***Integration strategies of electric vehicles into the electricity system and impacts on investment decisions and prices***

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## Overview

Europe has ambitious plans to decarbonize the energy system, of which the transport sector presents a considerable challenge. In this context, sector-coupling becomes a crucial asset to supply a low cost energy based on Variable Renewable Energies (VREs) to the transport sector, while providing flexibility to support the variable production from renewable sources. The transition from traditional Internal Conmbustion Engines (ICE) towards Electric Vehicle (EV) in private transport creates thereby new opportunities to use the cheap and low carbon energy generated in the electricity sector, thereby decarbonising transportation, while providing storage and flexibility services with electric batteries. Dependent on the charging scheme, the entire energy system is not only affected by changing electricity prices, but also by investments into technologies dependent on that.

EVs typically double households’ electricity consumption. Passive Charging (PC) then becomes a threat to the successful integration of EV. However, alternatives exist. Smart Charging (SC) concentrates EV charging during the low price hours, thereby reducing consumption peaks and wholesale price fluctuations and Vehicle-to-grid (V2G) allows to discharge energy to the grid and provides bidirectional flexibility services. As vehicles are available around 96% of the time, V2G offers the opportunity to serve high flexibility through discharging.

Previous research focused on the impact of EV implementation into the electricity system. It is proven that SC smoothens energy demand and stabilizes market prices. Peak load is further reduced and the integration of VRE sources is improved. Using a system-wide perspective, shows that V2G in Europe results in lower system cost and additional investment into VREs. Although the literatures shed lights on the benefits of EV integration, we argue that past studies are limited as they omit to consider a set of parameters that are critical in the assessment of EV flexibility, including in their representation of battery wear degradation and in the definition of charging constraints [5]. Furthermore, the result generated in current literature often lack resulting in thorough holistic pathway analysis on how to reach decarbonisation targets across sectors.

The present study fills this gap. We First, include the effect of degradating batteries to the flexibility potential in including it to the EV cost function. Second, we develop a better definition of State-Of-Charge (SOC) goals in the morning that allows us to reflect the realistically achievable flexibility in a less loose way than in the other studies. Third, we develop a pathway analysis resulting into optimal transistion strategies to support policy recommendations. Utilising this better representation of EV-based flexibility, we assess and compare the impacts of various integration strategies of EVs on energy systems investments and electricity prices in North-Western Europe. Our findings highlight pathways dependent on EV charging schemes from 2020-2050 which help us shape sound policy recommendations.

## Methods

In this study we develop a new methodology to model fleets of EV within an aggregated virtual storage investigating the three main charging schemes PC, SC and V2G. It accounts for longer SOC provision for later departure hours. Further, the methodology introduces forced charging of single vehicles arriving with a low SOC. The Danish National Transport Survey (TU) is used to generate regional and national driving demands including availability and demand characteristics. All factors are implemented within a newly developed addon in the energy system model Balmnorel. By including battery degradation in EV, the fleet reacts not only on market signals but also on the private objective of prolonging cell lifetime.

The methods are divided into two parts consisting of a throrough driving pattern analysis to generate an aggregated virtual storage of EV including constraints from single vehicle conditions and further, the integration of it within an addon into Balmorel.

The focus lays on differences in energy production along the decades and impact on system cost and prices as well as emissions. Additionally, the impact of the combination of EV charging schemes and transmission system expansion is investigated to provide comparative example. Subsequently the investigation quantifies the impact of electric vehicles in the energy system to support policy recommendation in the latter.

## Results

Our results are compared on the basis of the effects of EV charging schemes on differences in electricity production, energy system cost, spot price fluctuation as well as emissions.

Energy production results illustrates the competition and substitution effects that take place in the system. While wind and PV are the largest contributors in the PC scenario (supplying respectively 1019 TWh and 473 TWh in 2050), wind developpers benefit the most when increasing flexibility. Over 40 TWh of additional wind energy is substituting solar PV with V2G. This is because of EV charging during hours of larger and cheaper wind energy supply. PC is favouring production during day time as the largest demand is scheduled during those hours. With the additional flexibility however, this pattern is not needed anymore and therefore the model invests into cheaper but more variable technologies. The same effect is valid when introducing transmission investments. However, solar PV decreases less because Power-to-Heat (P2H) is stronger coming into play in the heat sector.

The findings show that energy system costs (production plants in the electricity and heat sector + network infrastructure) decrease along with the sophistication of charging schemes and the level of flexibility provided by EVs. Total accumulated system cost decreases by up to 1.83% in the V2G scenario compared to the case with passive charging. EV flexibility mainly substitutes to investment in stationary batteries in the SC and V2G scenarios and also to peak capacities powered with gas in the V2G scenario, after 2030, when the EV fleet is large enough to provide sufficient regulation flexibility. Subsequently, flexible EV fast forward the phase-out of fossil fuel-based back-up capacities. Allowing for transmission system expansion achieves further reduction in cumulated system cost (up to with 2.7%). More transmission lines, in addition to flexible charging schemes, further reduce the business opportunities for expensive peak power plants since the pan-European system gives access to larger flexible resources.

The charging schemes further have an impact on electricity prices. The model shows two main results. First the different charging schemes have a negligeable impact on the average spot prices throughout the period on the entire zone (the average yearly spot price is comprised between -0.008€/MWh and -0.012€/MWh regardless of the scenario). This of course masks differences at the country level. Distributional effects exists due to better utilization of transmission capacities through additional EV flexibility. Second, the variability of prices decrease significantly from PC from 221 (€/MWh)^2 to 159 (€/MWh)^2. The same effect is valid on model level and magnifies over time. The energy system adjusts to the available flexibility of EV and therefore invests into cheaper renewable technologies.

Due to the stronger integration of VRE and the peak shaving capability of EV the CO2 emissions are substantially reduced in SC and V2G. The savings amount to 1.7 mTonnes of CO2 with SC compared to PC, whereas V2G reaches cutbacks of 9.5 mTonnes, or 1.2% of the total emissions. Distributional effects appear between countries with historically large dependency on coal and countries with low carbon emission. Germany and Poland record the highest reduction, while other countries like Denmark and the Netherlands increase slightly emissions to support their neighboring countries. Grid investment exacerbate CO2 emissions cut. 11.5 mTonnes and 22.8 mTonnes are avoided compared to PC in SC and V2G respectivelly.

## Conclusions

This study investigates the effect of SC and V2G on the energy system development from 2020-2050. The electrification of the transport sector results in significant adjustment of the electricity generation technologies. SC and V2G create in particular a profitable business case for wind technologies. Further, smart and bidirectional charging fast forward the phase-out of peak power plants using gas and reduce significantly the business opportunity for stationary batteries. Increased flexibility of EV also show a stronger competition between other flexible technologies like heat pumps. Not only overall system cost are reduced across North-West Europe, also electricity price fluctuations are smoothened. This leads to adjustments in investment decisions and redistribution of revenue streams. Wind is the main beneficiary, which subsequently leads to higher income of regions with large wind potentials in the North Sea area. EV flexibility reduces overall GHG emissions with transnational effects.

In this study we show that EV flexibility can play a significant role in the pathway towards a carbon neutral energy system. At the same time, framework barriers have to be addressed by policy in order to utilize the full potential shown in this investigation. Redistributional effects can lead to conflicts across regions and stakeholders. At the same time, flexibility through sector-coupling has to be enhanced using a holistic approach in order to support competition between technologies leading to a least cost transistion of the entire energy system towards carbon neutrality.