehicles on the performance of V2G, thereby providing new insights into the pursued integration of the energy and transport systems.

Research approach

To evaluate the potential effects of AVs on the performance of V2G, factors that affect the performance of V2G have to be established. In this research, the performance of V2G is based on the feasibility of the potential drivers of a V2G transition and the impact of potential barriers on a V2G transition. Drivers add significant value to the progress of a V2G transition by, for instance, contributing to an increasing share of renewable energy in the grid, providing better services to stabilise the grid and generating revenues through these services. Barriers hamper a transition to V2G. Together these drivers and barriers are grouped as **V2G factors**, which are defined as factors that affect the transition of V2G by either making it valuable or hampering it.

First the V2G factors are identified, then the current performance of V2G is derived from available research on the V2G factors that considers a transport system without AVs. Afterwards, the expected effects of AVs on the performance of V2G are evaluated through the results from expert interviews. Finally, the wider implications of the results are described.

The current performance of V2G

Table 1 presents the V2G factors that were identified from a literature review. The left side of the table accounts for the factors that are perceived to be drivers to a V2G transition. The right side of the table holds the factors that are perceived to be barriers to a V2G transition. To effectively compare the effects of each factor on the overall current performance of V2G and later the effects of AVs on the performance of V2G, the results of the current performance were rated on a five-point scale: major barrier (--), barrier (-), neutral (0), driver (+), major driver (++).

A review of research specifically focusing on the V2G factors showed inconsistencies on some of the V2G factors that should reflect as drivers of a V2G transition leading to highly uncertain results. Potential revenues that can be obtained through frequency regulation, spinning reserve, active power support, and the overall V2G system vary widely, and according to some studies even result in a loss which then arguably makes them barriers. Furthermore, complex issues arise between the actors in a V2G system because the uncertainties about the potential revenues, for instance, mainly affect the EV owners and aggregators who receive the potential revenues through payments from the network operator as incentives for making their EVs available to the grid or coordinating a large group of EVs for grid services through V2G. If EV owners are not fairly compensated, their willingness to participate in V2G systems might be limited, especially in combination with the expected range anxiety. In addition, aggregators are not expected to be willing to coordinate grid services under these conditions.

Table 1: The V2G factors and the rating of their current performance

Frequency Regulation **(+)**	Battery Degradation **(-)**
Spinning Reserve **(+)**	Investment Cost **(--)**
Active Power Support **(+)**	Impact on the Distribution Network **(-)**
Reactive Power Support **(+)**	Range Anxiety **(--)**
Current Harmonic Suppression **(+)**	
Balance and Support Renewable Energy **(++)**	
System Revenues **(+)**	

Inconsistencies also exist within research on battery degradation and V2G. Although some researchers consider battery degradation a significant barrier to a V2G transition, other researchers believe it to be unrelated to V2G. Comparing all the varying outcomes becomes more difficult due to the differences in variables, assumptions, methods and strategies encountered in studies on this factor (and others).

The appropriate conclusion for the current performance of V2G is that research on the technology has to develop further to improve or mitigate the barriers and fulfil the potential promise of the drivers, which also demonstrates the relevance of this research. The evaluation of the current performance of V2G shows that the drivers and barriers affect the actors in a V2G system differently, which proves that drivers and barriers cannot just be considered as such for the complete system but need to be analysed from different perspectives to determine their overall effects on the performance of V2G.

The expected effects of AVs on the performance of V2G

The expected effects of AVs on the performance of V2G were determined through interviews with V2G experts. In the interviews, four high-level variables of the development of AVs that are also relevant to V2G were considered: the level of automation, the level of penetration of AVs, private ownership versus fleet ownership, and shared versus not shared. Table 2 shows the ratings of the current performance of the V2G factors, the expected effect of AVs on the rating of the performance of the V2G factors according to the V2G experts, and the aggregated rating for the expected effects of AVs on the performance of the V2G factors, with the ratings highlighted in green if the rating is expected to improve compared to the current performance, yellow if the rating is expected to remain the same, and red if the rating is expected to become worse.

The experts compared two different scenarios for AVs: fleet-owned shared AVs and privately-owned unshared AVs. Privately-owned unshared AVs were believed to not have significant effects on the performance of V2G because individual preferences and range anxiety remained major barriers. AVs were expected to have the most effects on the performance of V2G when they are fleet-owned, shared, and managed and coordinated in large central charging hubs. The ratings in Table 2 are based on this scenario. The expected effects of fleet-owned shared AVs on the performance of the V2G factors can be summarised as follows:

- The ability to provide spinning reserve services to the grid improves from a driver to a major driver, because of the flexibility of AVs and the response time allowed for spinning reserve services.
- The investment cost of V2G improves from a major barrier to a barrier because charging hubs provide the opportunity to realise a more effective charging infrastructure which includes savings on, for instance, cables and charging spots.
- The impact of V2G on the distribution grid disappears because the flexibility of AVs allows for strategic choices that solve a negative impact on the distribution grid locally.
- Range anxiety disappears due to the mobility services fleet owners will provide. Passengers do not worry about the effect of V2G on the battery because they do not own the vehicle anymore and they expect that the fleet owner will provide them with a vehicle that has sufficient range to reach the desired destination.

The effect of V2G on battery degradation and the potential revenues that can be obtained from frequency regulation, active power support, and the overall V2G system remain uncertain in combination with AVs.

Table 2: The expected effects of AVs on the V2G factors

Factor	**Current**	**I-1**	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**I-7**	**AV**
Frequency regulation	+	+	+	+	++	+	+	+	+
Spinning reserve	+	++	++	+	++	++	+	+	++
Active power support	+	+	++	+	+	++	+	+	+
Reactive power support	+	N/A	+	N/A	+	+	+	+	+
Current harmonic suppression	+	+	+	N/A	+	+	+	+	+
Balance and support RE	++	++	++	++	++	++	++	+	++
System revenues	+	++	+	++	+	+	+	0	+
Battery degradation	-	--	--	--	-	-	0	-	-
Investment cost	--	-	--	--	-	-	0	0	-
Impact on the distribution network	-	0	+	0	-	-	0	0	0
Range anxiety	--	0	0	--	-	-	0	0	0

The broader implications of the results

The expected positive effects, especially on the V2G factors that are perceived as barriers to a V2G transition, imply that the integration of shared fleet-owned AVs in the transport system would bring a V2G transition much closer. However, most of the interviewed experts predict that a business model that aims at the most successful operation of shared fleet-owned AVs would not give priority to V2G operation of the vehicles. The potential shift to an on-demand, subscription-based mobility service could become a serious threat to the existence of V2G (in this form) if fleet owners rather focus on charging the AVs as efficient as possible and maximise the utilisation rate of the vehicles for mobility purposes because the value of renting out the vehicle is much higher. The system revenues of V2G through shared fleet-owned AVs would be minimised which would result in a focus on different forms of V2G if available, alternative storage options or completely different technologies to balance the grid.

The expected effects of AVs including the broader implications of on-demand mobility services are summarised in Figure 1. The path highlighted in green has a positive effect on the performance of V2G, in yellow a neutral effect, and in red a negative effect.

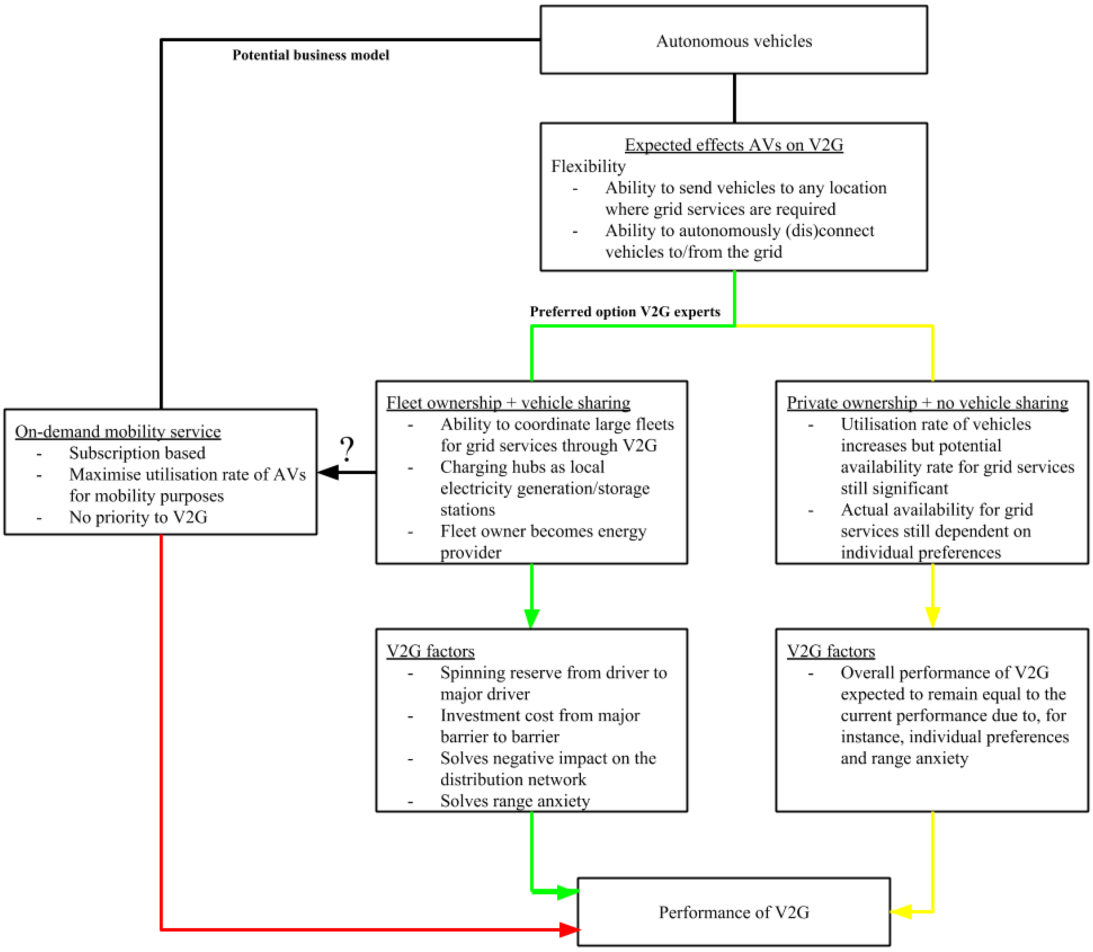

Figure 1: Expected effects of AVs on the performance of V2G

Conclusion

This research provided new insights for the future integration of the electricity and transport systems by considering an innovative combination of V2G and AVs. Although V2G is considered to be a suitable option to deal with the pressure on the stability of future electricity grids, an assessment of the current performance of V2G showed that the technology has to develop further to improve or mitigate the existing barriers and fulfil the potential promise of the drivers of a V2G transition. Therefore, the potential effects of AVs on the performance of V2G were evaluated for two scenarios: privately-owned unshared AVs and fleet-owned shared AVs. While privately-owned unshared AVs are expected to not have significant effects, fleet-owned shared AVs in combination with charging hubs are expected to enhance the performance of V2G because the ability to provide spinning reserve improves, the investment cost of the charging infrastructure decreases, negative impact on the distribution network can be controlled, and range anxiety disappears. However, uncertainties related to the potential revenues of some drivers and the impact of V2G on battery degradation remain an issue and require further research. In addition, the development of fleet-owned shared AVs is expected to include an on-demand business model that maximises the utilisation rate of AVs for mobility services because the value of renting out the vehicle is much higher than the value of V2G. If the final development path would contain this business model, the priority for V2G would be minimised which would create a new, insurmountable barrier that destroys the business case for V2G systems.

Recommendations

In light of a strategic plan of the European Commission to accelerate a European energy system transformation by, amongst others, integrating the energy and transport systems, recommendations for policymakers can be made. AVs could potentially improve some of the barriers to a V2G transition, but the integration of both technologies is not appropriate due to the high level of uncertainty around the drivers of V2G and the expected development path consisting of a focus on on-demand mobility services. AVs can, therefore, for now, develop independently from V2G. In the meantime, policymakers could focus on the question if grid services are to be performed by V2G. If due to future developments, a preference is developed for V2G over alternative storage options and AVs are on a different development path, the integration of both technologies can be reconsidered.

This research contributed to the body of knowledge on V2G by bridging a gap that existed between V2G and the integration of AVs. This resulted in a comprehensive overview of the current performance of V2G and first insights into the expected effects of AVs on the performance of V2G. Based on these findings, a number of directions for future research can be identified. First, inconsistencies within the scientific literature on drivers and barriers to a V2G transition have to be addressed to work towards a more elaborate overview of the current performance that includes the allocation of costs and benefits for all important actors. Also, the impact of different conditions, such as the types of electricity markets, on the feasibility of grid services through V2G is an important direction to discover the right conditions for V2G and if V2G should be considered as a technology that can provide all grid services or only a number of services under specific conditions. Another recommended research direction is an expansion towards social and institutional related research topics for the transition to V2G, which are currently underexamined. A research direction for V2G could also be to include FCEVs, especially if the adoption rate increases. Finally, research on V2G often does not consider the full spectrum of storage options. Future research into V2G should, therefore, include comparisons to alternative storage options to determine the position of V2G or supplementary options to strengthen the position of V2G.

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1. Introduction

1.1 The need for the car as a battery

Our energy systems have to change significantly due to the expected increase of 58% in renewable energy consumption by 2040 (EIA, 2017). The large-scale implementation of volatile, both in time and location, renewable energy sources, such as PV and wind, and the growing number of energy providers on the distribution grid level will severely affect the stability of the electricity grid (Muench et al., 2014). Balancing the power demand and supply becomes an unpredictable and complicated process. The perceived solution to these challenges is to introduce a more intelligent energy system that coordinates consumers of the electricity grid, thereby maintaining the net balance and establishing an efficient and reliable transmission and distribution of electricity (Vandael & Boucké, 2011). This energy system is called a smart grid. A core component of smart grids is a decentralised electricity storage functionality (Römer et al., 2012). Decentralised (or distributed) storage is a system of many small, on-site storage systems that temporarily separate generation and consumption. The ongoing electrification of the transport system has resulted into the belief that if electric vehicles (EVs) could be fully integrated with smart grids, their mobile batteries could play a crucial role in realising a decentralised storage functionality (Wentland, 2016). Since most vehicles are parked over 90% of the time, EVs could be used for storage purposes and the owners could be offered financial incentives for making their vehicles available to the grid (Kempton, 2010).

When EVs are used for decentralised storage, their functionality can be extended with vehicle-to-grid (V2G) technology. V2G technology allows EVs to provide control and management of bidirectional electricity flows through communication between the EV and the electricity network (Tan et al., 2016). Renewable energy can be stored in the EV when it is abundant and made available to the grid when the generation output is low. Ota et al. (2010) argue that V2G technology is a key technology for realising the integration of renewable energy sources in smart grids. V2G enables storage of excess energy, balancing supply and demand in a flexible way and, therefore, makes the increase of the amount of renewable energy in the electricity network feasible (Römer et al., 2012). In addition, V2G technology improves the quality of several grid services. The response time of V2G technology is very fast compared to, for instance, traditional power plants, which makes the technology suitable for voltage and frequency control (Steward et al., 2017). Nevertheless, a transition to V2G faces many barriers such as technological immaturity, cost hurdles and social acceptance (Sovacool et al., 2017). An example of a technical barrier is the acceleration of battery degradation caused by the increased use of the batteries of EVs with V2G technology (Yilmaz & Krein, 2013). Cost hurdles arise due to large investments needed to, for example, upgrade the power infrastructure to enable the use of V2G technology (Yilmaz & Krein, 2013). Barriers for social acceptance include, amongst others, issues related to the potential inconvenience for the EV owners of not having a fully charged vehicle when needed resulting into range anxiety (Sovacool et al., 2017). Consequently, V2G technology has to be improved and the conditions in which the transition takes place need to be more favourable to overcome the barriers and realise the large-scale implementation of robust decentralised storage functionalities through V2G technology that can provide stabilising services to the grid and support the energy transition towards a larger share of renewable energy sources.

1.2 Potential synergies between vehicle-to-grid and autonomous vehicles

An emerging technology in the transport system that might change our perception of mobility and therefore also influence the performance of V2G technology is autonomous driving. Autonomous vehicles (AVs) (or self-driving or robotic or driverless vehicles) are vehicles that drive itself without a human driver. This is considered the highest level of vehicle automation (Anderson et al., 2016). If widely accepted, AVs have the potential to significantly change the current transport system by realising, for example, more efficient road use, increased driver productivity and energy savings (Greenblatt & Shaheen, 2015). Lam et al. (2016) state that since AVs are likely to be EVs, they will be able to participate in the development of V2G technology. While convenience currently is an important factor to determine where the driver parks, AVs can be programmed to park in the right location to fully support V2G services where and when needed. In addition, the automation of vehicles could promote car sharing (Canzler & Knie, 2016). This would remove the dependence of the V2G system on private vehicle owners. AVs would be part of fleets, which would transport passengers based on intelligent applications. In the meanwhile, assuming the fleets would exist of autonomous EVs, algorithms could be made which efficiently deal with bidirectional flows between the vehicle and the electricity grid and the transport of passengers. This would create a decentralised storage facility based on fleets of autonomous EVs. Anderson et al. (2016) argue that when AVs would be fully integrated, wireless V2G services could become available and make V2G technology more flexible.

Despite the beneficial effects AVs might have for V2G technology, there is a lack of scientific research into the joint development of these technologies. This research bridges this knowledge gap by exploring the potential effects of AVs on the performance of V2G, thereby providing new insights into the pursued integration of the energy and transport systems. The findings of this research demonstrate that AVs are indeed expected to have positive effects on the performance of V2G, mostly by improving the current barriers to a V2G transition. While the required investment cost is expected to decrease significantly, the negative impact on the distribution grid and range anxiety are expected to disappear completely. However, AVs are also expected to develop into fleet-owned and shared vehicles which are used through an on-demand, subscription-based business model that drastically increases the utilisation rate of AVs for mobility purposes and minimises the availability for V2G services.

1.3 Problem statement and research objective

The electricity grid has to be upgraded to a smart grid with a decentralised storage functionality to deal with the expected pressure from the increasing amount of renewable energy on the stability of the grid. V2G is considered to be a key technology to realise such a decentralised storage functionality. However, barriers, such as the accelerated battery degradation and high investment cost, hamper the performance of V2G. A dramatic shift towards AVs in the future transport system drastically changes the conditions for a potential transition to V2G, potentially resulting in a more flexible V2G system that efficiently deals with bidirectional flows between AVs and the electricity grid and the transport of passengers. While Anderson et al. (2016) and Lam et al. (2016) briefly mention the potential applications and benefits for AVs in combination with V2G, there is no research available on the integration of AVs and V2G. To bridge this gap, this research takes the first steps in exploring the integration of the two technologies. The objective of this research is *to determine the likely effects of the development of autonomous battery electric vehicles on the performance of V2G technology.*

1.4 Research questions

Based on the problem statement and objective the following main research question is defined:

What are the potential effects of autonomous battery electric vehicles on the performance of vehicle-to-grid?

The following sub-questions are examined to answer the main research question:

I. *How can the performance of vehicle-to-grid be assessed?*
II. *What is the current performance of vehicle-to-grid?*
III. *What is the influence of the development of autonomous vehicles on the transport system?*
IV. *What are the expected effects of autonomous battery electric vehicles on the performance of the vehicle-to-grid factors?*
V. *What are the broader implications of the results for the performance of vehicle-to-grid?*

1.5 Scientific and practical relevance

The integration of the energy and transport systems through V2G technology has been subject to a substantial amount of scientific research in recent history. This research, however, focuses mainly on the transport system under current conditions. The shift to a transport system consisting of AVs seems to develop independently, while it could have a significant impact on the performance of V2G and, therefore, the integration with the energy system. This research addresses this gap in the scientific literature by including the emerging development of AVs into the scope of scientific research on the integration of the energy and transport systems resulting in several contributions to the body of knowledge of this topic. First, this research advances the knowledge of the current status of V2G through a comprehensive overview of the current performance of drivers and barriers to a V2G transition. Second, an exploration of the expected effects of AVs on the current performance of V2G offer meaningful insights into the potential role of V2G in future energy systems and provide directions for future research agendas.

The practical relevance of this research is also related to the integration of the energy and transport system. The European Commission has initiated a strategic plan to integrate the electricity, transport and heating systems, which is needed to accelerate a European energy system transformation (European Commission, 2015). Although the heating system is not included, this research contributes to the goal of the European Commission to pursue innovations that achieve a smarter, more flexible, more decentralised, more integrated, and more sustainable energy system. Moreover, this research touches upon an ongoing societal debate about the need for renewable energy and decreasing the amount of air pollution by reducing fossil fuel emissions. Based on the findings of this research, recommendations are made to policymakers on the integration of the energy and transport system through the combined development of AVs and V2G.

1.6 Relevance to the master's programme

This research was conducted as part of the graduation project for the master's programme Complex Systems Engineering and Management (CoSEM). The aim of the CoSEM graduation project is to design solutions for large and complex contemporary socio-technical problems, which includes the consideration of technical, institutional, economic and social aspects. This research contributes to the complex process of designing an integrated and sustainable energy and transport system by being the first scientific study to explore the integration of V2G and AVs. The combination of the energy and transport system gives the research a multidisciplinary character. The development and operation of V2G are explored in a complex socio-technical environment. The feasibility of V2G is considered from a multi-actor perspective and is believed to depend on the continuous development of the technology, the financial feasibility, the social impact and adoption, and in a later stage institutional support through the facilitation of policies. These complex socio-technical aspects are included in the research as much as possible.

1.7 Research scope

This research assumes that, if integrated successfully, V2G would have a stabilising effect on the grid as described in section 1.1. When considering the problem owner for this research, the electricity network operators initially seem the most relevant option, because V2G would have a direct impact on their operation by enabling them to balance the system when the penetration level of renewable energy increases and improve the quality of traditional grid services. In this research, however, V2G is seen as part of a utility, a service provided for the public, that needs to be adopted by the public to serve its purpose. In addition, multiple types of actors of a V2G system, such as EV owners and renewable energy generators, could experience advantages and disadvantages caused by V2G. The implementation of V2G is also believed to provide positive externalities for the environment, such as the reduction of greenhouse gasses. To address these wider implications of V2G, society is considered to be the problem owner for this research.

The development of EVs currently revolves around battery electric vehicles (BEVs), fuel cell electric vehicles (FCEV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEVs). These types of EVs have a different V2G operation and are affected differently by AVs as well or in case of HEV are not used in combination with V2G. This research focuses on V2G-enabled BEVs because the majority of the scientific literature considers BEVs when discussing V2G and the current penetration level of BEVs is significantly higher than FCEVs. Studies that cover battery PHEVs are used as input when relevant. FCEVs and HEVs are not in scope. Consequently, also when discussing AVs, the vehicles are assumed to be autonomous battery electric vehicles and V2G-ready, unless stated otherwise. With regards to the type of vehicles, only light-duty vehicles (or M1 vehicles) are considered, because these vehicles are widely available, most used, and the premise that vehicles are parked over 90% of the time and, therefore, can be used for V2G is mainly based on cars, which fall into this category.

1.8 Research design

To evaluate the potential effects of AVs on the performance of V2G, factors that affect the performance of V2G have to be established. In this research, the performance of V2G is based on the feasibility of the potential drivers of a V2G transition and the impact of potential barriers on a V2G transition. Drivers add significant value to the progress of a V2G transition by, for instance, contributing to an increasing share of renewable energy in the grid, providing better services to stabilise the grid and generating revenues through these services. Barriers hamper a transition to V2G, which include factors such as investment cost and range anxiety. Together these drivers and barriers are grouped as **V2G factors**, which are defined as factors that affect the transition of V2G by either making it valuable or hampering it.

The research design includes three components: the performance of V2G, V2G factors, and AVs. Under current conditions, the V2G factors influence the performance of V2G. The implementation of AVs changes the conditions for a potential transition to V2G and could, therefore, also affect the V2G factors or creates new factors. The V2G factors, however, also determine to what extent AVs could influence the performance of V2G. If a V2G factor is not affected by AVs, neither is the performance of V2G. These potential interactions between the

V2G factors and AVs and their combined effects on the performance of V2G are the main focus of this research.

1.9 Analytical framework

The analytical framework of this research links the theoretical main research question to empirical analysis by identifying the V2G factors under current conditions through a scientific literature review. The identified factors are then used to determine their current effects on the performance of V2G and as input for the assessment of the interaction with AVs and their combined effects on the performance of V2G.

The most important drivers and barriers to V2G were identified from the scientific literature and then translated into V2G factors. Since this research was performed with a social-technical perspective, the factors were intended to reflect a socio-technical perspective as well. However, the majority of the scientific literature on V2G tend to be mainly technical or techno-economic due to the early development phase the technology is still in. The time frame of the research did not allow for in-depth research into additional V2G factors. Only the factors that could clearly be identified from the available scientific literature were included. Consequently, social V2G factors are limited in this research, and institutional V2G factors could not be identified from the literature. Considering the early development phase V2G is in, it is believed that the lack of institutional V2G factors does not have a negative impact on the outcomes of the research. In this stage, the development of V2G is mainly focussed on advancing the technical and financial aspects, which might explain the focus of the scientific literature. However, socials factors are also believed to be important to be included early in the development process. Therefore, a social factor is included in the V2G factors despite the limited research into this type of V2G factors. While the development of V2G progresses, the need to include institutional aspects increases as well.

The scientific articles that were studied for the review are listed in Appendix B. The technical articles mainly discuss the grid services that V2G can provide into further detail or the impact of V2G on the grid, and more specifically the distribution system. The articles that focus on V2G from a techno-economic perspective usually consider the potential revenues that can be obtained through one or more grid services provided by V2G or stress the investment cost in relation to V2G technology. Two articles from the literature review only look at the financial perspective; one article describes the willingness to pay for V2G, while another article derives business models from consumer preferences for V2G. Two articles in the review consider V2G from a socio-technical perspective, which provided the input for a social V2G factor. Finally, one article focusses on a survey on EV transportation, including V2G, within a smart grid system.

The current performance of V2G was also based on empirical analysis. This analysis included both scientific and non-scientific literature. The perspective of the literature that was used for this analysis depended on the type of V2G factor. For instance, grid services such as spinning reserve and frequency regulation are often discussed in techno-economic literature because the added value of that factor is usually measured in potential revenues that can be obtained by the EV owner.

1.10 Research approach

The following paragraphs discuss the methods that were applied to answer the sub-questions.

I. *How can the performance of vehicle-to-grid be assessed?*

As described in the previous section, the drivers and barriers to a V2G transition were identified through a literature review and then translated to V2G factors. An extensive literature review was performed to create a comprehensive overview of the most important drivers and barriers. The research engines that were used for the review are Google Scholar, Scopus, Science Direct, and the TU Delft (online) library. The keywords that were used during the search included, but were not limited to, "advantages", "barriers", "benefits", "challenges", "decentralised storage", "disadvantages", "driver" "expectations", "impact", "performance", "vehicle-to-grid", and "V2G". Several strategies were used to find the most relevant literature for the review. Initially, only peer-reviewed articles were considered to ensure some degree of scientific accuracy. Exceptions were made if literature from important organisations, such as the International Energy Agency, were believed to add value to the research. The articles were then selected by making a combination of most cited articles and most recently published articles, which contain the state-of-the-art. If the articles frequently referred to the same article and this article had not appeared in the search results, "snowballing" was applied. A reference was assigned to a certain factor if the factor was mentioned as a driver or barrier to V2G. If the literature referred to the advantages or benefits of V2G, they were grouped under drivers. If the literature referred to disadvantages or challenges, they were grouped under barriers. The final list of V2G factors was validated by the experts that were interviewed for the analysis of this research (sub-question four) to ensure that all relevant (most important) factors were included. The group of experts included experts that are affiliated with a research institute and have proven experience in research on V2G technology and experts that were recently involved in either pilot projects or the implementation of V2G technology.

Finally, each V2G factor was operationalised to determine in what unit their effects on the overall performance of V2G could be measured. If a factor could not be operationalised, a description of the effects was taken as measurement.

II. *What is the current performance of vehicle-to-grid?*

The current performance of V2G was assessed through the aggregated performance of the V2G factors. The current performance of each of the factors was derived from an aggregation of results from existing and completed optimisations, simulations, pilots and other V2G projects. Input for these performances was obtained through scientific literature and reports of pilots initiated or supported by governmental organisations and relevant non-governmental organisations. Data from the scientific literature was searched through the same search engines as in sub-question one. The keywords for this search included but were not limited to "performance", "pilot", "vehicle-to-grid", "V2G" and the name of the specific V2G factors. Reports from other sources than the scientific literature were searched through the search engine Google. The keywords for this search were similar to the keywords for the scientific literature.

The search resulted in an overview of aggregated results for each factor. To effectively compare the effects of each factor on the overall current performance of V2G and later the effects of AVs on the performance of V2G, the results of the current performance were rated on a five-point scale ranging from a major barrier to a major driver. The final rating of each V2G factor was validated by the same experts that were interviewed for the analysis related to sub-question four. The rationale for each rating was briefly explained to the experts and the experts were asked if they agreed with the rating.

III. *What is the influence of the development of autonomous vehicles on the transport system?*

The influence of the changes in the transport system due to the development of AVs are the independent variables in this thesis. These changes are ongoing developments that might also influence the energy system through, for instance, having an impact on the performance of V2G. For this research question, scenarios around the development of AVs in the Netherlands for 2030 and 2050 by Milakis et al. (2017) were reviewed to discover the variables currently expected to affect the development of AVs. A selection of these variables, relevant to the interaction between V2G and AVs, were selected to give direction to the expert interviews.

IV. *What are the expected effects of autonomous battery electric vehicles on the performance of the vehicle-to-grid factors?*

To determine the expected effects of AVs on V2G, V2G experts were asked to rate the expected performance of each V2G factor based on the development of AVs on the same rating scale as described in sub-question two. This resulted in one aggregated rating for each factor that could be compared to the rating of the current performance. Based on these comparisons, the expected effects of AVs on the overall performance of V2G were derived.

Experts from different organisations and with different backgrounds were approached for an interview to avoid that the results of this research represent the thoughts of one group. The interviewees included four researchers from academia, one V2G specialist from a grid operator, one V2G specialist from a knowledge and innovation centre for smart charging, and two management consultants in sustainable mobility. The experts were approached to participate in this research because they either have proven experience in V2G projects or have performed research on V2G. Table 1 shows an overview of the interviewed V2G experts. The interviews took place in a semi-structured form to allow the experts to come up with new ideas during the interviews and encourage different perspectives on the effects of AVs. The interviewees received the identified factors, their current performance, examples of variables relevant to the development of AVs and interaction with V2G, and goals of the interview beforehand. The information was repeated again at the beginning of the interview to give the interviewees the opportunity to address any questions or objections. Ideally, a great number of interviews would have been conducted to ensure the reliability of the results. Since the available time for this research was limited, one of the objectives of the interviews was to ensure that every factor would be evaluated by at least five experts to mitigate the risk of subjectivity in the judgement of experts. This objective was achieved.

The results were validated by one expert who has a broad knowledge of the subject and, therefore, was able to make a complete assessment of the results. This expert was not involved in the first round of interviews to avoid bias. This validation interview was also done in a semi-structured form.

The validated findings were used as input for the discussion and conclusion.

Table 1: Interviewed V2G experts

Expert	Affiliation
Zweistra, M.	Alliander N.V.
Van Kerkhof, M.	APPM Management Consultants
Park Lee, E.H.	Delft University of Technology
Van Arem, Prof. dr. B.	Delft University of Technology
Van Wijk, Prof. dr. A.J.M.	Delft University of Technology
Van Eijsden, B.	ElaadNL
Moorman, S.	EVConsult
Validation Interview	
Chandra Mouli, G.R.	Delft University of Technology

V. *What are the broader implications of the results for the performance of vehicle-to-grid?*

Beyond the scope of the main research question which initially focussed on interactions between AVs and the currently relevant V2G factors, this sub-question addressed the broader implications related to the preferred design choices of the experts for the development of AVs. These implications could drastically change the outcome of the research.

1.11 Structure

The research approach is illustrated in the research flow diagram in Figure 1.

Chp. 1: Introduction

What are the potential effects of autonomous battery electric vehicles on the performance of vehicle-to-grid?

Chp. 2: Analytical Framework

Method: Literature Review

I. How can the performance of vehicle-to-grid be assessed?

Goal: To identify and operationalise the V2G factors.

Chp. 3: Current Performance

Method: Desk Research

II. What is the current performance of vehicle-to-grid?

Goal: To determine and rate the current performance of each of the V2G factors.

Chp. 4: Development of AVs

Method: Desk Research

III. What is the influence of the development of autonomous vehicles on the transport system?

Goal: To analyse the development of AVs and identify variables relevant to the interaction between V2G and AVs.

Chp. 5: Effects of AVs on V2G

Method: Expert Interviews

IV. What are the expected effects of autonomous battery electric vehicles on the performance of the vehicle-to-grid factors?
V. What are the broader implications of the results for the performance of vehicle-to-grid?

Goal: To determine the potential interaction between the V2G factors and AVs and the expected effects on the performance of V2G.

Chp. 6: Discussion

Chp. 7: Conclusion

Figure 1: Research flow diagram

2. Vehicle-to-grid

This chapter presents and operationalises the V2G factors that are used to describe the current performance of V2G in chapter three and to evaluate the effects of AVs in chapter five. First, the concept of V2G is discussed to provide more background and understanding of the components and operation of a V2G system. Then the most important drivers resulting from a transition to V2G are described followed by the most important barriers that hamper a transition to V2G. Finally, the drivers and barriers are translated into V2G factors and operationalised for further use in the next chapters.

2.1 The concept of vehicle-to-grid

The vehicle-to-grid concept was first proposed by Amory Lovins in 1995 and became known to a wider public after further research by Professor Kempton and his associates (Shaukat et al., 2018). In one of their early works, Kempton et al. (2001) introduce V2G as an opportunity to reduce air pollution and at the same time increase the reliability and efficiency of electric power systems by sending power to the grid through the use of the electric storage and/or generation capacity of EVs.

To operate EVs in a V2G configuration, they must have three required elements: a connection to the grid for electrical energy flow, a control that allows communication with the grid operator, and control and metering on-board of the vehicle to track energy flows (W. Kempton & Tomić, 2005a). The components and power flow of the complete V2G system, providing the abovementioned elements, are represented in Figure 2. Six major subsystems are recognised in a V2G system: 1) energy resources and electric utility; 2) an independent system operator (ISO) and aggregator; 3) charging infrastructure and locations; 4) two-way electrical energy flow and communication between each EV and ISO or aggregator; 5) on-board and off-board intelligent metering and control; and 6) the EV with a battery charger and management (Yilmaz & Krein, 2013). Energy resources and electric utilities form the basic foundation of the electricity system. Electric utilities are companies involved in electricity generation and distribution of electricity in the grid. EVs with V2G interfaces are connected to the grid through charging locations and charge or send power (discharge) to the grid when parked. Within the electricity system, ISOs are responsible for operating and controlling the bulk of the grid (Guille & Gross, 2009). In a V2G configuration, the operation between the EVs and the grid is, therefore, also supported by the ISO. However, since the impact of one EV on the grid is small and difficult to manage, aggregators act as a distributed energy resource by collecting EVs in larger groups to create a more manageable load (consumed electricity) for the grid (Guille & Gross, 2009). The aggregator then also provides an interface with the ISO and the providers of the electricity supply in the distribution grid to coordinate the grid operation. To maintain this system, two-way energy flow and communication is needed. The connection between the EVs and the grid must allow for bidirectional communications to receive commands and report battery status, such as the state of charge (SOC) and battery capacity (Yilmaz & Krein, 2013). The aggregator accumulates data from the EVs through on- and off-board (smart) metering. When the grid requires power, the ISO sends signals to the aggregator to conduct discharging of the EVs. The power flow runs bidirectional, from V2G and from grid-to-vehicle (G2V). In this research, "V2G" is used generically for both V2G and G2V energy flows. Unidirectional V2G, which consists of a basic battery charging process, can also contribute to the grid through reactive power and dynamic adjustment of charge rates (Yilmaz & Krein, 2013). This research will only consider bidirectional power flow because it is needed to integrate renewable energy sources in the grid and has the same benefits as unidirectional V2G and more (Tan et al., 2016).

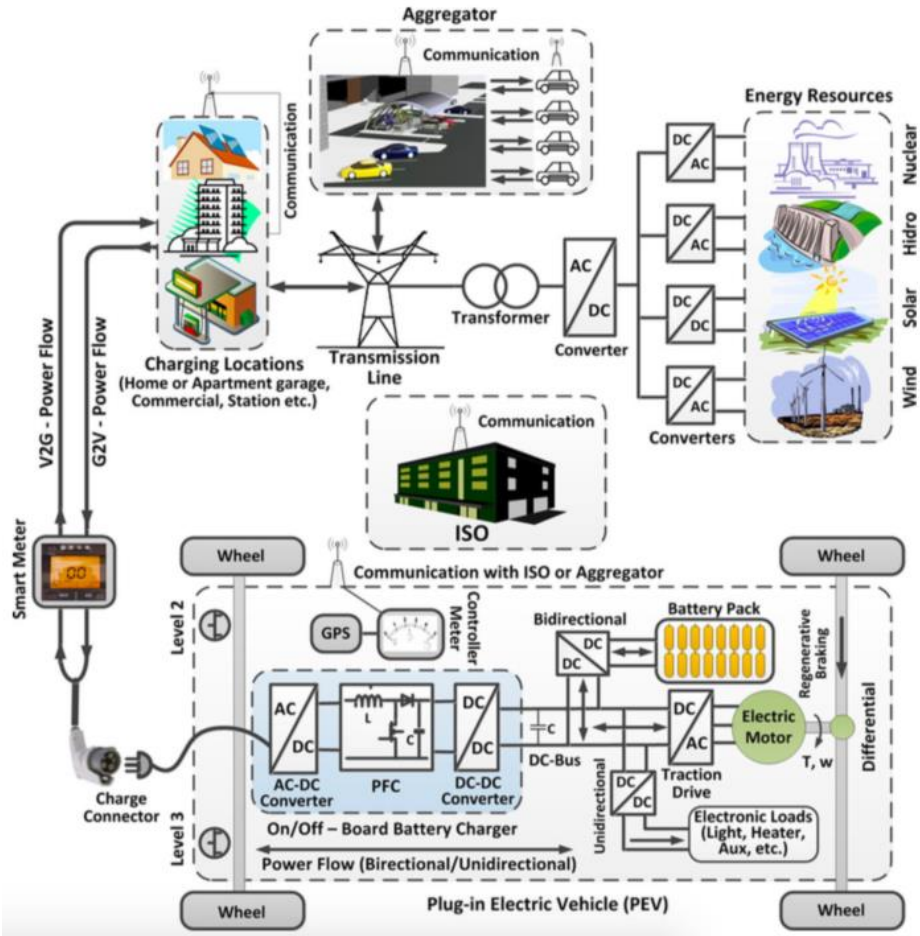

Figure 2: Components and power flow of a V2G system (Yilmaz & Krein, 2013)

2.2 Drivers of a vehicle-to-grid transition

The potential drivers of a V2G transition are mainly related to services that can be provided to support and stabilise the grid. Some of these services potentially generate revenues for, for instance, EV owners or reduce the operating cost for the network operator. Table 2 gives an overview of the most important drivers of a V2G transition based on the performed literature review and gives a short explanation of the added value of V2G for each of the drivers. The following sections explain the identified drivers and the added value of V2G in more detail.

2.2.1 Ancillary services

Ancillary services are power services, other than the regularly scheduled power generation, that help grid operators to maintain the stability and reliability of the grid (Brooks, 2002). In case of, for instance, mismatches between the power generation and load, unbalances can cause the grid to become unstable which may result in large disruptions of service. Ancillary services can be used as reserve power to react and balance supply and demand. EVs with a V2G configuration create a dynamic storage functionality for the grid that can provide higher quality ancillary services (Habib et al., 2015). The most promising ancillary services linked to V2G in the literature are frequency regulation and spinning reserve. The following paragraphs explain each of these services and their link to V2G.

Table 2: Drivers of a V2G transition

Drivers of V2G	Added value V2G	References
Ancillary Services	V2G can act as a dynamic storage functionality that allows for higher quality ancillary services	Bohnsack et al., 2015; Brooks, 2002; Habib et al., 2015; Kempton & Tomić, 2005a; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Peças Lopes et al., 2011; Sovacool & Hirsh, 2009; Yilmaz & Krein, 2012, 2013
• Frequency Regulation	V2G needs less response time to provide frequency regulation than conventional generators.	Brooks, 2002; Habib et al., 2015; Han et al., 2010; Kempton & Tomić, 2005a; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Shaukat et al., 2018; Yilmaz & Krein, 2012, 2013
• Spinning Reserve	V2G can provide spinning reserve on short notice in case of an unplanned event such as loss of generation.	Brooks, 2002; Habib et al., 2015; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Parsons et al., 2014; Peças Lopes et al., 2011; Shaukat et al., 2018; Yilmaz & Krein, 2012, 2013
Active Power Support	V2G-enabled EVs can charge and discharge their batteries to perform active power support.	Habib et al., 2015; Shaukat et al., 2018; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
• Load Levelling	V2G allows for load levelling by valley fillings.	Habib et al., 2015; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
• Peak Load Shaving	V2G allows for discharging electricity back to the grid during peak load periods	Brooks, 2002; Gough et al., 2017; Habib et al., 2015; Kempton & Tomić, 2005a; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Shaukat et al., 2018; Sovacool & Hirsh, 2009; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Reactive Power Support	V2G is a more flexible and efficient reactive power resource due to the bidirectional charger.	Brooks, 2002; Habib et al., 2015; Mwasilu et al., 2014; Shaukat et al., 2018; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Current Harmonic Suppression	The bidirectional chargers of V2G-enabled EVs allow for current harmonic suppression.	Habib et al., 2015; Ma et al., 2016; Shaukat et al., 2018; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Balance and Support Renewable Energy	V2G provides a storage functionality for renewable energy that can provide electricity back to the grid when required.	Bohnsack et al., 2015; Habib et al., 2015; Kempton & Tomić, 2005a, 2005b; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Peças Lopes et al., 2011; Sovacool et al., 2017; Sovacool & Hirsh, 2009; Yilmaz & Krein, 2012, 2013
System Revenues	The abovementioned grid services that could be provided through V2G generate revenues for actors in a V2G system.	Bohnsack et al., 2015; Habib et al., 2015; Ma et al., 2016; Mwasilu et al., 2014; Parsons et al., 2014; Peças Lopes et al., 2011; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
• Revenues for EV Owners	V2G-enabled EV owners obtain revenues by making their vehicle available for grid services.	Bohnsack et al., 2015; Ma et al., 2016; Parsons et al., 2014; Sovacool et al., 2017; Yilmaz & Krein, 2012, 2013
• Reduced Network Operating Cost	V2G allows for reduced charging costs and for equipment in the grid to be used more effectively.	Habib et al., 2015; Ma et al., 2016; Mwasilu et al., 2014; Yilmaz & Krein, 2012, 2013
• Improved Economics for the RE Industry	The market for renewable energy generation grows through V2G.	Habib et al., 2015; Peças Lopes et al., 2011; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016

Frequency regulation helps to keep the operating frequency at its nominal value so the power system can work properly, e.g. 50 Hz in Europe and 60 Hz in the U.S. (Lam et al., 2016). If the generated power in a grid is larger than consumption, the frequency of the system will be higher than the required nominal value while a shortage of generated power causes a smaller frequency. These situations are often recognised as "regulation down" and "regulation up", respectively. If the load, for example, exceeds the generation, the frequency decreases which indicates regulation up and discharging batteries into the grid is required (W. Kempton & Tomić, 2005a). These variations in frequency have an impact on the performance and service life of electrical equipment which is designed to operate at the nominal value. Therefore, frequency regulation is used as a measure to adjust the system frequency to the nominal value when needed by injecting power into the grid or subtracting power from the grid (Lam et al., 2016). Currently, frequency regulation is mostly performed by electricity generators that bid into the regular electricity market and are also contracted to be able to increase or decrease generation when requested by the network operator (Brooks, 2002). The fast charging rate and ability to respond quickly to commands from the ISO make EVs with V2G configuration a very promising option to provide frequency regulation instead of the current generators (Han et al., 2010). Since a typical EV could only supply a power capacity between 10-20 kW and the frequency regulation in the grid is performed on a MW basis, aggregators are needed to handle the small-scale power of EVs while supporting frequency regulation on a large scale (Han et al., 2010).

Spinning reserve is an additional generating capacity that can supply power to the grid rapidly, within 10 minutes, when requested by the ISO (Kempton & Tomić, 2005a). The generation capacity is provided by generators that operate at part capacity within the grid and sell their remaining unused capacity as spinning reserve. The generators are already synchronised to the grid and can, therefore, provide extra generation in case of an unplanned event such as loss of generation somewhere else (Kempton & Tomić, 2005a). The difference between spinning reserve and non-spinning reserve is that spinning reserve generators are always online and available for the ISO, while non-spinning reserve generators are disconnected from the grid and need longer response time to supply electricity to the grid (Kempton et al., 2001). V2G-configured EVs can function as spinning reserve by lowering the charging rates and supplying electricity back to the grid when needed (Tan et al., 2016). This extra capacity can be called on short notice as required (Brooks, 2002). Spinning reserve generators are compensated for the time they are available, the amount of capacity they have available during that period and for the electricity that is actually delivered (Kempton et al., 2001). EV owners, and the aggregators managing the service, are thus guaranteed of revenues while the EVs are plugged in.

2.2.2 Active power support

Active power support uses the excessive energy of EVs to support the grid. When this excessive power is needed by the grid, V2G-enabled EVs can discharge their batteries to perform this service (Tan et al., 2016). One of the main advantages of active power support is that by flattening the load profile of the grid through battery discharging, the overall operating capacity of the grid is lower which leads to a reduction of power losses and the cost of system infrastructure are reduced (Tan et al., 2016; Wang & Wang, 2013). The literature refers to two active power support services related to V2G technology that mostly contribute to flattening the load profile: peak load shaving and load levelling. Compared to other peak load shaving and load levelling methods, V2G-configured EVs can realise a more effective and economical solution in combination with the benefit of a quick response to grid-demand variations (Wang & Wang, 2013). The next paragraphs discuss these services.

Peak load shaving deals with reducing the peak load spikes that threaten the safety and reliability of the electricity grid (Wang et al., 2016). Currently, highly variable generation capacity is needed to meet the load during peak hours, which only occurs a short period of time throughout the day and is significantly higher than the average load. During peak load periods, charging of EVs can be limited to lower demand in the grid. In addition, EVs with a V2G configuration could provide electricity back to the power grid during this period if required (Tan et al., 2016).

Load levelling, also known as load balancing, is linked and comparable to peak shaving, but while peak shaving is focused on reducing peak demand, load levelling decreases the differences between the lowest and highest point of the rest of the demand profile (Agamah & Ekonomou, 2016). Load levelling can be achieved by so-called "valley fillings" (Habib et al., 2015). Valley fillings stimulate additional energy use during periods of low energy demand, such as charging EVs at night. Figure 3 shows the comparison between a load profile before and after peak load shaving and levelling.

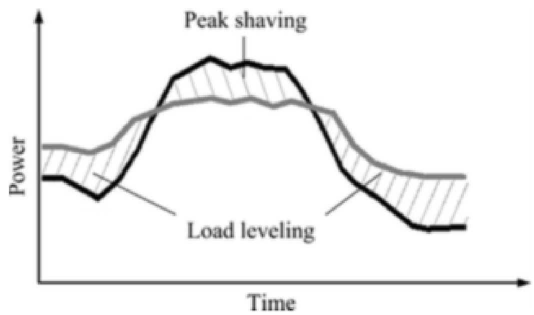

Figure 3: Load profile comparison before and after peak load shaving and load levelling (Tan et al., 2016)

2.2.3 Reactive power support

Reactive power is the power that flows to loads through the grid but is not actually consumed. The same amount of power that flows into the load also flows back out, which is caused by the voltage and current going up and down at different times, i.e. the voltage and current are not in phase (Sauer, 2003). The demand for reactive power is created by, for instance, inductors and capacitors (Sauer, 2003). If the amount of reactive power flow in the grid is high, the power factor, which indicates the ratio of actual power absorbed by the loads, decreases. In addition, unbalanced reactive power flows cause the voltage level to drop and contribute to power losses, which creates grid instability (Bolognani & Zampieri, 2013). Reactive power support is, therefore, important to ensure voltage regulation, power loss reduction and power factor correction (Jiang & Fei, 2013). Currently, this is done by drawing reactive power from distributed generators or static volt-ampere reactive compensators that have fixed locations and limited capacity (Jiang & Fei, 2013). The bidirectional charger of a V2G-configured EV also allows for reactive power support through the DC-link capacitor (Tan et al., 2016). This provides a more flexible and efficient reactive power resource (Jiang & Fei, 2013). In addition, the exchange of reactive power support does not include any transfer of active power. Therefore, it has no impact on important concerns related to V2G and active power transfer, such as battery degradation and range anxiety (Buja et al., 2017).

2.2.4 Current harmonic suppression

The increase in the number of EVs connected to the grid may affect the dynamics and performance of the distribution system (Yilmaz & Krein, 2013). Due to this increase, current harmonics could be produced in the distribution system. In a normal functioning power system, linear electrical loads draw a current that has a sinusoidal waveform that is proportional to the voltage (Chowdhury, 2001). When other linear electrical loads are connected to the distribution system, they are not disruptive to the utility networks, other consumer or the distribution system itself. However, non-linear electrical loads, such as the battery chargers of EVs, produce a current that neither has a sinusoidal waveform nor is proportional to the voltage, as shown in Figure 4 (Chowdhury, 2001). The distortion of the sinusoidal waveforms induced by non-linear loads is called harmonics. A large number of current harmonics, generated during, for instance, the charging process of EVs, may result into more line loss in the grid, increase the electric equipment heating problem, interrupt the production or operation of the grid, and cause a large-scale blackout (Yang et al., 2012). The bidirectional charger of V2G-configured EVs can again play an important role in improving the harmonic distortion. Current harmonics can be suppressed through appropriate control methods within the voltage source rectifier of the bidirectional charger, which enables the EVs to provide the abovementioned ancillary services to the grid (Youjie Ma et al., 2016).

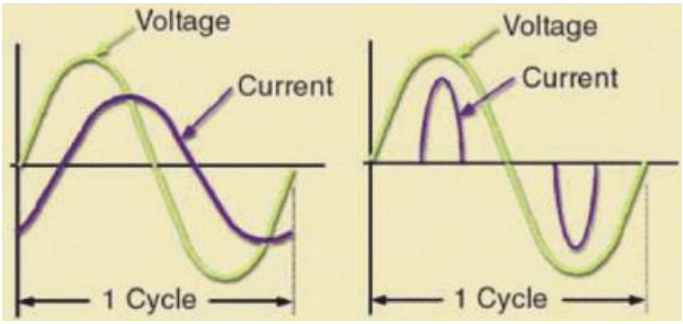

Figure 4: Voltage and current relationships in (a) linear load, and (b) non-linear load (Chowdhury, 2001)

2.2.5 Balance and support renewable energy

As mentioned before, one of the most important drivers of V2G technology is the possibility to balance and support renewable energy. Both PV and wind turbines, the largest renewable energy sources expected to be extensively used in the near future, are intermittent. The peak solar radiation, for instance, takes place a few hours before peak energy demand in many power markets (Yilmaz & Krein, 2013). Power generation by wind turbines is more complex and greatly varies because of wind gusts, cloud cover, thermal cycles, the movement of weather fronts, and seasonal changes (Sovacool & Hirsh, 2009). Low levels of renewable energy penetration in the grid can be managed by tools currently available for supply and load fluctuations. The deployment of renewable energy on a large scale, however, requires energy storage or backup to handle the fluctuating supply and match it to the already fluctuating load (Kempton & Tomić, 2005b). EVs with a V2G configuration can act as a storage facility by absorbing the excessive power supplied by renewable energy sources, such as wind energy generated at night. In addition, they can act as backup for the grid by providing power back to the grid when needed, for example during peak demand hours (Tan et al., 2016).

2.2.6 System revenues

Providing the abovementioned services to the grid can lead to revenues. The scientific literature often refers to three types of revenues related to V2G: revenue for EV owners, reduced network operating cost, and improved economics for the renewable energy generation industry. The following paragraphs discuss these types of revenues.

In addition to the electricity cost savings EVs owners can obtain by charging when electricity prices are low, they can also obtain revenues through V2G by selling excessive electricity

(Bohnsack et al., 2015). Moreover, they can obtain revenues by making their EVs with V2G technology available for aggregation to provide services back to the grid, such as frequency regulation and spinning reserve (Sovacool et al., 2017). The actual value EV owners could get out of the V2G technology depends on the business model that is chosen for the concept and specific conditions within local electricity markets (Bohnsack et al., 2015; Sovacool et al., 2017). Examples of these business models are, for instance, paying the owner for grid services as mentioned above and “battery and charging as a package service” where the vehicle owner pays a (monthly) fee for the battery and charging instead of owning it (Kempton et al., 2013).

The grid services V2G-enabled EVs can provide can also reduce the operating cost of the electricity system. The economic impact does, however, depend on several factors, such as the level of penetration of EVs and intelligent scheduling of charging (Yilmaz & Krein, 2013). If V2G technology in combination with smart charging could reduce the charging costs, both EV owners and the network operator would benefit (Schuller et al., 2014). Furthermore, off-peak charging, with a significant level of EV penetration, allows network operators to use their equipment more effectively which would reduce the overall cost of service and help recover fixed costs and loan expenses more rapidly (Sovacool et al., 2017).

Finally, if V2G technology can support in realising a cleaner and more sustainable grid by accommodating a large-scale integration of renewables, it will automatically have a positive effect on the economics of the renewable energy generation industry (Tan et al., 2016). A properly managed and well-functioning electricity system with V2G-enabled EVs could significantly increase the market share of renewable energy generation.

2.3 Barriers to a vehicle-to-grid transition

The barriers to a V2G transition are related to the battery of the vehicle, investments required for V2G systems, the impact on the distribution grid for the network operator and range anxiety experienced by EV owners. Table 3 provides an overview of the most important barriers to a V2G transition and a short explanation of the rationale for each barrier based on the performed literature review. The following sections describe the barriers in more detail.

2.3.1 Battery degradation

The grid services EVs can provide through V2G are believed to considerably influence battery life (Yilmaz & Krein, 2013). The increasing number of charging and discharging cycles due to grid services provided through V2G develop more internal resistance of the battery and lower the useable capacity. In addition to the charging and discharging cycles, battery degradation depends on many other aspects, such as the depth of discharge (DOD), temperature, weather, voltage and driving practices (Sovacool et al., 2017; Tan et al., 2016). The accelerated battery degradation results in higher effective battery cost for the consumer and more battery disposal (Parsons et al., 2014). A parameter that is used to predict the life cycle of batteries is the Equivalent Series Resistance (ESR). The higher the ESR, the higher the battery degradation. Studies have shown that the ESR is likely to increase when the temperature of the battery is low and the SOC is either high or low (Tan et al., 2016; Yilmaz & Krein, 2013). The battery cycle should, therefore, be kept in the middle range of the SOC to reduce battery degradation. DOD is also an important aspect to lower battery degradation (Tan et al., 2016). The DOD of the battery should not exceed 60% to keep the battery life cycle within an acceptable range (Millner, 2010). Reducing battery degradation and, consequently improving battery life cycle through these and other measures are important factors to enhance the cost equation for V2G which makes the technology more competitive (Loisel et al., 2014; Mullan et al., 2012).

Table 3: Barriers to a V2G transition

Barriers to V2G	Rationale	Reference(s)
Battery Degradation	Accelerated battery degradation due to increasing charging and discharging cycles caused by V2G services.	Bohnsack et al., 2015; Gough et al., 2017; Habib et al., 2015; Loisel et al., 2014; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Investment Cost	Large investments required to upgrade the power system and deal with the expected impact on battery life.	Habib et al., 2015; Loisel et al., 2014; Mwasilu et al., 2014; Peças Lopes et al., 2011; Shaukat et al., 2018; Sovacool & Hirsh, 2009; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Impact on the Distribution Network	Battery chargers can rapidly overload local distribution equipment if charging policies are not managed properly. This can lead to, for instance, voltage deviations, losses in the distribution transformer, and effects on distribution equipment. The increasing number of charging cycles due to V2G cause more conversion losses.	Habib et al., 2015; Mwasilu et al., 2014; Peças Lopes et al., 2011; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Range Anxiety	V2G increases range anxiety which prevents social adoption.	Sovacool et al., 2017; Tan et al., 2016
• Sharing Battery with the Grid	The inconvenience of a potentially fluctuating driving range results in increased range anxiety.	Parsons et al., 2014; Sovacool et al., 2017; Tan et al., 2016
• Distrust	Distrust in the aggregator and technology that control the V2G system leads to fear for the EV not being sufficiently charged.	Sovacool et al., 2017

2.3.2 Investment cost

The financial promise of V2G systems is, despite the potential system revenues, currently constrained by the high costs associated with the implementation. EVs with a V2G configuration can be more expensive than regular EVs, which at this point are more expensive than the traditional options (Sovacool et al., 2017). The expected impact of V2G technology on battery life has also shown that battery degradation needs to be reduced to create a more competitive business case. In addition to these financial barriers, substantial investments are needed to upgrade the power system to realise the implementation of V2G technology (Tan et al., 2016). This upgrade includes enhancements in hardware and software infrastructure. V2G functionalities cannot become available without, for instance, the vehicle owners investing in appropriate technologies to use V2G in their home area network and network operators investing in the appropriate measures to support V2G transactions (Mullan et al., 2012). In addition, each EV that takes part in a V2G system needs to be equipped with a bidirectional charger. Also, a reliable and real-time advanced communication and control network is needed to successfully operate the interaction between the V2G-enabled EVs and the grid (Mwasilu et al., 2014). Since this network would require more access points than there are participating vehicles and would always have to be open to provide real-time applications, it would be very expensive to implement (Mullan et al., 2012). These and other high investment costs are difficult to justify as long as the economic and business models for the V2G concept are unproven (Shaukat et al., 2018).

2.3.3 Impact on the distribution network

A large penetration of V2G-enabled EVs could have an impact on the distribution network of the grid due to high power when increasing the electricity demand by acting as a fast response type load (Habib et al., 2015). Depending on the level of penetration and if EVs follow a free charging policy, battery chargers can rapidly overload local distribution equipment. Moreover, if charging takes place in a congested distribution network, it can result into undesirable peak loads, harmonic distortion, voltage deviations, distribution transformer losses, effects on distribution equipment, and a low power factor (Habib et al., 2015; Yilmaz & Krein, 2013). The increased number of charging and discharging cycles performed by V2G-configured EVs include many energy conversions, which contribute to more conversion losses (Tan et al., 2016). If these conversion losses are caused by a large fleet of EVs with V2G technology, it can result in serious power losses. To limit the impact on the distribution network, charging policies should be managed and controlled through the development of intelligent charging schemes, which, for instance, include charging the EVs in valley periods and optimise the use of available electricity (Mwasilu et al., 2014; Peças Lopes et al., 2011).

2.3.4 Range anxiety

The implementation of V2G requires a large number of EV owners willing to participate in the system. The absence of public acceptance of V2G technology, however, seems to be one of the potential barriers preventing large-scale V2G adoption (Tan et al., 2016). Sharing the battery with the grid and distrust in the aggregator and V2G technology contribute to an increase of range anxiety, which among drivers is already the biggest concern for conventional EVs without V2G configuration (Sovacool et al., 2017). The following paragraphs discuss these issues based on examples mentioned by Sovacool et al. (2017).

The potential inconvenience caused by sharing the battery with the grid is related to the available driving range of the V2G-enabled EV that could be affected at any given time. Selling the electricity back to the grid and a delayed or slow charging process initiated by the grid operator or aggregator could hinder the EV owner’s driving behaviour and lifestyle. The inconvenience of the fluctuating available range, for instance in case of emergency, leads to range anxiety among the EV owners.

Another barrier related to range anxiety is distrust of the EV owner in the electric utility or the aggregator that is controlling the V2G system. Distrust is induced by the control that is taken away from the EV owner. In addition, lack of trust in control technology leads to fear for system errors which could prevent the EV from being charged when needed.

Ensuring a well-organised EV charging network is needed to reduce range anxiety (Tan et al., 2016). Furthermore, taking into consideration the EV SOC level could provide an option to make sure that the battery has a sufficient amount of electricity for daily usage. The V2G-enabled EV would then stop providing services to the grid when the SOC is lower than an initially determined percentage (Tan et al., 2016).

2.4 Identifying the vehicle-to-grid factors

The list of identified drivers and barriers to a V2G transition was also shared with V2G experts for validation. One expert argued that the list is incomplete because the potential drivers that can be obtained through battery storage options such as V2G include more services than stated. In addition, the realisation of charging standards and the lack of policies pushing the integration of V2G were also seen as barriers to V2G which are not reflected in the list. With regard to the missing grid services, it is indeed true that the list of drivers does not reflect all the services that could be provided to the grid through V2G. The drivers that are mentioned are believed to be the most important drivers, adding the most value to a V2G transition and are most often mentioned in the literature. The missing services mentioned by the expert, such as “black start”, were considered during the literature review but were perceived to have less effect on the performance of V2G than the drivers in Table 2. The barriers that were missing according to the expert are grouped under institutional or regulatory barriers. As described in section 1.9, this type of barrier is not included.

Next to the identified barriers from Table 3, the optimisation of V2G algorithms was also presented to the V2G experts as a potential barrier. Several articles mention this factor as an important precondition for V2G because the dynamic and random behaviours of V2G-enabled EVs add more complexity to the power system. To manage the interaction between the EVs and the grid, optimisation techniques have to be applied for the integration of a V2G system (Tan et al., 2016). However, the consulted experts believed that optimising these algorithms would not be more complex than other systems, such as the financial system. This factor was therefore not included for further analysis.

After validation of the drivers and barriers, they were translated to V2G factors. Some of the drivers and barriers consisted of subcategories. For those drivers and barriers, it was determined if the main category or the subcategories were more appropriate to be considered as V2G factors. In the case of ancillary services, not all ancillary services, such as non-spinning reserve and black start, that could potentially be provided through V2G were recognised as important drivers for this research. Selecting ancillary services as a V2G factor would imply that all ancillary services are included. Consequently, frequency regulation and spinning reserve were both identified as separate V2G factors. Active power support was also classified as a driver that consists of two subcategories; peak load shaving and load levelling. Since these subcategories are the only subcategories found in the literature for active power support and the literature usually discusses both subcategories collectively, active power support is used to describe the V2G factor. Another driver identified with subcategories was system revenues. The subcategories of this driver all contribute to the complete system. In addition, not all studies conform to the discussed subcategories when evaluating (part of the) system revenues. Therefore, the main category was used as V2G factor. Finally, for range anxiety two subcategories were recognised. However, both subcategories have range anxiety as a result. Range anxiety was, thus, seen as the most appropriate name for the V2G factor.

Table 4 presents the V2G factors. The left side of the table accounts for the factors that are perceived to be drivers to a V2G transition. The right side of the table holds the factors that are perceived to be barriers to a V2G transition if not improved or mitigated.

Table 4: V2G factors

Frequency Regulation	Battery Degradation
Spinning Reserve	Investment Cost
Active Power Support	Impact on the Distribution Network
Reactive Power Support	Range Anxiety
Current Harmonic Suppression	
Balance and Support Renewable Energy	
System Revenues	

2.5 Operationalising the vehicle-to-grid factors

To make the V2G factors suitable for further analysis, the factors are operationalised based on the measurements most often applied in studies on these factors. For the majority of the factors, the expected effects are measured in terms of the potential economic value or the expected effects are merely described. The potential economic value is mainly expressed in potential revenues, savings or costs for one or more actor groups in a V2G system. The potential revenues usually consist of the annual revenues that can be obtained by EV owners for providing a V2G service. Potential savings are mostly linked to the network operator. Potential costs are often allocated to both EV owners and network operators. Since one of the key drivers of V2G is the expected increase of renewable energy in the grid, it was expected that next to a financial measurement the grid services could also be operationalised with a sustainable measurement related to renewable energy, such as the amount or percentage of polluting emissions that could be reduced. However, a sustainable measurement was only be found in one study related to spinning reserve.

Table 5 shows the operationalised V2G factors. For some factors, multiple measurements are defined. In the next chapter, these measurements are used to determine the current performance of each V2G factor.

Table 5: Operationalisation of the V2G factors

V2G Factor	Measurement
Frequency Regulation	Potential revenues (in € per EV per year)
Spinning Reserve	Potential revenues (in € per EV per year or in € per V2G unit per year) Reduction of polluting emissions (in %)
Active Power Support	Potential revenues (in € per EV per year)
Reactive Power Support	Effect on battery degradation (description) Effects of different modes of V2G operation (description)
Current Harmonic Suppression	Effect on current harmonic distortion (description)
Balance and Support Renewable Energy	Effect on penetration level of renewable energy (in %) Potential savings for electricity and transport systems (in € per EV per year)
System Revenues	Potential revenues (in € per EV per year)
Battery Degradation	Effect of energy throughput of V2G on battery (in % or description) Potential cost (in € per charge or description)
Investment Cost	Required infrastructural and operational investments (in € or description)
Impact on the Distribution Network	Effect on distribution equipment (in % or description) Effect of different modes of V2G operation (description)
Range Anxiety	Consumer-based experiences (description)

3. The current performance of vehicle-to-grid

In this chapter, the current performance of each of the V2G factors is determined using the measurements defined in section 2.5. The current performance of V2G is believed to be an aggregation of the performances of the V2G factors. V2G is still in an early development phase. Hence, the current performance of these factors is based on expectations derived from research including experiments, technical simulations, and quantitative modelling. In addition to scientific research, input for the current performance of the V2G factors is complemented by findings from Reynolds et al. (2018), who provide a global review of the lessons learned from 50 pioneering V2G projects. These projects represent a mixture of scientific, governmental and industry supported projects.

Since the measurements of the V2G factors differ significantly, a five-point rating scale is introduced to allow for an easier comparison between the factors and their effect on the overall performance of V2G. This rating scale also provides a structured approach for the comparison of the current performance and the effects of AVs on the performance of V2G in chapter five. The five-point rating scale is shown in Table 6.

Table 6: Five-point rating scale

--	-	0	+	++
Major barrier	Barrier	Neutral	Driver	Major driver

The following sections discuss the current performance of each of the V2G factors. At the end of each section, the performance of each V2G factor is rated on the five-point scale. If a V2G factor initially is perceived as a barrier by the literature, the rating of that factor is either – or --. If the V2G factor initially is perceived as a driver by the literature, the rating of that factor is either + or ++. The magnitude of the rating of each factor depends on the current performance from studies on that specific factor. If the aggregated performances of multiple studies indicate a significant effect of a factor on the performance of V2G, the factor is rated as -- or ++ (depending on how it is initially perceived by the literature). If the aggregated performances of multiple studies indicate a minor impact or the results of different studies varied considerably making it difficult to come to one aggregated performance, the factor is rated as – or + (depending on how it is initially perceived by the literature). Since the first step of the rating process divides the factors into barriers and drivers based on the literature, the 0 rating is not applied in this part of the research. This rating is considered in chapter five if according to V2G experts the effects of AVs make the effects of a V2G factor neutral instead of a barrier or driver.

This chapter concludes with an evaluation of the current performance of each V2G factor and the overall current performance of V2G.

3.1 The current potential of frequency regulation

Several studies have focused on the potential performance of frequency regulation in combination with V2G by determining the potential future revenues that can be obtained through this grid service. The results of the studies provide a range of potential revenues based on different variables and assumptions. According to Tomić & Kempton (2007) “important variables are (a) the market value of regulation services, (b) the power capacity (kW) of the electrical connections and wiring, and (c) the energy capacity (kWh) of the vehicle’s battery”. Common differences in assumptions are, for instance, related to the SOC of the EVs and the expected daily availability of the EV for grid services. Differences related to the SOC can vary from the starting and target SOC to the levels of the SOC that disallow charging or discharging.

Since the calculations include so many variations in variables and assumptions, these variations are not considered when comparing different studies. Instead, the different findings are combined into one range per factor. The following paragraphs discuss some studies related to the potential revenues of frequency regulation.

Tomić & Kempton (2007) evaluate the economic potential of two different fleets of EVs to provide regulation services in four regional regulation services markets in the U.S. They assume that the availability of EVs for V2G services is 23 hours per day. Regulation services include in this case both frequency regulation and voltage regulation, which somewhat affects the results for this specific section. Tomić & Kempton, (2007) find that overall, across all four markets analysed, V2G power for regulation is profitable. The first fleet providing only regulation down services, charging the battery when needed, achieved annual revenues from €53 to 530 per vehicle[1]. The second fleet, that provided both regulation down and up, realised annual revenues of €72 to 782 per vehicle. Hence, the authors concluded that in addition to improving the stability of the grid, regulation services through V2G could provide a significant revenue stream.

Han et al. (2010) propose an aggregator that makes efficient use of the power of EVs to realise V2G frequency regulation services. The main goal of the aggregator is to maximise revenue, which is obtained through a payment from the grid operator by providing power capacity for frequency regulation. Han et al. (2010) find that through, amongst others, their optimal control strategy and based on the data from PJM, a regional transmission organisation in North America, a maximum revenue of €0.31 can be achieved per EV when available for 12 hours. Extrapolating this number to annual maximum revenues, assuming the availability of 12 hours per day, results in €112.5 per EV.

Thingvad et al. (2017) investigate unidirectional and bidirectional frequency control in Denmark. They find that bidirectional V2G frequency control allows EVs to deliver services at higher power which makes it more lucrative. The annual revenues that can be achieved if the service is performed every day for 15 hours are €371.5 per EV.

Finally, Reynolds et al. (2018) note that within the 50 evaluated V2G projects, frequency regulation has been one of the main focus areas due to its high value. The Parker project in Denmark has been able to provide frequency regulation commercially. This project has also shown that vehicles are able to perform frequency regulation in less than 2 seconds, which is faster than conventional frequency regulation. A report related to the Parker project notes that the EVs used in their V2G project obtain potential revenues of €120 per month per vehicle if available for frequency regulation 14 hours per day (Andersen, 2017). The potential annual revenues per EV is then €1440.

The performance of frequency regulation varies per study depending on multiple variables and assumptions. The Parker project, which is the only observational study considered in this section, shows the highest potential revenues per V2G-enabled EV for frequency regulation. However, in contrast to the other studies, the Parker project includes electric vans with batteries with higher energy capacity. The lowest potential revenues for frequency regulation is shown at the lower end of the range of a fleet of EVs studied by Tomić & Kempton, (2007). Since this research included both frequency and voltage regulation, the potential revenues for only

[1] This report uses euro as currency. If an amount is expressed in a different currency in the original source, that amount is converted to euros based on the conversion rate of the publication date of the original source.

frequency regulation could be lower. Due to the dependencies, the final performance is presented as a range between the lowest and highest identified potential revenues: €53 – 1440 per EV per year.

The wide range of potential revenues for the EV owner for providing frequency regulation services makes it difficult to assess the magnitude of the impact of this factor. In addition, if the revenues of this factor end up at the lower end of the range, it is expected to prevent consumers and aggregators from participating in the V2G market. Therefore, the rating for frequency regulation is set at + (driver).

3.2 The current potential of spinning reserve

Studies that focus on the performance of spinning reserve in combination with V2G also use different variables and assumptions. In addition, most of these studies are not very recent which means that the values might have changed over time. The most recent study that is considered in this section indicates a significant loss when assessing the potential revenues for spinning reserve through V2G. The expert interviews, further discussed in chapter five, showed that spinning reserve is only relevant in some parts of the U.S. and developing countries because in other countries this service is not allowed. Consequently, providing spinning reserves through V2G is location dependent and the financial feasibility of the service seems rather uncertain. The following paragraphs describe the findings for spinning reserve in relation to the potential revenues, savings on the operation cost of the power system and the mitigation of the emission of pollutants.

Kempton et al. (2001) conduct research on the annual revenues the owner of a V2G-configured EV can obtain through spinning reserves in the U.S. The EVs, that have a power capacity in the order of 10 kW, are expected to achieve average revenues of €263 per year. In a later study, Kempton (2008) also calculates the potential revenues for V2G-enabled EVs, but over a period of 10 years and with a power capacity varying from 2 kW to 15 kW. The revenues for the battery with the lowest power capacity is estimated at around €784 and the highest at €5488, resulting in an annual net revenue per EV within a range of €78.4 – 548.8 depending on the power capacity of the battery.

Rahmani-andebili (2013) focuses on the compromise between the reliability of the grid and the increased cost caused by the increase of spinning reserve capacity through EVs with V2G technology. Through an agent-based model, Rahmani-andebili (2013) shows that with the presence of an aggregator the spinning reserve market has positive impacts on the reliability of the grid and the total cost of the system. A case study comparison between a modelled power system with spinning reserve through V2G including an aggregator and a modelled power system with a conventional spinning reserve market shows a total cost reduction of 34% for the entire system. In addition, the spinning reserve capacity is 96% higher in the case with V2G.

Chukwu & Mahajan (2017) model the V2G net energy injection into the grid for a parking lot facility. Instead of calculating the potential revenues per vehicle for the vehicle owner, the authors calculate the annual revenues per V2G unit that is used to provide, amongst others, spinning reserve. Hence, this is the potential revenue an aggregator would obtain for providing spinning reserves from a V2G unit. Chukwu & Mahajan (2017) find that a V2G unit would generate a revenue of around -€3000 per year, which could be caused by the limited V2G availability and volatility of the EV owner.

Sioshansi & Denholm (2009) describe the impact of V2G and spinning reserve on the generator emissions. However, this study bases its findings on a PHEV, not EVs. The impact of EVs with V2G is expected to be significantly higher. Sioshansi & Denholm (2009) discuss the generator emissions of a fleet of regular PHEVs and a fleet of V2G-enabled PHEVs who can provide spinning reserve. The penetration level is varied from 1% to 15%, which results in a CO2 reduction from 19.2% - 25.8% compared to a PHEV fleet without V2G services. The SO2 emission is reduced within a range of -0.2% to 8%. The NOx emissions are divided into ozone and non-ozone emissions. Ozone NOx emissions are reduced between a range of 20.2% - 48%, Non-ozone NOx emissions are reduced between a range of 29.7 – 39%.

Sioshansi & Denholm (2009) show that (for PHEVs) spinning reserve through V2G is a clear driver of a V2G transition when considered from an environmental perspective. However, also for this service, the range of potential annual revenues for the EV owners is wide and, thus, uncertain. Chukwu & Mahajan (2017) even calculate a significant loss for aggregators when spinning reserve is provided by V2G-enabled EVs. To consider spinning reserve as a major driver of a V2G transition, the reduction in emissions needs to go hand in hand with a positive business case. The rating of this factor is, therefore, set at + (driver).

3.3 The current potential of active power support

The majority of the literature on active power support through V2G focusses on a combination of peak load shaving and load levelling (or load balancing) and aims to optimise the load profile. Peak load shaving is often seen as the main goal with load levelling as an important component to shift (part of) the load from peak hours. The results are usually presented in relation to the effect on peak demand. The following paragraphs describe the results of some of these studies.

The potential benefits of peak load shaving and load levelling are recognised in the literature, but the scenarios differ. Wang & Wang, (2013) propose a strategy for peak load shaving and load levelling by valley fillings using V2G. In the strategy, they analyse the influence of the number of connected EVs using V2G and the daily target load of a power system. Their simulation shows that with the increase of connected EVs the effectiveness of peak shaving and valley filling through a V2G system is increased as well, which makes V2G an effective and controllable option for peak load shaving. Lee et al. (2017) agree that V2G can achieve a considerable reduction of peak demand power. Their simulation results based on an algorithm for shaving the peak load in a distribution system could cut peak load due to the high SOC EVs usually have. López et al. (2015) note in their research on demand fluctuations in electric power systems that big fleets of EVs with V2G need to be considered to improve flattening of the load curve. Their smart grid model relying on demand-side management strategies to reduce peak demand shows only a small effect on the load curve for the case study when EVs with V2G capabilities are introduced. In a comparative economic analysis of managing loads in power grids, Zhuk et al. (2016) argue that battery storage for peak demand is only economically justified for periods of 1 hour or less per day. Finally, White & Zhang (2011) look at the annual revenues for EV owners when using V2G for peak reduction in New York based on the distance driven per day and a battery lifetime of 1500 cycles or 5300 cycles. Potential annual revenues are identified in a range from -€202 – 221, obtaining a maximum profit with a battery life of 5300 cycles covering a distance between 0 - 16 kilometres per day.

In the review on 50 V2G projects by Reynolds et al., (2018), the added value of V2G is also recognised for markets with high peak pricing. In 7 out of 10 highlighted projects, some sort of peak shaving or load levelling is applied. In one project, the peak was shaved by 12.7% on average. All of the projects have, however, not passed the demonstration phase yet.

The rating for this factor is set at + (driver). Although some studies describe the expected added value of active power support, a wide range of potential annual revenues make the actual current performance of the factor uncertain.

3.4 The current potential of reactive power support

Studies on reactive power support mainly focus on the characteristics of the bidirectional charger and optimised charging schedules for EVs needed for reactive power support. The following paragraphs discuss some of these studies.

In an early analysis, Brooks (2002) argues that V2G-enabled EVs could be programmed in a residential setting to balance voltage fluctuations caused by other household loads or minor voltage fluctuations from the grid. Results from a test vehicle in a test facility show that the vehicle is able to provide reactive power support by moving the voltage 3 volts up or down.

Kisacikoglu et al. (2010a) show that, in contrast to for instance peak load shaving, reactive power support for voltage regulation has no effect on battery degradation, because the dc link capacitor of the bidirectional battery is sufficient to provide full support. In another study, Kisacikoglu et al. (2010b) find that different operation modes of the bidirectional charger, such as reactive power support and battery charging, affect the components of the charger. They argue that the full operational objectives of the battery should either be determined first or otherwise be limited. Buja et al., (2017) explore the required capabilities of a V2G-configured EV to perform reactive power support. They investigate two bidirectional charger topologies and analyse two tasks for each of those topologies, namely reactive power transfer only and a simultaneous transfer of active and reactive power. This analysis allows them to create and prove a theory that calculates the maximum amount of reactive power that a bidirectional charge is able to provide as a function of the SOC of the battery. Wu et al. (2016) quantify the potential added value of reactive power support for a distribution grid of a parking lot. They propose an algorithm to maximise the revenue of the grid. They compare the revenues for two situations; one with only active power and one with active and reactive power. The expected revenues of the situation with active and reactive power are 19% higher for 30 EVs compared to active power only.

Studies on reactive power support clearly show that this service indeed can be seen as a driver of a V2G transition. However, since the performance of this factor is mainly based on descriptions, it cannot be determined if the impact of this factor is significant enough for it to be rated as a major driver. Therefore, the rating for this factor is set at + (driver).

3.5 The current potential of current harmonic suppression

Research on the effects of harmonics due to a large penetration of EVs indicates that charging of EVs can account for 20 – 45% of total current harmonic distortion in smart grids (Shaukat et al., 2018). While the integration of V2G is associated with a significant increase in EVs, bidirectional chargers can provide a solution for the potential current harmonic distortion. Only two studies were found that specifically address the relationship between suppressing current harmonics and V2G. These studies are discussed in the next paragraphs.

Ma et al. (2016) look, amongst others, at bidirectional chargers to solve harmonics distortion. For three different EV charger topologies, they demonstrate if the expected current harmonics are either high or low. To deal with current harmonics, Ma et al. (2016) propose a control method that is able to reduce harmonic distortion. Although they find modern types of nonlinear and intelligent controls not yet mature, they expect that with further development the prospects are good.

Li et al. (2014) focus on the harmonics of EV charging stations with a V2G application and propose a simulation model that considers the structure of bidirectional chargers and the control strategy. They find that when in the constant voltage charging phase, the total harmonic distortion rises significantly. However, when the number of bidirectional chargers increases, the total harmonic distortion stabilises. A higher charging power results in a decrease of the total harmonic distortion.

The two studies that were considered for the potential performance of current harmonic suppression show that this factor is expected to be a driver of V2G, but that further development is required. Moreover, since the performance of this factor is mainly based on descriptions, it cannot be determined if the impact of this factor is significant enough for it to be rated as a major driver. Therefore, the rating for this factor is set at + (driver).

3.6 The current potential of balancing and supporting renewable energy

Introducing large fleets of EVs to the transport system can have a significant influence on the reduction of the emission of pollutants. Kintner-Meyer et al. (2007), for instance, calculate that by replacing conventional vehicles for PHEVs, CO2 emissions would be reduced with an average of 42% per mile (~1.6 km) driven. Another study finds that in the U.K. EVs could reduce CO2 emissions by 62 – 65% compared to conventional vehicles by 2030 (Sovacool et al., 2017). Furthermore, the potential commercial value of renewable energy is very high. According to Reynolds et al. (2018), in Germany alone, 5.5TWh of renewable energy was curtailed in 2017, at a total cost of €1.4 billion. This is enough to charge around 2 million EVs for 1 year. A V2G transition can increase environmental benefits and profit from the potential commercial value by providing balance and support for renewable energy through storage. The following paragraphs discuss some studies that focus on the potential balance and support V2G can provide to the integration of renewable energy.

Kempton & Tomić (2005b) discuss the implementation of V2G to support large-scale renewable energy in the U.S. They find that stabilisation of large-scale wind power accounting for half of U.S. electricity could be achieved through V2G-enabled EVs with 3% of the fleet providing regulation for wind and 8 – 38% of the fleet taking care of operating reserves or storage for wind. Kempton & Tomić (2005b) also look at the potential of providing peak energy in the U.S. through V2G-enabled EVs and PV solar electricity. They estimate that 26% of the fleet in the U.S. would be needed to supply this service.

Lund & Kempton (2008) model the integration of renewable energy into the transport and electricity systems of Denmark through V2G. They conclude that adding EVs and V2G to the national energy system improves the efficiency of the electric power system which results into the ability to support the integration of much higher levels of wind electricity, lower excess electricity production, and significantly reduce national CO2 emissions. A wind scenario of 50%, for instance, in combination with V2G lowers the excess electricity production by half.

Turton & Moura (2008) use an energy-systems model to make a global analysis of the potential of a V2G system over the long term. With this model, the authors predict the integration and impacts of V2G-enabled EVs over a period from 2000 to 2100. The scenario including V2G systems shows an increase in renewable energy generation by 30 – 75% compared to a scenario without V2G availability.

Saber & Venayagamoorthy (2011) discuss the cost and emission reductions when using V2G-enabled EVs and renewable energy sources. They perform a simulation study of 50,000 EVs being charged through renewable energy sources and discharged to support grid services. The results show that a reduction in emissions from the electricity industry and savings of at least €2.53 per vehicle per day (or €923 per vehicle per year) for electricity and transport industries can be obtained.

Studies into the current potential of balancing and supporting renewable energy through V2G show that a significant amount of renewable energy could be integrated into the energy system combined with significant savings per vehicle for electricity and transport industries. Therefore, the rating of this factor is set at ++ (major driver).

3.7 The current potential system revenues

The reviewed performances of the V2G factors in the sections above show varying potential revenues mainly for EV owners (annual revenues per vehicle). The more general studies into the system revenues of V2G show a similar result, ranging from significant system revenues to minor revenues or even expected losses. The following paragraphs discuss some of these studies.

Richardson (2013) states that an increasing number of studies have evaluated the economic viability of V2G participation in different markets. The studies identified by Richardson (2013) find annual revenues for EV owners in a range from -€231 - 3539 per vehicle, with most indicating revenues in the range of €77 – 231, which according to the author may not be enough to encourage participation from EV owners and potential aggregators that also need to be compensated. Noori et al. (2016) perform an integrated modelling assessment of V2G across different system operators in the U.S. They project that average revenues for EV owners could range from €16150 – 37682 per vehicle over a 16-year lifetime depending on assumptions, which results in average annual revenues ranging from €1009 – 2355 per vehicle.

Salpakari et al. (2017) estimate annual energy cost savings in a range of 8 – 20% per household in Denmark. Surender Reddy et al. (2016) find a 7% reduction in annual travel expenditures through V2G. Gough et al. (2017) conclude that around €3000 system cost could be saved, including infrastructure cost by a pool of 30 V2G-enabled EVs at a science park in the U.K. A study by Haddadian et al. (2015) on the integration of V2G in combination with the day-ahead scheduling for the power system projects that operational costs for the electric utility could be reduced by 3% of the revenues.

Other studies conclude that EVs should not be used for grid services through V2G because there is no positive business case. Kiaee et al. (2015) evaluate a simulation of 5000 V2G-configured PHEVs at parking lots. They find that for 52% of the vehicles it would cost more to charge than they generate in revenues for the owners. Based on electricity market data from Germany, Brandt et al. (2017) argue that selling energy to EV owners leads to significantly higher revenues than using those vehicles for ancillary services. Finally, Wang et al. (2016) conclude that integrating V2G does not result in major cost savings. They calculate savings of around €1 per day.

Comparable to the performance of frequency regulation, spinning reserve, and active power support, the potential system revenues are highly uncertain due to wide-ranging values. These wide ranges make it difficult to estimate the true value of V2G and to convince consumers and aggregators to participate in a V2G system. Due to this uncertainty, the rating for this factor is set at + (driver).

3.8 The current potential battery degradation

Accelerated battery degradation is the most frequently mentioned barrier to a V2G transition. However, according to Yilmaz & Krein (2013), the cost of battery degradation is difficult to estimate because batteries are still developing. Sovacool et al. (2018) note that many studies around V2G and battery degradation argue that costs related to battery degradation are a serious barrier, while some find that degradation is mild. The following paragraphs discuss a sample of these studies with different expectations on battery degradation through V2G.

Bishop et al. (2013) evaluate the impact of V2G services on the degradation of batteries. They find that energy throughput has the most effect on battery degradation and that battery degradation is most sensitive to the DOD when providing ancillary services. Supplying bulk energy and services through V2G increase degradation of the battery and result in a more frequent replacement. Although the authors suggest some measures to minimise the energy throughput, they state that it is still expected that V2G-enabled EVs have to use multiple battery packs over their service lives. Van der Kam & Van Sark (2015) perform a simulation that shows that V2G has a significantly higher throughput, thus shorter battery lifetime, compared to other options without V2G. Hu et al. (2017) show that their optimisation for a unified cost-optimal approach for PHEV does not allow for V2G activities, because the battery degradation cost caused by V2G outweighs additional revenue that can be captured through V2G.

Peterson et al. (2010) also find that the energy throughput is the most important indicator for battery degradation. They do, however, argue that the relation between V2G and services and battery degradation is not severe. Shinzaki et al. (2015) built a V2G-capable vehicle and let it participate in the regulation market in the U.S. They conclude that the additional degradation caused by V2G is only around 2%, which is negligibly small compared to the 8% degradation from driving the vehicle. Wang et al. (2016) argue that battery degradation through V2G is minimal as well. The authors state that the extra degradation from V2G is not important when compared to naturally occurring battery degradation caused by, for instance, driving and calendar ageing. For example, the average capacity losses in each frequency regulation event are, according to Wang et al. (2016), to be expected in a range of 0.0010 – 0.0023%, which equals to a battery degradation cost of €0.18 – 0.41 per charge.

Reynolds et al. (2018) argue, based on the review of 50 V2G projects, that contemplating the marginal battery degradation cost of V2G is important. However, the impact of battery degradation cost seems to be much smaller than the effect of differences in driving behaviour on battery life and cost, particularly regenerative breaking. The potential damage caused by V2G depends on the V2G service, with full charge/discharge cycles being the most harmful.

Studies on battery degradation through V2G show two perspectives. One perspective considers battery degradation as a major barrier to a V2G transition. The other perspective claims the effects of V2G on battery degradation are negligible. The rating of this factor is set at – (barrier), because general literature on V2G considers battery degradation as a barrier but the differences in specific studies on battery degradation and V2G make it unclear what the actual magnitude of this barrier is.

3.9 The current potential investment cost

In addition to costs associated with the accelerated battery degradation, other high investments costs, such as investments required for a communications network and bidirectional chargers, form a barrier to a V2G transition. No studies were found that specifically focus on estimations for the total investment cost. This might be due to the developing nature of V2G and the difference in investments needed per energy system. The literature on V2G does sometimes refer to costs required for some parts of a V2G system. The following paragraphs describe some of the costs.

Brandt et al. (2017) evaluate a business model for V2G integration in Germany. They describe the cost structure of V2G which includes substantial initial investments into hardware and software infrastructure and operational expenses. One of the major operating costs they find is to provide incentives to EV owners to participate in a V2G programme. Sovacool et al. (2017) argue that the first-cost hurdle that has to be taken by EV owners is difficult because consumers are not interested enough in cost savings to value the potential revenues generated through V2G. In addition, the authors refer to studies that show that consumers do not consider future fuel savings when discussing vehicle expenses. Parsons et al. (2014) come to the same conclusion by finding that respondents in the U.S. discount cash back from V2G contracts heavily, using a 53.5% discount rate.

Reynolds et al. (2018) find that many V2G projects indicate that few bidirectional chargers are commercially available, and the total cost is high, more than 5 times the price of unidirectional chargers. They also note a potential scope for cost reduction through mass production. Also, high costs for settlement meters are identified. These meters prove that a V2G service is provided by the vehicle. However, different meters are usually needed for different services and these meters are designed to be used on a much larger scale. The costs for the V2G providers in the projects are, therefore, proportionally high. Finally, Reynolds et al. (2018) mention that the total cost to upgrade the network in Germany to manage renewables is €18 billion.

Although not many actual numbers are mentioned for the potential investment cost for V2G, the investments are considered to be substantial, such as for instance for the bidirectional chargers. In addition, the lack of interest in cost savings through V2G of consumers make the barrier even harder to overcome. Therefore, the rating for this factor is set at -- (major barrier).

3.10 The current potential impact on the distribution network

Most of the V2G factors discussed in this chapter have an impact on or are related to the distribution network, which is managed by the network operator. Managing and controlling charging policies through the development of intelligent charging schemes are required to restrain potential negative impacts. The following paragraphs present findings related to possible impacts on the distribution grid if intelligent charging schemes are not developed and the general impact of V2G on the distribution grid.

Three charging rates for EVs are available in the industry; level one, level two and level three. The levels range from a low power level (one) to a high power level (three), with level three being a fast commercial charger. Yilmaz & Krein (2013) argue that large penetration of EVs with level two and three battery chargers can result in a quick overload of local distribution equipment. Lassila et al. (2012) find that additional investments in larger cross-sections of underground cables and overhead lines, and more transformer capacity are required to deal with the overload. In another study Clement-Nyns et al. (2010) show that in a local distribution grid a 30% penetration level of EVs results in increased power demand in the grid that is out of range for the transformers and conductors which, consequently, need to be replaced. Moghe et al. (2011) look at the transformer degradation caused by EV charging. They conclude that with uncontrolled charging, transformer life is reduced by 200 – 300% at a 50% penetration level. With controlled charging at the same penetration level, however, transformer life improves 100 – 200% with respect to uncontrolled charging. Regarding potential energy loss, Pieltain Fernández et al. (2011) find that depending on the charging strategies a scenario with 60% EV penetration can lead to an increase in energy loss up to 40% in off-peak hours. They also note that investment cost in the distribution network can increase up to 15%. In addition to the potential impacts on the distribution grid, some studies focus on managing and controlling intelligent charging schemes to mitigate the impacts. Clement-Nyns et al. (2011) show through a simulation that coordinated charging and discharging of PHEVs in a distribution grid can reduce power losses and efficiently match generation and consumption. Ma et al. (2012) create a decision-making strategy for EVs and V2G that results in minimal power losses and voltage fluctuations in the distribution grid. In a reliability evaluation of distribution systems, Xu & Chung (2016) find that V2G can show great promise for reliability enhancement.

Reliability with respect to the distribution grid was also an important factor mentioned by Reynolds et al. (2018). They note that distribution system operators are accustomed to the grid infrastructure having a high level of reliability, more than 99.9%. They, therefore, argue that the availability and performance of the EVs need to be carefully considered within service and contract specifications if EVs are to play a significant role in deferring grid reinforcement or expansion cost.

Under current conditions, V2G is already able to improve the impact on the distribution grid V2G through coordinated charging and discharging, Since the reliability of the distribution grid is considered an important factor, the potential impact on the distribution grid is still perceived as a potential barrier. However, with the current possibilities of V2G, this is not expected to be a major barrier. Therefore, the rating is of this factor is set at – (barrier).

3.11 The current potential range anxiety

Range anxiety in relation to V2G has not received much attention in the scientific literature. As mentioned in section 3.9, Parsons et al. (2014) find that new vehicle buyers are very reluctant about buying V2G-enabled EVs. Sovacool et al., (2017) identify some range anxiety related barriers to V2G based on consumer-based research. The following paragraphs discuss the results of these studies.

In a survey on the comparison of V2G scenarios, Bailey & Axsen (2015) indicate that respondents wanted to pay €168 more per year to increase the 64km range of their PHEV. 33% of the respondents were even willing to pay more than €200. A discrete choice simulation model by Axsen et al. (2015) shows that if the guaranteed driving range of an EV would decrease 20% because of V2G, consumer enrolment in a V2G programme would be 7 - 12% lower. Out of 21 households that were interviewed, 10 households expressed discomfort with V2G because they preferred to keep their EVs to be fully charged at all times.

Another potential concern, according to Bailey & Axsen (2015), is distrust of the consumer in the aggregator or electric utility in a V2G programme. 39% believed that a V2G programme would take some sort of control away from the respondents that they would not like. Axsen et al. (2017) report concerns related to, for instance, computer glitches which could result in the vehicle not being charged. In interviews with new vehicle buyers, Axsen et al. (2017) also find that "mainstream" buyers had difficulties with understanding the advantages of the V2G concept, such as improving grid efficiency and reducing the environmental impact of fossil fuels.

Reynolds et al. (2018) find that social issues are often overlooked in V2G projects. Only 27% of the 50 reviewed V2G projects focused on social aspects. Some V2G projects across Europe scaled back on their ambitions on the number of chargers with one of the reasons being the lack of willingness of consumers to participate. Reynolds et al. (2018) note that the lack of social considerations is a problem because the potential of V2G depends on user acceptance. Therefore, they believe that social considerations should be addressed in future projects and within the context of broader changes in mobility.

Without user acceptance, a V2G transition will not take place. Consumer-based research has shown some clear signs that V2G currently worsens range anxiety, which has a negative impact on the participation level in V2G programmes and, thus, a V2G transition. Therefore, the rating for this factor is set at -- (major barrier).

3.12 Evaluating the aggregated current performance of vehicle-to-grid

The performances of the V2G factors indicate that V2G is indeed expected to increase the share of renewable energy in the grid but a V2G transition is not yet feasible. In addition to the barriers to a V2G transition, inconsistencies within research on some of the V2G factors that should reflect as drivers of a V2G transition lead to highly uncertain results. The potential revenues that can be obtained through frequency regulation, spinning reserve, active power support, and the overall V2G system vary widely, and according to some studies even result in a loss which then arguably makes them barriers. Furthermore, complex issues arise between the actors in a V2G system because the uncertainties about the potential revenues mainly affect the EV owners and aggregators who receive the potential revenues through payments from the network operator as incentives for making their EVs available to the grid or managing a large group of EVs for V2G services. If V2G services would be performed, network operators would benefit because it enables them to balance and stabilise the grid and realise a larger share of renewable energy. All together this also benefits society because electricity is a utility and it leads to a cleaner environment. The EV owners, however, might end up not being fairly compensated for the impact these services have on their vehicle, which in combination with the expected range anxiety would limit the willingness to participate in a V2G system. Moreover, while aggregators are seen as an important component to coordinate and manage V2G activities between EV owners and the grid, they are not explicitly included in the potential revenues for frequency regulation, active power support, and the overall system. If the potential revenues of the EV owners have to be shared with the aggregators, both EV owners and aggregators might not be encouraged to participate in a V2G system. For spinning reserve, the potential revenues for aggregators calculated by one study show a significant loss per V2G unit. Under current conditions, aggregators are therefore not expected to be willing to coordinate such a service.

One of the reasons EV owners are compensated when making their vehicle available to the grid for V2G services is the expected accelerated battery degradation. While it seems important to establish the actual impact of V2G on the battery to determine the costs for the EV owner and, consequently, the willingness to participate in a V2G system, inconsistencies also exist within research on this V2G factor. Although some researchers consider battery degradation a significant barrier to V2G, other researchers believe it to be unrelated to V2G. Comparing all the varying outcomes becomes more difficult due to the differences in variables, assumptions, methods and strategies encountered in studies on this factor (and others). Different opinions on battery degradation were also found amongst the V2G experts that were asked for validation of the ratings assigned to the V2G factors. These opinions ranged from identifying this factor as a major barrier to believing that the impact of V2G on battery degradation is neutral. Since the opinions varied both for the experts and in the literature, the rating for this factor was kept at – conforming to the previously discussed approach for rating the V2G factors.

In contrast to battery degradation, studies on V2G agree on the required investment cost being a major barrier to a V2G transition. The literature is not clear on what the actuals costs are and who they should be allocated to. For instance, governments could be responsible for investments needed to install bidirectional chargers, but the bidirectional technology could also be installed on-board of the EV, which probably increases production costs and, thus, costs for EV owner. Moreover, significant investments in an upgrade of the grid made by the network operator might increase electricity bills of consumers if the business case of V2G does not allow to recover these investments.

Finally, studies on the impact on the distribution network suggest that the network operator and aggregator (or EV owners) could improve the impact on the distribution network through coordinated charging and discharging but it remains a barrier. One expert did not agree with the rating for this V2G factor. The expert believed that this factor is caused by EVs and solved by integrating V2G technology. Although V2G does have a positive effect on this barrier compared to EVs without V2G, most of the other experts believed that negative impacts could still occur on local distribution grids. This rating was, therefore, held at –.

The appropriate conclusion for the current performance of V2G is that research on the technology has to develop further to improve or mitigate the barriers and fulfil the potential promise of the drivers, which also demonstrates the relevance of this research. The evaluation of the current performance of the V2G factors shows that the drivers and barriers affect the actors in a V2G system differently, which proves that drivers and barriers cannot just be considered as such for the complete system but needs to be analysed from different perspectives to determine their overall effects on the performance of V2G.

Table 7 provides a summary of the aggregated current performance of V2G. The V2G factors are highlighted in **dark red** if they are rated a major barrier, in **red** if they are rated a barrier, in **green** if they are rated a driver, and in **dark green** if they are rated a major driver. An important note to this table is that all the items under "potential current performance" are potential performances for a specific factor that were identified independently. Consequently, a summation of the potential performances identified for one factor does not automatically reflect the complete performance of that factor.

Table 7: Aggregated current performance of the V2G factors

V2G factor	Potential current performance
Frequency regulation + driver	• Annual revenues for EV owners: €53 – 1440 per EV
Spinning reserve + driver	• Annual revenues for EV owners: €78 – 549 per EV • Annual revenues for aggregators: -€3000 per V2G unit • System cost reduction for system operators: 34% when in combination with an aggregator • Emission reduction PHEVs with V2G compared to PHEVs without V2G, penetration level from 1 – 15%:

	○ CO_2: 19.2 – 25.8% ○ SO_2: -0.2 – 8% ○ NOx (ozone): 20.2 – 48% ○ NOx (non-ozone): 29.7 – 39%
Active power support + driver	• Annual revenues for EV owners: -€202 – 221 per EV • Peak shaving is only economically justified for periods of 1 hour or less
Reactive power support + driver	• No effect on battery degradation • Different modes of uncontrolled operation affect components of the bidirectional charger • Revenues of simultaneous transfer of active and reactive power 19% higher than reactive power only
Current harmonic suppression + driver	• The increase of bidirectional chargers and charging power positively influence current harmonic distortion
Balance and support renewable energy ++ major driver	• Renewable energy generation 30 – 75% higher with V2G availability compared to no V2G availability • Potential to stabilise large-scale wind power accounting for half U.S. electricity • Potential to provide peak energy in the U.S. through PV solar electricity • Annual savings for electricity and transport industries by charging and discharging EVs with renewable energy sources: at least €923 per EV
System revenues + driver	• Annual revenues for EV owners: -€231 – 3539 per EV • Annual system cost savings for network operators: up to €100 per EV • Annual operational cost savings for electric utility: 3% of the revenues
Battery degradation - barrier	• Varying results from a serious barrier to negligible impact: • Barrier: ○ Higher energy throughput with V2G leading to multiple battery packs needed over vehicle life ○ Battery degradation cost outweigh additional revenues of V2G • Negligible impact ○ V2G only accounts for 2% of degradation, driving the vehicle 8% ○ In the case of frequency regulation degradation minimal: ○ Average capacity loss per frequency regulation event: 0.0010 – 0.0023% ○ Cost battery degradation per charge: €0.18 – 0.41
Investment cost -- major barrier	• Substantial investments in hardware and software infrastructure and operational expenses: ○ Bidirectional chargers ○ Settlement meters ○ Grid upgrade to manage renewable energy, for instance: €18 billion in Germany ○ Provide incentives to EV owners to participate in V2G programmes
Impact on the distribution network - barrier	• In case of distribution equipment overload additional investments in larger cross-sections of underground cables and overhead lines, and more transformer capacity are needed • At a 50% EV penetration level, uncontrolled charging reduces transformer life by 200 – 300%, controlled charging improves transformer life 100 – 200% with respect to uncontrolled charging • At a 60% EV penetration level can increase power losses up to 40% in off-peak hours and can increase investment cost in the distribution network up to 15% depending on the charging strategies • Coordinated charging and discharging with V2G can result in a reduction of power losses, efficiently match generation and consumption, and improve the reliability of the distribution grid
Range anxiety -- major barrier	• Concerns of EV owners about sharing the battery with the grid • Control over the charging process taken away from EV owner

4. Autonomous vehicles

The current performance of V2G needs to be improved to realise a V2G transition. To assess the potential effects of AVs on the current performance of V2G, the potential interactions between AVs and V2G have to be identified. This chapter first explains the operation of AVs in more detail to provide a better understanding of the concept. Afterwards, variables of the development of AVs that are relevant to the interaction between AVs and V2G are discussed. Finally, hypotheses for the effects of AVs on the V2G factors are formulated.

4.1 The concept of autonomous vehicles

AVs offer the possibility of drastically changing the transport system by, for instance, preventing deadly crashes, allowing more groups of people to travel, increasing road capacity, saving fuel and lowering emissions (Fagnant & Kockelman, 2015). In addition, shared rides and vehicles may result in a shift from private vehicle ownership to an on-demand service. The automation of vehicles can be conceptualised in five levels, ranging from level one where the human driver is in complete control of all functions of the car to level five where the car can drive itself without a human driver (Anderson et al., 2016). For vehicles to operate autonomously navigation technology is needed. This navigation technology can be visualised as five main components: perception, localisation and mapping, path planning, decision making, and vehicle control (Van Brummelen et al., 2018). An overview of the autonomous navigation process is shown in Figure 5. To create perception, sensors are used to continuously scan and monitor the environment (Maurer et al., 2016). Localisation and mapping include algorithms that calculate the global and local location of the vehicle and outline the environment from outputs from the perception component (Maurer et al., 2016). In path planning, the possible safe routes are determined based on the components perception and localisation and maps (Katrakazas et al., 2015). The decision-making component calculates the best route based on the routes possible, the state of the vehicle, and information on the environment, such as weather conditions (Maurer et al., 2016). Finally, the vehicle control component is responsible for calculating the appropriate vehicle command, such as torque and acceleration, to follow the best route decision from the previous component, such as lane changes and right or left turns (Gruyer et al., 2016). To effectively deal with high-speed motion and dynamic objects, for example, pedestrians and other vehicles, the autonomous navigation process is a high-frequency recursive process (Van Brummelen et al., 2018).

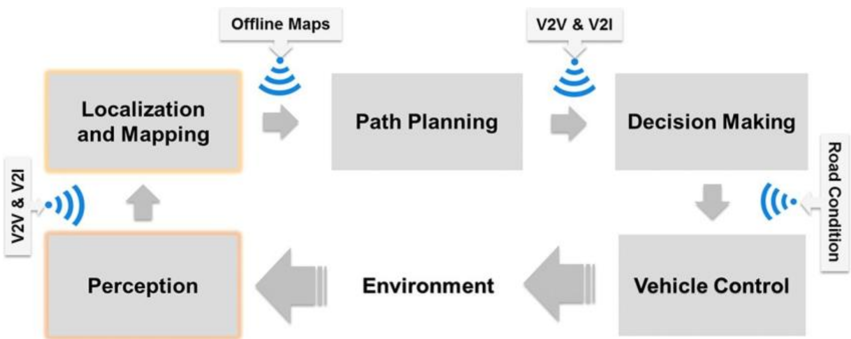

Figure 5: Overview of the autonomous navigation process (Van Brummelen et al., 2018)

4.2 The development of autonomous vehicles

The ongoing development of AVs has received a lot of attention in various industries. Currently, there are multiple fully AV projects in different stages of development, including extended on-road testing of multi-vehicle fleets (Koopman & Wagner, 2016). The literature on the development of AVs provides a wide range of potential development paths, often into much more detail than relevant to this research. To give some direction to the assessment of the potential effects of AVs on the performance of V2G, four high-level variables that are relevant to the interaction between AVs and V2G were chosen from the literature and used as input for the interviews with the V2G experts. These variables were derived from four scenarios discussed by Milakis et al. (2017) in a report on the projected development of automated vehicles in the Netherlands for 2030 and 2050. The identified variables are as follows:

- **Level of automation.** The main objective of this research revolves around autonomous (fully automated) vehicles. However, Milakis et al. (2017) argue that the rise of automated vehicles could first be a combination of autonomous and conditionally automated vehicles, although AVs are expected to be the game changer towards an increased demand for automated vehicles. In conditional automation, the driver is expected to be available for occasional control of the vehicle. The level of automation is included as a variable to evaluate if the expected effects on V2G only apply for AVs or also for lower levels of automation.
- **Level of penetration of AVs.** According to Milakis et al. (2017), the penetration rates of AVs are expected to vary among different scenarios. Those different penetration rates could also have an effect on the performance of V2G.
- **Private ownership versus fleet ownership.** The development of AVs could push the demand for autonomous taxi services or other on-demand services instead of private ownership which changes the actors of a V2G system and their potential to deliver services to the grid.
- **Shared versus not shared.** The development of AVs could push the demand for sharing services which has an impact on the availability of AVs for V2G.

4.3 Hypothesising the effects of autonomous vehicles on the vehicle-to-grid factors

Before evaluating the potential effects of AVs on the performance of V2G, hypotheses were formulated for the effects of AVs on the performance of the V2G factors. These hypotheses were based on a comparison between the current performances identified for each V2G factor in chapter three and the general idea that AVs provide more flexibility to send vehicles to any required location at any time in combination with the relevant variables of the development of AVs identified in the previous section. The hypotheses are listed below:

- AVs are not expected to have significant effects on <u>frequency regulation</u>, because of the short response time. Although AVs can be sent to any required location, they have to be constantly connected to the grid to provide this service. The performance of this factor is, therefore, expected to remain equal.
- AVs are expected to improve the performance of <u>spinning reserve</u> because the longer response time that is allowed for this service enables the opportunity to send AVs to the required location in the grid to provide this service.
- AVs are also expected to improve the performance of <u>active power support</u> based on the longer response time that is allowed for this service.
- AVs are not expected to have any effects on <u>reactive power support</u>, because the added value of V2G is related to the bidirectional charger.
- AVs are not expected to have any effects on <u>current harmonic suppression</u>, because the added value of V2G is related to the bidirectional charger.

- AVs are expected to improve the ability to balance and support renewable energy, because charging and discharging are performed more effectively through automation of the process.
- AVs are expected to improve the system revenues, because the improvement of grid services, such as frequency regulation and spinning reserve, result in more revenues.
- AVs are expected to have a negative effect on battery degradation because the battery throughput increases due to the more effective use of the vehicles.
- AVs are expected to have a positive effect on the investment cost because charging and discharging of the vehicles can be done more effectively in central locations which improves the return on investment per charger and might decrease the investments needed for the charging infrastructure.
- AVs are expected to solve the negative impact on the distribution network because AVs can be automatically sent to any location in the grid where issues related to the distribution network need to be handled.
- AVs are expected to solve range anxiety caused by V2G if cars are not privately owned anymore but owned in fleets. The fleet owner will be able to manage the process of charging and discharging the vehicles effectively and consumers rely on the fleet owner to get a vehicle that is sufficiently charged.

5. The expected effects of autonomous vehicles on the performance of vehicle-to-grid

In this chapter, the expected effects of AVs on the V2G factors and the overall performance of V2G are identified based on expert interviews. Section 5.1 presents the structure of the expert interviews. Section 5.2 reports the results of the expert interviews. Finally, the expected effects are evaluated in section 5.3.

5.1 Interview structure

Seven V2G experts were interviewed to determine the effects of AVs on the performance of V2G. The V2G experts were invited for a one-hour interview and were sent a template of the interview structure including the topics to be discussed, an explanation of all the V2G factors, their potential current performance and rating (Appendix C). Each interview started with a short introduction to the objective of the research, the objective of the interview and the structure of the interview. The experts were then asked to express their general opinion on the potential effects of AVs on the performance of V2G. Afterwards, the V2G factors were explained in combination with the five-point rating scale and the current rating for each factor. In addition, the variables related to the development of AVs and interaction with V2G were discussed. Then the experts were asked to assess per factor what the effect of AVs could be, what this would do to the rating and why. Sometimes experts were not sure what rating to assign to a factor, because different developments of AVs could have different effects on the factors. In such a case, the experts were asked to assign the rating based on the developments that according to them served the performance of V2G best. Potential other effects were added to the comments section. After assigning the ratings, the last question of the interview revolved around how in the opinion of the experts the development of AVs should be shaped to create the best possible conditions for a V2G transition.

After the results of the interviews with the seven experts had been processed, an interview was scheduled to validate the results. One V2G expert was invited for a 45-minute interview. The interview started with an introduction to the objective of the research, the objective of the interview and an explanation of the obtained results. The expert was then asked to validate the outcomes per V2G factor and the overall conclusion.

Table 8 presents an overview of the interviewed experts and the number that is referred to when a specific expert interview is discussed in this chapter. The interviews with I-2, I-3, I-4, and I-7 were performed face-to-face. Interviews with I-1, I-5, I-6, and I-8 were done by phone upon request from the expert or due to the long distance between the interviewer and expert. Each interview was summarised (Appendix D). The summaries were sent to the experts for confirmation unless the expert indicated that this was not necessary.

Table 8: Interviewed V2G experts with reference numbers

Nr.	Expert	Affiliation
I-1	Zweistra, M.	Alliander N.V.
I-2	Van Kerkhof, M.	APPM Management Consultants
I-3	Park Lee, E.H.	Delft University of Technology
I-4	Van Arem, Prof. dr. B.	Delft University of Technology
I-5	Van Wijk, Prof. dr. A.J.M.	Delft University of Technology
I-6	Van Eijsden, B.	ElaadNL
I-7	Moorman, S.	EVConsult
Validation Interview		
I-8	Chandra Mouli, G.R.	Delft University of Technology

5.2 Results

The interviews with the V2G experts showed that a combination of AVs and V2G could lead to synergies, especially when AVs are owned in fleets and shared. The experts mentioned the flexibility of AVs as the most interesting feature that could improve the performance of the V2G factors. This flexibility allows AVs to be autonomously sent to locations with, for instance, congestion in the grid and to connect to and disconnect from the grid without any human support. Especially grid services that allow for a response time were indicated as services where AVs could add value in combination with V2G. Opposite to the potential synergies, the respondents recognised the potential threat an on-demand business model for AVs could become to a V2G transition. If AVs would be owned in fleets, are shared and become part of an on-demand mobility service, mobility service providers would be expected to increase the utilisation rate of the vehicles as much as possible to maximise revenues and give no priority to V2G.

When considering the effects of AVs, all respondents assumed that AVs eventually would be fully automated and that compared to other levels of automation only AVs would be able to have an impact on V2G. Therefore, only AVs were considered during the interviews. Differences in the level of penetration of AVs were barely used to describe the effects of AVs on V2G. The level of penetration of AVs was assumed to increase gradually resulting first in a mix of AVs and regular vehicles that over time would transition to a transport system consisting of only AVs. The effects of AVs on V2G were believed to be best for a high level of penetration of AVs. Differences in the potential effects were often linked to sharing and two different types of ownership; private ownership and fleet ownership. Privately-owned vehicles were usually considered not to be shared. Unshared privately-owned AVs were believed to potentially achieve some synergies with V2G due to the flexibility of AVs and because the utilisation rate of the vehicles would be lower than when owned in fleets and shared, which in theory would make them more available for grid services. However, the availability of the vehicles for V2G would still be dependent on the individual preference of AV owners and range anxiety would remain an issue. Therefore, the overall performance of V2G was perceived not to be different from the performance of V2G with EVs. The overall potential synergies between AVs and V2G were therefore mainly considered from the perspective of fleet ownership and sharing. Fleet ownership and sharing were often considered in one scenario and seen as part of a mobility service that based on subscriptions made it easier to coordinate the vehicles for grid services through V2G, manage software for the required updates, define who is responsible for the vehicles and insure the vehicles. The AVs could then be charged and discharged in a central charging hub that would be managed by a fleet owner or an aggregator. This would improve the business case for fleet owners and make the fleet owner an energy provider. Since this scenario was perceived to be the best option to achieve synergies between AVs and V2G, the respondents based their assessments of the ratings of the effects of AVs on the V2G factors on a transport system where AVs were owned in fleets and shared.

Table 9 shows the expected effects of AVs on the rating of the performance of each of the V2G factors based on expert interviews. The expected ratings of the V2G experts are compared with the identified ratings of the current performance of the V2G factors. The ratings are highlighted in green if the rating is expected to improve, in yellow if the rating is expected to remain the same, and in red if the rating is expected to become worse. If a respondent was not familiar with a specific factor or indicated that he/she did not have expertise in a factor, the rating is classified as N/A. In the last column, the aggregated rating for each factor is shown. If more than 70% of the responders (at least five out of seven) agreed on the expected rating and deviating scores differed no more than 1 point on the scale, the rating of the majority was accepted as the aggregated rating. If the final score could not be aggregated based on the beforementioned conditions, the aggregated score was argued for. These aggregated ratings are marked with an asterisk. The following sections discuss the motivation of the experts for the assigned ratings in further detail and explain the choices made for aggregated ratings with an asterisk.

Table 9: The expected effects of AVs on the performance of the V2G factors

Factor	**Current**	**I-1**	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**I-7**	**AV**
Frequency regulation	+	+	+	+	++	+	+	+	+
Spinning reserve	+	++	++	+	++	++	+	+	++ *
Active power support	+	+	++	+	+	++	+	+	+
Reactive power support	+	N/A	+	N/A	+	+	+	+	+
Current harmonic suppression	+	+	+	N/A	+	+	+	+	+
Balance and support RE	++	++	++	++	++	++	++	+	++
System revenues	+	++	+	++	+	+	+	0	+ *
Battery degradation	-	--	--	--	-	-	0	-	- *
Investment cost	--	-	--	--	-	-	0	0	- *
Impact on the distribution network	-	0	+	0	-	-	0	0	0 *
Range anxiety	--	0	0	--	-	-	0	0	0 *

5.2.1 Effect on frequency regulation

Aggregated effect of AVs on frequency regulation through V2G: +

Most of the respondents remarked that the effects of AVs on frequency regulation depend on the different type of ownership of AVs in combination with the fact that the vehicle has to be connected to the grid to perform this service, while two respondents looked at the size of the frequency regulation market. Overall, the experts do not expect a significant difference between the effect of AVs on frequency regulation through V2G compared to EVs.

I-1 commented that the performance of this service would somewhat improve, but not enough to give a higher rating. I-5 stated that the performance would be equal to the current situation because it would take too much time to send and connect AVs to the required location in the grid. I-2 also believed that this would be the case for private ownership but stated that if the business case for frequency regulation could be made more interesting, fleets of AVs would be able to provide this service. If fleet owners then could be persuaded to provide frequency regulation, the performance of the service would improve to ++. I-4 argued that because AVs can connect to the grid without human support and can drive to the required charging/discharging locations, their potential to provide frequency regulation improves to ++.

I-3 believed that not fleet ownership but private ownership of AVs would be a better scenario for frequency regulation through V2G because the vehicle would then be available for grid services more often. In the case of fleet ownership, it would become more difficult to coordinate vehicles for all V2G services, because the fleet owners would have to consider driving needs of many consumers, especially if these consumers would be allowed to book a vehicle on-demand (with short response time). In addition, the expected margins for grid services are not high enough for fleet owners to purchase extra vehicles solely for the purpose of providing grid services and recover the investments. I-7 also believed that in the case of fleet ownership, AVs would not be available for frequency regulation due to the utilisation rate for driving purposes. I-1 highlighted this as an option as well.

Finally, I-5 and I-7 remarked that the overall market for frequency regulation is not large enough for AVs to participate if implemented on a large scale. Therefore, the integration of AVs does not influence the performance of this service.

5.2.2 Effect on spinning reserve

Aggregated effect of AVs on spinning reserve through V2G: ++*

The respondents mostly believed that the flexibility of AVs and the response time that is allowed for spinning reserve improves the effect that can be obtained for this service through V2G. I-5 mentioned that this is one of the services where AVs would be highly beneficial because in case of an emergency AVs could be sent to areas to connect to the network and provide reserves. I-1 agreed that the performance of spinning reserve would improve substantially, but remarked that in some countries, such as the Netherlands, spinning reserve is not allowed by law due to anti-islanding. Anti-islanding requires a system shutdown during power outages to protect utility workers. Therefore, in theory, AVs could add value by providing spinning reserve to the grid, but in some countries this service cannot be performed.

Respondents I-2, I-3, I-6, and I-7 argued that also for this service if the most optimal business case for fleet owners is to let the AVs drive as often as possible instead of letting them idle or be used for V2G services, the performance of the service would not change because the availability of vehicles for this service might not differ from the current situation.

The aggregated rating for spinning reserve is set on ++. The majority of the respondents gave this rating. In theory, in case of an emergency or if a large generator drops out with serious consequences, AVs with V2G functionality could be made available to provide this service even when the business model focuses on maximising the utilisation rate for driving purposes. In that case, AVs would add value to the service. However, in reality, the added value might only be achieved in a limited number of countries that allow this service.

5.2.3 Effect on active power support

Aggregated effect of AVs on active power support through V2G: +

Five out of seven respondents compared the expected effect on active power support to their expectation for spinning reserve because active power support also allows for sufficient response time. I-1 and I-4, however, predicted that the effect of AVs on active power support through V2G remains the same as in the current situation while for spinning reserve they predicted an improvement. I-1 noted that, in general, we know where congestion takes place in the grid. Solutions for congestion are found locally. If V2G is used as a solution, the location of the charging infrastructure and how it is operated are important to provide support. AVs do not provide additional value. I-4 argued that under the current conditions EV owners can also connect their EVs to the grid (or disconnect from the grid) during certain time periods agreed upon with the aggregator. AVs do not necessarily improve this situation. Consequently, most of the respondents anticipated no changes in the potential active power support. The performance of this service is therefore rated at + for AVs.

5.2.4 Effect on reactive power support

Aggregated effect of AVs on reactive power support through V2G: +

All the respondents that shared their expectation for reactive power support agreed that this factor is related to the bidirectional charger and that AVs have no impact. Therefore, the performance stays the same based on the currently available charging infrastructure. I-2 and I-4 mentioned that AVs could induce a change to, for instance, an inductive charging infrastructure. If the charging infrastructure would change, the effect on reactive power support through V2G could change as well. I-6 believed that inductive charging would not have a negative effect on grid services through V2G. General guidelines would make sure of that. Under current charging conditions, AVs do not have an impact on this factor and for inductive charging, no problems are expected either.

5.2.5 Effect on current harmonic suppression

Aggregated effect of AVs on current harmonic suppression through V2G: +

All the respondents that shared their expectation for current harmonic suppression agreed that the effect on this factor is similar to the effect on reactive power support.

5.2.6 Effect on balancing and supporting renewable energy

Aggregated effect of AVs on balancing and supporting renewable energy through V2G: ++

Most of the respondents expect that with AVs balancing and supporting renewable energy through V2G remains a major driver. The rating is equal to the current performance of V2G because 3 respondents believed that AVs have no effect on the rating for this factor and for 3 respondents that considered AVs to possibly have a positive effect, the effect was not perceived to be significant to increase the rating or the rating scale did not allow a higher rating than ++. I-7 argued that AVs would have a negative effect on this factor, because AVs increase the utilisation for driving purposes and, therefore, reduces the time for V2G.

I-1 mentioned that AVs could be connected closer to the renewable energy generators, but in general, do not provide significant added value for this factor. I-4 stated that the most important issue related to renewable energy is the difference between seasonal generation. AVs will not influence the factor differently than currently is the case for EVs in combination with V2G.

I-2 noted that if private ownership would be replaced by fleet ownership, this would also remove the individual interests. In that case, AVs in combination with V2G would give aggregators the opportunity to create a more balanced process, which could improve the overall performance of this factor. I-3 agreed that the flexibility of AVs would allow for vehicles to be easily moved when their battery is full to create open charging spots for other AVs. The latter would increase the utilisation rate of the charging spots and the balance of the system. I-5 added that the operation process of AVs and V2G is important. If there is a central location to park the AVs instead of parking them in the streets, it will be easier to deliver this and other services.

5.2.7 Effect on the system revenues

Aggregated effect of AVs on the system revenues of V2G: +*

Four respondents expect that the system revenues of V2G increase due to AVs. Two of those respondents, however, estimated that with respect to the overall performance of V2G this improvement is not significant enough for an improved rating. I-2 argued that AVs improve the system revenues of V2G because through charging hubs the cost for charging infrastructure could be recovered by more vehicles. I-4 stated that AVs can be used more efficiently and strengthen the transition to fleet ownership which slightly improves the system revenues.

I-1 and I-3 anticipate that the system revenues for V2G could be significantly improved by AVs. I-1 said that since AVs will probably be fleet-owned, the business cases of the network operator and aggregator improve because they have to share the revenues with fewer parties.

I-5 commented that if AVs are parked in a central location, better services can be delivered but it remains uncertain if the system revenues would improve. Recent studies implicitly assume that EVs are connected and disconnected automatically, while this is probably only true when AVs are implemented. In addition, current revenues are based on current markets which include, for instance, cheaper electricity that is generated at night through cheap fossil fuels, such as coal. A larger share of renewables in the grid will change the market and, therefore, also the potential system revenues.

I-7 assumed that the expected increased utilisation rate of AVs would minimise potential system revenues for V2G.

Although multiple respondents stressed that a potential on-demand, subscription-based business model that maximises utilisation rate of AVs and minimises the availability for V2G could become a threat to V2G, six respondents initially expect the system revenues to remain the same or improve. The aggregated rating, therefore, still shows system revenues as a driver of V2G. The aggregated rating of the factor is set at + because most of the respondents rated this factor a + and uncertainties related to the different business models and the abovementioned comments by I-5 make a higher rating unrealistic. The on-demand business model for AVs is addressed in the last section of this chapter.

5.2.8 Effect on battery degradation

Aggregated effect of AVs on battery degradation through V2G: -*

Comparable to the studies discussed in section 3.8, on the current status of battery degradation, the expectations of the experts for this factor varied significantly. I-1, I-2 and I-3 argued that if AVs could be used more often for V2G than current vehicles, the throughput of the battery and, therefore, the battery degradation would increase as well which leads to an expected rating of --. I-1 mentioned that frequent usage of AVs in combination with V2G services would also result in improved revenues for the vehicle. I-4 agreed that due to an increased utilisation rate, efficient use, and sharing of AVs battery degradation is accelerated and more value is generated, but that it is not linked to V2G. I-5 and I-7 also thought that AVs in combination with do not affect battery degradation. Hence, they did not foresee a change in the rating for this factor. I-6 believed that there is no relation between V2G and battery degradation.

In general, AVs are expected to accelerate battery degradation due to the more frequent use of the vehicles for driving purposes, but the additional effect of AVs in combination with V2G is unclear. The aggregated rating is therefore determined in a similar way as in chapter 3. Most of the respondents perceive battery degradation as a barrier to V2G but disagree on the magnitude of the barrier. Since it cannot be convincingly determined that battery degradation is expected to be a major barrier, the aggregated rating is set at -.

5.2.9 Effect on investment cost

Aggregated effect of AVs on investment cost of V2G: -*

Five respondents expect that AVs significantly decrease the required investment cost for a V2G system. These respondents predict that if AVs are charged/discharged in a central location, a so-called charging hub, V2G systems would not have to be installed nearby the majority of the houses or offices. This could reduce costs for cables and chargers. In addition, the chargers could be used more effectively. I-5 mentioned the upgrade of the electricity system would only be needed at those charging hubs instead of all homes. This could lead to cheaper charging and electricity infrastructure. I-1, I-4, and I-5, therefore argued that the investment cost for V2G in combination with AVs would decrease and rated this factor at -. I-6 and I-7 believed that these new conditions would completely remove investment cost as a barrier to a V2G transition.

I-2 and I-3 commented that the expected investment cost would be lower but would remain substantial. I-2 added that research has also shown that if parking garages would be used as hubs, at least the same number of parking garages would be required as currently available.

The aggregated rating for this factor is set at -. A majority of the experts, five out of seven, foresee an improvement of this factor compared to current conditions, which includes two experts who expect that investment cost would not be a barrier anymore. Five out of seven experts foresee that investment cost remains a barrier, with two experts that rated it a major barrier. By setting the aggregated rating on -, the rating reflects the rating expected by the majority of the experts, the opinion of the experts who expect an improvement and the experts who expect investment cost to remain a barrier.

5.2.10 Effect on the impact on the distribution network

Aggregated effect of AVs on the impact on the distributed network caused by V2G: 0*

Most of the experts foresee that if AVs would be combined with V2G, the potential negative impact of EVs and V2G on the distribution grid would disappear. If the charging locations and the AVs are placed and coordinated well, the impact on the distribution grid can be solved. Due to the flexibility of AVs, strategic choices can be made, such as placing chargers on locations that regularly deal with congestion. AVs can be sent to these locations to support the distribution network. I-2 argued that this factor would become a driver of V2G because V2G in combination with AVs results in less dependency on the distribution network. This would create a somewhat autarchic system. In addition, AVs make it easier to predict demand and supply which is interesting for the network operator. The charging hubs become small electricity generation stations, which is better for the distribution grid than V2G installations near, for example, houses and offices.

I-4 and I-5 did not see any difference between the expected impact on the distribution network with and without AVs. I-5 mentioned that the impact on the distribution network is mainly related to charging EVs, not to V2G. Central charging hubs could lead to lower investment costs for cables needed to support the increased impact on the distribution network and lead to more effective discharging of EVs. However, the latter is also included in smart charging which is already applied.

The aggregated rating is set at 0. Four of the five experts that predicted an improvement rated this factor at 0, while one expert believed that the effects of AVs make this factor into a driver. In this case, the rating chosen by the majority of the experts is adopted as the aggregated rating.

5.2.11 Effect on range anxiety

Aggregated effect of AVs on range anxiety related to V2G: 0*

If AVs are not privately owned but in fleets, and mobility becomes part of a service, range anxiety is expected to be reduced according to most of the respondents. I-1, I-2, I-6 and I-7 predict that range anxiety completely disappears when AVs are part of a mobility service because passengers of AVs would not worry if they would arrive at their destination or what V2G would do to the battery. Sufficient range would be guaranteed by the service provider. I-4 and I-5 also foresee reduced range anxiety but believe it would not be completely solved. I-4 argued that an AV will not drive to a passenger if it is not sufficiently charged. Since the use of AVs would be based on a subscription, the passenger would probably be guaranteed to be able to request a vehicle that would bring him/her to the required destination. AVs would improve the range and therefore potentially change the distance for which range anxiety occurs, but it will not solve it. I-5 emphasised that if AVs would be privately owned, AVs would have no effect on range anxiety.

I-3 stated that AVs offer improvements in relation to range anxiety, but also create new issues. On the one hand, AVs could independently search for a charging spot to ensure the battery is sufficiently charged whenever needed to transport a passenger. On the other hand, AVs could increase the number of V2G services provided by the vehicle which could cause range anxiety. The rating for range anxiety, therefore, remains the same.

The aggregated rating for range anxiety is set at 0. Six experts expect an improvement through AVs, of which four believe range anxiety disappears. Although this rating differs two points from the rating done by I-3, it is assumed that if in case of fleet ownership the number of V2G services would increase, a mobility service provider would ensure that the fleet is managed in such a way that consumers are able to cover the required distance. This aggregated rating applies to fleet ownership. In the case of private ownership, the rating is expected to remain the same as for EVs in combination with V2G.

5.3 Evaluating the overall expected effects of autonomous vehicles

First, this section evaluates the synergies that can be obtained between AVs and V2G. Afterwards, implications beyond the V2G factors are discussed.

5.3.1 Synergies between autonomous vehicles and vehicle-to-grid through fleet ownership and sharing

The results show that AVs are expected to have a significant impact on the V2G factors when they are owned in fleets, shared, and managed and coordinated in large central charging hubs. The fleet owners then also become energy providers and the charging hubs can be considered as local electricity or storage stations. The expected synergies between fleet-owned shared AVs and V2G compared to the current performance of V2G without AVs are as follows:

- The ability to provide spinning reserve services to the grid improves from a driver to a major driver, because of the flexibility of AVs and the response time allowed for spinning reserve services.
- The investment cost of V2G improves from a major barrier to a barrier because charging hubs provide the opportunity to realise a more effective charging infrastructure which includes savings on, for instance, cables and charging spots.
- The impact of V2G on the distribution grid disappears because the flexibility of AVs allows for strategic choices that solve a negative impact on the distribution grid locally.
- Range anxiety disappears due to the mobility services fleet owners will provide. Passengers do not worry about the effect of V2G on the battery because they do not own the vehicle anymore and they expect that the fleet owner will provide them with a vehicle that has sufficient range to reach the desired destination.

With the exception of spinning reserve, the synergies between AVs and V2G are mainly obtained for the V2G factors that are perceived as barriers. The only V2G factor perceived as a barrier that AVs are expected to not have significant effects on is battery degradation. The experts expressed different opinions on battery degradation through V2G in combination with AVs, similar to the current performance of this factor. The effects of V2G both with and without AVs on the battery degradation, therefore, remains uncertain for EV owners. Consequently, battery degradation needs to be studied in further detail to discover if there is a relation with V2G, determine the impact of that relationship if there is one, and determine what measures can be taken to improve the battery life if that relationship has a negative effect. Afterwards, it can be determined what the effects of AVs in combination with V2G would be and if grid services provided through V2G-enabled AVs could potentially recover the investment cost of the battery.

With regard to the V2G factors perceived as drivers, the aggregated rating only changed for spinning reserve. Since spinning reserve is rated as a major driver by the experts, it is expected that the potential revenues would also improve due to AVs, which would decrease the level of uncertainty for this factor. However, since spinning reserve is not allowed in all electricity markets, not every V2G system benefits from the enhanced performance of this factor. For the factors frequency regulation, active power support, and system revenues, the aggregated rating remains the same as under current conditions. Consequently, if these services would be performed the benefits still seem to be only for the network operator and eventually society, while the financial incentives for EV owners and aggregators to participate in these V2G services remain uncertain. Further research into these factors is required to determine the actual potential revenues that can be obtained, if these revenues positively contribute to the performance of V2G and if they provide enough incentives to EV owners and aggregators to participate in a V2G system.

5.3.2 Looking beyond the V2G factors

The expected positive effects, especially on the V2G factors that are perceived as barriers to a V2G transition, imply that the integration of shared fleet-owned AVs in the transport system would bring a V2G transition much closer. However, most of the interviewed experts predict that a business model that aims at the most successful operation of shared fleet-owned AVs would not give priority to V2G operation of the vehicles. The potential shift to an on-demand, subscription-based mobility service could become a serious threat to the existence of V2G (in this form) if fleet owners rather focus on charging the AVs as efficient as possible and maximise the utilisation rate of the vehicles for mobility purposes because the value of renting out the vehicle is much higher. The system revenues of V2G through shared fleet-owned AVs would be minimised which would result in a focus on different forms of V2G if available, alternative storage options or completely different technologies to balance the grid. I-5 raised an interesting point by mentioning that (most of) the studies on revenues related to V2G are based on current markets. In the case of AVs, most experts also based their opinion of the business model on the current electricity markets. Since the profit margins in the electricity market are low, letting AVs drive is expected to generate substantially more revenue. However, a larger share of renewables in the grid that creates a different dynamic in the electricity market might have a positive effect on the profit margins that can be made from grid services. Research into these different markets and comparing them to the potential business cases for AVs could provide a clear insight into the financial feasibility of V2G in combination with shared AVs. In the validation interview, I-8 argued that even if the potential revenues of grid services would increase, the competition for V2G from other technologies, such as stationary storage (or dedicated battery bank), to provide these grid services would increase as well. Fleet owners of AVs would then still have mobility services as a main priority because, in the end, they are a mobility provider. Competing technologies for grid services are then expected to have a higher chance of providing grid services and receive those additional revenues.

Consequently, a V2G transition with AVs creates a situation where if the AVs would actually be used to provide grid services there would be positive effects on most of the barriers currently perceived to hamper a V2G transition, but an on-demand business model for AVs would create a new insurmountable barrier to V2G due to the lack of system revenues. Since this business model is considered as the most appropriate business model for AVs and changes in profit margins within the electricity market are believed to not improve the business case for V2G either, AVs are expected to destroy the business case for a V2G transition.

Figure 6 shows an overview of the expected effects of AVs on the performance of V2G including the broader implications of an on-demand mobility service. The path highlighted in green has a positive effect on the performance, in yellow a neutral effect, and in red a negative effect.

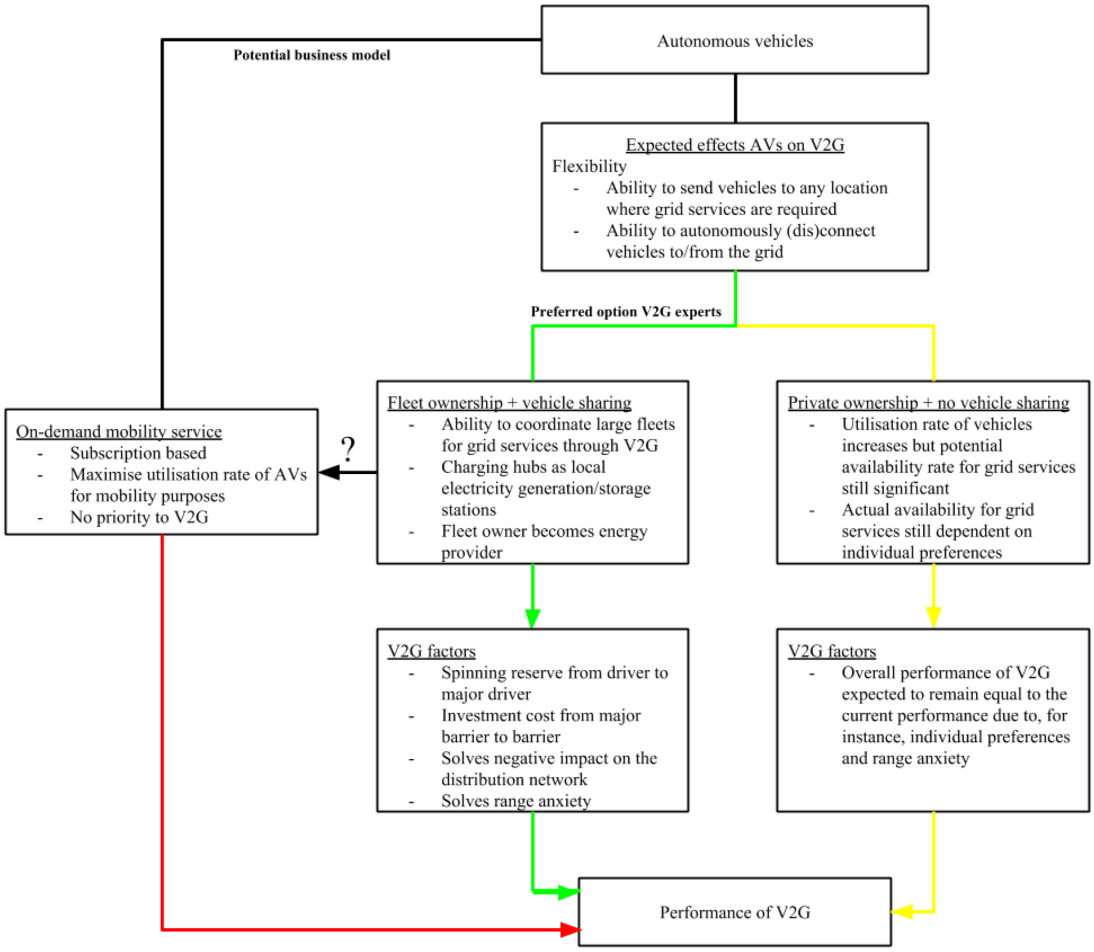

Figure 6: Expected effects of AVs on the performance of V2G

6. Discussion

This chapter first reflects on the research design and methods. Afterwards, the research findings are discussed in light of the existing literature and related expectations.

6.1 Reflecting on the research design and methods

The following paragraphs discuss elements of the research design and methods that are believed to have influenced the outcomes of the research.

The first elements to be discussed are the scope and assumptions made to perform this research within a limited time frame. Only BEVs were included in the scope, while V2G can also be performed with FCEV. Hence, the outcomes of this research do not present an overview of what the expected effects of AVs are on the complete V2G concept, but the expected effects on part of the concept. In case of an increased penetration level of FCEVs, the effects of AVs on the V2G concept might differ which would have to be explored further. Also, AVs were assumed to be V2G-ready when the experts evaluated the effects. Since, according to one, expert currently only four types of EVs produced by two car manufacturers are actually V2G-ready, a transition to a transport system consisting of V2G-ready vehicles would include multiple institutional and regulatory measures to support and stimulate the V2G-readiness of EVs, such as charging standards, which have not been considered in this research.

An element related to the research design is the level of uncertainty which stresses the exploratory character of this research. Both V2G and AVs are in an early development phase. The early development phase of V2G led to a current performance based on expectations or results from studies that were mainly obtained through simulation or experiments. Inconsistency within the literature created a level of uncertainty for the individual performances of the V2G factors. The effects of AVs on these factors were again based on expectations of experts which also include a certain level of uncertainty.

The next element is the literature review that was performed to identify the V2G factors. Given the limited time frame of this research, only the most important or clearly identifiable drivers and barriers were selected in this review. Due to the development phase of V2G, the literature review mainly included technical and techno-economic articles. Consequently, almost all V2G factors were either technical or financial. The only social factor that could be included in this research showed to be a major barrier, while institutional factors were not included at all. Related grid stabilising measures such as demand side response demonstrate that more social and institutional factors are potentially also relevant to the performance of V2G. In-depth research into these factors might have resulted in a different or longer list of V2G factors, which could have changed the expected effects on the performance of V2G as well.

Another element to reflect upon is the rating scale that was constructed to clearly rate and compare the current performance of V2G to the performance based on the expected effects of AVs, and to somewhat reduce the level of uncertainty. The five-point scale was chosen to establish a difference in magnitude of the barriers and drivers between a ‘normal’ or a ‘major’ barrier or driver and to not make the comparison too vague by having too many points on the scale. The neutral rating was added to indicate that a factor was not perceived as a barrier or driver anymore. The chosen rating scale influenced the outcomes of the research. For balancing and support renewable energy, for instance, some experts believed the rating improved through AVs to +++, if the scale would have allowed such a rating. In addition, sometimes an expert indicated that a factor improved but not enough to change the rating. A different rating scale might have been able to show those nuances.

The following element is the potential bias of the V2G experts. The evaluation of the current performance in chapter three demonstrated that for some V2G the results for the current performance varied significantly. Hence, the information on which the experts based their opinions might have been different as well which might have biased their evaluation. The variables for the development of AVs that were shared with the experts might have also created a bias towards a certain development. The initial idea of the variables was to give some direction to the potential development paths for AVs. After the interviews were conducted, it turned out that all experts had compared the effects of AVs for two development paths: unshared privately-owned AVs and shared fleet-owned AVs. A different set of variables or no variables at all might have resulted in different ratings for the V2G factors.

Finally, a limited number of V2G experts were consulted due to time constraints. Although the goal of at least five experts from different organisations and backgrounds per factor was achieved, it was not possible to interview a V2G expert from a car manufacturer within the given time frame. While the rating of one expert might not have changed the overall result, it would have given an insight into the expectations of car manufacturers for the effects of AVs on the performance of V2G and how this would relate to the expectations of the experts from different fields.

6.2 Reflecting on the research findings

In the introduction of this research, the need for the car as a battery is emphasised with V2G highlighted as an essential decentralised storage functionality that can stabilise the grid and realise the large-scale integration of renewable energy sources. Research on the performance of BEVs in combination with V2G, however, shows that under current conditions that promise cannot be fulfilled. While the scientific literature on V2G positions several grid services that can be provided through V2G as a driver of the technology, studies into these specific services indicate a high level of uncertainty through widely varying ranges for the potential revenues that can be obtained by EV owners (and aggregators) through these services. In addition, multiple variables, such as the different composition of electricity markets, seem to be of importance for the outcome of these potential drivers.

Although the integration of AVs has positive effects on the majority of the barriers to a V2G transition, the performances of most of the drivers are expected to remain the same compared to the current V2G performance, which maintains the perceived level of uncertainty regarding their potential revenues. This raises the question if next to the promising technological possibilities, a V2G transition would actually provide added value or would come at a cost, and whom the added value or cost should be allocated to. The assessment of the current performance of V2G shows that actors in a V2G system are affected differently by the drivers and barriers which demonstrates the complexity of the system. For the system to function properly, all actors need to benefit sufficiently to be able and willing to participate. The uncertainties related to the potential revenues of the identified drivers of a V2G transition directly affect EV owners and aggregators because they would provide services to the grid with the chance of not being fairly compensated. If these actors cannot benefit from a V2G transition through these services, other incentives are needed to persuade EV owners to make their vehicles available for V2G and aggregators to manage and coordinate this process or they might not be willing to participate at all. While this research mainly addresses these multi-actor issues in relation to EV owners, system operators and aggregators, other important actors, such as (renewable energy) generators and (local) governments, should also be included in further research to provide a complete overview of the allocation of costs and benefits of a V2G system and the implications for a potential transition.

Uncertainties related to V2G were also shared by some of the V2G experts. One expert mentioned that the development of V2G did not turn out what it promised to be, while another expert believed that V2G was hyped by a group of people but that it remains to be seen if it will actually develop into something valuable. Smart charging was often mentioned as something that is already applied through EVs to balance the grid and has shown good results which reduces the needs for V2G, especially when considering the large investments needed for V2G and the small profit margins in the electricity market to recover those investments. Another point that was raised, and also applies to this research, is that the development of V2G mainly focusses on BEVs, while according to some experts BEVs do not meet all the requirements for V2G. BEVs are believed to not be able to provide seasonal storage and charge from the same network as where it supplies the electricity during discharge. BEVs are, therefore, mainly useful for balancing daily supply and demand due to the price differences in the electricity market. Some experts, therefore, believe that V2G studies should always also consider FCEVs. FCEVs are not dependent on the electricity network. They use hydrogen which can be stored more easily and cheaper. In addition, hydrogen can also be distributed through the gas network that is much larger than the electricity network and, thus, needs significantly lower investments to make the system V2G-ready. Since on a global scale most countries and car manufacturers have not decided yet for either FCEVs or BEVs, V2G studies should focus on both options too.

Competing storage options have to be considered as well when discussing the performance of V2G. During the interviews, one V2G expert argued that these alternative options are often underestimated. Mullan et al. (2012) agree by stating that many V2G studies consider V2G technology as the best available storage option, while there are alternatives available for the electricity system which are much more suitable. Four competing storage options are, for instance, pumped hydroelectric storage, thermal energy storage systems, flywheel, and dedicated battery banks (Mullan et al., 2012). Especially the last option is interesting in relation to this research because it could be argued that if system revenues could be obtained through V2G with (autonomous) BEVs, the same would apply to dedicated battery banks. As discussed in section 5.3.2, it is even expected that the latter option would have an advantage over V2G, because they are dedicated to providing services to the grid. Moreover, potential improvements in battery degradation would benefit both V2G and the dedicated battery bank equally (Mullan et al., 2012).

Concluding, the notion of using BEVs in combination with V2G at first seems like a promising option for decentralised storage in the electricity system. An integration with AVs could have positive effects on most of the existing barriers to a V2G transition, but AVs might not be available for V2G purposes. The high level of uncertainty of the financial value of the drivers also prevents large-scale implementation. Considering that EVs currently already provide some stability for the grid through smart charging and the availability of alternative storage options, the performance of V2G has to improve considerably for it to play a major role in stabilising the grid while realising a larger share of renewable energy sources. In addition to the barriers and the drivers of a V2G transition, emphasis has to be put on a fair distribution of the costs and benefits among the actors within a V2G system. If V2G becomes available under current conditions, it is believed to be a supplementary service providing a limited number of services to the grid depending on the specific electricity markets.

7. Conclusion

This research provided new insights for the future integration of the electricity and transport systems by considering an innovative combination of V2G and AVs. Although V2G is considered to be a suitable option to deal with the pressure on the stability of future electricity grids, an assessment of the current performance of V2G showed that the technology has to develop further to improve or mitigate the existing barriers and fulfil the potential promise of the drivers of a V2G transition. Therefore, the potential effects of AVs on the performance of V2G were evaluated for two scenarios: privately-owned unshared AVs and fleet-owned shared AVs. While privately-owned unshared AVs are expected to not have significant effects, fleet-owned shared AVs in combination with charging hubs are expected to enhance the performance of V2G because the ability to provide spinning reserve improves, the investment cost of the charging infrastructure decrease, negative impact on the distribution network can be controlled, and range anxiety disappears. However, uncertainties related to the potential revenues of some drivers and the impact of V2G on battery degradation remain an issue and require further research. In addition, the development of fleet-owned shared AVs is expected to include an on-demand business model that maximises the utilisation rate of AVs for mobility services because the value of renting out the vehicle is much higher than the value of V2G. If the final development path would contain this business model, the priority for V2G would be minimised which would create a new, insurmountable barrier that destroys the business case for V2G systems.

7.1 Recommendations

To conclude this research report, recommendations are made for policymakers and future research.

In light of a strategic plan of the European Commission to accelerate a European energy system transformation by, amongst others, integrating the energy and transport systems, recommendations for policymakers can be made. It appears that under current conditions V2G needs to be further developed and strengthen its position towards alternative storage options for it to become a feasible option and contribute to the integration of the energy and transport systems. AVs could potentially improve some of the barriers to V2G, but the integration of both technologies is not appropriate due to the high level of uncertainty around the drivers of V2G and the expected development path consisting of a focus on on-demand mobility services. AVs can, therefore, for now, develop independently from V2G. In the meantime, policymakers could focus on the question if grid services are to be performed by V2G. If due to future developments, a preference is developed for V2G over alternative storage options and AVs are on a different development path, the integration of both technologies can be reconsidered.

This research contributed to the body of knowledge on V2G by bridging a gap that existed between V2G and the integration of AVs. This resulted in a comprehensive overview of the current performance of V2G and first insights into the expected effects of AVs on the performance of V2G. Based on these findings, a number of directions for future research can be identified. First, inconsistencies within the scientific literature on drivers and barriers to a V2G transition have to be addressed to work towards a more elaborate overview of the current performance that includes the allocation of costs and benefits for all important actors. The potential revenues of grid services and the relationship between V2G and battery degradation, for instance, are topics that need clarification to determine the current status of V2G and what needs to be done to fulfil the promise of V2G. Also, the impact of different conditions, such as the types of electricity markets, on the feasibility of grid services through V2G is an important direction to discover the right conditions for V2G and if V2G should be considered as a technology that can provide all grid services or only a number of services under specific conditions. Another recommended research direction is an expansion towards social and institutional related research topics for the transition to V2G. This could start, for instance, with a review of the already identified social and institutional barriers for other grid stabilising measures such as demand-side response to determine if these barriers are relevant to V2G as well. In addition, while V2G is strongly linked to the increase of renewable energy in the grid the environmental impact of V2G is also underexamined. With regard to institutional research topics, charging standards for V2G need to be discussed to progress the development of the technology. A research direction for V2G could also be to include FCEVs, especially if the adoption rate increases. Finally, research on V2G often does not consider the full spectrum of storage options. Future research into V2G should, therefore, include comparisons to alternative storage options to determine the position of V2G or supplementary options to strengthen the position of V2G.

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Appendices

Appendix A: Scientific paper

Evaluating the transition from V2G to AV2G

The autonomous battery electric vehicle as decentralised bidirectional electricity storage system

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ARTICLE INFO

16 March 2019

Keywords:

Autonomous vehicles
Decentralised storage
Expectations
Performance
Vehicle-to-grid

ABSTRACT

A transition to V2G is hampered by many barriers, such as battery degradation and high investment cost. A dramatic shift towards autonomous vehicles (AVs) in the future transport system drastically changes the conditions for a transition to V2G, potentially resulting in a more flexible V2G system that efficiently deals with bidirectional flows between AVs and the electricity grid and the transport of passengers. Despite the beneficial effects AVs might have on a V2G transition, there is a lack of scientific research into the joint development of these technologies. This paper bridges this knowledge gap by exploring the potential effects of autonomous battery electric vehicles on the performance of V2G for two scenarios: privately-owned unshared AVs and fleet-owned shared AVs. While privately-owned unshared AVs are expected to not have significant effects, fleet-owned shared AVs in combination with charging hubs are expected to enhance the performance of V2G because the ability to provide spinning reserve improves, the investment cost of the charging infrastructure decreases, negative impact on the distribution network can be controlled, and range anxiety disappears. However, uncertainties related to the potential revenues of some drivers and the impact of V2G on battery degradation remain an issue and require further research. In addition, the development of fleet-owned shared AVs is expected to include an on-demand business model that maximises the utilisation rate of AVs for mobility services because the value of renting out the vehicle is much higher than the value of V2G. If the final development path would contain this business model, the priority for V2G would be minimised which would create a new, insurmountable barrier that destroys the business case for V2G systems.

1. Introduction

Our energy systems have to change significantly due to the expected increase of 58% in renewable energy consumption by 2040 (EIA, 2017). The large-scale implementation of volatile, both in time and location, renewable energy sources, such as PV and wind, and the growing number of energy providers on the distribution grid level will severely affect the stability of the electricity grid (Muench et al., 2014). Balancing the power demand and supply becomes an unpredictable and complicated process. The perceived solution to these challenges is to introduce a more intelligent energy system that coordinates consumers of the electricity grid, thereby maintaining the net balance and establishing an efficient and reliable transmission and distribution of electricity (Vandael & Boucké, 2011). This energy system is called a smart grid. A core component of smart grids is a decentralised electricity storage functionality (Römer et al., 2012). Decentralised (or distributed) storage is a system of many small, on-site storage systems that temporarily separate generation and consumption. The ongoing electrification of the transport system has resulted into the belief that if electric vehicles (EVs) could be fully integrated with smart grids, their mobile batteries could play a crucial role in realising a decentralised storage functionality (Wentland, 2016). Since most vehicles are parked over 90% of the time, EVs could be used for storage purposes and the owners could be offered financial incentives for making their vehicles available to the grid (Kempton, 2010).

When EVs are used for decentralised storage, their functionality can be extended with vehicle-to-grid (V2G) technology. V2G technology allows EVs to provide control and management of bidirectional electricity flows through communication between the EV and the electricity network (Tan et al., 2016). Renewable energy can be stored in the EV when it is abundant and made available to the grid when the generation output is low. Ota et al. (2010) argue that V2G technology is a key technology for realising the integration of renewable energy sources in smart grids. V2G enables storage of excess energy, balancing supply and demand in a flexible way and, therefore, makes the increase of the amount of renewable energy in the electricity network feasible (Römer et al., 2012). In addition, V2G technology improves the quality of several grid services. The response time of V2G technology is very fast compared to, for instance, traditional power plants, which makes the technology suitable for voltage and frequency control (Steward et al., 2017). Nevertheless, a transition to V2G faces many barriers such as technological immaturity, cost hurdles and social acceptance (Sovacool et al., 2017). An example of a technical barrier is the acceleration of battery degradation caused by the increased use of the batteries of EVs with V2G technology (Yilmaz & Krein, 2013). Cost hurdles arise due to large investments needed to, for example, upgrade the power infrastructure to enable the use of V2G technology (Yilmaz & Krein, 2013). Barriers for social acceptance include, amongst others, issues related to the potential inconvenience for the EV owners of not having a fully charged vehicle when needed resulting into range anxiety (Sovacool et al., 2017). Consequently, V2G technology has to be improved and the conditions in which the transition takes place need to be more favourable to overcome the barriers and realise the large-scale implementation of robust decentralised storage functionalities through V2G technology that can provide stabilising services to the grid and support the energy transition towards a larger share of renewable energy sources.

An emerging technology in the transport system that might change our perception of mobility and therefore also influence the performance of V2G technology is autonomous driving. Autonomous vehicles (AVs) (or self-driving or robotic or driverless vehicles) are vehicles that drive itself without a human driver. This is considered the highest level of vehicle automation (Anderson et al., 2016). If widely accepted, AVs have the potential to significantly change the current transport system by realising, for example, more efficient road use, increased driver productivity and energy savings (Greenblatt & Shaheen, 2015). Lam et al. (2016) state that since AVs are likely to be EVs, they will be able to participate in the development of V2G technology. While convenience currently is an important factor to determine where the driver parks, AVs can be programmed to park in the right location to fully support V2G services where and when needed. In addition, the automation of vehicles could promote car sharing

(Canzler & Knie, 2016). This would remove the dependence of the V2G system on private vehicle owners. AVs would be part of fleets, which would transport passengers based on intelligent applications. In the meanwhile, assuming the fleets would exist of autonomous EVs, algorithms could be made which efficiently deal with bidirectional flows between the vehicle and the electricity grid and the transport of passengers. This would create a decentralised storage facility based on fleets of autonomous EVs. Anderson et al. (2016) argue that when AVs would be fully integrated, wireless V2G services could become available and make V2G technology more flexible.

Despite the beneficial effects AVs might have for V2G technology, there is a lack of scientific research into the joint development of these technologies. This paper bridges this knowledge gap by exploring the potential effects of AVs on the performance of V2G, thereby providing new insights into the pursued integration of the energy and transport systems. The objective of this paper is therefore *to determine the likely effects of the development of autonomous battery electric vehicles on the performance of the system integration of vehicle-to-grid technology.*

2. Approach

To evaluate the potential effects of AVs on the performance of V2G, factors that affect the performance of V2G have to be established. In this paper, the performance of V2G is based on the feasibility of the potential drivers of a V2G transition and the impact of potential barriers on a V2G transition. Drivers add significant value to the progress of a V2G transition by, for instance, contributing to an increasing share of renewable energy in the grid, providing better services to stabilise the grid and generating revenues through these services. Barriers hamper a transition to V2G. Together these drivers and barriers are grouped as **V2G factors**, which are defined as factors that affect the transition of V2G by either making it valuable or hampering it.

First the V2G factors are identified through a literature review, then the current performance of V2G is derived from available research on the V2G factors that considers a transport system without AVs. Afterwards, the expected effects of AVs on the performance of V2G are evaluated through the results from expert interviews. Finally, the wider implications of the results are described.

3. V2G factors

The most important drivers and barriers to V2G were identified from the scientific literature and then translated into V2G factors. Since this research for this paper was performed with a social-technical perspective, the factors were intended to reflect a socio-technical perspective as well. However, the majority of the scientific literature on V2G tend to be mainly technical or techno-economic due to the early development phase the technology is still in. Consequently, social V2G factors are limited in this paper, and institutional V2G factors could not be identified from the literature.

The potential drivers of a V2G transition are mainly related to services that can be provided to support and stabilise the grid. Table 1 gives an overview of the most important drivers of a V2G transition based on the performed literature review and gives a short explanation of the added value of V2G for each of the drivers. The barriers to a V2G transition are related to the battery of the vehicle, investments required for V2G systems, the impact on the distribution grid for the network operator and range anxiety experienced by EV owners. Table 2 provides an overview of the most important barriers to a V2G transition and a short explanation of the rationale for each barrier based on the performed literature review.

Table 1: Drivers of a V2G transition

Drivers of V2G	Added value V2G	References
Ancillary Services	V2G can act as a dynamic storage functionality that allows for higher quality ancillary services	Bohnsack et al., 2015; Brooks, 2002; Habib et al., 2015; Kempton & Tomić, 2005a; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Peças Lopes et al., 2011; Sovacool & Hirsh, 2009; Yilmaz & Krein, 2012, 2013
• Frequency Regulation	V2G needs less response time to provide frequency regulation than conventional generators.	Brooks, 2002; Habib et al., 2015; Han et al., 2010; Kempton & Tomić, 2005a; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Shaukat et al., 2018; Yilmaz & Krein, 2012, 2013
• Spinning Reserve	V2G can provide spinning reserve on short notice in case of an unplanned event such as loss of generation.	Brooks, 2002; Habib et al., 2015; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Parsons et al., 2014; Peças Lopes et al., 2011; Shaukat et al., 2018; Yilmaz & Krein, 2012, 2013
Active Power Support	V2G-enabled EVs can charge and discharge their batteries to perform active power support.	Habib et al., 2015; Shaukat et al., 2018; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
• Load Levelling	V2G allows for load levelling by valley fillings.	Habib et al., 2015; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
• Peak Load Shaving	V2G allows for discharging electricity back to the grid during peak load periods	Brooks, 2002; Gough et al., 2017; Habib et al., 2015; Kempton & Tomić, 2005a; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Shaukat et al., 2018; Sovacool & Hirsh, 2009; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Reactive Power Support	V2G is a more flexible and efficient reactive power resource due to the bidirectional charger.	Brooks, 2002; Habib et al., 2015; Mwasilu et al., 2014; Shaukat et al., 2018; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Current Harmonic Suppression	The bidirectional chargers of V2G-enabled EVs allow for current harmonic suppression.	Habib et al., 2015; Ma et al., 2016; Shaukat et al., 2018; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Balance and Support Renewable Energy	V2G provides a storage functionality for renewable energy that can provide electricity back to the grid when required.	Bohnsack et al., 2015; Habib et al., 2015; Kempton & Tomić, 2005a, 2005b; Kempton et al., 2001; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Peças Lopes et al., 2011; Sovacool et al., 2017; Sovacool & Hirsh, 2009; Yilmaz & Krein, 2012, 2013
System Revenues	The abovementioned grid services that could be provided through V2G generate revenues for actors in a V2G system.	Bohnsack et al., 2015; Habib et al., 2015; Ma et al., 2016; Mwasilu et al., 2014; Parsons et al., 2014; Peças Lopes et al., 2011; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
• Revenues for EV Owners	V2G-enabled EV owners obtain revenues by making their vehicle available for grid services.	Bohnsack et al., 2015; Ma et al., 2016; Parsons et al., 2014; Sovacool et al., 2017; Yilmaz & Krein, 2012, 2013
• Reduced Network Operating Cost	V2G allows for reduced charging costs and for equipment in the grid to be used more effectively.	Habib et al., 2015; Ma et al., 2016; Mwasilu et al., 2014; Yilmaz & Krein, 2012, 2013
• Improved Economics for the RE Industry	The market for renewable energy generation grows through V2G.	Habib et al., 2015; Peças Lopes et al., 2011; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016

Table 2: Barriers to a V2G transition

Barriers to V2G	Rationale	Reference(s)
Battery Degradation	Accelerated battery degradation due to increasing charging and discharging cycles caused by V2G services.	Bohnsack et al., 2015; Gough et al., 2017; Habib et al., 2015; Loisel et al., 2014; Ma et al., 2016; Mullan et al., 2012; Mwasilu et al., 2014; Parsons et al., 2014; Shaukat et al., 2018; Sovacool et al., 2017; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Investment Cost	Large investments required to upgrade the power system and deal with the expected impact on battery life.	Habib et al., 2015; Loisel et al., 2014; Mwasilu et al., 2014; Peças Lopes et al., 2011; Shaukat et al., 2018; Sovacool & Hirsh, 2009; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Impact on the Distribution Network	Battery chargers can rapidly overload local distribution equipment if charging policies are not managed properly. This can lead to, for instance, voltage deviations, losses in the distribution transformer, and effects on distribution equipment. The increasing number of charging cycles due to V2G cause more conversion losses.	Habib et al., 2015; Mwasilu et al., 2014; Peças Lopes et al., 2011; Tan et al., 2016; Yilmaz & Krein, 2012, 2013
Range Anxiety	V2G increases range anxiety which prevents social adoption.	Sovacool et al., 2017; Tan et al., 2016
• Sharing Battery with the Grid	The inconvenience of a potentially fluctuating driving range results in increased range anxiety.	Parsons et al., 2014; Sovacool et al., 2017; Tan et al., 2016
• Distrust	Distrust in the aggregator and technology that control the V2G system leads to fear for the EV not being sufficiently charged.	Sovacool et al., 2017

Some of the drivers and barriers consisted of subcategories. For those drivers and barriers, it was determined if the main category or the subcategories were more appropriate to be considered as V2G factors. In the case of ancillary services, not all ancillary services, such as non-spinning reserve and black start, that could potentially be provided through V2G were recognised as important drivers for this paper. Selecting ancillary services as a V2G factor would imply that all ancillary services are included. Consequently, frequency regulation and spinning reserve were both identified as separate V2G factors. Active power support was also classified as a driver that consists of two subcategories; peak load shaving and load levelling. Since these subcategories are the only subcategories found in the literature for active power support and the literature usually discusses both subcategories collectively, active power support is used to describe the V2G factor. Another driver identified with subcategories was system revenues. The subcategories of this driver all contribute to the complete system. In addition, not all studies conform to the discussed subcategories when evaluating (part of the) system revenues. Therefore, the main category was used as V2G factor. Finally, for range anxiety two subcategories were recognised. However, both subcategories have range anxiety as a result. Range anxiety was, thus, seen as the most appropriate name for the V2G factor.
To make the V2G factors suitable for further analysis, the factors were operationalised based on the measurement most often applied in studies on these factors. Table 3 shows the operationalised V2G system integration factors. In the next section, these measurements are used to determine the current performance of each V2G factor.

Table 3: Operationalisation of V2G factors

V2G Factor	Measurement
Frequency Regulation	Potential revenues (in € per EV per year)
Spinning Reserve	Potential revenues (in € per EV per year or in € per V2G unit per year) Reduction of polluting emissions (in %)
Active Power Support	Potential revenues (in € per EV per year)
Reactive Power Support	Effect on battery degradation (description) Effects of different modes of V2G operation (description)
Current Harmonic Suppression	Effect on current harmonic distortion (description)
Balance and Support Renewable Energy	Effect on penetration level of renewable energy (in %) Potential savings for electricity and transport systems (in € per EV per year)
System Revenues	Potential revenues (in € per EV per year)
Battery Degradation	Effect of energy throughput of V2G on battery (in % or description) Potential cost (in € per charge or description)
Investment Cost	Required infrastructural and operational investments (in € or description)
Impact on the Distribution Network	Effect on distribution equipment (in % or description) Effect of different modes of V2G operation (description)
Range Anxiety	Consumer-based experiences (description)

4. The current performance of V2G

V2G is still in an early development phase. Hence, the current performance of these factors is based on expectations derived from research including experiments, technical simulations, and quantitative modelling. In addition to scientific research, input for the current performance of the V2G factors is complemented by findings from Reynolds et al. (2018), who provide a global review of the lessons learned from 50 pioneering V2G projects. These projects represent a mixture of scientific, governmental and industry supported projects.

The current performance of V2G is determined through the aggregated performance of the V2G factors. To effectively compare the effects of each factor on the overall current performance of V2G and later the effects of AVs on the performance of V2G, the results of the current performance are rated on a five-point scale: major barrier (--), barrier (-), neutral (0), driver (+), major driver (++). If a V2G factor initially is perceived as a barrier by the literature, the rating of that factor is either – or --. If the V2G factor initially is perceived as a driver by the literature, the rating of that factor is either + or ++. The magnitude of the rating of each factor depends on the current performance from studies on that specific factor. If the aggregated performances of multiple studies indicate a significant effect of a factor on the performance of V2G, the factor is rated as -- or ++ (depending on how it is initially perceived by the literature). If the aggregated performances of multiple studies indicate a minor impact or the results of different studies varied considerably making it difficult to come to one aggregated performance, the factor is rated as – or + (depending on how it is initially perceived by the literature). Since the first step of the rating process divides the factors into barriers and drivers based on the literature, the 0 rating is not applied in this part of the paper. This rating is considered in section five if according to V2G experts the effects of AVs make the effects of a V2G factor neutral instead of a barrier or driver. Table 4 shows the aggregated current performance of the V2G factors. The V2G factors are highlighted in **dark red** if they are rated a major barrier, in **red** if they are rated a barrier, in **green** if they are rated a driver, and in **dark green** if they are rated a major driver. An important note to this table is that all the items under "potential current performance" are potential performances for a specific factor that were identified independently. Consequently, a summation of the potential performances identified for one factor does not automatically reflect the complete performance of that factor.

A review of research specifically focusing on the V2G factors showed inconsistencies on some of the V2G factors that should reflect as drivers of a V2G transition leading to highly uncertain results. Potential revenues that can be obtained through frequency regulation, spinning reserve, active power support, and the overall V2G system vary widely, and according to some studies even result in a loss which then arguably makes them barriers. Furthermore, complex issues arise between the actors in a V2G system because the uncertainties about the potential revenues, for instance, mainly affect the EV owners and aggregators who receive the potential revenues through payments from the network operator as incentives for making their EVs available to the grid or coordinating a large group of EVs for grid services through V2G. If EV owners are not fairly compensated, their willingness to participate in V2G systems might be limited, especially in combination with the expected range anxiety. In addition, aggregators are not expected to be willing to coordinate grid services under these conditions.

Inconsistencies also exist within research on battery degradation and V2G. Although some researchers consider battery degradation a significant barrier to a V2G transition, other researchers believe it to be unrelated to V2G. Comparing all the varying outcomes becomes more difficult due to the differences in variables, assumptions, methods and strategies encountered in studies on this factor (and others).

The appropriate conclusion for the current performance of V2G is that research on the technology has to develop further to improve or mitigate the barriers and fulfil the potential promise of the drivers, which also demonstrates the relevance of this paper. The evaluation of the current performance of V2G shows that the drivers and barriers affect the actors in a V2G system differently, which proves that drivers and barriers cannot just be considered as such for the complete system but need to be analysed from different perspectives to determine their overall effects on the performance of V2G.

Table 4: Aggregated current performance of the V2G factors

V2G factor	Potential current performance
Frequency regulation + driver	• Annual revenues for EV owners: €53 – 1440 per EV

Spinning reserve
 	
+ driver
	• Annual revenues for EV owners: €78 – 549 per EV
	• Annual revenues for aggregators: -€3000 per V2G unit
	• System cost reduction for system operators: 34% when in combination with an aggregator
	• Emission reduction PHEVs with V2G compared to PHEVs without V2G, penetration level from 1 – 15%:
	  ○ CO_2: 19.2 – 25.8%
	  ○ SO_2: -0.2 – 8%
	  ○ NOx (ozone): 20.2 – 48%
	  ○ NOx (non-ozone): 29.7 – 39%

Active power support + driver	• Annual revenues for EV owners: -€202 – 221 per EV • Peak shaving is only economically justified for periods of 1 hour or less
Reactive power support + driver	• No effect on battery degradation • Different modes of uncontrolled operation affect components of the bidirectional charger • Revenues of simultaneous transfer of active and reactive power 19% higher than reactive power only
Current harmonic suppression + driver	• The increase of bidirectional chargers and charging power positively influence current harmonic distortion

Balance and support renewable energy ++ major driver	• Renewable energy generation 30 – 75% higher with V2G availability compared to no V2G availability • Potential to stabilise large-scale wind power accounting for half U.S. electricity • Potential to provide peak energy in the U.S. through PV solar electricity • Annual savings for electricity and transport industries by charging and discharging EVs with renewable energy sources: at least €923 per EV
System revenues + driver	• Annual revenues for EV owners: -€231 – 3539 per EV • Annual system cost savings for network operators: up to €100 per EV • Annual operational cost savings for electric utility: 3% of the revenues

Battery degradation
 	
- barrier
	• Varying results from a serious barrier to negligible impact:
	• Barrier:
	  o Higher energy throughput with V2G leading to multiple battery packs needed over vehicle life
	  o Battery degradation cost outweigh additional revenues of V2G
	• Negligible impact
	  o V2G only accounts for 2% of degradation, driving the vehicle 8%
	  o In the case of frequency regulation degradation minimal:
	    o Average capacity loss per frequency regulation event: 0.0010 – 0.0023%
	    o Cost battery degradation per charge: €0.18 – 0.41

Investment cost
 	
-- major barrier
	• Substantial investments in hardware and software infrastructure and operational expenses:
	  o Bidirectional chargers
	  o Settlement meters
	  o Grid upgrade to manage renewable energy, for instance: €18 billion in Germany
	  o Provide incentives to EV owners to participate in V2G programmes

Impact on the distribution network - barrier	• In case of distribution equipment overload additional investments in larger cross-sections of underground cables and overhead lines, and more transformer capacity are needed • At a 50% EV penetration level, uncontrolled charging reduces transformer life by 200 – 300%, controlled charging improves transformer life 100 – 200% with respect to uncontrolled charging • At a 60% EV penetration level can increase power losses up to 40% in off-peak hours and can increase investment cost in the distribution network up to 15% depending on the charging strategies • Coordinated charging and discharging with V2G can result in a reduction of power losses, efficiently match generation and consumption, and improve the reliability of the distribution grid
Range anxiety -- major barrier	• Concerns of EV owners about sharing the battery with the grid • Control over the charging process taken away from EV owner

5. The expected effects of AVs on the performance of V2G

The expected effects of AVs on the performance of V2G were determined through interviews with V2G experts. In the interviews, four high-level variables of the development of AVs that are also relevant to V2G were considered: the level of automation, the level of penetration of AVs, private ownership versus fleet ownership, and shared versus not shared. Table 5 shows the ratings of the current performance of the V2G factors, the expected effect of AVs on the rating of the performance of the V2G factors according to the V2G experts, and the aggregated rating for the expected effects of AVs on the performance of the V2G factors, with the ratings highlighted in green if the rating is expected to improve compared to the current performance, yellow if the rating is expected to remain the same, and red if the rating is expected to become worse.

Table 5: The expected effects of AVs on the V2G factors

Factor	Current	I-1	I-2	I-3	I-4	I-5	I-6	I-7	AV
Frequency regulation	+	+	+	+	++	+	+	+	+
Spinning reserve	+	++	++	+	++	++	+	+	++
Active power support	+	+	++	+	+	++	+	+	+
Reactive power support	+	N/A	+	N/A	+	+	+	+	+
Current harmonic suppression	+	+	+	N/A	+	+	+	+	+
Balance and support RE	++	++	++	++	++	++	++	+	++
System revenues	+	++	+	++	+	+	+	0	+
Battery degradation	-	--	--	--	-	-	0	-	-
Investment cost	--	-	--	--	-	-	0	0	-
Impact on the distribution network	-	0	+	0	-	-	0	0	0
Range anxiety	--	0	0	--	-	-	0	0	0

The experts compared two different scenarios for AVs: fleet-owned shared AVs and privately-owned unshared AVs. Privately-owned unshared AVs were believed to not have significant effects on the performance of V2G because individual preferences and range anxiety remained major barriers. AVs were expected to have the most effects on the performance of V2G when they are fleet-owned, shared, and managed and coordinated in large central charging hubs. The ratings in Table 2 are based on this scenario. The expected effects of fleet-owned shared AVs on the performance of the V2G factors can be summarised as follows:

- The ability to provide spinning reserve services to the grid improves from a driver to a major driver, because of the flexibility of AVs and the response time allowed for spinning reserve services.
- The investment cost of V2G improves from a major barrier to a barrier because charging hubs provide the opportunity to realise a more effective charging infrastructure which includes savings on, for instance, cables and charging spots.
- The impact of V2G on the distribution grid disappears because the flexibility of AVs allows for strategic choices that solve a negative impact on the distribution grid locally.
- Range anxiety disappears due to the mobility services fleet owners will provide. Passengers do not worry about the effect of V2G on the battery because they do not own the vehicle anymore and they expect that the fleet owner will provide them with a vehicle that has sufficient range to reach the desired destination.

The effect of V2G on battery degradation and the potential revenues that can be obtained from frequency regulation, active power support, and the overall V2G system remain uncertain in combination with AVs.

6. The broader implications of the results

The expected positive effects, especially on the V2G factors that are perceived as barriers to a V2G transition, imply that the integration of shared fleet-owned AVs in the transport system would bring a V2G transition much closer. However, most of the interviewed experts predict that a business model that aims at the most successful operation of shared fleet-owned AVs would not give priority to V2G operation of the vehicles. The potential shift to an on-demand, subscription-based mobility service could become a serious threat to the existence of V2G (in this form) if fleet owners rather focus on charging the AVs as efficient as possible and maximise the utilisation rate of the vehicles for mobility purposes because the value of renting out the vehicle is much higher. The system revenues of V2G through shared fleet-owned AVs would be minimised which would result in a focus on different forms of V2G if available, alternative storage options or completely different technologies to balance the grid.

The expected effects of AVs including the broader implications of on-demand mobility services are summarised in Figure 1. The path highlighted in green has a positive effect on the performance of V2G, in yellow a neutral effect, and in red a negative effect.

7. Conclusion

This paper provides new insights for the future integration of the electricity and transport systems by considering an innovative combination of V2G and AVs. Although V2G is considered to be a suitable option to deal with the pressure on the stability of future electricity grids, an assessment of the current performance of V2G shows that the technology has to develop further to improve or mitigate the existing barriers and fulfil the potential promise of the drivers of a V2G transition. Therefore, the potential effects of AVs on the performance of V2G were evaluated for two scenarios: privately-owned unshared AVs and fleet-owned shared AVs. While privately-owned unshared AVs are expected to not have significant effects, fleet-owned shared AVs in combination with charging hubs are expected to enhance the performance of V2G because the ability to provide spinning reserve improves, the investment cost of the charging infrastructure decreases, negative impact on the distribution network can be controlled, and range anxiety disappears. However, uncertainties related to the potential revenues of some drivers and the impact of V2G on battery degradation remain an issue and require further research. In addition, the development of fleet-owned shared AVs is expected to include an on-demand business model that maximises the utilisation rate of AVs for mobility services because the value of renting out the vehicle is much higher than the value of V2G. If the final development path would contain this business model, the priority for V2G would be minimised which would create a new, insurmountable barrier that destroys the business case for V2G systems.

8. Recommendations

In light of a strategic plan of the European Commission to accelerate a European energy system transformation by, amongst others, integrating the energy and transport systems, recommendations for policymakers can be made. AVs could potentially improve some of the barriers to a V2G transition, but the integration of both technologies is not appropriate due to the high level of uncertainty around the drivers of V2G and the expected development path consisting of a focus on on-demand mobility services. AVs can, therefore, for now, develop independently from V2G. In the meantime, policymakers could focus on the question if grid services are to be performed by V2G. If due to future developments, a preference is developed for V2G over alternative storage options and AVs are on a different development path, the integration of both technologies can be reconsidered.

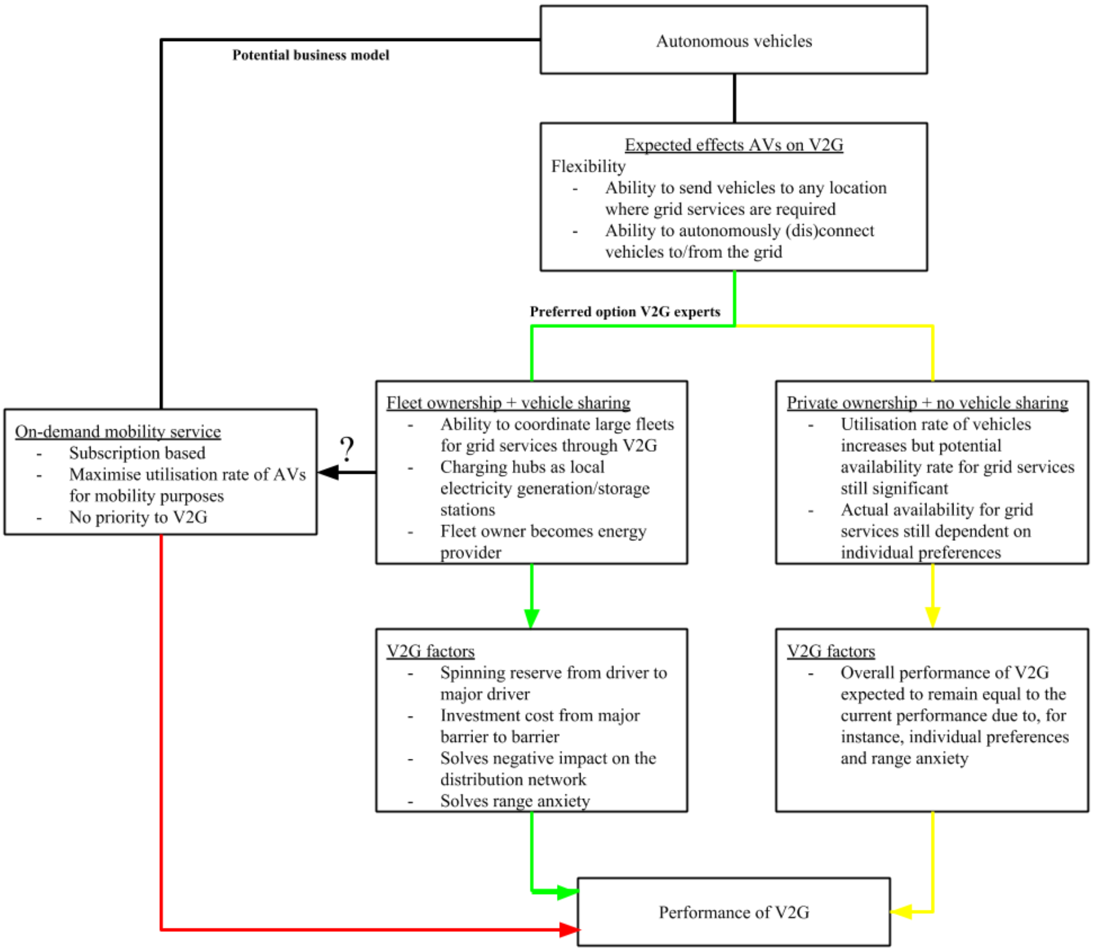

Figure 1: Expected effects of AVs on the performance of V2G

This paper contributed to the body of knowledge on V2G by bridging a gap that existed between V2G and the integration of AVs. This resulted in a comprehensive overview of the current performance of V2G and first insights into the expected effects of AVs on the performance of V2G. Based on these findings, a number of directions for future research can be identified. First, inconsistencies within the scientific literature on drivers and barriers to a V2G transition have to be addressed to work towards a more elaborate overview of the current performance that includes the allocation of costs and benefits for all important actors. Also, the impact of different conditions, such as the types of electricity markets, on the feasibility of grid services through V2G is an important direction to discover the right conditions for V2G and if V2G should be considered as a technology that can provide all grid services or only a number of services under specific conditions. Another recommended research direction is an expansion towards social and institutional related research topics for the transition to V2G, which are currently underexamined. A research direction for V2G could also be to include FCEVs, especially if the adoption rate increases. Finally, research on V2G often does not consider the full spectrum of storage options. Future research into V2G should, therefore, include comparisons to alternative storage options to determine the position of V2G or supplementary options to strengthen the position of V2G.

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Appendix B: Articles and reports included in the literature review

Author(s)	Title	Year
Bohnsack, R., Van den Hoed, R., & Oude Reimer, H.	Deriving vehicle-to-grid business models from consumer preferences	2015
Brooks, A	Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle	2002
Gough, R., Dickerson, C., Rowley, P., & Walsh, C.	Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage	2017
Habib, S., Kamran, M., & Rashid, U.	Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks - A review	2015
Han, S., Han, S., & Kaoru, S.	Development of an Optimal Vehicle-to-Grid Aggregator for Frequency Regulation	2010
Kempton, W., & Tomić, J.	Vehicle-to-grid power fundamentals: Calculating capacity and net revenue	2005
Kempton, W., & Tomić, J.	Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy	2005
Kempton, W., Tomić, J., Letendre, S., Brooks, A., & Lipman, T.	Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California	2001
Loisel, R., Pasaoglu, G., & Thiel, C.	Large-scale deployment of electric vehicles in Germany by 2030: An analysis of grid-to-vehicle and vehicle-to-grid concepts	2014
Ma, Y., Zhang, B., Zhou, X., Gao, Z., Wu, Y., Yin, J., & Xu, X.	An overview on V2G strategies to impacts from EV integration into power system	2016
Mullan, J., Harries, D., Bräunl, T., & Whitely, S.	The technical, economic and commercial viability of the vehicle-to-grid concept	2012
Mwasilu, F., Justo, J. J., Kim, E. K., Do, T. D., & Jung, J. W.	Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration	2014
Parsons, G. R., Hidrue, M. K., Kempton, W., & Gardner, M. P.	Willingness to pay for vehicle-to-grid (V2G) electric vehicles and their contract terms	2014
Peças Lopes, J. a., Joel Soares, F., & Rocha Almeida, P.	Integration of Electric Vehicles in the Electric Power System	2011
Shaukat, N., Khan, B., Ali, S. M., Mehmood, C. A., Khan, J., Farid, U., Majid, M., Anwar, S.M., Jawad, M., Ullah, Z.	A survey on electric vehicle transportation within smart grid system	2018
Sovacool, B. K., Axsen, J., & Kempton, W.	The Future Promise of Vehicle-to-Grid (V2G) Integration: A Sociotechnical Review and Research Agenda	2017
Sovacool, B. K., & Hirsh, R. F.	Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition	2009
Tan, K. M., Ramachandaramurthy, V. K., & Yong, J. Y.	Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques	2016
Yilmaz, M., & Krein, P. T.	Review of benefits and challenges of vehicle-to-grid technology	2012
Yilmaz, M., & Krein, P. T.	Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces	2013

Appendix C: Template expert interviews

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

Question 2:
Based on the scientific literature, important factors to the implementation of V2G were identified. The current status of each of these factors was rated based on the following scale:

--	-	0	+	++
Major barrier	Barrier	Neutral	Driver	Major driver

First, the factors were divided in two categories, drivers and barriers, based on how they are perceived in the scientific literature. If multiple studies on one of these factors showed a significant impact, the factor was rated as a major driver or barrier (++ or --). If the results showed a minor impact or the results from different studies varied considerably, the factor was rated as an driver or a barrier (+ or -). Appendix A (see section 3.12 in this report) shows an overview of all the factors, their potential performance and current rating. Appendix B (see sections 2.2 and 2.3 in this report) gives a short explanation of all factors.

The integration of autonomous vehicles could change the conditions in which the development of V2G takes place. These conditions are, for instance, influenced by the following aspects of autonomous driving:

- Level of automation (for instance: ‘conditional’ and ‘full’ automation. In conditional automation the driver is expected to be available for occasional control of the vehicle while in full automation s/he is not. Full automation comprises both occupied and unoccupied vehicles)
- Shared vs. not shared
- Private ownership vs. fleet ownership (aggregator)
- Level of penetration of autonomous electric vehicles

How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	**Current**	**AV**		**Factor**	**Current**	**AV**
Frequency regulation	+			System revenues	+	
Spinning reserve	+			Battery degradation	-	
Active power support	+			High investment cost	--	
Reactive power support	+			Impact on distribution network	-	
Current harmonic suppression	+			Range anxiety	--	
Balance and support RE	++					

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

Appendix D: Summaries expert interviews

I-1 Summary Interview Marisca Zweistra

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

Ideally, the V2G charging infrastructure is located in an area that often experiences congestion in the network. However, if vehicle owners do not live close to such a location, a charging infrastructure has no added value. AVs solve this issue, because they allow for vehicle owners to live in a different location. The AVs will be able to drive to the required location and connect to the grid autonomously.

Question 2:
How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	Current	AV	Comment
Frequency regulation	+	+	It is very important to have many vehicles available at specific locations to provide this service. AVs will somewhat increase the performance of this service, because they can be sent to such locations. However, currently cars stand idle 95% of the time. If AVs develop further, it is expected that they will be used more frequently which make them less available for freq. reg. (and other services).
Spinning reserve	+	++	The flexibility of AVs improves the performance of this service substantially. However, in the Netherlands, for instance, spinning reserve is not allowed by law due to anti-islanding. Anti-islanding requires a system shutdown during power outages to protect utility workers. Therefore, in theory spinning reserve could add value to the grid, but in some countries this service cannot be performed.
Active power support	+	+	In general, we know where congestion takes place in the grid and find solutions locally. If V2G is used as a solution, the location of the charging infrastructure and how it is operated are important to provide support. AVs do not provide additional value.
Reactive power support	+		N/A
Current harmonic suppression	+	+	AVs will have no influence, because this factor is related to the bidirectional charger.
Balance and support RE	++	++	AVs could be connected close to the renewable energy generators, but in general do not provide significant added value for this factor.
System revenues	+	++	The business case of the network operator and aggregator improves, because the AVs will probably not be privately owned. Consequently, the revenues of, for instance, electricity trading has to be shared with less parties.

Battery degradation	-	--	If AVs will be used more frequently than currently is the case and provide V2G services, the battery lifetime will decrease because of the higher throughput. However, frequent usage and V2G services also result into an increase of the economic value of the vehicle.
High investment cost	--	-	If AVs are charged/discharged in a central location, the investment cost for V2G will decrease, because it will not be necessary to install a V2G system nearby the homes of every vehicle owner. In addition, the investment cost per vehicle are lower due to the reasons mentioned under battery degradation. The use of public space also improves.
Impact on distribution network	-	0	A large fleet of AVs with V2G capabilities could provide support to the distribution network. If the fleet is large enough to ensure the availability of a sufficient number of AVs, the negative impact on the distribution network could be solved.
Range anxiety	--	0	Range anxiety can disappear if AVs are not privately owned, are managed by a fleet owner/aggregator, can be charged/discharged at a central location and the fleet is large enough to ensure availability for both passengers and grid services. Passengers of AVs will not worry if they will arrive at their destination or what V2G will do to the battery, because the AV is part of a mobility service. Fleet owners, on the other hand, will be able to generate revenue when the vehicle stands idle.

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

Ideally V2G-enabled AVs are not privately owned but leased and shared to limit range anxiety and concerns about battery lifetime. Consequently, the vehicles can be used more efficiently. Currently, a disadvantage of car sharing is that you have to go to a specific location to pick up and return the car. If the car can be requested through an on-demand system and arrives at your location autonomously, this issue is solved.

I-2 Summary Interview Mark van Kerkhof

General:
Development of V2G is still in the beginning of the transition process, before the market introduction phase. The development of autonomous vehicles is also in an early phase of the transition process. It is expected that in the next 10 – 15 years the main focus for autonomous driving will be related to safety which makes the connection with V2G limited. The next step will be the introduction of autonomous vehicles in specific areas, such as distribution services. Only after these steps, passenger transport, starting with taxis for instance, will be realised. Even if AVs would develop more rapidly, it is uncertain if they will have a direct relationship with V2G. V2G is often presented as a promising technology, but barriers such as high investment cost might limit its future potential.

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

The development of AVs can include two different types of vehicle ownership; private ownership as currently is the case or fleet ownership in combination with mobility services. If vehicles continue to be mostly private property, the introduction of AV will not result into significant added value for V2G. If AVs become part of a mobility service, it could have an effect on the implementation of V2G. The AVs could then be charged and discharged in a central hub that can be managed by an aggregator. The ideal situation would be that the AV picks people up and drops them off at the desired location and in the meantime drives to a central hub to charge and provide services to the grid.

Question 2:
How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	Current	AV	Comment
Frequency regulation	+	+	If considered from the perspective of the private vehicle owner, the performance would stay the same due to the quick response time needed for the service and the availability of the vehicle which would be similar to the current situation. If considered from the perspective of aggregator or fleet owner that might be able to create a better business case by making (more) AVs available for the service for longer periods of time, this might be preferred over passenger transport. This would improve the freq. reg. performance to ++.
Spinning reserve	+	++	Based on the current situation and from the perspective and business case of the energy market, the performance would improve because the service allows for response time. However, if the most optimal business case for fleet owners is to let the AVs drive as often as possible instead of letting it idle (which currently happens more than 90% of the times), the performance of the service might stay the same because the availability of vehicles for this service might not change.
Active power support	+	++	Same as spinning reserve.
Reactive power support	+	+	Based on the currently available charging infrastructure, the performance stays the same. However, the introduction of AVs might change the charging infrastructure to, for instance, (dynamic) inductive charging. This different type of charging might influence the performance of the factor.
Current harmonic suppression	+	+	Same as reactive power support.
Balance and support RE	++	++	AVs in combination with V2G (and without private ownership) would remove individual interests. An

			aggregator would be able to create a more balanced process, which improves the overall performance.
System revenues	+	+	The system revenues will improve because the charging hubs can be used and amortised by multiple vehicles. However, the performance remains a + because with respect to the overall performance of V2G it is still not perceived a major driver.
Battery degradation	-	--	It is expected that the vehicles will be used more often. Therefore, the battery throughput will increase as well which increases battery degradation.
High investment cost	--	--	The investment cost (and other factors) depend on the implementation choices made for AVs. If central charging hubs will become reality, investments needed for these hubs are lower than the investments needed for an V2G installation in every house. However, research has also shown that if parking garages would be used as hubs, at least the same number of parking garages would be required as currently available.
Impact on distribution network	-	+	V2G in combination with AV results in less dependency of the distribution network. This creates a somewhat autarchic system. In addition, AVs make it easier to predict demand and supply which is interesting for the network operator. The charging hubs become small electricity generation stations, which is better for the distribution grid than V2G installations in houses.
Range anxiety	--	0	AVs solve range anxiety. Mobility will be part of a service that guarantees sufficient range.

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

The development of residential areas seems to include less visibility of cars. If V2G can be combined with AVs, AVs could be used to provide full mobility service or “the last mile” between transportation hub and the final destination. When not used for transport purposes, the AVs could independently drive to central charging hubs nearby the residential area to charge and serve as electricity supplier.

I-3 Summary Interview Esther Park Lee

General:
Pilot projects have shown that implementation of V2G technology is possible in the future. Future developments will make it easier to reduce investment cost, which is currently one of the main barriers. It is important to consider how V2G is presented to the EV driver and how we deal with uncertainties, such as battery degradation. In addition, it depends under which conditions we use the vehicles. If we allow batteries of the vehicles to be drained, it will have a negative impact on the technology. Therefore, we should find the right conditions or constraints with respect to the technical aspects and how much V2G services consumers are willing to provide. Since controlled charging has already been applied, V2G integration should also be feasible when the right conditions for charging and discharging are defined. There is a

big responsibility for future aggregators and network operators to not increase the problems related to V2G. If V2G will become available, it will be an option to make the system work better and will be combined with smart charging. A certain percentage of the EV owners will participate in V2G, a certain percentage in smart charging, and a certain percentage in a mix of both. These activities have to be properly coordinated.

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

One of the interesting features of V2G is that you can use the vehicle in parts of the grid where it is needed. AVs create an opportunity to autonomously send vehicles to these required locations. Therefore, there could be some valuable synergies between V2G and AVs. AVs will not necessarily help the implementation of V2G, but it could improve the potential of V2G in helping the electricity system.

Question 2:
How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	Current	AV	Comment
Frequency regulation	+	+	See comments under spinning reserve
Spinning reserve	+	+	The added value of AVs depends on the ownership structure. If AVs are privately owned, vehicles could be used for V2G services more often because currently they often stand idle. The EV owner would have the opportunity to earn money during these periods. If the ownership structure shifts to fleet ownership, it would become more difficult to coordinate the vehicles for V2G services. The fleet owner would have to consider the driving needs of many consumers that use vehicles from the fleet. Especially if consumers are allowed to book a vehicle on-demand, coordination becomes more difficult. The aggregator would then have to make a trade-off between renting out the car and providing V2G services. Renting the car would probably generate more revenue. In addition, a fleet owner would not have a surplus of vehicles just to participate in V2G, because it will be difficult to recover the investment.
Active power support	+	+	See comments under spinning reserve
Reactive power support	+	N/A	
Current harmonic suppression	+	N/A	
Balance and support RE	++	++	AVs could be flexible resources for the electricity system which increase the potential to earn money through V2G in the electricity market. If in one part of the grid a lot of

			renewable energy enters the grid, aggregators could take advantage of the cheaper tariffs by sending the AVs to those parts of the grid. In addition, AVs could be easily moved to a different location when their battery is full which creates an open charging spot for another AV to charge and balance the system. This increases the utilisation rate of charging spots.
System revenues	+	++	In a scenario where you know that the vehicles will not be used for a certain number of hours, the system revenues for fleet owners could improve. It that case, it does not matter where the vehicles are parked, because you can use send them to any preferred location. In case of private ownership, the system revenues increase as well because cars often stand idle which creates opportunities for V2G services.
Battery degradation	-	--	If AVs can provide more V2G services, the battery degradation will accelerate. Fast charging is expected to have a bigger impact on the battery degradation than V2G. Car manufacturers will probably change the business models for batteries. They might make different contracts where they not just sell the battery but give some kind of guarantee on the battery or lease the battery.
High investment cost	--	--	Depending on the revenues that might be obtained through the increased utilisation rate of the charging spots, the investment costs might somewhat decrease. In general, the required investments remain substantial.
Impact on distribution network	-	0	AVs improve this factor because vehicles can be sent to any location to try to balance the impact on the distribution grid locally. From a system perspective it will be solved. However, if you have a lot of demand in one area and the impact on the distribution network is made worse by charging a lot of vehicles, AVs can be sent to discharge. This raises a question about transaction cost, because vehicles will be used to solve a problem that is caused by other vehicles. How much should be paid by the vehicles causing the impact and paid to the vehicles dealing with the impact?
Range anxiety	--	--	AVs will offer improvements in relation to range anxiety, but also create disadvantages. On the one hand, AVs could search for a charging spot to ensure the battery is charged. On the other hand, AVs could increase the number of V2G services provided by the vehicle which could cause range anxiety.

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

AVs should be fully automated, so they can move without a driver present. The charging technology of these vehicles should be improved towards inductive charging, which will be better for V2G. There should be a mix between private ownership and fleet ownership of the AVs. Each type of ownership could provide V2G services that fit their profile. With fleet ownership, there is a trade-off challenge of what to focus on; energy or mobility. The challenge of private ownership is to convince consumers to participate in V2G programmes. The charging infrastructure would not have to change radically, because central and distributed charging locations will be required based on where the vehicles are needed.

I-4 Summary Interview Prof. Bart van Arem

General:
There are quite some discussions on in what way AVs will be implemented. Automation level 5 will not to be implemented for a long time. Level 4, autonomous driving on the highway, might be feasible at some point. Currently, level 2 is available is more and more vehicles on different locations.

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

The link between V2G and AV can mainly be found on institutional level. It is expected that AVs, especially from level 3 – 5, will used on a subscription basis through private or business lease, not privately owned. This will make it easier to define who is responsible for the vehicle, insure them, manage software updates and manage the fleet. If these vehicles would be shared as well, they can be used more efficiently by more people. This will improve the business case for the vehicles and enables fleet owners to replace the cars faster. This can be beneficial for V2G as well. The car manufacturer or fleet owner/aggregator then also becomes an energy provider.

Question 2:
How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	Current	AV	Comment
Frequency regulation	+	++	AVs can connect to the grid without human support and can drive to the required charging/discharging locations. Their potential to provide freq. reg., therefore, improves.
Spinning reserve	+	++	Improves because AVs have enough response time to provide the service.
Active power support	+	+	Compared to current EVs, AVs do not influence the performance. EV owners could also connect their EVs to the grid during certain time periods agreed upon with the aggregator.
Reactive power support	+	+	With AVs it becomes easy to determine where the vehicle is positioned on the road. This could be an important condition for inductive charging. The performance of this factor will not change for the current charging infrastructure. If AVs support a change to, for instance, an inductive charging infrastructure, the performance might be different.

Current harmonic suppression	+	+	Same as reactive power support.
Balance and support RE	++	++	The most important issue is the difference between seasonal generation of renewable energy which cannot be covered by batteries. AVs will not influence the factor differently than currently can be done through EVs and V2G.
System revenues	+	+	The revenues will increase slightly, because the vehicles can be used more efficiently, and AVs strengthen the transition to fleet ownership.
Battery degradation	-	-	The battery might have to be replace faster, but this is mainly due to the fact that the vehicles will be used more often. By sharing the vehicles and using them more efficiently, more value is generated. One important question is if people will be able to choose battery power. If the operation of the car can be adjusted, it might still lead to inefficient use of the battery of the vehicles.
High investment cost	--	-	Investment costs can be decreased through sharing and by creating central charging hubs (including more facilities such as maintenance and cleaning). Governments have to be involved in creating these hubs. The hubs could, for instance, be created close to train stations or within residential areas.
Impact on distribution network	-	-	Same as without AVs.
Range anxiety	--	-	An AV will not drive to a passenger if it is not sufficiently charged. Since vehicle use will be based on a subscription, the passenger is probably guaranteed to be able to request a vehicle that will bring him/her to the required destination. AVs will improve the range and therefore potentially change the distance for which range anxiety occurs, but it will not solve it. A shift to inductive charging could solve range anxiety. If inductive charging could be applied, the required battery capacity of a car could be decreased which makes the vehicle lighter and more efficient.

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

Spatial changes are required, such as good geographical availability of charging stations. An important feature of the AV is that it can automatically drive to the required location, park and connect to the grid. AVs need to be charged in a central location/e-hub to realise fleet management and have an on-demand system that drives to a passenger when requested. We do not have to own the vehicle. A personalized experience can be created through account login.

I-5 Summary Interview Prof. dr. Ad van Wijk

General:

The development of EVs and V2G should not only focus on BEVs, because BEVs cannot provide seasonal storage and charge from the same network as where it supplies the electricity to during discharge. BEsV are mainly useful for balancing daily supply and demand due to the price differences in the electricity market. Fuel cell electric vehicles (FCEV), on the other hand, are not dependent on the electricity network. FCEV use hydrogen to power an electric motor. Hydrogen can be stored more easily and cheaper. It can also be distributed through the gas network. The capacity of the gas network is 10 – 20x larger than the electricity network. In case of large-scale implementation of BEVs, the electricity network needs to be upgraded significantly to meet the requirements of all systems. The hype around BEVs mainly takes place in the Netherlands and in Norway around Oslo. Most other countries (in Europe) and car manufacturers have not made a clear decision yet for either FCEVs or BEVs and continue to investigate both. When discussing V2G, both options should be considered as well.

Question 1:

What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

The development of AVs is, amongst others, important to stimulate the integration of V2G technology. AVs could positively influence V2G services, because they will be able to connect and disconnect from the charging stations without any human support. This feature of automated connecting and disconnecting from the grid is an important precondition for AVs to be beneficial for V2G technology. This will result into more flexibility. AVs would work best for services where a response time is allowed. If needed, AVs not connected to the grid can be called to areas where they are needed to support the grid.

Question 2:

How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	**Current**	**AV**	**Comment**
Frequency regulation	+	+	Market for freq. reg. is not large enough for all vehicles to participate and vehicles have to be connected to the network to participate. It takes too much time to send AVs that are not connected to the grid to a charging station to provide freq. reg.
Spinning reserve	+	++	This is one of the services where AVs would be highly beneficial. In case of an emergency, AVs could be sent to areas to connect to the network and provide reserves.
Active power support	+	++	When a deficiency of electricity can be predicted and there is sufficient response time to send the AVs to relevant areas, the quality of active power support can be improved.
Reactive power support	+	+	This factor is related to the equipment used for the network, not the battery or the vehicle. AVs will have no influence.
Current harmonic suppression	+	+	This factor is related to the equipment used for the network, not the battery or the vehicle. AVs will have no influence.

Balance and support RE	++	++	Remains a major driver. An important question is how AVs (and V2G) will be organised. If there will be a central location to park the AVs instead of parking them in the streets, it will be easier to deliver this and other services.
System revenues	+	+	If AVs are parked centrally, better services can be delivered, but it is not sure if system revenues will increase. Recent studies implicitly assume that EVs are connected and disconnected automatically, while this is probably only true when AVs are implemented. In addition, current revenues are based on the current market which includes cheaper electricity for instance at night that is generated through cheap fossil fuels, such as coal. A larger share of renewables in the grid will change the market and, therefore, also the potential system revenues.
Battery degradation	-	-	Battery degradation related to V2G depends on the charging cycles. AVs do not influence this. AV will improve the battery degradation through better driving practices.
High investment cost	--	-	If AVs would be charged and discharged centrally, the charging infrastructure and cables can be organised more efficiently. Investment cost could be decreased through optimal charging points and the upgrade of the electricity system is mainly needed at those central locations instead of all homes. This could lead to cheaper charging infrastructure and electricity infrastructure.
Impact on distribution network	-	-	AVs will not influence this factor. The impact on the distribution network is mainly related to charging EVs. As mentioned for investment cost, central charging locations could lead to cheaper investment cost for cables needed to support the increased impact on the distribution network and lead to more effective discharging of EVs. However, the latter is also included in smart charging which is already applied.
Range anxiety	--	-	Only expected to positively influence range anxiety if private ownership would change into a shared system. If not, no effect expected. In addition to range anxiety, a big problem is that EVs are currently connected to the grid much longer than needed (for instance at night). The charging infrastructure is not sufficient yet. AV could help to move vehicles when fully charged and find available charging points. Also, fast charging currently takes around 30 minutes which is too long for social adoption.

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

Highest level of automation possible. A shift from private ownership to shared/fleet ownership (‘Uber model’) could have an important impact in cities. Waiting time for the AV to arrive cannot be too long, so it might not work outside of cities. With regard to V2G, it is not expected to have a significant impact if only BEVs are considered, because BEV will have a limited role in the future electricity system. AVs can improve V2G if the AVs are charged/discharged in a central location. However, this will especially be relevant for FCEV.

I-6 Summary Interview Bram van Eijsden

General:
V2G does not develop as fast as expected. There are pilots on V2G, but it is not ready for roll-out. Network operators believe that smart charging is very important to shave peaks. V2G is not considered to as important by the operators. It is unclear what the added value of V2G is and who it is for. TSO? In addition, it is unclear if vehicle owners are willing to participate in V2G. However, if V2G would be implemented, vehicle owners would probably not notice that their vehicle is used for grid services.

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

Autonomous driving is an expensive technology. Revenues will have to be generated through driving. Fleet owners are, therefore, probably not willing to provide services to the grid if the utilization rate needs to be maximised. On the other hand, it could also mean that fleet owners can earn money when the vehicle stands idle. It depends on the business model of the vehicle owner. If vehicles would be privately-owned and available for V2G services, it becomes interesting because the vehicle can drive to the required location autonomously. AVs could only have impact on V2G if the vehicle is fully automated.

Question 2:
How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	Current	AV	Comment
Frequency regulation	+	+	Depends on if the utilisation rate of the AVs needs to be maximised for mobility services. If so, AVs have no effect on this factor. If not, the performance of this factor might be improved.
Spinning reserve	+	+	Depends on if the utilisation rate of the AVs needs to be maximised for mobility services. If so, AVs have no effect on this factor. If not, the performance of this factor might be improved.
Active power support	+	+	Depends on if the utilisation rate of the AVs needs to be maximised for mobility services. If so, AVs have no effect on this factor. If not, the performance of this factor might be improved.
Reactive power support	+	+	If we move to autonomous driving, it will also include autonomous charging or inductive charging. Inductive charging will not have a negative effect on the grid. General guidelines will make sure of that. Under current conditions AVs do not have impact on this factor and for inductive charging no problems are expected either.

Current harmonic suppression	+	+	See reactive power support.
Balance and support RE	++	++	This factor improves (higher rating not possible due to scale. Private owners of AVs can store electricity that is generated by their own solar panels (or other renewable energy sources) and use it later.
System revenues	+	+	Depends on if the utilisation rate of the AVs needs to be maximised for mobility services. If so, AVs have no effect on this factor. If not, the performance of this factor might be improved.
Battery degradation	-	0	Further research is required to determine the actual impact of V2G. Simulations of impact on the battery are usually not reliable. V2G probably have a neutral impact on the battery, especially if you consider potential impact on the battery in the algorithms for V2G operation. If battery is not allowed to be completely empty or full and switching between charging and discharging does not happen too fast, the effect is expected to be neutral.
High investment cost	--	0	Is the required investment cost really that high? The costs for the technology are hardware are not too bad. The same goes for the charging station. Most of the costs are included in creating a market model for the aggregator. By the time AVs are integrated, the investment cost will be neutral. V2G could then be an option to add to your AV.
Impact on distribution network	-	0	Impact on the distribution network is solved because AVs can be sent to any required location in the grid to address congestion locally.
Range anxiety	--	0	Range anxiety is not a big problem. Currently, there are EVs that have a range of 300/400 kilometres. This will be the standard for AVs. Range anxiety will then completely disappear. In addition, it will be possible to charge the vehicle faster, in 10 minutes.

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

It is not a given that people will be willing to share vehicles. It might make more sense to have a second vehicle that is shared. Privately-owned vehicles have a minimal impact on the grid and might not be able to guarantee availability of the vehicle to an aggregator. If one owner owns a fleet of a large number of vehicles, this fleet owner actually has something to offer to V2G aggregators.

I-7 Summary Interview Sjoerd Moorman

General:
V2G is a form of electricity storage. The demand for storage might not be as high as initially expected, because there are enough options to shift the demand, like smart charging. However, there will be a future for storage. V2G might play a role in that future. The costs for the chargers

will decrease. The second generation of V2G chargers is coming. These (wall) chargers are smaller than first generation V2G chargers. The most cost-efficient way to operate V2G is by integrating it into the cars. Then it can be included in the production of the car and separate V2G charging stations are not needed anymore.

Question 1:
What effect do you expect autonomous electric vehicles to have on the implementation of V2G technology?

If vehicles are fully automated, AVs can be charged through fast charging and in clusters. If AVs would discharge to the grid, it will take extra time to charge the car which cancels out the effect of smart charging. Therefore, if fast charging will be applied to AVs to increase the utilisation rate as much as possible, the vehicle will have no time to provide V2G services. Especially during the day. At night it might be different, because there is less demand for mobility. However, there is also less demand for V2G services. One of the most important reasons to implement V2G is because vehicles stand idle often which provides an opportunity to create value. If the vehicles can be used for mobility services, it will always be more valuable than V2G.

Question 2:
How and why would the rating of (some of) the V2G factors change if autonomous electric vehicles would be integrated in the transport system?

Factor	**Current**	**AV**	**Comment**
Frequency regulation	+	+	Potentially high value, but it depends of the country and the market is small which makes it saturated quickly. Therefore, in countries with a high value for this service, the potential value for V2G increases quickly and the beginning and then stagnates. In addition, if AVs increase utilisation of the vehicle for mobility services, the availability for V2G is reduced. Therefore, the performance is not improved and could potentially go towards 0.
Spinning reserve	+	+	This service is mainly valuable for parts of the U.S. and emerging countries. If AVs increase utilisation of the vehicle for mobility services, the availability for V2G is reduced. Therefore, the performance is not improved and could potentially go towards 0.
Active power support	+	+	Peak load shaving is already applied on a large scale for the electricity network. V2G can mainly be used on local level. if AVs increase utilisation of the vehicle for mobility services, the availability for V2G is reduced. Therefore, the performance is not improved and could potentially go towards 0.
Reactive power support	+	+	Not related to AVs
Current harmonic suppression	+	+	Not related to AVs

Balance and support RE	++	+	If AVs increase utilisation of the vehicle for mobility services, the availability for V2G is reduced. Therefore, the performance is not improved and could potentially go towards 0.
System revenues	+	0	If AVs increase utilisation of the vehicle for mobility services, the availability for V2G is reduced. Therefore, the performance is not improved and could potentially go towards 0.
Battery degradation	-	-	AVs do not affect the impact of V2G services on the battery.
High investment cost	--	0	Depends on the amount of sharing: i) when private: AV does not affect charger cost ii) when shared: charger is shared, so costs can be shared and investment cost are not a barrier anymore.
Impact on distribution network	-	0	If placed and coordinated well, impact can be reduced to 0.
Range anxiety	--	0	AVs make range anxiety negligible

Question 3:
How would you shape the development of autonomous electric vehicles to create the best possible conditions for V2G technology?

The development of shared AVs includes a shift towards fast charging to maximise utilisation rate of the vehicles. This implies that the vehicles will not be available for V2G services. The services needed to balance the grid through storage could also be provided by alternative storage options. V2G could still be relevant if some of the AVs are privately owned, because they will still stand idle some part of the day. However, effect of privately-owned AVs on the current performance of V2G is minimal.

I-8 Summary Interview Gautham Ram Chandra Mouli

General:

AVs will kill the business case for V2G. AVs are driving as much as possible, parked as least as possible. Fleet owners will always have to meet demand and supply so at night less people will need the car, and thus there will be some time that these cars are not moving much. During the day it will be difficult to plan when the vehicles would be available for V2G services due to the on-demand mobility service. If AVs are not shared, then their availability rate would increase. However, this is not expected to significantly improve the performance of V2G.

Under current conditions, people would be more openminded for V2G if the bidirectional charger would be part of the vehicle by default (an on-board charger). This would remove the complexity of having to install a V2G charger. In addition, the costs of the charger will be lower and vehicle owners would not have to make additional investments.

Hydrogen fuels can impact the current performance of V2G. Hydrogen can provide energy forever as long as you have a hydrogen tank.

People seem to underestimate the competition from other technologies. V2G competes with stationary storage and, in case of AVs, would compete V2G by non-autonomous vehicles. Increasing revenues from V2G services would also mean alternative storage options have a bigger chance of getting that extra revenue because they are usually dedicated to providing these services. Supercapacitors and hyper capacitors (which combine a capacitor and a battery) are also fast responding and great for grid services. In addition, a future can also be imagined where big trucks loaded with batteries can go to emergencies and give back up services (or music festivals to locations in the middle of nowhere). Some of the benefits of V2G can already be obtained by making smart electrical charging obligatory, which, for instance, includes not being allowed to plug in at peak hours. Policy needs to introduce this.

There is a positive business case for the services V2G needs to provide. However, the business case is expected to not be positive for V2G.