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Smart EV Charging: A Global Review of Promising Practices

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Abstract: The electrification of transport in Europe is in the early stages of a market transformation that has the potential to significantly cut emissions in both the transportation and energy sectors, while generating wider benefits for society. The research underpinning this study finds that the greatest value from integrating electric vehicles (EVs) into the power grid can be generated by charging them when and where it is most beneficial for the power system, while ensuring consumers' mobility needs are met at an affordable cost. An emerging body of research on electric vehicle grid integration focuses on modeling the cost of integration under various scenarios, but few studies look at the existing promising practices that are based on policy tools in use today. The authors of this study conducted a qualitative review of policies for EV grid integration in the EU and U.S. markets. We found that, in order to unlock the environmental and economic opportunities associated with market uptake, three policy strategies are most effective: cost-reflective pricing, intelligent technology, and integrated infrastructure planning. The study also explores the implications of these practices for policymakers and regulators in the EU (A short version of this paper was presented at the 32nd Electric Vehicles Symposium in Lyon, France, in May 2019).

Keywords: electric vehicle; BEV; EV; utility; electricity; grid; smart charging; smart meter; tariff design; beneficial electrification

1. Introduction

The number of electric vehicles (EVs) in Europe has increased exponentially. More than one million electric passenger vehicles were on the roads of EU, European Free Trade Association countries, and Turkey by the end of 2018 [1]. It is agreed that "the benefits of transport electrification on climate change mitigation will be greater if EV deployment takes place in parallel with the decarbonisation of power systems" [2]. However, decision-makers on the European, national, and local levels are only starting to recognize the importance of managed or "smart" charging as a key element for the environmentally beneficial and cost-efficient integration of electric vehicles into the grid [3,4]. This article builds on earlier research conducted by the authors [5], and on a global review of promising practices for beneficial EV grid integration [6] in a dynamically developing market for charging and grid services. It offers insights for decision-makers and identifies further needs for research.

With the term "EVs," we include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). For the sake of simplicity, we use the term EVs throughout. This article mainly focuses on passenger cars but also takes other vehicle segments into account. References to beneficial electrification of transport define "beneficial" as an electrified end use, or integration of an electrified end use, into the power grid that satisfies at least one of the following conditions without adversely affecting the other two: it saves consumers money over the long run, enables better grid management, and reduces detrimental environmental impacts.

EVs' flexibility also makes them a grid resource with considerable advantages: As "batteries on wheels," they can either pull electricity from the grid for charging or feed it back into the system whenever the vehicle is not in use. In the current phase of the mobility transition [7], which still focuses on private ownership of cars, vehicles are idle about 95 percent of the time, and users generally need only 10 percent of the hours in a day for charging [8]. This leaves at least 85 percent of the time free for potentially providing flexibility services, and EVs are increasingly recognized, also by utilities, as a valuable demand-response resource for the grid [9]. But as the mobility paradigm transitions, we will see growth in vehicle use through increasingly intelligent and shared new mobility services [10–13]. Some flexibility for optimizing the way users charge their vehicles is likely to remain, along with strong incentives to minimize the cost of charging.

Previous research highlights the benefits of strategic EV integration, stating that "smart EV charging can integrate increasing amounts of renewable energy resources, increase utilization of the existing network infrastructure, lower the operating cost of EVs, and minimize the need for new investment" [5]. Subsequently, there is a growing body of literature that assesses EV grid integration costs and the associated benefits [14–17]. Studies undertaken for and by stakeholders and other researchers broadly agree that the grid can cope with integrating the anticipated growth in electric vehicles without issue, provided charging is managed [18]. This means that users are provided with incentives to move their vehicle charging to off-peak hours, thus using the existing grid assets more efficiently. According to the European Association of the Electricity Industry (Eurelectric), smart charging could result in improved grid utilization rates. The association also finds that any higher overall electricity peaks would not be substantial and therefore are not cause for concern [18]. Grid operators note that it is, of course, possible that grid expansion could be necessary in given locations [19]. A recent analysis of Europe's largest car market, Germany, confirms these findings even if high levels of electrification are assumed, provided that the broader transition to a more efficient, less vehicle-based transport sector continues [20]. Previous estimations based on data from France and Germany show that a significant proportion of existing distribution network grid capacity remains unused that is well suited for charging a higher penetration of EVs with little or no need for additional capacity [21]. The studies also show that, without managed charging, the costs of providing the power needed to charge rising numbers of EVs could grow dramatically [18]. If the vehicles are charged during times of system peak, the overall peak could even increase twofold [19]. This could lead to substantial, and avoidable, investment in new generation resources and grid capacity that has limited value, as it would only serve the higher peak.

The authors of this article explored best practices for ensuring that charging is managed and unnecessary investment costs can be avoided. While the majority of current research uses a modeling approach to address this question [22], few studies have explored existing market and policy practices that already successfully illustrate the benefits of smart charging. We seek to make an empirical contribution to the current debate by presenting case studies of real-world examples. As a result of our research, we have identified three particularly important opportunities for ensuring EVs are integrated beneficially into the grid, and costly exacerbation of peak load is avoided.

- **Cost-reflective pricing** leverages the fluctuations in retail energy and network prices over the course of the day and night to encourage consumers to change how and when they charge their vehicles. An effective program will motivate consumers to change their charging behavior in a way that both lowers their costs and reduces power system costs.
- **Smart technology** is a critical resource for capturing the flexibility EVs can provide, especially when used in conjunction with smart pricing. Charging processes can even be automated if price and other data can be communicated. This feature is generally found only in more advanced

programs. The goal is to enable consumers to make choices to reduce their bills without needing to constantly pay attention to the relevant technology.

- **Smart infrastructure** refers to the strategic siting of EV charging infrastructure. More precisely, if the public or private infrastructure is carefully planned, it can serve mobility demands, take advantage of existing grid infrastructure and capacity, and provide balancing services. This powerful combination can substantially reduce the cost of integrating electric vehicles into the power system. The higher objective of this strategy is also to steer the time and location of EV charging to best serve consumers and the grid.

2. Materials and Methods

Research for this study focused on a qualitative method of data collection (See Supplementary Materials) with the objective of establishing a comprehensive definition of and recommendations to promote "smart charging," a term often used in policy discussions but seldom clarified, through real-world case studies [23]. The research process involved collection, review, and documentation of reports and material available in European Member States and the United States, as well as interviews with various stakeholders (see Appendix A, Table A1). In addition, the authors gathered information in various informal exchanges, such as expert workshops, and incorporated the feedback from external experts (see Acknowledgements). The research was conducted between June 2018 and March 2019.

3. Results

In this section, we identify three areas of opportunity for beneficial EV integration through "smart charging" and discuss selected examples of best practices. For the purposes of this paper, we define "smart charging" as electric vehicle charging that can be shifted to times "when the costs for producing and delivering electricity are lower, without compromising the vehicle owner's needs" [4].

3.1. Smart Pricing

Cost-reflective, or "smart" pricing, sends price signals to consumers about the actual cost of generating and delivering electricity at a given time. The objective of this mechanism is to reward customers with lower prices when they shift their vehicle charging to times that are beneficial to the grid, i.e., times of low demand or load. Well-designed tariffs ensure efficient use of existing power system infrastructure and can help obviate the need for some future investments in the system [24]. The cost savings from smart pricing do not only accrue for EV users; all customers reap the benefits of the lower system costs.

At present, the most common type of pricing across Europe is the standard tariff, which is a rate that does not vary with time. Standard pricing is based on a flat, per kilowatt-hour charge for consumers' electricity demand. Because customers cannot lower their electricity bills by shifting their power use, they charge their vehicles at a desired time, regardless of grid conditions and regardless of the cost to generate and deliver electricity.

Utilities across most of Europe offer their customers forms of time-varying price structures, but the uptake by consumers has been low on the whole. Pilot programs, featuring smart pricing, show that those consumers who do participate are responsive to price signals and willing to change their charging behaviors. The current pricing models range from the simplest, time-of-use (TOU) tariffs, to the most complex, real-time pricing. With time-of-use pricing, the utility sets different prices for different blocks of time. These are usually simple delineations, such as a day and night tariff or a weekday and weekend price, and the tariffs are typically based on consumers' past power usage. This most prevalent design, dating back to the 1970s and 1980s, does not require advanced metering technology. Its effectiveness varies greatly among countries, depending on the design and the ratio between the highest and lowest price periods. The difference between the two rates needs to be large enough to encourage customers to change their behavior.

Real-time pricing, by contrast, changes according to the actual situation on the power grid over set intervals and thus requires smart metering. Smart meter rollout has been a challenging hurdle, with several Member States still far behind their target.

Two other designs of note are critical peak pricing and peak-time rebates. France is currently the only country offering critical peak pricing [25], where prices rise substantially for a limited number of hours, and this time frame is announced in advance. As the name suggests, a peak-time rebate plan pays a set amount to consumers who shift their electricity consumption away from peak hours. If they do use power during this time, the price is the same as for non-peak hours.

Electricity tariffs that support managed EV charging require consumers to learn how to best use them to save money (and, at the same time, to create grid benefits). Customer education is key, in particular to attract new user groups, who are not already convinced of the specific advantages of electric vehicles. Experience from the United States confirms that many energy suppliers reported positive experiences when testing the introduction of time-varying tariffs in smaller pilot projects [26].

Cost-reflective pricing takes on vital importance as the EV market transformation accelerates. With today's low EV market share and a moderate, albeit growing, share of renewables, simpler tariff designs such as TOU rates can ensure beneficial EV grid integration. This will not be sufficient, however, in a fully developed electric transport sector that also aims to integrate higher amounts of renewable energy. In this case, more granular tariff designs, supported by technology (see below), will be required to ensure grid-friendly EV charging.

The following examples in Table 1 illustrate lessons learned from experiences in the EU and the United States with designing tariffs to support beneficial EV integration.

Table 1. Examples of time-varying rate design.

Tariff Design	Main Features	Prerequisites	User Experience
Two-period time-of-use tariff for energy (Spain) [27]	80% discount for EV drivers charging during pre-defined night hours, at 0.03 €/kWh, compared to the day charge of around 0.16 €/kWh.	Simple binary meter.	A Nissan Leaf owner will save approximately 167 euros per year by charging the EV at the night tariff instead of the standard rate.
Octopus Agile (UK) [28]	Tied to half-hourly day-ahead market, promotes renewable energy use and flexibility.	Smart meter, phone app, active participation of customers.	150 euros per year saved compared to standard tariff. Energy consumption shifted to low-demand hours.
Radius (Denmark) [29]	Time-of-use network tariff with a surcharge for winter peak hours (5–8 pm) of 0.9 €/kWh, compared to standard rate of 0.35 €/kWh.	None, standard rate applicable to customers connected to low-voltage (households) and medium-voltage grid (commercial).	

A more detailed discussion is available in Figure 1 below and in reference [5].

Under the Spanish TOU tariff, the owner of an electric passenger vehicle (assuming a 24 kWhs battery and a maximum range of around 160 km), will pay approximately 0.72 euros to charge his or her vehicle during the nighttime hours. By comparison, fully charging the vehicle at the flat, standard rate of 0.14 euros per kWh would cost around 3.4 euros, or nearly five times as much as the EV tariff. This standard rate calculation assumes 10,000 km driven per year, with all charging taking place during the nighttime (off-peak) hours. Thus, the EV-dedicated tariff offers significantly lower costs than the standard tariff and only requires the user to change when the vehicle is charged.

One alternative to driving grid-beneficial charging through pricing models is active control of charging, as practiced by some suppliers in Germany.

3.2. Smart Technology

Intelligent technology can increase the impact of cost-reflective prices by making them more convenient for consumers. In other words, the technology enables customers to react to price signals quickly and without much effort. Sophisticated tariff designs generally require more complex technology that automatically monitors and adjusts consumption based on price signals, without active intervention by the consumer. Even intelligent technologies are less likely to encourage smart charging if they are not coupled with dynamic pricing schemes. As a result, implemented in isolation, responsive technology is not likely to use existing grid capacity more effectively or reduce peak demand. Figure 1 illustrates this effect for several pilot programs that tested the dynamic price designs mentioned above. Greater reductions in demand were achieved when intelligent technology was deployed.

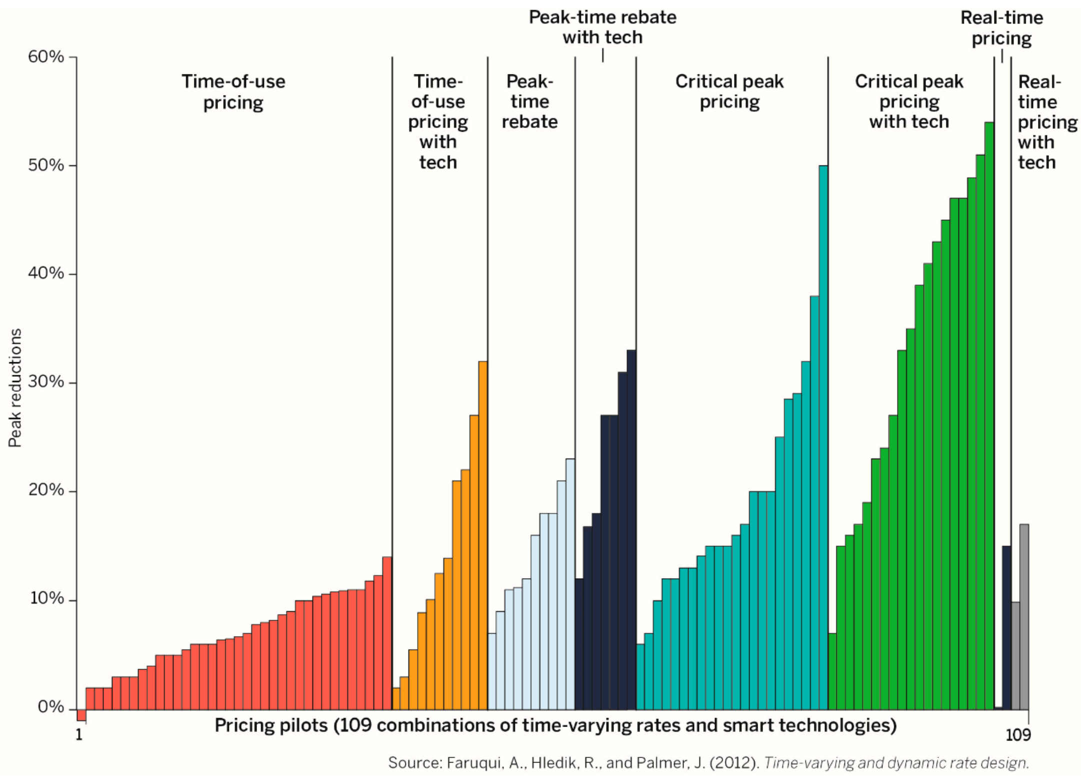

Figure 1. Average peak reduction from time-varying tariff pilots. Reproduced from Faruqui et al. [30].

Technology can be considered smart, or intelligent, if it meets the following minimum requirements:

- It can measure consumers' real-time, or near real-time, energy consumption.
- It can transmit this data to the consumer and to other authorized parties.
- It has the ability to automatically control consumption.

Simpler forms of intelligent technology include smart meters and other similar devices. These can generally monitor and communicate real-time power usage, allowing consumers to easily access data through an in-house display or mobile application. To optimize their energy consumption, however, consumers are still required to either take action themselves, directly or remotely, or to do so through a third party, such as an aggregator.

Among the more sophisticated intelligent charging technologies are systems with functionality for automatically responding to prices or other signals. Some smart chargers, for example, are capable of adjusting charging levels based on grid conditions. Other technology allows the user to give priority to cost, by charging his or her vehicle during previously communicated lower pricing periods or in response to real-time pricing. Some systems can even identify the fuel used to generate electricity and charge only with renewable energy sources.

At present, it is difficult to foresee which business models and technologies for managing electric vehicle charging will survive the current rapid-growth phase. Some manufacturers install the metering equipment in the vehicle, others place it in the charging equipment, and yet others in the charging cable. The electric vehicle users of the future may have the option of choosing from different levels of technological capability, different price categories and a variety of solutions to their mobility challenges. Table 2 contrasts and compares various smart charging technology concepts and their value to consumers.

Table 2. Examples of smart technology development.

Technology	Main Features	Level of Consumer Intervention Required
Green Mountain Power (Vermont, U.S.) [31,32]	Technology and pricing package; charging is controlled by utility and shifted to off-peak hours, includes an opt-out choice.	None. Utility supplies a seven-kilowatt charger free of charge to consumers who buy a new EV, and for a $10 monthly payment to consumers who already own one. The EV owner indicates when the vehicle is available.
Jedlix (NL) [33,34]	Application assesses optimal charging profile, including grid capacity, sustainable energy availability, and energy prices, shifts charging to preferential hours.	Very low. Consumer only communicates travel times.
Maxem (NL) [35]	Wall box/ application to integrate EV charging station, along with any self-generation (e.g., solar photovoltaic), and other uses and appliances (e.g., electrical heating) into a smart home or office building.	None to very low. Application monitors the electricity draw and feed-in for the different applications and implements smart EV charging to ensure safety (e.g., decreases EV charging if the home's demand is greater than its own production and network connection).
MyEnergi (UK) [36]	Smart meter paired with application recognizes fuel source (for example, domestically produced solar energy) and directs it to EV charging.	Very low. User has option to manually determine charging time and mode.

In areas where a large number of users access charging facilities, intelligent balancing technology can help manage load to provide charging services to consumers while avoiding stress on the grid during peak hours and the resulting higher costs. Charging even a few electric vehicles in shared garages can affect the energy consumption of larger structures, such as multi-unit residential dwellings and commercial spaces. Owners can use load balancing solutions to charge a greater number of vehicles during the night-time hours without increasing the building's peak demand or their costs. Balancing technology can also be implemented to avoid unnecessary capacity investments to integrate larger, concentrated loads such as electric bus depots. ChargePoint, an electric vehicle supply equipment provider, used intelligent technology to manage load for a bus depot in a major European city, lowering the peak demand needed to charge around 130 buses by more than half, from approximately 5 MW to 2 MW [37].

3.3. Smart Infrastructure

Research also shows that cost-effective EV grid integration requires holistic planning. By taking into account power system and user needs, charging infrastructure can be strategically sited to increase the utilization rates of existing power system infrastructure, and to ensure the location is also convenient for meeting EV drivers' charging and driving patterns [38]. Monitoring users' driving and charging behavior helps identify the density of charging equipment required to help consumers drive the kilometers they need with their electric vehicle while avoiding stranded investments from underutilized charging infrastructure [39]. These siting decisions are difficult for policymakers and investors in a nascent market and, to further complicate matters, the use cases and resulting demand for EV charging will continue to evolve with increasing electrification in other vehicle segments. While most charging can be expected to happen at home or at work, research and industry broadly agree that a small but significant share of (fast) charging will occur at publicly accessible sites, depending on the uptake of electric fleets, fleet use and mobility-as-a-service schemes [40]. Fast charging is currently defined as charging with more than 22 kW [41].

The use case for workplace charging illustrates how grid-friendly infrastructure planning is key: charging equipment can take advantage of the existing network connections for office buildings. In addition, it can make more efficient use of the grid by shifting the charging cycles for employees' EVs away from peak hours (for example, by delaying charging), toward hours when solar power is available on the grid, or both. Load management technologies, coupled with time-of-use tariffs that lower the cost of charging at times of abundant renewable energy supply, can make smart workplace charging beneficial for all parties involved.

Table 3 summarizes examples of our research on integrated charging infrastructure planning and use.

Table 3. Examples for smart infrastructure deployment.

Infrastructure Solution	Main Features	Advantages for Grid Integration
Public park-and-charge programme (UK) [42,43]	Convert street infrastructure such as light poles into 3–5 kW charging outlets.	Uses existing electrified infrastructure, reduces cost of installation from 8000 to 1000 pounds sterling [44], encourages off-peak use for parked cars, additional efficiency gain through shared infrastructure.
Study: public fast charging points along existing grid (San Francisco, U.S., and Ottawa, Canada) [45]	Utility mapping tool identified more than 14,000 locations where fast charging points could be installed to provide every EV driver with a fast charger within a one-mile (1.6 km) radius. Identifies upgrade costs.	Joint energy and transport planning, use of existing infrastructure.
Transmission system operator mapping tool for highway fast charging stations (UK) [46]	UK's transmission system operator, National Grid, studied 50 optimal locations for fast chargers (up to 350 kW) along highways, allowing 90% of UK motorists to reach a location within 50 miles.	Estimated cost 1 billion pounds, also avoids cost of building new infrastructure by linking these locations to the high-voltage grid.
Battery-assisted charging for cars (Greenlots/Hawaii, U.S.) [47]; for ferries (Ampera, Electric Ferry, Norway) [48]	Hawaii: battery-assisted fast charging infrastructure was built to avoid a more expensive connection to the grid; battery-electric ferry offers "fast charge" for ships ashore and slower charging when the ferry is not plugged in.	

4. Discussion

The review of promising examples has shown that, in various EU countries, existing policy tools for tariff design, technology deployment and integrated planning can be used to enhance beneficial EV grid integration. Three primary conclusions can be drawn from the analysis and can inform European policymakers, as outlined below. They are also part of a broader scholarly and regulatory discussion on how to leverage electric vehicles as decentralized energy resources [49] in the overall power sector transformation [50].

4.1. Time-Varying Electricity Pricing Can Motivate Electric Vehicle Drivers to Charge at Times that are Advantageous for the Power System

Several provisions of the EU electricity sector reform that was concluded at the end of 2018, the so-called "Clean Energy for All Europeans" package, recognize that time-varying pricing can accelerate the integration of electric vehicles into the grid. It remains to be seen, however, how ambitiously Member States will implement the legislation. Our analysis underscores two crucial requirements for creating a suitable framework for dynamic pricing, with two objectives. First, it is critical that real-time energy prices are based on the full value of flexibility on the customer side, or the demand side. Second, electric vehicle users should be subject to fair retail tariffs for energy charges and network fees. In other words, all users should reap the benefits of smart charging and, in equal measure, should bear their rightful share of the costs for uncontrolled charging. When implementing the rules, EU countries are required to prepare a foundation for more dynamic pricing structures that support smart charging by capturing and communicating to EV customers the cost of producing electricity. Future research will be needed to closely monitor tariff designs for EV uptake, to learn from consumer experiences with tariffs, and to make data from these lessons publicly available. This is being practiced to a larger extent in some U.S. states, where regulators require energy suppliers to respond to the EV grid integration challenge through tariff design, infrastructure investments, and similar methods [51].

4.2. Leveraging Smart Pricing with Responsive Technology Generates Substantial Benefits

Policymakers can capitalize on the opportunity to maximize the benefits of time-varying pricing by ensuring responsive technology is broadly available to consumers. In this transition phase, Member State governments can help build a more dynamic market for charging solutions by taking an ambitious approach to translating the provisions of the Clean Energy for All Europeans package [52], by complying with existing legislations on smart meter rollout thoroughly and swiftly, and by revising standardization requirements to ensure broad distribution of market solutions. Research shows that granular data, for example from smart meters, is pivotal for integrating demand-side flexibility into the grid, such as that provided by electric vehicles [53]. The UK [54], for example, is considering whether it should require all new, non-public EV charging infrastructure to have the ability to react to price signals.

4.3. Grid-Friendly Charging Infrastructure is Key to Minimising Costs

Beneficial EV integration is dependent on strategically located, grid-friendly charging infrastructure that determines where, when and how EVs can be charged. This still presents a major hurdle for EV market take-up at the time this article was written. Elaborate models have been developed to assess use patterns for charging infrastructure. For example, researchers have identified load allocation strategies to support revenue calculation [55]. A body of research has also emerged around modeling the density requirements for charging infrastructure [56,57] and analyzing users' behavior at fast charging stations in cities [58] to inform planners. The findings highlight the gap between planned infrastructure rollout and future user needs [59], as well as the importance of appropriate planning. Specifically, more data and knowledge is needed to assess the long-term costs and benefits associated with infrastructure build-out such as location, installation, operation, and long-term maintenance, as well as a discussion of successful models for charging infrastructure ownership and the regulatory changes needed to realize them.

Policymakers are tasked with the challenge of developing public charging infrastructure in a range of circumstances: urban areas, along highways, and in rural settings. The common denominator is the existing energy and transport infrastructure, which should be considered together. The EU institutions will evaluate the Alternative Fuels Directive [60], which is the existing legal framework underpinning charging infrastructure development. In order to ensure we can meet future charging needs for different groups of EV users, it will be important to implement an integrated approach to energy and transport planning in this review. The implementation of the revised European Energy Performance of Buildings Directive [61], as part of the Clean Energy for All Europeans package, presents an opportunity to revisit building codes with a view toward facilitating vehicle charging at workplace and residential settings, including multifamily homes. It is also crucial to direct infrastructure funding in a way that bolsters the development of a competitive market for EV charging services. Municipalities can support this, for example, by including performance indicators in public tenders.

Further research will be needed as technology and business models for cost-efficient, low-carbon and grid-friendly EV grid integration develop in parallel with EV market uptake. Most importantly, the relevance of consumer education as a key condition for the success of smart charging programs further analysis, including the question of which public and private stakeholders are well placed to engage. For example, the question of how to adequately design tariffs for accessible public EV charging will become crucial for uptake. Taxation of EV use will also arise in different contexts.

5. Conclusions

This paper underscores that beneficial EV grid integration is not only possible, it is already happening, using existing tools for electricity tariff design, deployment of intelligent technologies and integrated planning. We suggest a comprehensive definition of beneficial EV grid integration and smart charging that aims at supporting policymakers in reducing emissions from both the transport and energy sectors. Findings suggest that, without this joint effort, the electrification of transport could stagnate, and burden drivers, electricity consumers, and the public sector with unnecessary costs. The other clear risk is that we will not attain the necessary reductions in carbon dioxide emissions and air pollution in the transport sector—the only sector where carbon emissions are still growing.

Supplementary Materials: A webinar summarizing the paper's findings is available online at https://www.raponline.org/knowledge-center/accelerating-the-benefits-of-electric-vehicle-integration/.

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Appendix A

The following interviews were undertaken as part of data collection for this study.

Table A1. Stakeholder interviews.

Organisation	Date	RAP Author	Duration
ChargePoint	26 November 2018	Dr. Julia Hildermeier, Christos Kolokathis	1:30
Norwegian E-Mobility Association	11 September 2018	Dr. Julia Hildermeier, Christos Kolokathis Catharina Wiese	1:30
Norwegian Water Resources and Energy Directorate	25 September 2018	Dr. Julia Hildermeier, Christos Kolokathis Catharina Wiese	1:30

References

1. European Union. European Alternative Fuels Observatory. Available online: https://www.eafo.eu/vehicles-and-fleet/m1 (accessed on 7 November 2019).
2. *Global EV Outlook*; International Energy Agency: Paris, France, 2019. Available online: https://webstore.iea.org/global-ev-outlook-2019 (accessed on 20 September 2019).
3. European Union. Energy Union: Commission Takes Action to Reinforce EU's Global Leadership in Clean Vehicles. Available online: https://ec.europa.eu/transport/modes/road/news/2017-11-08-driving-clean-mobility_en (accessed on 20 September 2019).
4. Buck, M.; Graf, A.; Graichen, P. Ten Priorities for the Next European Commission to Meet the EU's 2030 Targets and Accelerate Towards 2050. In *European Energy Transition 2030: The Big Picture*; Agora Energiewende: Berlin, Germany, 2019. Available online: https://www.agora-energiewende.de/fileadmin2/Projekte/2019/EU_Big_Picture/153_EU-Big-Pic_WEB.pdf (accessed on 20 September 2019).
5. Hildermeier, J.; Kolokathis, C.; Rosenow, J.; Hogan, M.; Wiese, C.; Jahn, A. *Start with Smart: Promising Practices for Integrating Electric Vehicles into the Grid*; Regulatory Assistance Project: Brussels, Belgium, 2019. Available online: https://www.raponline.org/knowledge-center/start-with-smart-promising-practices-integrating-electric-vehicles-grid/ (accessed on 10 October 2019).
6. Farnsworth, D.; Shipley, J.; Lazar, J.; Seidman, N. *Beneficial Electrification: Ensuring Electrification in the Public Interest*; Regulatory Assistance Project: Montpelier, VT, USA, 2018. Available online: https://www.raponline.org/wp-content/uploads/2018/06/6-19-2018-RAP-BE-Principles2.pdf (accessed on 20 September 2019).
7. Geels, F.W.; Kemp, R.; Dudley, G.; Lyons, G. (Eds.) *Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport*; Routledge Taylor & Francis Group: New York, NY, USA, 2012.
8. Langton, A.; Crisostomo, N. *Vehicle-Grid Integration: A Vision for Zero Emission Transportation Interconnected Throughout California's Electricity System*; California Public Utilities Commission: San Francisco, CA, USA, 2013. Available online: http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M080/K775/80775679.pdf (accessed on 20 September 2019).
9. Allison, A.; Whited, M. *Electric Vehicles still not Crashing the Grid: Updates from California*; Synapse Energy Economics: Cambridge, MA, USA, 2018. Available online: http://www.synapse-energy.com/sites/default/files/EV-Not-Crashing-Grid-17-025.pdf (accessed on 7 November 2019).
10. Canzler, W.; Knie, A. Mobility in the age of digital modernity: Why the private car is losing its significance, intermodal transport is winning and why digitalisation is the key. *Appl. Mobil.* **2016**, *1*, 56–67. [CrossRef]
11. Hochfeld, C.; Jung, A.; Klein-Hitpaß, A.; Maier, U.; Meyer, K.; Vorholz, F. *Mit der Verkehrswende die Mobilität von Morgen Sichern. 12 Thesen zur Verkehrswende*; Agora Verkehrswende: Berlin, Germany, 2017. Available online: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/12_Thesen/Agora-Verkehrswende-12-Thesen-Kurzfassung_WEB.pdf (accessed on 20 September 2019).
12. Slowik, P.; Kamakate, F. *New Mobility: Today's Technology and Policy Landscape*; The International Council for Clean Transportation: Washington, DC, USA, 2017. Available online: https://theicct.org/sites/default/files/publications/New-mobility-landscape_ICCT-white-paper_27072017_vF.pdf (accessed on 20 September 2019).
13. Beckmann, K.J.; Klein-Hitpaß, A. (Eds.) *Nicht Weniger Unterwegs, Sondern Intelligenter? Neue Mobilitätskonzeptei*; German Institute of Urban Affairs (Difu): Berlin, Germany, 2013. Available online: https://difu.de/publikationen/2013/nicht-weniger-unterwegs-sondern-intelligenter.html (accessed on 20 September 2019).
14. *Metastudie Forschungsüberblick Netzintegration Elektromobilität*; Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e.V. (FGH): Mannheim, Germany, 2018. Available online: https://www.vde.com/resource/blob/1790048/d86a2bb62b27caa2345ff810c4d9c816/e-mobilitaet-downloadstudie-data.pdf (accessed on 20 September 2019).
15. Koeller, S. Electrive.net. E.ON: 100% E-Autos im Jahr 2045 für Netze zu Stemmen. Available online: https://www.electrive.net/2019/05/22/e-on-100-e-autos-im-jahr-2045-fuer-netze-zu-stemmen/ (accessed on 20 September 2019).
16. Sebastain. Elektroauto-News.net. EnBW: Strombedarf ist aus Heutiger Sicht keine Herausforderung für die Elektromobilität. Available online: https://www.elektroauto-news.net/2019/enbw-strombedarf-keine-herausforderung-elektromobilitaet/ (accessed on 20 September 2019).

17. Bünger, U.; Nicolai, S.; Zerhusen, J.; Monsalve, C.; Kharboutli, S.; Michalski, J.; Ruhe, S.; Albrecht, U. *Infrastrukturbedarf E-Mobilität: Analyse Eines Koordinierten Infrastrukturaufbaus zur Versorgung von Batterie- und Brennstoffzellen-Pkw in Deutschland*; Ludwig-Bölkow-Stiftung: Ottobrunn, Germany, 2019. Available online: https://stiftung.adac.de/app/uploads/2019/06/IBeMo_Abschlussbericht_final_190625_LBST_Zerhusen.pdf (accessed on 20 September 2019).
18. Sanchez Duran, R. Smart Charging: Steering the Charge, Driving the Change. Presented at the EURELECTRIC Talking Smart Grids, Brussels, Belgium, 24 March 2015. Available online: https://www3.eurelectric.org/media/171787/sanchez-duran.pdf (accessed on 10 October 2019).
19. Wargers, A.; Kula, J.; Ortiz de Obregon, F.; Rubio, D. *Smart Charging: Integrating a Large Widespread of Electric Cars in Electricity Distribution Grids*; European Distribution System Operators for Smart Grids: Brussels, Belgium, 2018. Available online: https://www.edsoforsmartgrids.eu/wp-content/uploads/EDSO-paper-on-electro-mobility-2.pdf (accessed on 20 September 2019).
20. Maier, U.; Peter, F.; Jahn, A. *Verteilnetzausbau für die Energiewende—Elektromobilität im Fokus*; Agora Verkehrswende, Agora Energiewende, Regulatory Assistance Project: Berlin, Germany, 2019. Available online: https://www.agora-verkehrswende.de/fileadmin/Projekte/2019/EV-Grid/AgoraRAP2019_VerteilnetzausbauElektromobilitaet_2019-08-26.pdf (accessed on 20 September 2019).
21. Hogan, M.; Kolokathis, C.; Jahn, A. *Treasure Hiding in Plain Sight: Launching Electric Transport with the Grid We Already Have*; Regulatory Assistance Project: Brussels, Belgium, 2018. Available online: https://www.raponline.org/knowledge-center/treasure-hiding-in-plain-sight-launching-electrictransport-with-the-grid-we-already-have/ (accessed on 20 September 2019).
22. Element Energy. *Batteries on Wheels: The Role of Battery Electric Cars in the EU Power System and Beyond*; European Federation for Transport & Environment: Brussels, Belgium, 2019. Available online: https://www.transportenvironment.org/publications/batteries-wheels-role-battery-electric-cars-eu-power-system-and-beyond (accessed on 20 September 2019).
23. Yin, R.K. *Case Study Research Design and Methods*, 5th ed.; Sage: Thousand Oaks, CA, USA, 2014.
24. Lazar, J.; Gonzalez, W. *Smart Rate Design for a Smart Future*; Regulatory Assistance Project: Montpelier, VT, USA, 2015. Available online: https://www.raponline.org/wp-content/uploads/2016/05/rap-lazar-gonzalez-smart-rate-design-july2015.pdf (accessed on 10 October 2019).
25. Kolokathis, C.; Hogan, M.; Jahn, A. *Cleaner, Smarter, Cheaper: Network Tariff Design for a Smart Future*; Regulatory Assistance Project: Brussels, Belgium, 2018. Available online: https://www.raponline.org/knowledge-center/cleaner-smarter-cheaper-network-tariff-design-for-a-smart-future/ (accessed on 20 September 2019).
26. Liberkowski, A. *Compliance Filing, Residential Electric Vehicle Charging Tariff*; Docket No. E002/M-15-111; Xcel Energy: Minneapolis, MN, USA, 2018. Available online: https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=eDocketsResult&docketYear=15&docketNumber=111# (accessed on 10 October 2019).
27. Iberdrola. Electric Vehicle Plan. Available online: https://www.iberdrola.es/en/movilidad-electrica/electric-vehicle-plan (accessed on 20 September 2019).
28. *Agile Octopus: A Consumer-Led Shift to a Low Carbon Future*; Octopus Energy: London, UK, 2018.
29. Radius. Tariffer og Netabonnement. Available online: https://radiuselnet.dk/Elkunder/Priser-og-vilkaar/Tariffer-og-netabonnement (accessed on 10 October 2019).
30. Faruqui, A.; Hledik, R.; Palmer, J. *Time-Varying and Dynamic Rate Design*; Regulatory Assistance Project and The Brattle Group: Montpelier, VT, USA, 2012.
31. Green Mountain Power. In-Home Level 2 EV Charger. Available online: https://greenmountainpower.com/product/home-level-2-ev-charger/ (accessed on 10 October 2019).
32. Dostis, R. Green Mountain Power Electric Vehicle Programs & Outlook. Presented at the Senate Committee on Transportation, Montpelier, VT, USA, 1 March 2019. Available online: https://legislature.vermont.gov/Documents/2020/WorkGroups/Senate%20Transportation/Electric%20Vehicle%20Charging%20Tariff%20Testimony/W~{}Robert%20Dostis~{}Green%20Mountain%20Power%20Electric%20Vehicle%20Programs%20Outlook~{}3-1-2019.pdf (accessed on 20 September 2019).
33. Jedlix. Smart Charging with Jedlix. Available online: https://www.jedlix.com/en/ (accessed on 20 September 2019).

34. Next-Kraftwerke. Next Kraftwerke and Jedlix Launch Initiative to Use Electric Car Batteries for Grid Stability. 2018. Available online: https://www.next-kraftwerke.com/news/next-kraftwerke-jedlix-launch-initiative-to-use-electric-car-batteries-for-grid-stability (accessed on 10 October 2019).
35. Maxem. Your Smart Energy Monitor. Available online: https://maxem.io/thuis (accessed on 10 October 2019).
36. Zappi. Eco-Smart EV Charger. Available online: https://myenergi.com/product/zappi/ (accessed on 10 October 2019).
37. ChargePoint; Regulatory Assistance Project, Brussels, Belgium. Personal Communication, 26 November 2018.
38. Pasaoglu, G.; Fiorello, D.; Martino, A.; Scarcella, G.; Alemanno, A.; Zubaryeva, A.; Thiel, C. *Driving and Parking Patterns of European Car Drivers—A Mobility Survey*; EUR 25627 EN; Technical Report for European Commission; Joint Research Centre: Brussels, Belgium, 2012. Available online: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC77079/driving%20and%20parking%20patterns%20-%20final_online.pdf (accessed on 7 November 2019).
39. Helmus, J.R.; Spoelstra, J.C.; Refa, N.; Lees, M.; van den Hoed, R. Assessment of public charging infrastructure push and pull rollout strategies: The case of the Netherlands. *Energy Policy* **2018**, *121*, 35–47. [CrossRef]
40. Nicholas, M.; Hall, D. *Lessons Learned on Early Electric Vehicle Fast-Charging Deployments*; The International Council on Clean Transportation: Washington, DC, USA, 2018. Available online: https://www.theicct.org/sites/default/files/publications/ZEV_fast_charging_white_paper_final.pdf (accessed on 20 September 2019).
41. European Alternative Fuels Observatory. Alternative Fuels (Electricity) Charging Infrastructure Statistics. Available online: https://www.eafo.eu/alternative-fuels/electricity/charging-infra-stats (accessed on 20 September 2019).
42. Ubitricity. Zap-Map Integrates Ubitricity Charge Points. Available online: https://www.ubitricity.co.uk/unternehmen/newsroom/zap-map-integrates-ubitricitys-london-and-oxford-charge-points/ (accessed on 20 September 2019).
43. Zap-Map. Ubitricity Network. Available online: https://www.zap-map.com/charge-points/public-charging-point-networks/ubitricity-network (accessed on 20 September 2019).
44. Pakenham, T. If You Build It, They Will Charge. Utility Week. 9 February 2018. Available online: https://utilityweek.co.uk/build-will-charge/ (accessed on 21 January 2019).
45. Ribberink, H.; Wilkens, L.; Abdullah, R.; McGrath, M.; Wojdan, M. Impact of Clusters of DC Fast Charging Stations on the Electricity Distribution Grid in Ottawa, Canada. Presented at the Electric Vehicle Symposium 30, Stuttgart, Germany, 9–11 October 2017.
46. Hanley, S. National Grid Planning Fast Charging Network for UK. 21 February 2018. Available online: https://cleantechnica.com/2018/02/21/national-grid-planning-fast-charging-network-uk/ (accessed on 20 September 2019).
47. Greenlots. Hawaiian Electric & Greenlots Test EV Charging and Energy Storage as Ideal Grid Allies. 15 February 2016. Available online: https://www.prnewswire.com/news-releases/hawaiian-electric-greenlotstest-ev-charging-and-energy-storage-as-ideal-grid-allies-300225926.html (accessed on 20 September 2019).
48. Battery Electric Car Ferry in Norway; Paris Process on Mobility and Climate (PPMC). Available online: http://www.ppmc-transport.org/battery-electric-car-ferry-in-norway/ (accessed on 20 September 2019).
49. Migden-Ostrander, J. Power sector transformation in state utility regulation: To boldly go where no regulator has gone before. *Electr. J.* **2019**, *32*, 106626. [CrossRef]
50. Glitman, K.; Farnsworth, D.; Hildermeier, J. The role of electric vehicles in a decarbonized economy: Supporting a reliable, affordable and efficient electric system. *Electr. J.* **2019**, *32*, 106623. [CrossRef]
51. California Public Utility Commission. *Order Instituting Rule Making to Continue the Development of Rates and Infrastructure for Vehicle Electrification*; California Public Utility Commission: San Francisco, CA, USA, 19 December 2018.
52. European Commission. *Clean Energy Package for All Europeans*; Publications Office of the European Union: Luxembourg, 2019.
53. Golden, M.; Scheer, A.; Best, C. Decarbonization of electricity requires market-based demand flexibility. *Electr. J.* **2019**, *32*, 106621. [CrossRef]
54. *Making Electric Vehicles Integral Parts of the Power System*; Smart Energy Europe: Brussels, Belgium, 2019. Available online: https://www.smarten.eu/wp-content/uploads/2019/07/FINAL-smartEn-White-Paper-E-Mobility.pdf (accessed on 1 October 2019).

55. Zhao, Y.; Huang, H.; Chen, X.; Zhang, B.; Zhang, Y.; Jin, Y.; Zhang, Q.; Cheng, L.; Chen, Y. Charging Load Allocation Strategy of EV Charging Station Considering Charging Mode. *World Electr. Veh. J.* **2019**, *10*, 47. [CrossRef]
56. Nicholas, M.; Hall, D.; Lutsey, N. *Quantifying the Electric Vehicle Charging Infrastructure Gap across U.S. Markets*; The International Council on Clean Transportation: Washington, DC, USA, 2019.
57. *Roll-Out of Public EV Charging Infrastructure in the EU Is the Chicken and Egg Dilemma Resolved?* Transport & Environment: Brussels, Belgium, 2018. Available online: https://www.transportenvironment.org/sites/te/files/publications/Charging%20Infrastructure%20Report_September%202018_FINAL.pdf (accessed on 1 October 2019).
58. Wolbertus, R.; Van den Hoed, R. Electric Vehicle Fast Charging Needs in Cities and along Corridors. *World Electr. Veh. J.* **2019**, *10*, 45. [CrossRef]
59. Motoaki, Y. Location-Allocation of Electric Vehicle Fast Chargers—Research and Practice. *World Electr. Veh. J.* **2019**, *10*, 12. [CrossRef]
60. *Directive 2014/94/EU of the European Parliament and of the Council of the Deployment of the Alternative Fuels Infrastructure*; European Parliament and Council of the European Union: Brussels, Belgium, 2014. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=en (accessed on 20 September 2019).
61. *New Energy Performance in Buildings Directive Comes into force on 9 July 2018*; European Commission: Brussels, Belgium, 19 June 2019. Available online: https://ec.europa.eu/info/news/new-energy-performance-buildings-directive-comes-force-9-july-2018-2018-jun-19_en (accessed on 20 September 2019).