Coversheet

How to cite this publication
Please cite the final published version:

Noel, L., Zarazua de Rubens, G., & Sovacool, B. K. (2018). Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark. *Energy, 153*, 628-637. doi:https://doi.org/10.1016/j.energy.2018.04.076

Publication metadata

Title:	*Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark*
Author(s):	*Noel, L., Zarazua de Rubens, G., & Sovacool, B. K.*
Journal:	*Energy*
DOI/Link:	*https://doi.org/10.1016/j.energy.2018.04.076*
Document version:	*Accepted manuscript (post-print)*

Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark

Lance Noel[1,*], Gerardo Zarazua de Rubens[1], Benjamin K. Sovacool[1,2]

*Corresponding Author. Email: lnoel@btech.au.dk

[1] Center for Energy Technologies, Department of Business Development and Technology,
Aarhus University, Denmark

[2] Science Policy Research Unit, University of Sussex, United Kingdom

Abstract: This paper examines the social costs and benefits of potential configurations of electric vehicle deployment, including and excluding vehicle-to-grid. To fully explore the benefits and costs of different electric vehicle pathways, four different scenarios are devised with both today's and 2030 electricity grid in Denmark. These scenarios combine different levels of electric vehicle implementation and communication ability, i.e. smart charging or full bi-directionality, and then paired with different levels of future renewable energy implementation. Then, the societal costs of all scenarios are calculated, including carbon and health externalities to find the least-cost mix of electric vehicles for society. The most cost-effective penetration of electric vehicles in the near future is found to be 27%, increasing to 75% by 2030. This would equate to a $34 billion reduction to societal costs in 2030, a decrease of 30% compared to business as usual. This represents a projected annual savings per vehicle of $1,200 in 2030. However, current vehicle capital cost differences, a lack of willingness to pay for electric vehicles, and consumer discount rates are substantial barriers to electric vehicle deployment in Denmark in the near term.

Keywords: vehicle-to-grid; electric vehicles; renewable energy integration; externalities; climate change mitigation

Acknowledgements: The authors would like to thank Torbjørn Christensen and Jens Holger Helbo Hansen of the Ministry for Taxation (Skatteminister) for their assistance in understanding and calculating the Danish vehicle tax scheme. The authors would also like to thank Christian Thiel of the Directorate-General Joint Research Center, Sustainable Transport Unit for providing data regarding charging profiles. The authors would also like to thank Johannes Kester for his help reviewing the manuscript. This research is supported by the Danish Council for Independent Research (DFF) Sapere Aude Grant 4182-00033B "Societal Implications of a Vehicle-to-Grid Transition in Northern Europe."

List of acronyms and abbreviations

EVs – electric vehicles
EVSE – electric vehicle supply equipment
ICEV – internal combustion engine vehicle
V1G – one way communication vehicle-to-grid
V2G – vehicle-to-grid
WTP – willingness-to-pay

1. Introduction

The general benefits of electric vehicles (EVs) are well-documented in the literature on transport and energy policy. For example, it has been estimated that gasoline combustion for passenger vehicles causes $26 billion in health damages annually [1]. Likewise, EVs are an integral part of modeling of systems with the aim of complete carbon emission mitigation [2]. In combination with renewable electricity, many studies have found the large-scale de-carbonization transition to be cost optimal, especially including electrification of heat and transport [3]. Moreover, EVs have the ability to provide storage to intermittent renewable electricity sources, using vehicle-to-grid (V2G) technology [3], [4]. However, these previous studies utilize computationally intensive models, which limit their resolution (i.e. they only model every 5% EV penetration), as well as their technologies of choice. As such, many large-scale renewable energy models do not include V2G-capable (or any kind of) EVs [5]–[7]. Many others include only a cursory look at the interaction between EVs and renewable energy [3], [8]–[10]. This paper aims to more comprehensively explore the role of EVs and renewable energy to supplement larger socioeconomic studies that aim to model complex interactions between renewable energy and electrification of transport, using Denmark as a case study Denmark offers an illustrative case study as its primary transport and energy challenges, like most European countries, center on decarbonization and electrification [11], and Denmark also can provide a laboratory of real world experience related to EV and V2G diffusion [12].

Granted, there has been a plethora of studies that investigated the integration of electric vehicles into the electric power system, particularly from a technical (as opposed to socioeconomic) perspective of grid impacts and renewable energy integration [13]. Indeed, most of the recent literature tends to not compare different levels of communication ability (i.e., non-controlled or random charging, often called "dumb charging," vs. controlled charging, known as "smart charging" or V1G, vs V2G), and usually does not calculate societal costs nor cost optimize, and instead focuses exclusively on the grid's performance. For example, a recent paper found that increasing levels of EV penetration would increase renewable energy utilization and reduce carbon emissions in Croatia [14], but did not cost optimize nor discuss V1G/V2G. Other papers have found that the technical impacts of EV grid integration are potentially negative [15], [16], but could provide benefits with market formation and communication.

Another common topic was how EV integration influences renewable energy usage [17], [18], but these papers tend not to calculate total societal costs. In this thread, Forrest et al. modeled various combinations of renewable energy penetration and combinations of dumb charging, V1G and V2G communication ability, finding that V2G can completely obviate the need for secondary stationary storage to reach high renewable energy levels [19] (but only modeled certain combinations of EVs and renewables, and did not calculate any cost-related metrics). Those that did include cost in their calculation did not compare costs between all the possible charging scenarios, and took comparatively narrow approaches to cost. For example, Kara et al. finds that implementation of V1G can reduce a consumer's monthly bill by about 25%, largely due to reductions in maximum demand [20]; though this paper does not include V2G, nor cost optimizes across all possible penetrations. Next, Graabak et al. modeled the impact of 100% EV penetration on the Nordic region transmission grid and compares dumb and V1G charging strategy's, finding that V1G can greatly decrease requisite investment in Nordic transmission upgrades while maximizing electricity-grid related welfare [21]. Some, such as Seddig et al, compared both renewable energy integration and consumer cost, and found that that V1G charging increases renewable energy utilization and reduces consumer costs [22]. Most comprehensively, Ekman compared dumb, V1G, and V2G communication and found that electrification of transport and increased communication has a positive impact on renewable energy utilization in Denmark [23], but did not present the societal cost-benefit across different levels of implementation.

As compared to the existing literature, this work aims to make four novel contributions. First and foremost, the model here introduces comprehensive socioeconomic cost-optimization for all levels of EV penetration, with and without externalities. Secondly, the results show both the specific societal cost-benefits and renewable energy integration benefits between dumb charging, V1G, and V2G. Thirdly, this paper includes a more realistic cost of EV deployment, using a WTP cost premium, instead of assuming there is no cost (and also no transportation-related benefit) of switching from ICEVs to EVs. Fourthly, the results also show the role that the future integration of wind and reduction of battery prices has on the overall cost optimized EV penetration, as well as the necessity of EV communication. The model and results are presented for the three scenarios (Dumb, V1G and V2G) in Danish power system exclusively between 2015-2030, the end date of 2030 corresponding with national policy targets for a carbon-free electricity sector [24].

2. Research Methods: Modeling, Data Collection, and Cost Calculation

As our primary method, an iterative model was developed that calculates the costs of transportation and electricity for each percent of EV implementation, i.e. 1% to 100% of total vehicles in Denmark are electrified, under each of the three scenarios. As a baseline, the total costs of the system assuming minimal EV implementation, i.e., 1% penetration was calculated. Next, the costs and benefits of "Dumb" EVs were calculated, meaning the EVs have no communication ability, and charge blindly, which largely reflects current practices. Secondly, the costs of EV implementation assuming one-way communication ("V1G") that facilitates so-called "smart charging" were calculated. Essentially, this allows the EVs to shift demand over the day to when renewable electricity production is highest. Lastly, the costs and benefits of EVs assuming full communication and power bi-directionality were calculated, termed as "V2G". While there are many benefits of V2G EVs, such as participation in the frequency regulation, spinning reserves, and other markets (many of which are not even developed yet), the model only calculates the benefits of V2G providing storage for excess renewable electricity, and decreasing dispatched conventional electricity, and the existing ancillary services market. For each of these various scenarios, the model calculated the net present cost over a lifetime of 25 years, see section 2.3 below.

2.1 Model Description

For each of the above-mentioned scenarios, the Danish electricity grid was modeled, based on 2015 hourly load, 2015 hourly actual wind and solar production [25], and estimated charging profiles, based on an EU study [26]. All modeling was conducted in MATLAB using scripts written by the authors. For each percentage point of EV implementation, the additional load from EV charging was modeled on the electricity system at each hour for the year 2015, based on an aggregated charging profile. For the “Dumb” EV scenario, it was assumed that the charging profile could not be shifted. If that specific hour had excess renewable generation, then the additional EV load could be met through renewable energy – otherwise, the system would necessitate increased conventional generation, or if already at maximum capacity, the construction of new combined heat and power (CHP) natural gas plants to meet this load. See Figure 1. For both the V1G and V2G scenarios, the difference in the *total* daily EV load and excess renewable generation was calculated, in order to estimate the benefit of the EVs being able to shift load throughout the day. If the daily EV load exceeded the amount of renewable generation throughout the day, this additional load was proportionally allocated throughout the day in order to reduce the maximum conventional, and likewise reduce the need to build new natural gas plants. Finally, in the V2G scenario, the model also allowed for the possibility of V2G storing the excess renewable electricity to displace both new and current conventional generation (assuming EV load had already been met). In addition, as discussed above, V2G currently participates in ancillary services [27], and the model includes the cost-benefits of participation as V2G capacity increased, with aggregator costs removed. At the end of the year, the model calculates the required new capacity to be built, as well as the energy distributed into current conventional generation, renewable generation, and new natural gas generation. Based on these results, the model then calculates the net present cost over 25 years (the usual life-span of an electricity generation plant [28]) for each of the various scenarios and combinations of EV penetration.

[*Insert Figure 1 here*]

2.2 Data Collection

The model is based on collecting several inputs for cost and other technical parameters from a review of the current literature. See Table 1 for a summary of the data utilized by the model. The data collected can be broken into three categories; costs related to EVs, costs related to internal combustion engine vehicles (ICEVs), and costs related to the electricity system.

2.2.1 Electric Vehicle Related costs

EVs have several costs to society as EV penetration increases. First and foremost, the primary cost of EVs is the potentially higher capital cost when compared to a typical ICEV. However, due to the relative novelty of EVs, the switch from an ICEV to an EV would require either a behavior change to adapt to a lesser driving range (at no additional, and perhaps a lower capital cost) or a substantially more expensive EV that has a range similar to current ICEVs (e.g. a Tesla Model S). This choice depends on individual characteristics and decisions and is heterogeneous across the Danish population. To capture the variation of individual's willingness to purchase an EV, recent willingness-to-pay (WTP) was used that allowed differentiation of WTP across a population [29]. The stated WTP was then added, or in some cases subtracted, from the estimated cost of an EV to see what the "true" societal capital cost would be, as shown in Equation 1. Then, the model calculates the difference between this adjusted EV capital cost and the average capital cost of a comparable ICEV vehicle within the same class, based on average sales in Denmark [30] [31], with taxes removed, for each percentage point of the Danish population. One should note that, with taxes excluded, an average small ICEV car in Denmark can cost as little as $8,500, and Denmark has had historically the cheapest ICEVs within the EU when excluding taxes [32]. For more information, see the Appendix. To estimate future differences between EV and ICEV capital costs, battery cost was adjusted in Equation 1 based on estimated future decreases to battery prices [33], based on innovation and technological learning, in turn decreasing the cost difference between ICEVs and EVs.

Equation 1. Estimated Cost of Electric Vehicle j for person i

$$EV\_Cap_{ijy} = \left((k * BC_y * S_j) - ICEV_j\right) - WTP_{i,j}$$

Where	EV_Cap	*equals*	Capital Cost to Incentivize Person i to Purchase EV_j (in $/car)
	k		Estimated Proportion of Battery of Total Electric Vehicle Cost
	BC		Cost of Battery (in $/kWh)
	ICEV		Average Gasoline/Diesel Vehicle Cost (in $)
	WTP		Stated WTP (in $)
	S		Size of Battery (in kWh)
	y		Year

Next, the second cost associated with EV implementation is the charger, also known as the electric vehicle supply equipment (EVSE). It was assumed for each EV there would be two EVSE's - one at home, and one public – while the optimal mix of EVSE was assumed to be 90% level 2 AC (at home and at work) and 10% public level 3 DC [34]. The AC EVSE cost $3,000, and the level 3 DC charger $30,000, based on estimates from the literature [35]–[37].

Thirdly, one advantage of the EV is decreased maintenance cost in comparison to an ICEV, as result of the reduction of moving parts. Thus, for every vehicle that was modeled to switch from an ICEV to an EV there would be a yearly benefit to society in a reduction of maintenance cost. This cost differential, while not completely understood due to the youth of the EV industry, was estimated based on the literature [31], which found such benefit to be $280 per year.

Finally, the fourth cost associated with EVs is the additional electricity load as result of charging batteries from driving. To accurately model the additional load, the model calculates an hourly charging profile per average individual EV, based on a recent report on load profiles (inclusive of driving and parking patterns) [26]. This hourly charging profile was then scaled up, depending on the total amount of EVs modeled, and then added to the total electricity load. The costs of this additional load to the electricity system, and potential increases in externalities due to EV charging is described below in Section 2.2.3.

2.2.2 Internal Combustion Engine Vehicle Related Costs

Conversely, there are various societal costs associated with the continued use of gasoline and diesel in ICEVs. Unlike EVs, it was assumed that there would be no capital costs associated with ICEVs, as the Danish population already had purchased ICEVs, and the counterfactual would be continued ICEV operation. However, for every vehicle that remains an ICEV, there are several costs to society, namely; fuel costs, health costs, and climate change emissions.

To estimate the fuel costs, first the average mileage efficiency of ICEVs was calculated, which was based on a recent Danish transport study, modeled for various types of vehicles for the years 2015 and 2030 [31]. Based on this report, average gasoline ICEVs will achieve 18 km/l in 2015 and will increase to 26.5 km/l by 2030, and the average diesel ICEV will achieve 20.3 km/l in 2015, increasing to 27.6 lm/l by 2030 (28). The total average annual kilometers driven per car based on average daily distances driven was calculated [38], and then divided by the average mile efficiency to find total annual gasoline consumption. Next, this was multiplied by the current average gasoline prices, with taxes excluded [39]. To account for the natural increase in gasoline prices, the cost of gasoline was then increased, based a recent EIA report on global oil barrel prices, increasing from a current $50 per barrel to just about $100 per barrel [41] .

2.2.3 Externality costs (air pollution and climate change)

In the scenarios that include externalities, the damages associate with particulate matter emissions from the combustion of gasoline were monetized. This was calculated based on a health-cost analysis done specifically for Danish ICEV emissions and their impacts on Denmark and the neighboring European Union [42]. This was then scaled up or down based on the amount of gasoline consumed [43]. Likewise, gasoline also emits climate change inducing gases. The carbon content of gasoline was obtained from the EIA, and then converted into metric tons per liter for both gasoline and diesel [44]. These were then converted into monetary damages by multiplying these contents by a social cost of carbon, which increased from $41 per ton of CO_2 in 2015 to $58 per ton by 2030, based on a recent comprehensive report on the social cost of carbon [45].

2.2.4 Grid Integration Costs

Finally, the cost of the Danish electricity system was also calculated. Similar to the way the model treated ICEVs, the capital cost for the existing electricity system was not included. However, given that the Danish electricity system is expected to change rapidly over the next 15 years, with the amount of annual wind generation practically doubling [46]. Because the installation of wind and solar plants would occur regardless of the type of vehicles driven, the model did not include the capital costs of new capacity additions. However, if the additional load due to charging demand caused load to be greater than the available hourly capacity, then the model built new natural gas plants exclusively for providing electricity for this purpose. If built, then the cost of the requisite capacity was calculated, using the capital cost for new natural gas plants, based on the literature [47].

Next, the model calculated the hourly fuel and maintenance cost for both existing generation and new natural gas plants [48]. One of the main benefits of the “smart” EVs (the V1G and V2G scenarios) is that they can be controlled and store electricity to maximize use of renewable energy, implying the introduction of “smart” EVs can reduce electricity system costs. The model accounts for this by calculating total annual electricity fuel and maintenance cost for each iteration of EVs. Likewise, the model also calculated the health costs associated with combustion of both coal and natural gas, based on the impacts of particulate matter on Denmark and the neighboring European Union [42], updated for the current fuel mix in Denmark [43]. Likewise, carbon emissions associated with coal and natural gas were estimated based on carbon content and the social cost of carbon [49], [45]. It should be noted that the additional societal costs of conventional generation to meet increased EV charging load are included in these calculations. Similar to fuel and maintenance cost, total annual health and carbon costs were calculated for each system to estimate the societal electricity system benefit of V1G and V2G EVs.

[*Insert Table 1 here*]

2.3 Cost Calculation

For each iteration of EV penetration under each of the three modeled scenario, the total societal costs were calculated in net present value over a 25 year period, assuming a social discount rate of 3% [45], [50]. As described above, the total cost includes both transportation and electricity related costs due to EVs, and including and excluding externalities. See Equation 2.

Equation 2. Total 25 Year Net Present Cost Calculation

$$Total\ Cost$$

$$= EV \times EV_{CAP} + NNG_{\ MW} \times NNG_{CAP}$$

$$+ \sum_{i=1}^{25} \frac{EV\ \times EV\_O\&M_i + (ICEV_{GAL}\ \times (FuelCost_i + H_{GAS} + SCC_{GAS}) + ElecGen_{i,k} \times (VOM_k + H_k + SCC_k)}{(1+r)^i}$$

EV	Total Amount Electric Vehicles
EV_Cap	Capital Cost to Incentivize Purchase of EV_j (in \$/car)
NNG_{MW}	Requisite Capacity of New Natural Gas (MW)
NNG_{CAP}	Capital Cost a New Natural Gas Plant (\$/MW)

Where	EV_O&M	*equals*	EV Operation and Maintenance Benefit ($/car/year)
	$ICEV_{GAL}$		Total Annual Gasoline/Diesel Consumption (in liters)
	FuelCost		Average Cost of Gasoline/Diesel (in $/liter)
	VOM		Variable Operation and Maintenance (in $/MWh)
	H		Health Damages ($/liter or $/MWh)
	SCC		Social Cost of Carbon ($/liter or $/MWh)
	ElecGen		Total Annual Electricity Generated (in MWh for generation type k)
	r		Discount rate

For year i and electricity generation type k

3. Results: Examining Vehicle-to-Grid Scenario

For each of the three charging scenarios, the minimum cost penetrations of EVs were found for each year, both with and without externalities. Table 2 shows the minimum cost penetration with and without including externalities for the year 2015, with the three charging scenarios, and also depicts the costs of these EV penetrations. First, the optimal penetration of EVs excluding externalities range from 26% to 37%, depending on the level of communication. In spite of the comparatively cheap costs of ICEVs in Denmark the model shows that ignoring taxes, EVs should be adopted a much higher rate than they currently are. However, tax differences and consumer irrationality regarding discount rate may be major impediments, see section 4 below. Looking across the columns, Table 2 shows that surprisingly, increasing communication-capabilities likewise barely impacts the optimal penetration of EVs. Adding fully bi-directionality to make EVs V2G-capable only slightly increases the optimal penetration of EVs, and decreases total societal costs only very marginally. In the short term, the results imply that there is only very slight, albeit positive impacts on reducing total societal costs by furthering communications to full bi-directionality.

Next, there continues to be only small (though more noticeable) differences between the communication scenarios when including externalities in the cost function. Firstly, when comparing to market costs, the optimal penetration of EVs increases in all communication scenarios. The benefit of communication between Dumb and V1G scenarios is essentially nothing, though V2G increases the optimal EV penetration more noticeably. As Figure 3 shows below, the differentiation in cost for the three charging scenarios is not obvious until at least EV penetration over approximately 30% to 40%, though the differences are more noticeable in 2022 and 2030 (due to higher penetrations and thus utilization of renewable energy). Overall, the optimal penetration barely increases with communication ability, the total cost savings is likewise barely decreased, by less than 1% difference across the three charging scenarios. On the other hand, including externalities does incentivizes further EV penetration by an additional ~8-10%, though the total societal benefits of communication are slight, especially in the near term. All in all, assuming that society aims to mitigate health and climate change damages, then the near-term target for EV penetration in Denmark should be drastically increased to nearly 37%.

Next, using 2030 costs and expected increases in renewable energy in the Danish electricity system (the current 37% renewable share of load to the projected 73% in 2030), noticeably changes the results. The optimal penetration of EVs drastically increases in all scenarios, regardless of communication ability. However, adding communication abilities now markedly decreases costs while increasing optimal EV penetration, see Table 2. This is more noticeable in the cost difference between the Dumb scenario and V1G, where total costs are reduced by about 3%. In comparison, the cost savings of adding bidirectionality is only 1.8%. Thus, while V2G increases optimal EV penetration and further reduces cost, these benefits are only marginal. Nonetheless, compared to the low percentages of EV penetration found in 2015, the differentiation across the communication scenarios are positive and more evident. Next, including externalities further increases the optimal EV penetration, although they generally follow the same trends as the market cost scenario across the communication scenarios. Again, assuming society intends to mitigate health and climate change damages, the optimal goal for Denmark should be reaching 75% penetration of EVs by 2030.

[*Insert Table 2 here]*

[*Insert Figure 2 here*]

Figure 2 shows how the different capacities of each EV communication ability reduce the use of conventional generation (in brown in Figure 2) and increase the utilization of renewable generation (in green). Throughout the year, the amount that V1G smart charging and V2G energy arbitrage (shown in dark and light blue, respectively) decrease the total load (and thus conventional generation) is relatively moderate. To be precise, smart charging reduces load by 2.5% throughout the year, while V2G arbitrage reduces load by 4.1%. More importantly, V1G smart charging reduces conventional dispatch by nearly 7%, while V2G arbitrage reduces conventional dispatch by 10% over the course of the year. At the same time, the total amount of renewable generation spilled (shown in dark orange) is also decreased by V2G storage capacity (light orange), as well as shifting EV demand to match hourly renewable generation, which is termed as “renewable energy adjusted” (yellow). The impacts on renewable energy utilization is more dramatic, V1G smart charging decreases spilled renewable generation by 21%, and V2G storage decreases spilled renewable generation by 45% over the modeled year. However, given the moderate cost differences shown in Table 2, the marginal value of V2G over V1G in displacing the 3% conventional dispatch is relatively limited. Indeed, the value of V2G may be limited due to the model’s restriction of using only intra-daily energy arbitrage for V2G. As shown in Figure 2, there are several times where there is a substantial amount of renewable generation spilled (red spikes above the load line) a few days before high amounts of conventional generation is dispatched. Looking towards future research, a key implication for V2G and renewable energy integration would be investigating the possibility of inter-day energy arbitrage of V2G and how driving demands would implicate long-term V2G storage. On the other hand, when the model added V2G and showed large reductions in renewable energy spillage, there was very minor economic value added, which may implicate the value of long-term V2G storage as well.

Figure 3 shows the total net present cost for each percentage EV penetration for the three charging scenarios (Dumb, V1G, and V2G), for the years (a) 2015, (b) 2022 and (c) 2030. First and foremost, these graphs show the cost difference between the three charging scenarios. Note that from 0-30% there is little cost differentiation between the level of communication available. However, beyond the 40% penetration of EVs there is a marked difference, especially between “Dumb” and either of the V1G or V2G scenarios. There is a very slight cost savings across all percentages of EV penetration for implementing V2G over V1G, which is due entirely to participating in ancillary services. When previous iterations of the model conducted analyses without the possibility of ancillary services, there was practically no cost difference between V1G and V2G, implying that energy arbitrage did not provide substantial societal cost savings, especially in the near-term. Next, across the three graphs, the slopes showing least-cost EV penetration appear to pass a threshold and become more dramatic, showing the substantial decreasing of costs as EVs become cheaper and renewable energy is more abundant. In fact, having no electric vehicles in the system goes from being, for all intents and purposes, nearly as inexpensive as the optimal penetration of EVs in 2015 to by nearly the most expensive choice by 2030. Due to the rapidly decreasing costs of batteries and potential threshold effects of reaching cost parity with ICEVs (even with current WTP cost premiums for EVs), the shift to EVs may occur rapidly. Indeed, in previous model runs, when an older battery cost was used

($325/kWh [51], as opposed to $226/kWh [33]), the optimal EV penetration was found to be 0% in all charging scenarios cases. Finally, in all three graphs and communication scenarios, the cost of EV penetration above 80% substantially increases. One important aspect of this analysis that causes this exponential increase is the inclusion of WTP cost premiums for EVs, for which the final ten percent of drivers is prohibitively expensive. Thus, a barrier to complete electrification of transport will likely be some consumer resistance to the adoption of EVs, especially when considering many governments wish to completely phase-out the selling of ICEVs in the near future.

[*Insert Figure 3 here*]

Figure 4 shows the cost minimum EV penetration from each year from 2015 to 2030, including only (a) market costs and also (b) when including externalities. While the central results find that the optimal EV penetration in 2015 to be comparatively higher than it is now (current market share is less than 1% (51)), there is an even sharper increase in optimal EV penetration from 2015 to 2010. Throughout the next fifteen years, there appears to be several steps where cost thresholds are reached that dramatically increase EV penetration in a short period, as EVs become cheaper than ICEVs for certain percentages of the population, including aforementioned cost premiums. Looking from 2020 to 2025, the increase in cost minimum EV penetrations is distinct between the Dumb charging scenario and the V1G and V2G charging scenario. Here communication allows for linear integration of EVs into the grid, whereas Dumb charging would cause the EV penetration to stall, especially when including externalities. The overall shape of the curves remains the about same in the two graphs, however, the thresholds of ICEV cost parity for each group of the population is reached faster, increasing EV penetrations beyond the market cost scenario. While these graphs show a high optimal deployment of EVs, such a considerable increase in EVs in Denmark as compared to their existing penetration may be difficult to reach, especially considering the recent loss of momentum (51). However, these graphs show the societal and economic foundation to allow policymakers to sizably increase EV goals in Denmark, both in the short-term as well as the long-term future.

[*Insert Figure 4 here*]

Next, Figure 5 shows the amount of renewable energy used towards providing load for each EV penetration under the three communication capability scenarios, for both the years 2015 and 2030. Looking first at 2015, the graphs show the additional benefit of increased communication is especially key from “Dumb” to V1G, with the largest increase in renewable generation between these two scenarios. Both V1G and V2G increase renewable energy usage, but only to a certain point (around 20% EV penetration), where additional flexible load and storage capacity does not increase renewable energy production. However, the overall impact on renewable energy in the current grid is relatively limited, as depicted by the limited range on the y-axis. In comparison, as renewable energy capacity is expected to drastically increase by 2030, the integration of EVs and communication make a much larger impact on the amount of renewable energy used. Indeed, since renewable energy will be providing more of a baseload role, added communication is beneficial, but so is just increasing general energy demand by increasing EV penetration.

[*Insert Figure 5 here*]

Finally, Figure 6 shows the required construction of new natural gas as EV penetration increases for the three charging scenarios, for both the years 2015 and 2030. Most importantly, the benefit of communication ability is seen most clearly on this graph. Without any communication ability Dumb EVs, after approximately 45% penetration, would require construction of new natural gas power plants in order to meet their load. At worst case, they would require just over 3 GW assuming 100% penetration of Dumb EVs. This amount is required exclusively for new EVs, and not used for any other loads. However, when adding either V1G or V2G level of communication, the need for new natural gas capacity is entirely obviated. When looking at 2030, the overall story remains the same – without communication capabilities, Dumb EVs will require much more new natural gas capacity than either V1G or V2G-enabled EVs. However, by 2030 and over 80% EV penetration (an equivalent of 2.4 million cars), both V1G and V2G will need a minimal amount of new natural gas (<500 MW). Surprisingly, adding bidirectionality does not change the amount of requisite new natural gas capacity, as compared to V1G, implying load shifting is more important to avoided costs than energy arbitrage. The increase in requisite new capacity for 2030, as compared to the same scenarios in 2015, is due to the expected increase of the total amount of vehicles in Denmark, rather than a lack of renewable energy.

[*Insert Figure 6 here*]

4. Sensitivity Analysis

In addition to the central results that have been already presented, several sensitivity analyses were also conducted to test how the assumptions affect the results. The summary of the results of these sensitivity analyses are summarized in Table 3. First and foremost, a scenario called "Business as usual" (BAU) was calculated – this assumes characteristics similar to the current situation in Denmark, with very limited amounts of EVs (i.e., 1%). This scenario is listed first in Table 3 as a point of reference to the current costs of the Danish transportation and energy system. In addition, the central results are next presented as another point of comparison. The first sensitivity analysis conducted was to test how the assumptions of future oil costs would impact the optimal implementation of EVs, based on a projected low and high oil barrel cost cases [41]. The results are presented as a range in Table 3, and as expected, a lower future oil price greatly reduces the optimal EV penetration, while a higher future oil price greatly increases the optimal EV penetration. Thus, the evolution of future oil prices are a key factor in the optimal development of EV deployment.

Next, the following sensitivity analysis conducted tested the assumptions of how lifetime cost of the system was calculated. First, the lifespan of the cost calculations was changed down from 25 years to 12 years, to reflect the time-frame in which people own their cars (as opposed the 25-year lifespan reflecting electricity-related timeframes). Even though the discount rate remained at a social discount rate of 3%, simply reducing the time frame of the calculation has substantial impacts on the cost minimum EV penetration, reducing penetration by 18% to 27%. With or without externalities, this optimum decreases, though the cost-optimum is still an order of magnitude larger than the BAU scenario.

[*Insert Table 3 here*]

In a similar vein, changing the discount rate from a social discount rate to mirror a market-based discount rate of 7% likewise drastically changes the optimally deployment of EVs. Essentially the future fuel savings of EVs, when discounted to such a degree, do not pay the difference of the EV cost premiums, especially beyond the small percent who are most geared towards EV purchases (see Appendix A). Thus, both market cost calculation as well as including externalities incentivize a small proportion of EVs. Because fuel savings and fuel damages in the future are discounted (even over the 25 year time frame) at such a rate, there would be much less EVs than the central results. Next, even more alarmingly, if an implied discount rate is used, based on literature that has shown individuals discounting fuel savings at 15% [53], [54], the optimal EV penetration drops to the default of 1%, even when health and climate externalities are internalized in the prices. Thus, in order to achieve socially optimal levels of EV penetration, a key barrier is to get people to think more long-term and rationally about future fuel savings and external damages – or to make calculations on the full social cost without discounting.

The next two assumptions tested regarded the comparative price of EVs, both to similar results on optimal EV penetration. First, to attempt to recreate the EV tax exemption policy Denmark had instituted in the recent past [52], all taxes were included again on ICEVs, while keeping EVs tax exempt (but including the WTP cost premium). Whereas the EV capital cost was substantially higher and required fuel savings in order to be paid back off, the reinstatement of the EV tax exemption resulted in only slightly higher capital costs. In a similar thread, the cost premium for EVs, as based on WTP studies, was also removed, essentially assuming people have neutral preferences to purchase EVs as they have to purchase ICEVs, but excluded taxes for both EVs and ICEVs. In both of these cases these assumptions heavily tilt the results in favor of EVs, though they still have higher capital costs than the average ICEV (see Table A1) but also lower operating costs, and the analyses show the cost minimum to actually be practically 100% EV conversion. Compared to the medium amounts of EV penetration found in the central results and the previous sensitivity analyses, changing these assumptions on the capital cost of EVs is essential to the success of EV deployment.

Lastly, two more sensitivity analyses were conducted to gauge how consumers may react to EVs more realistically, i.e., using an implied individual discount rate. First, the analysis was redone using the 15% discount rate but also assuming 2030 prices of batteries, 100$/kWh [33]. While using 15% discount rate and today's prices leads to essentially no EVs being deployed in Denmark, future battery cost reductions will cause EVs to pass capital cost thresholds such that even higher discount rates on fuel savings matter less in a consumer’s choice, and results in optimal EV penetrations of around 37%. However, this substantially less than the optimal EV penetration in 2030 when including externalities, implying that waiting for the market to take care of itself would still result in suboptimal levels of EVs. Indeed, according to the model, assuming consumers are irrational about future fuel savings, EV penetration will only reach the current social optimum 15 years later (i.e. 37%).

Finally, a sensitivity analysis was conducted where the implied discount rate is used in combination with a shorter time frame, in order to capture the mindset of the average consumer faced with purchasing a vehicle, but with the reinstatement of the EV tax exemption. This combination of factors could be seen as a projection for how the average Dane would realistically react to the reinstatement of the Danish EV tax exemption. This policy, with a high discount rate over a smaller time span, would result in optimal EV penetration that are very comparable to the central results. Thus, while exempting EVs and using a more social discount rate would result in near complete conversion of the Danish transportation system, a higher implied individual discount rate would result in orders of magnitude less electrification. On the other hand, these results match very closely to what the central results presume is cost optimal, implying that the EV tax exemption would be reasonably incentivize the social optimum amount of EVs in the short-term. Nonetheless, when this analysis was conducted for the year 2030, the resulting EV penetration, 60%, was 15% lower than what the central results considers socially optimal by 2030. Thus, the EV tax exemption would be a good start to encourage optimal EV development, but the high WTP cost premium of the late majority and laggards in tandem with high discount rates require further policy mechanisms to reach the socially optimal level of EVs. In sum, electrification of personal vehicles will likely face two major barriers; the cost difference between ICEVs and EVs (especially when including WTP cost premiums), and individual tendencies to undervalue future fuel savings.

5. Conclusion & Policy Implications

The results presented in this paper show that EV penetration in Denmark is substantially less than what is socially optimal, possibly due to the actual and perceived cost differences, and the markedly inexpensive ICEVs currently. However, the model shows that optimal EV penetration to rapidly increase over the next fifteen years as both battery costs continue to drop and as renewable energy requires more controllable loads, driving down EV costs. In both cases, current EV policies should be revamped to target a rapid transition to electrification in the near- to mid-future. Along those lines, the value of the development communication and bidirectionality of EVs increases over time as EV deployment and renewable energy are both expected to grow. While the current marginal value of V1G and V2G are practically zero, it is recommended that by when EV penetration reaches about 40% (which according to model *should* be by the mid-2020's), these systems should be developed and in place for EVs, as this is when communication makes visible differences in optimal EV integration. Put another way, EVs and V2G systems achieve a social optimality, a diffusion that produces far more social and economic benefits than a transport environment wedded to fossil fuels and business as usual. The model project that a 27% penetration of V2G EVs, rising to 75% by 2030, would generate $34 billion in avoided social costs, a decrease of 30% compared to business as usual, equivalent to an annual savings of $1,200 per vehicle.

One policy implication arising from this finding is that when externalities are monetized, the social and economic benefits of a V2G transition more than pay for themselves—and the assumptions made in the model are likely conservative given that there are only projected two types of externalities, carbon and health, yet many more exist, including economic security, jobs, and enhanced competitiveness; energy security and diversification; avoided imports of oil; and other forms of pollution including water, materials, and waste. A second is that while the model calculated the amounts of costs and benefits, future research should investigate how they are distributed. Further policy analysis would be needed to confirm if the main sets of “winners” in the a V2G transition would be the drivers of cars, saving money on fuel, operations and maintenance, along with those at greater risk to the health problems associated with transport related air pollution and greenhouse gas emissions. Possible “losers” could be traditional providers of ancillary grid services, petroleum companies (selling less oil), and incumbent firms offering maintenance and servicing for ICEVs. From a technical perspective, future research should also investigate the feasibility and value of inter-day storage using V2G.

Furthermore, across both the time component of the central results as well as the sensitivity analyses, there appears to be various threshold effects that may lead EV penetration to remain low in the near term, but then exponentially balloon as cost thresholds are surpassed. With this potential growth in mind, policymakers should prepare charging infrastructure and local level grid effects not modeled here (e.g., transformer upgrades) for when a swift transition may occur. Alternatively, it may benefit society for policymakers to smooth out EV deployment in order to avoid “shocks” to the system. Keeping in mind that optimal EV penetration in 2030 is 75%, a more linear approach to EV deployment may be easier and more economically efficient to achieve. Indeed, the model shows that the socially optimal EV penetrations are orders of magnitude higher than they currently are in Denmark [52], so policymakers may want to consider greatly increasing EV policies while concomitantly acknowledging the socially optimal level of EVs may not be feasible to achieve in the short term.

The main drivers of these thresholds are the cost differences between EVs and the tendency for individuals to use an inflated discount rate regarding future energy benefits. Thus, in tandem with preparing for a potentially rapid transition, policymakers should also act to lower these social barriers. The analysis suggests that reintroducing the tax exemption would be a good place to start, not only economically, but also signaling to the public that a transition to EVs is the future of Danish transportation may alter preferences of EVs, resulting in a reduction of WTP cost premiums, further making the transition easier and less costly. Policymakers may also consider ways to educate and inform Danish residences of the benefits of EVs to change preferences. For example, policymakers could consider implementing knowledge-based programs to advertise the better acceleration, reduction of noise, and lowering of pollution of EVs, as compared to ICEVs. Correspondingly, policymakers should also address the internal calculation of individuals purchasing vehicles, in order to correct the habitual undervaluation of fuel savings that EVs will provide. Because the central barriers of EV deployment are not technical, but rather social or economic, policymakers should consider broadening their design and scope of policy mechanisms. Despite clearing having a host of social benefits, future research should investigate the social barriers that EVs will face in Denmark, especially as the transition to large-scale EVs is underway, to ensure such advantages are secured rather than squandered.

Bibliography

[1] K. von Stackelberg, J. Buonocore, P. V. Bhave, and J. A. Schwartz, "Public health impacts of secondary particulate formation from aromatic hydrocarbons in gasoline," *Env. Health*, vol. 12, p. 13, 2013.

[2] M. Z. Jacobson *et al.*, "Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight," *Energy Policy*, vol. 57, pp. 585–601, Jun. 2013.

[3] C. Budischak, D. Sewell, H. Thomson, L. Mach, D. E. Veron, and W. Kempton, "Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time," *J. Power Sources*, vol. 225, pp. 60–74, Mar. 2013.

[4] W. Kempton and J. Tomić, "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," *J. Power Sources*, vol. 144, no. 1, pp. 280–294, Jun. 2005.

[5] A. E. MacDonald, C. T. M. Clack, A. Alexander, A. Dunbar, J. Wilczak, and Y. Xie, "Future cost-competitive electricity systems and their impact on US CO2 emissions," *Nat. Clim. Change*, Jan. 2016.

[6] T. Mai, D. Mulcahy, M. M. Hand, and S. F. Baldwin, "Envisioning a renewable electricity future for the United States," *Energy*, vol. 65, pp. 374–386, Feb. 2014.

[7] B. Elliston, I. MacGill, and M. Diesendorf, "Least cost 100% renewable electricity scenarios in the Australian National Electricity Market," *Energy Policy*, vol. 59, pp. 270–282, Aug. 2013.

[8] L. Noel, J. F. Brodie, W. Kempton, C. L. Archer, and C. Budischak, "Cost minimization of generation, storage, and new loads, comparing costs with and without externalities," *Appl. Energy*, vol. 189, pp. 110–121, Mar. 2017.

[9] M. A. Delucchi and M. Z. Jacobson, "Meeting the world's energy needs entirely with wind, water, and solar power," *Bull. At. Sci.*, vol. 69, no. 4, pp. 30–40, Jul. 2013.

[10] H. Lund and W. Kempton, "Integration of renewable energy into the transport and electricity sectors through V2G," *Energy Policy*, vol. 36, no. 9, pp. 3578–3587, Sep. 2008.

[11] B. K. Sovacool, J. Kester, G. Z. de Rubens, and L. Noel, "Expert perceptions of low-carbon transitions: Investigating the challenges of electricity decarbonisation in the Nordic region," *Energy*, vol. 148, pp. 1162–1172, Apr. 2018.

[12] J. Kester, L. Noel, G. Zarazua de Rubens, and B. K. Sovacool, "Promoting Vehicle to Grid (V2G) in the Nordic region: Expert advice on policy mechanisms for accelerated diffusion," *Energy Policy*, vol. 116, pp. 422–432, May 2018.

[13] D. B. Richardson, "Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 247–254, Mar. 2013.

[14] T. Novosel *et al.*, "Agent based modelling and energy planning – Utilization of MATSim for transport energy demand modelling," *Energy*, vol. 92, pp. 466–475, Dec. 2015.

[15] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, "Integration of Electric Vehicles in the Electric Power System," *Proc. IEEE*, vol. 99, no. 1, pp. 168–183, Jan. 2011.

[16] L. Drude, L. C. Pereira Junior, and R. Rüther, "Photovoltaics (PV) and electric vehicle-to-grid (V2G) strategies for peak demand reduction in urban regions in Brazil in a smart grid environment," *Renew. Energy*, vol. 68, pp. 443–451, Aug. 2014.

[17] R. Atia and N. Yamada, “More accurate sizing of renewable energy sources under high levels of electric vehicle integration,” *Renew. Energy*, vol. 81, pp. 918–925, Sep. 2015.

[18] S. Bellekom, R. Benders, S. Pelgröm, and H. Moll, “Electric cars and wind energy: Two problems, one solution? A study to combine wind energy and electric cars in 2020 in The Netherlands,” *Energy*, vol. 45, no. 1, pp. 859–866, Sep. 2012.

[19] K. E. Forrest, B. Tarroja, L. Zhang, B. Shaffer, and S. Samuelsen, “Charging a renewable future: The impact of electric vehicle charging intelligence on energy storage requirements to meet renewable portfolio standards,” *J. Power Sources*, vol. 336, pp. 63–74, Dec. 2016.

[20] E. C. Kara, J. S. Macdonald, D. Black, M. Bérges, G. Hug, and S. Kiliccote, “Estimating the benefits of electric vehicle smart charging at non-residential locations: A data-driven approach,” *Appl. Energy*, vol. 155, pp. 515–525, Oct. 2015.

[21] I. Graabak, Q. Wu, L. Warland, and Z. Liu, “Optimal planning of the Nordic transmission system with 100% electric vehicle penetration of passenger cars by 2050,” *Energy*, vol. 107, pp. 648–660, Jul. 2016.

[22] K. Seddig, P. Jochem, and W. Fichtner, “Integrating renewable energy sources by electric vehicle fleets under uncertainty,” *Energy*, vol. 141, pp. 2145–2153, Dec. 2017.

[23] C. K. Ekman, “On the synergy between large electric vehicle fleet and high wind penetration – An analysis of the Danish case,” *Renew. Energy*, vol. 36, no. 2, pp. 546–553, Feb. 2011.

[24] B. K. Sovacool, “Contestation, contingency, and justice in the Nordic low-carbon energy transition,” *Energy Policy*, vol. 102, pp. 569–582, Mar. 2017.

[25] Energinet.dk, “Download of Market Data,” *Electricity: The Wholesale Market*, 21-Jul-2016. [Online]. Available: http://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx. [Accessed: 01-Aug-2016].

[26] G. Pasaoglu *et al.*, *Projections for electric vehicle load profiles in Europe based on travel survey data*. Luxembourg: Publications Office, 2013.

[27] B. K. Sovacool, L. Noel, J. Axsen, and W. Kempton, “The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review,” *Environ. Res. Lett.*, vol. 13, no. 1, p. 013001, Jan. 2018.

[28] Lazard, “Lazard’s Levelized Cost of Energy Analysis - Version 11.0,” Lazard, 2017.

[29] M. K. Hidrue, G. R. Parsons, W. Kempton, and M. P. Gardner, “Willingness to pay for electric vehicles and their attributes,” *Resour. Energy Econ.*, vol. 33, no. 3, pp. 686–705, Sep. 2011.

[30] Statistics Denmark, “BIL50: New Registration of Passenger Cars by Ownershi, Car Segment and Unit,” *StatBank Denmark | Price and consumption*, 11-Nov-2016. [Online]. Available: http://www.statbank.dk/BIL50. [Accessed: 28-Feb-2017].

[31] EA Energy Analyses, “Vehicle energy use and cost – Methodology used in Grøn Transport Roadmap 2030,” Nov. 2015.

[32] European Commission, “Car Price Report,” European Competition, Jul. 2011.

[33] S. M. Knupfer, R. Hensley, P. Hertzke, P. Schaufuss, N. Laverty, and N. Kramer, “Electrifying insights: How automakers can drive electrified vehicle sales and profitability,” McKinsey & Company, Jan. 2017.

[34] L. Zhang, T. Brown, and S. Samuelsen, “Evaluation of charging infrastructure requirements and operating costs for plug-in electric vehicles,” *J. Power Sources*, vol. 240, pp. 515–524, Oct. 2013.

[35] W. Kempton, Y. Perez, and M. Petit, “Public Policy for Electric Vehicles and for Vehicle to Grid Power,” *SSRN Electron. J.*, 2014.

[36] M. Yilmaz and P. T. Krein, “Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles,” *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013.

[37] A. Schroeder and T. Traber, “The economics of fast charging infrastructure for electric vehicles,” *Energy Policy*, vol. 43, pp. 136–144, Apr. 2012.

[38] G. Pasaoglu *et al.*, *Driving and parking patterns of European car drivers: a mobility survey.* Luxembourg: Publications Office, 2012.

[39] EOF, “Prisudvikling - benzin,” *energi-og olieforum*, Jul-2016. [Online]. Available: http://www.eof.dk/Priser-og-Forbrug/Benzin-udvikling. [Accessed: 26-Aug-2016].

[40] IEA, *World Energy Outlook 2015*. OECD Publishing, 2015.

[41] EIA, “Assumption to the Annual Energy OUtlook 2017,” U.S. Department of Energy, Washington, DC 20585, Jul. 2017.

[42] J. Brandt *et al.*, “Assessment of Health-Cost Externalities of Air Pollution at the National Level using the EVA Model System,” CEEH Scientific Report No. 3, Mar. 2011.

[43] European Commission, *EU Energy in figures 2015*. Luxembourg: Publications office of the European Union, 2015.

[44] EIA, “How much carbon dioxide is produced by burning gasoline and diesel fuel?,” 06-May-2016. [Online]. Available: http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11. [Accessed: 26-Aug-2016].

[45] Interagency Working Group on the Social Cost of Carbon, “Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866,” United States Government, Washington, D.C., 2013.

[46] Energinet.dk, “Energinet.dk’s analysis assumptions 2013-2035,” Apr. 2013.

[47] World Energy Council, “World Energy Perspective: Cost of Energy Technologies,” World Energy Council, Bloomberg New Energy Finance, London, UK, 2013.

[48] Danish Energy Agency, “The Danish Energy Model: Innovative, Efficient and Sustainable,” 16, 2015.

[49] W. Moomaw, P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, and A. Verbruggen, “Annex II: Methodology,” in *IPCC Special Report on Renewable Energy and Climate Change Mitigation*, Cambridge, UK and New York, NY, USA, 2011.

[50] Interagency Working Group on the Social Cost of Carbon, “Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866,” United States Government, Feb. 2010.

[51] DOE, “EV Everywhere Grand Challenge,” Department of Energy, DOE/EE-1024, Jan. 2014.

[52] IEA, “Global EV Outlook 2017,” OECD/IEA, Paris, France, 2017.

[53] H. Allcott and N. Wozny, “Gasoline Prices, Fuel Economy, and the Energy Paradox,” *Rev. Econ. Stat.*, vol. 96, no. 5, pp. 779–795, Dec. 2014.

[54] J. A. Hausman, “Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables,” *Bell J. Econ.*, vol. 10, no. 1, p. 33, 1979.

Appendix

[*Insert Table A1 here*]

[*Insert Figure A1 here*]