Electrical Power and Energy Systems 172 (2025) 111330

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Predictive modeling of vehicle-to-grid flexibility: A bottom-up approach demonstrated for a case-study in Germany☆

Samuel Hasselwander *, Murat Senzeybek, Gabriel Möring-Martínez

German Aerospace Center (DLR), Institute of Vehicle Concepts, Pfaffenwaldring 38-40, Stuttgart, 70569, Germany

ARTICLE INFO

Keywords:
Battery electric vehicle
Vehicle-to-grid
Market potential

ABSTRACT

Germany's energy transition requires substantial energy storage capacity to manage grid stability and renewable energy integration. Conventional storage technologies may face limitations in meeting the projected demand, while the growing battery electric vehicle (BEV) fleet represents a potential distributed storage resource with uncertain vehicle-to-grid (V2G) capacity currently. In order to bridge this uncertainty, this study develops a bottom-up approach to calculate the gross battery capacity that passenger vehicle fleets could provide for grid services. The approach is demonstrated through application to the German market, identifying key factors that influence realistic V2G deployment scenarios.

We enhanced our bottom-up vehicle technology scenario model by integrating different battery technologies and vehicle models offering bidirectional charging. In the reference scenario, considering annual benefits of 150 to 270 Euro for different bidirectional charging use cases and costs of 900 Euro for a dedicated wallbox, our simulations indicate up to 18.3 million bidirectional-capable BEVs by 2045, resulting in nearly 1300 GWh of gross battery capacity. Even with more conservative estimates from our sensitivity analyses, the potential battery capacity of the bidirectional BEV fleet would exceed Germany's future energy storage capacity by a factor of four, demonstrating the considerable potential of passenger vehicles as distributed grid storage resources.

1. Introduction and motivation

Rising electricity prices, the removal of environmental incentives, and fluctuating raw material costs have created a dynamic market situation for battery electric vehicles, significantly impacting new vehicle registrations in Germany. For instance, after the withdrawal of incentives for electric vehicles in Germany, the share of newly registered BEVs decreased from 18% in 2023 to 13% in 2024 [1].

Alongside these market effects, advancements in new battery technologies, increasing installed battery capacities, and the start of vehicle-to-grid-capable models are driving continuous diversification within the vehicle market [2]. This diversification adds complexity to the market composition, creating opportunities to enhance previous projection methods that relied on trend curves or policy targets by incorporating more detailed technology-specific considerations [3,4]. However, to properly scale power grids, it is essential to quantify future charging demands and the possibilities for relieving grid load [5–7]. Therefore, a bottom-up approach to model the vehicle market including potential future available models is essential [8]. This method enables a more accurate estimation of the future total battery capacity of the vehicle fleet by aggregating individual vehicle models.

A key consideration is how to accurately capture the impact of various battery technologies and vehicle models on the overall battery capacity of the fleet. To address this challenge, we expanded the capabilities of the bottom-up vehicle technology scenario model VECTOR21 [9] by integrating different battery technologies and vehicle models which offer V2G functionality. This enhancement enabled us to develop a comprehensive bidirectional vehicle scenario for Germany's passenger vehicle fleet, allowing for precise estimates of future battery capacity and V2G potential. The resulting data is utilized in conjunction with the PowerForecastMapper (PFM), a tool developed by the German Aerospace Center (DLR) that spans transportation and energy sectors [10]. This paper lays the foundation for future work with the PFM, providing a reference scenario that paves the way for high-resolution predictions of Germany's charging demands and grid interactions.

Building on this groundwork, our research contributes to the development of more efficient and sustainable energy systems by providing

☆ This article is part of a Special issue entitled: 'EV Integration and V2G Interaction' published in International Journal of Electrical Power and Energy Systems.

* Corresponding author.
E-mail address: samuel.hasselwander@dlr.de (S. Hasselwander).

https://doi.org/10.1016/j.ijepes.2025.111330
Received 26 June 2025; Received in revised form 8 October 2025; Accepted 27 October 2025
Available online 1 November 2025

policymakers, grid operators, and other stakeholders with valuable insights into the potential V2G flexibility of the future German vehicle fleet. By integrating advanced battery technologies and V2G capabilities into our bottom-up vehicle scenario model, we facilitate the efficient integration of BEVs into the energy system, to help mitigating grid load and ultimately supporting the creation of a more resilient energy system.

2. Emerging market for bidirectional BEVs

2.1. Trends and technologies of bidirectional BEVs

Bidirectional charging enables the flow of electricity from a storage device, such as the traction battery of a BEV, back to the grid. This process involves converting the direct current (DC) of the vehicle's battery to alternating current (AC) for the grid (or household in case of vehicle-to-home (V2H)), which can be done either within the onboard charger or via a DC wallbox.

Several vehicles, including the Volkswagen ID series [11], Polestar 3 [12], Hyundai Ioniq 5 [13], Renault 5 [14] and also GM's upcoming BEVs based on its Ultium platform [15] are prepared for or already feature V2G functionalities, with some models also supporting V2H and most of current BEVs already offering vehicle-to-load (V2L) features.

While the market for bidirectional BEVs is clearly growing, compatible infrastructure remains largely proprietary to manufacturers. This poses challenges for standardization and interoperability across different brands and models. The recently introduced ISO 15118-20 [16] standard aims to address these issues by establishing a universal protocol for bidirectional charging. If both the vehicle and the wallbox are equipped with components that use ISO 15118-20, then they can exchange information like desired departure time, required state-of-charge (SOC) in order to calculate the available operating range for bidirectional charging.

However, legal and regulatory hurdles must still be overcome to fully realize the potential of this technology. In Germany taxes must still be paid on electricity fed back into the grid by bidirectional electric vehicles. Only a small proportion of the government-induced electricity price components are currently exempt (2021: 6% [17]). One possible regulatory adjustment would be to treat them the same as stationary storage systems, which are only subject to the concession levy which would correspond to an exemption of 17.1 ct/kWh or 91% of the price components [17].

2.2. AC vs. DC wallboxes

One of the ongoing discussions in the industry revolves around the choice between AC and DC wallboxes for bidirectional charging. AC wallboxes are generally cheaper, with costs ranging from around 900 to 2100 Euro in 2025 [18–20], but they come with higher certification needs for the vehicle manufacturer, particularly concerning the energy sold by the car. The first manufacturers which follow the AC pathway are Renault who joined with technology partners to develop an own AC wallbox and offer bidirectional charging within their new Renault R5 vehicle series [21] and Volvo with its new EX90 [22].

On the other hand, DC wallboxes, which are more expensive due to the additional inverters, ranging from 2095 to over 10,000 Euro in 2025 [23–26], but they eliminate the need for further certification requirements of the original equipment manufacturer (OEM). In September 2025, BMW introduced its DC bidirectional charging solution with the new iX3. Here the German manufacturer offers a complete package together with the energy provider E.ON speaking about possible yearly benefits of up to 720 Euro at additional costs of only 2095 Euro for the DC wallbox [26].

2.3. Economic benefits

The economic benefits of bidirectional BEVs widely varies depending on the country, housing situation, vehicle size and driving profiles [17,27,28]. In [17], the 'Forschungsstelle für Energiewirtschaft' (FfE) showed that, in Germany, operating cost savings of up to 610 Euro per year would be possible compared to the use case of smart charging when V2G is being combined with photovoltaic (PV) self-consumption increase, time arbitrage and exemptions from certain taxes and grid fees to avoid double surcharges. However, this use case would result in an equivalent of 96 additional full cycles for the traction battery which would most likely not be included within the vehicles warranty [17]. Therefore they added an use case that limits the V2G usage to 20 additional full cycles in order to not exceed the vehicles warranty. Then a BEV that would be used for V2G in combination with a PV self-consumption increase could benefit of operating cost savings of up to 270 Euro per year. To accommodate customers who lack the capability to increase their PV self-consumption, the use case of V2G cost savings through time arbitrage alone results in approximately 150 Euro per year [17].

In order to successfully implement V2G applications economically, technical feasibility must be ensured through V2G-ready vehicles, wallboxes and standardization. Additionally, electricity fed back into the grid by vehicles should be exempt from taxes, levies and surcharges. A corresponding regulatory framework could benefit all stakeholders by facilitating a more efficient use of distributed battery storage resources.

3. Bottom-up approach to model the V2G fleet capacity

In this study, the future German passenger vehicle market is modeled using DLR's internal vehicle technology scenario model called VECTOR21 (V21). For consistency and comparability, we base our analysis on the established Ariadne scenario assumptions [29], updating them slightly in terms of energy price trends and political framework conditions as well as extending this to future BEV models with different battery sizes and cell chemistries. To further extend the battery diversification work as described in [8], V2G-capable vehicle models are also added, allowing for a more detailed projection of the future V2G fleet capacity.

3.1. Vehicle technology scenario model: VECTOR21

The VECTOR21 scenario model is a comprehensive tool designed to simulate the complex decision-making process of consumers when purchasing a new vehicle, taking into account the intricacies of the German and European vehicle markets. To achieve this, the model creates detailed profiles of customers as individual agents, each with unique characteristics such as annual mileage, housing situation, income level, and different vehicle preferences. These agent profiles are then used to calculate personalized utility values for various vehicle options, enabling the model to simulate the purchasing behavior of a diverse range of consumers [30–32].

Our model incorporates a wide range of vehicle types, including internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV), as well as different fuel types such as conventional fossil fuels, synthetic fuels, and compressed natural gas. For each agent, the model generates a set of vehicle options that reflect the latest technological advancements and cost developments in the automotive industry, including improvements in battery systems, electric motors, and power electronics.

The purchase decision is simulated within a dynamic environment that accounts for various external factors, as shown in Fig. 1, such as government policies (e.g., CO_2 fleet emissions regulations, fuel taxation, purchase incentives), global market trends, and technological innovations. Agents are assumed to select the vehicle that best aligns

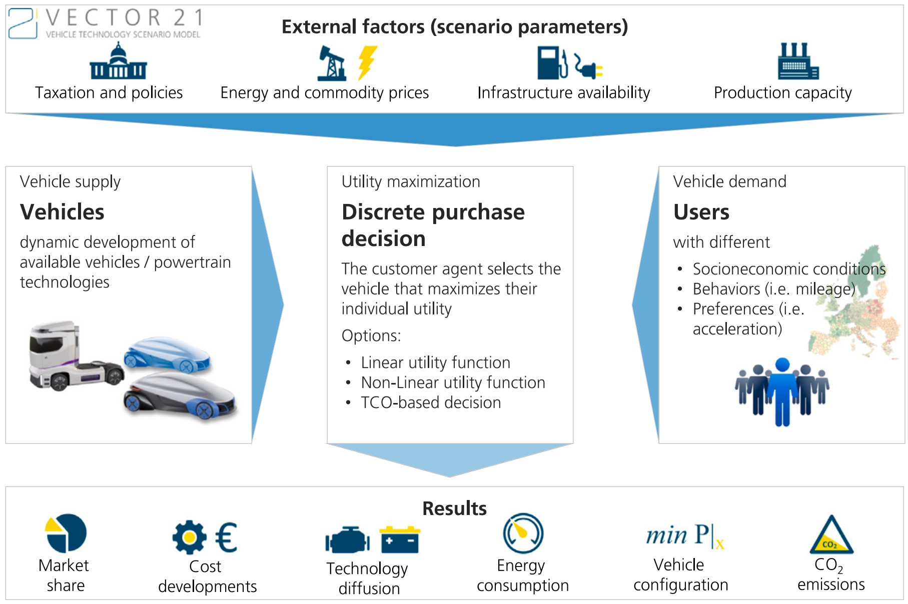

Fig. 1. Method of bottom-up vehicle technology scenario model VECTOR21 [9].

with their specific needs, preferences, and infrastructure requirements, representing the most utility-effective option.

The agents are categorized into distinct adopter groups based on their willingness to embrace new technologies and pay a premium for environmentally friendly vehicles. Additionally, other performance-related factors such as acceleration and range requirements are weighted differently for each agent, reflecting their unique priorities and preferences. By simulating the interactions between these complex factors, the V21 model provides a nuanced understanding of the future vehicle market and the potential adoption of alternative powertrains and fuels.

The outcomes of the scenario, specifically the projected new registrations by powertrain type, are combined with a cohort-based empirical survival model to estimate the evolution of the national vehicle fleet. For Germany, the age-specific number of surviving vehicles is determined using cumulative survival probabilities derived from historical registration and vehicle stock data. The core cohort model is based on Oguchi and Fuse [33] and refined by Held et al. [34], and its application to the VECTOR21 framework is detailed in Möring-Martínez et al. [35]. This approach allows to account for the gradual retirement of older vehicles while integrating the inflow of new registrations, providing a detailed, age-resolved fleet composition by powertrain. Empirical survival curves are calibrated using data from the Kraftfahrt-Bundesamt [36,37], with the fitted Weibull distribution achieving an R^2 of 0.99 for 2021. We assume a constant vehicle lifespan when projecting the fleet composition up to 2050, although a slight increase in average fleet age was observed between 2008 and 2021 [35]. By combining projected new vehicle sales with empirical fleet turnover rates, the model provides a realistic simulation of fleet electrification over time.

The V21 framework has been extensively validated in previous peer-reviewed studies [32,35]. These validations compared modeled BEV new registrations and stock fleet shares with observed data and independent projections, including those from the International Energy Agency [38]. The model achieved low prediction errors compared to other models in literature [39], with root mean square error values of 1.5% for EU-27 BEV new registrations, 0.18% for EU-27 BEV stock calculations, and 0.1% for Germany between 2014 and 2023, confirming its reliability for market forecasting. Building on this validated framework, the present study extends VECTOR21 to incorporate battery electric vehicles with bidirectional charging capabilities for the German vehicle market and fleet.

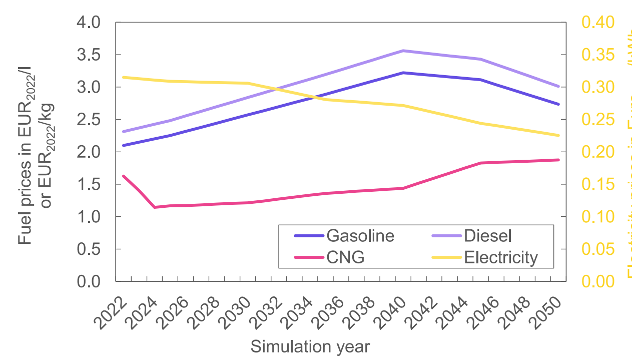

Fig. 2. Energy prices assumed in the bidirectional vehicle scenario as based on [29].

3.2. Key framework assumptions

The V21 model relies on several key framework assumptions, including regulatory, energy, infrastructure, and technology-related factors. The regulatory assumptions include CO_2 fleet limits in line with the Fit-for-55 package [40], which mandates reductions of 15% in 2025, 55% in 2030 (both relative to 2021 levels), and a registration ban for vehicles with combustion engines from 2035 onwards. Additionally, penalities of 95 Euro per g_{CO2}/km are applied to the vehicle prices if emissions exceed the limits. Energy prices as shown in Fig. 2 are based on Ariadne climate neutrality scenarios [29]. In this scenario, the rising CO_2 price as well as the growing drop-in rate of e-fuels to decarbonize the vehicle fleet contribute to steadily increasing gasoline and diesel prices. Meanwhile, electricity prices are assumed to decrease slightly, which, in combination with improving infrastructure availability (considering the agents' housing situation), drives the adoption of BEVs.

3.3. Bottom-up vehicle calculation

A critical component of the V21 model is the bottom-up calculation of vehicle costs, particularly with regards to battery systems. This involves a complete cost calculation of the battery system, including all relevant components such as cells, modules, housing, and battery

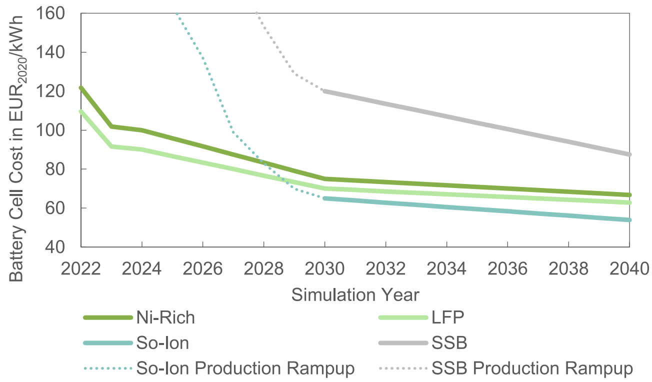

Fig. 3. Assumed battery cell costs for lithium-ion, sodium-ion (So-Ion), and solid-state battery (SSB) technologies from 2022 to 2040. Derived based on techno-economic analysis [41] and market data [42].

management systems. The underlying battery cell cost shown in Fig. 3 is derived from our own techno-economic analysis based on literature reviews, product data sheets, expert interviews, and teardown reports [41]. The cost trajectory for the production ramp-up of emerging battery technologies like Sodium-Ion (So-Ion) or solid-state batteries (SSBs) are developed using market data from BloombergNEF [42].

To further extend the battery diversification work as shown in [8], bidirectional-capable BEV variants (BEV BiDi) were added, allowing for a more detailed projection of the future V2G fleet capacity. Despite the current ambiguity surrounding the technology used for V2G-capable vehicle models (AC or DC), as detailed in Section 2.2, we optimistically assume the market entry of BEVs with AC V2G capability for the bidirectional BEV scenario. This is because AC V2G represents a more favorable use case for end customers, given that wallboxes currently only cost between 900 to 2100 Euro in 2025 (cf. Section 2.2). Manufacturers must adapt the vehicle's on-board charging device to support both charging (AC to DC) and discharging (DC to AC). However, it is assumed that the adaptation of on-board charging devices for bidirectional capabilities will not significantly impact OEM costs, resulting in a comparable production costs to conventional BEVs. This benefit is partially offset by the additional need for agents to invest around 900 Euro in a wallbox that offers bidirectional charging capabilities [18]. If DC V2G vehicles would be implemented, the market potential would be correspondingly lower due to the significantly more expensive purchase costs for DC bidirectional wallboxes. For the bidirectional BEV scenario of the PFM, we therefore initially assume the optimistic technology case and will consider the other cases later in the sensitivity analyses allowing for a detailed understanding of the economic and technological factors influencing the future V2G fleet capacity.

3.4. Assumed yearly economic benefits of bidirectional BEVs

As described in Section 2.3, the annual economic benefit varies depending on the different possible use cases. Due to the living situation of the agents taken into account in V21, we can consider the two use cases: timed arbitrage as well as PV self-consumption increase plus timed arbitrage separately. As shown in Table 1, agents with very low and low charging infrastructure availability only receive the lower annual economic benefits of 150 Euro per BEV BiDi according to the FfE study [17] and agents with medium, high and very high charging infrastructure availability receive the higher benefits of 270 Euro per BEV BiDi per year as based on FfE study [17], Figure 8-3. Based on the difference between managed (or smart) charging and calculated possible yearly V2G earnings if Germany would change their regulations to reduce the levies on V2G.

Table 1
Assumed yearly economic benefits of bidirectional BEVs in the PowerForecastMapper reference scenario based on [17].

V21 infrastructure cluster	Yearly economic benefits	Note
Lowest and low	150 Euro/vehicle	Yearly economic benefits from arbitrage only. See [17], Figure 7-2[a].
Medium, high and highest	270 Euro/vehicle	PV self-consumption increase with time arbitrage. See [17], Figure 8-3[a].

[a] Value refers to the difference between managed charging and V2G earnings if Germany would change their regulations to reduce the levies on V2G.

Given the potential impact on the battery's lifespan, we have assumed that V2G processes will be capped at a maximum of 20 equivalent full cycles (similar to the use cases in the FfE study [17]). This should ensure, that the usage for bidirectional purposes falls within the vehicle's warranty. Moreover, recent studies suggest that managed bidirectional charging can actually lead to less battery degradation compared to uncontrolled charging, as highlighted in Gong et al. [43].

In addition, the solution space that would result from more optimistic or more pessimistic framework assumptions is determined in a series of sensitivity analyses (cf. Table 2) with different assumptions on the yearly economic benefits and the additional BiDi wallbox costs.

3.5. Differentiation of battery electric vehicle models

To accurately model the future German passenger vehicle market, this study integrates over 40 distinct BEV models into VECTOR21, including specific bidirectional-capable variants for the first time. Each model is defined using our bottom-up battery model, enabling comprehensive examination of how the future vehicle diversification is influencing overall market dynamics. Fig. 4 shows an example selection of available BEV models, differentiated by calculated range, price, and cell chemistry.

Vehicle specifications are standardized by assuming identical installation space per segment (small, medium, large) across all models, while individual range calculations derive from physical battery capacity and drive-cycle-based energy consumption to reflect actual performance characteristics. The analysis encompasses standard and long-range variants as well as high-performance models featuring enhanced acceleration. In addition, all BEV models include bidirectional model variants that come with additional costs for a wallbox, but also with yearly economic benefits as described in Sections 3.3 and 3.4, enabling a comprehensive assessment of the V2G market potential.

3.6. Specific framework assumptions

The simulated market potentials define a corridor of possible outcomes based on specific framework conditions and scenario assumptions. Critical assumptions for the bidirectional BEV scenario of the PowerForecastMapper include:

- BEV model availability and market entry as shown in Fig. 4
- Battery costs as shown in Fig. 3 assuming mass production
- Unlimited availability of raw materials, components, and batteries
- No production capacity constraints
- Compliance with European Fit-for-55 CO_2 fleet reduction targets
- Phase-out of vehicles with internal combustion engines from 2035

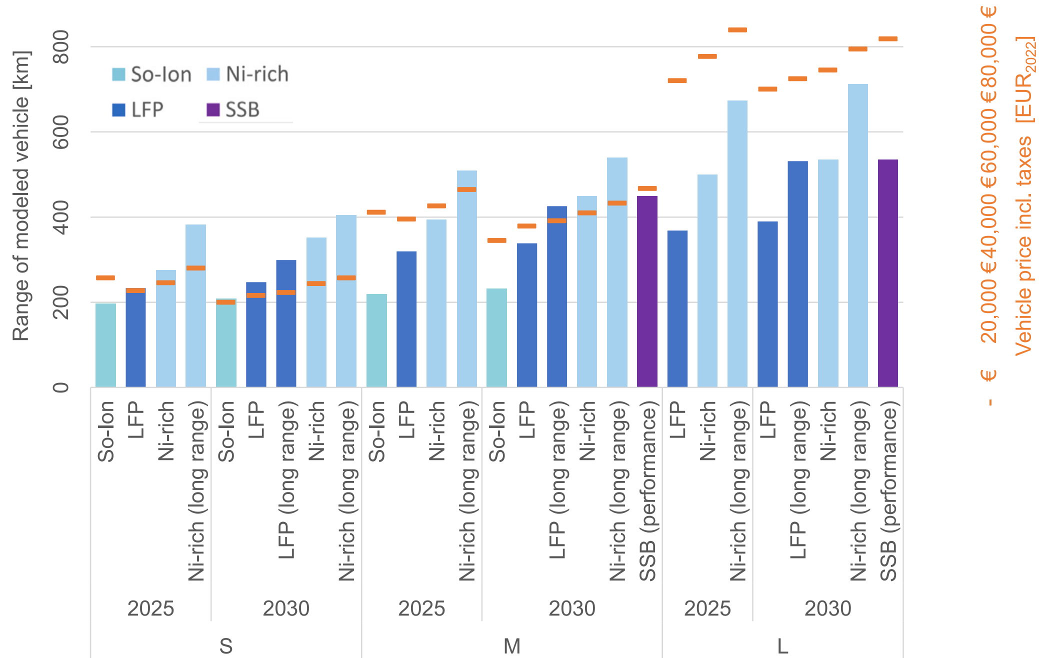

Fig. 4. Example selection of available BEV options modeled within VECTOR21, categorized by size (small, medium, large) and cell chemistry, ordered by calculated range shown in pillars and vehicle price incl. taxes shown by the orange lines.

4. Scenario results: Bidirectional vehicle fleet in Germany

4.1. Market potential of new passenger vehicles

Fig. 5 shows the market potential of various powertrain options simulated by VECTOR21 for the German passenger vehicle market within the PowerForecastMapper reference scenario of the PowerForecastMapper. In addition to the known powertrain options such as gasoline (G), diesel (D), full-hybrids and plug-in-hybrids, the market potential for BEVs is broken down here by cell chemistry and bidirectional vehicle variant. Here, the shaded blocks represent the proportion of bidirectional vehicle variants from the BEV model with the respective cell chemistry.

It can be seen that the market penetration of BEVs will increase in the future, primarily due to the European Fit-for-55 CO_2 fleet reduction targets. Currently, the Ni-Rich and LFP model variants in particular share the BEV market potential. The latter, however, would be reduced by the market entry of vehicles with Sodium-Ion (So-Ion) batteries once price parity is achieved. Customers with high range requirements initially prefer PHEVs and could eventually switch to Ni-Rich vehicle models as soon as the fleet limits become too strict. High battery costs limit solid-state batteries to the less price-sensitive segment of large vehicles. Fuel cell electric vehicles show no significant market potential in the passenger car sector before 2035.

By 2030, the proportion of Ni-Rich BEVs featuring bidirectional charging could exceed 65%, significantly higher than the 35% observed for LFP variants. This disparity can be attributed to the additional costs associated with bidirectional BEVs and the cost-sensitive nature of LFP buyers. In 2030, bidirectional BEVs constitute nearly 48% of the total BEV market, resulting in an overall market share of 30%. When internal combustion engine vehicles are phased out by 2035, the simulated market potential for bidirectional BEVs under the given framework assumptions amounts to almost 43%.

4.2. Resulting German passenger vehicle fleet development

By aggregating the annually modeled new vehicle registrations, the VECTOR21 vehicle technology scenario model derives the resulting vehicle fleet. For the PowerForecastMapper reference scenario, a slight increase of new vehicle sales up to three million vehicles in 2030 was assumed, resulting in a fleet development as shown in Fig. 6. To provide a better visual overview, the different BEV cell chemistry variants have been clustered under BEV and BEV BiDi respectively for their bidirectional counterparts.

It shows that the increase in the number of BEVs in the fleet is slower than the market ramp-up due to the extended lifespan of vehicles within the fleet. Consequently, the government's goal of achieving 15 million electric vehicles by 2030 will fall significantly short, with only 7.9 million BEVs expected. By 2045, the year Germany aims to achieve climate neutrality, there will still be over 8.5 million vehicles with internal combustion engines alongside nearly 42 million BEVs. These remaining ICEVs and Hybrids would then need to be decarbonized through the use of biogenic or synthetic fuels.

As market availability is currently still insufficient, the market penetration of bidirectional vehicles is even slower than that of conventional BEVs. For the year 2030, the PFM reference scenario results in 2.4 million bidirectional BEVs. Given sufficient model availability and the simulated market potentials as shown in Fig. 5, a bidirectional vehicle fleet of over 18.3 million units is to be expected by 2045. This would mean that almost 44% of all the BEVs would be able to charge bidirectionally.

Taking into account different key input parameters such as more expensive bidirectional wallboxes as examined in PFM sensitivity run number 5 (cf. Table 2), the resulting bidirectional BEV fleet would be 7.4 million vehicles smaller. Conversely, if we assume significantly more optimistic yearly bidirectional benefits of 610 Euro for bidirectional vehicle owners as based on the most optimistic use case of the FfE study [17], the bidirectional fleet could reach up to 30.4 million vehicles by 2045 as shown in PFM sensitivity run 2 (cf. Table 2).

4.3. Vehicle-to-grid potential of the German vehicle fleet

Using the specific vehicle data exemplified in Fig. 4, our model can simulate both the vehicle fleet composition and the total battery capacity of these vehicles. This calculation is performed on a model-specific basis, accounting for standard and long-range models, as well

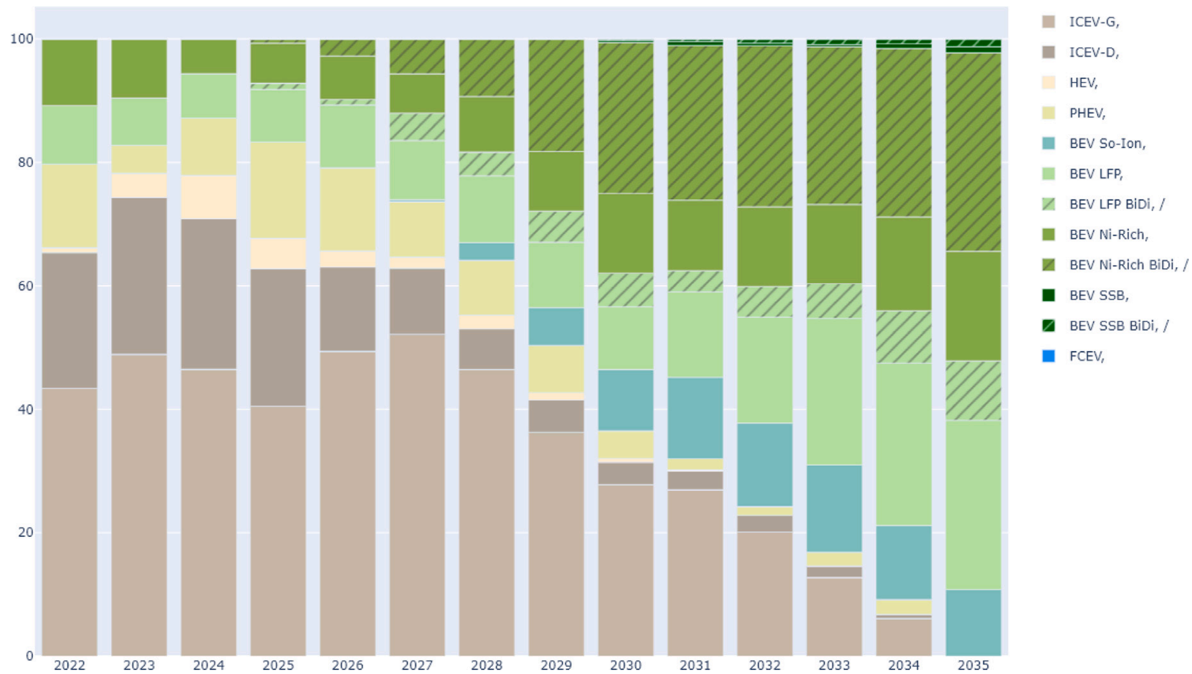

Fig. 5. Market potential of various powertrain options as part of the PowerForecastMapper reference scenario done with VECTOR21 for the German passenger vehicle market until 2035. The shaded blocks represent the proportion of bidirectional vehicle variants from the BEV model with the respective cell chemistry.

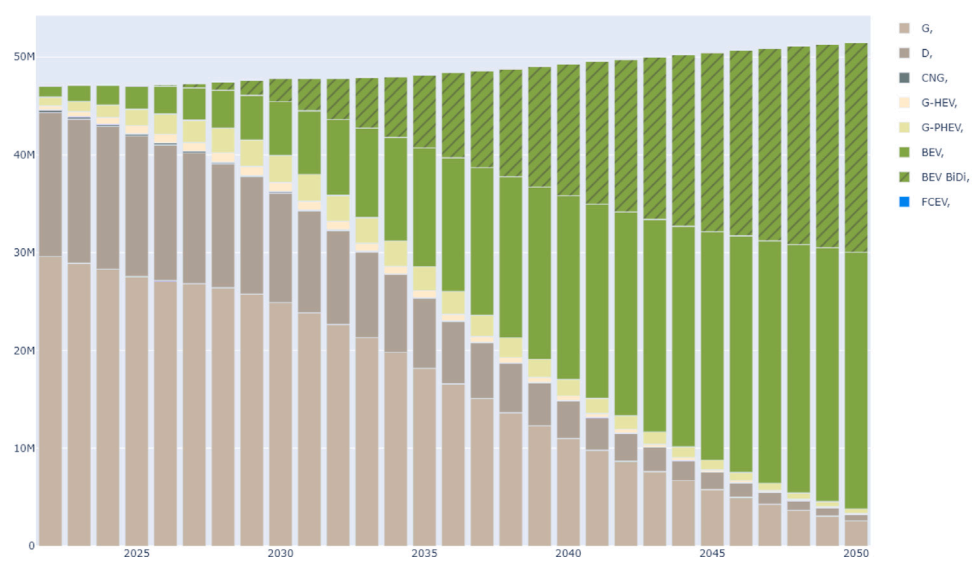

Fig. 6. Resulting German passenger vehicle fleet split by powertrain as part of the PowerForecastMapper reference scenario simulated with VECTOR21 until 2050.

as evolving installed battery capacities. The model-specific bottom-up approach enables precise calculation of both total and bidirectional BEV capacities, allowing VECTOR21 to estimate the vehicle-to-grid-capable battery capacity of the German vehicle fleet for various years, as shown in Fig. 7.

It becomes clear that the potential of bidirectional vehicles is substantial for the German energy system. Current storage capacities comprise only about 12 GWh of stationary battery storage and 40 GWh of pumped hydro storage [45] - totaling approximately 52 GWh. In comparison, a bidirectional BEV fleet would provide multiples of this capacity according to the PFM reference scenarios: 170 GWh by 2030 and nearly 1300 GWh by 2045. This represents a 3- to 25-fold increase compared to today's total storage capacities. And even if compared to the expected battery storage as estimated by [44], the simulated BEV BiDi gross energy content in 2045 would still exceed the total storage capacities by a factor of seven. It is worth noting that the gross energy content of the BEV fleet is split almost 50/50 between BEVs and BEVs with bidirectional charging, although the BEV BiDi share in 2045 is only around 44% according to the V21 calculations (cf. Fig. 6). This is due to the fact that the vehicles that are purchased with bidirectional functionality are usually also the long-range vehicles and therefore have a larger available battery capacity.

The error bars illustrate the uncertainty of the bidirectional BEV gross battery capacity results, ranging from 795 GWh for the most pessimistic up to 2082 GWh for the most optimistic of the five different sensitivity scenarios. This variability accounts for different assumptions regarding yearly bidirectional earnings, wallbox costs and model availabilities as described in Table 2. It becomes clear that even with

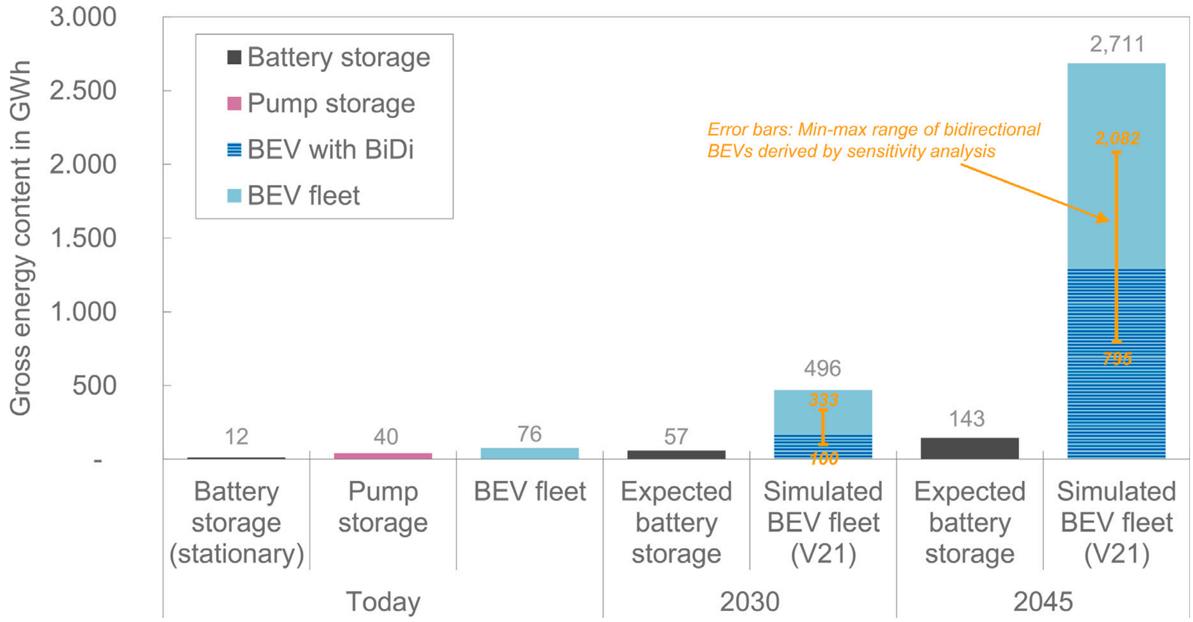

Fig. 7. Bottom-up calculated vehicle-to-grid potential of the German BEV fleet compared to current energy storage capacities and projected battery storage expansion according to [44]. Error bars represent the minimum–maximum range derived from sensitivity analysis (n=5 scenarios).

Table 2
Sensitivity analysis results showing the impact of key input parameters on the simulated bidirectional BEV fleet size in 2045, ordered by their impact.

Simulation run	Description	Wallbox cost in Euro	BiDi earnings in Euro[a]	BiDi fleet in 2045 in Mio	Gross battery capacity in GWh
PFM Sensi 5	Wallbox cost doubled	1800	150 | 270	10.9	795
PFM Sensi 4	BiDi earnings halved	900	75 | 135	14.2	1011
PFM Ref	**Reference scenario**	900	150 | 270	**18.3**	**1298**
PFM Sensi 3	Same model availability	900	150 | 270	24.5	1731
PFM Sensi 1	No Wallbox add-on cost	0	150 | 270	26.8	1854
PFM Sensi 2	610 Euro BiDi earnings	900	610	30.4	2082

[a] First value for customers with low and second value for customers with high infrastructure availability.

conservative estimates, e.g. wallbox costs of 1800 Euro or only half of the yearly earnings for bidirectional charging, the resulting gross V2G potential would still exceed Germany's future energy storage capacities by four times but the resulting BEV BiDi fleet of 10.9 million vehicles would be significantly smaller.

In the most optimistic scenario, assuming a yearly benefit for the use of bidirectional charging of 610 Euro, derived from the FfE study focusing on time arbitrage and increased PV self-consumption, achievable through 96 additional equivalent full cycles, and a low-cost bidirectional wallbox priced at 900 Euro, the market share of bidirectional BEVs within the vehicle fleet could reach nearly 75% by 2045. Resulting in a gross battery capacity of 2082 GWh as shown in Table 2.

4.4. Limitations

This analysis focuses on the technical V2G potential based on the simulated vehicle fleet and does not account for several operational factors that significantly influence actual V2G capacity utilization. Key limitations include the absence of detailed plug-in behavior modeling, which affects both charging infrastructure utilization patterns and available power capacity. Total plugged-in fleet potential in GWh can reduce by 10 to 50% depending on the time of day, housing situation and location (home or work) [46]. Similarly, Anderson et al. [47] shows that two out of three EV users are willing to charge smartly, and with monetary incentives, up to nine out of ten would do so, suggesting that V2G applications could achieve high acceptance if supported by suitable business models. Additionally, battery state-of-charge (SOC) constraints are not yet explicitly modeled, but will be added in the future. In this case, the maximum capacity may be further reduced, primarily due to the permitted depth-of-discharge range and the desired minimum SOC set by the car owner [48].

However within the PowerForecastMapper [10] we use this vehicle fleet data as an input for the charging demand model that takes vehicle usage patterns, charging behavior and available charging infrastructure into account in order to assess the vehicle-to-grid flexibility and interactions with the energy system within the German electricity network.

In order to put these limitations into perspective, we provide a preliminary estimate of potential grid flexibilities from the resulting 18.3 million bidirectional BEVs in 2045, totaling roughly 1300 GWh of built-in battery capacity. Following the methodology of Signer et al. [46], assuming 70 to 90% plug in probability at home and 50% at work, a typical battery SOC of 80%, typical charging infrastructure power ratings of 11 kW and a reserved minimal SOC for all vehicles of 30%, this fleet could deliver up to 240 GW of grid support during 30 min peak discharge periods [46]. Our estimate is slightly lower than the 372 GW reported by Signer et al. (2045) [46]. The difference arises because their scenario includes the entire BEV fleet, while our more detailed analysis explicitly accounts only for vehicles designed with bidirectional charging capabilities.

5. Conclusion

To assess the future V2G potential of Germany's vehicle fleet, we enhanced our bottom-up Vehicle Technology Scenario Model VECTOR21 by integrating different battery technologies as well as vehicle models with bidirectional charging capabilities. Through aggregation of annually modeled new vehicle registrations, we determined the future fleet composition and the resulting battery capacity that is available to increase grid flexibility, enabling a comprehensive analysis of V2G load shift potentials.

Even with conservative estimates, as demonstrated in our sensitivity analyses, the potential V2G gross battery capacity of the German passenger vehicle fleet would exceed Germany's entire projected energy storage capacity by a factor of four, representing a paradigmatic shift in the energy storage landscape.

For the reference scenario of the PowerForecastMapper, we applied viable annual benefits of 150 to 270 Euro from bidirectional charging depending on the housing situation of different customers. The benefits could end up being be higher, but to stay within the vehicle's warranty, the usage of bidirectional charging was limited to a maximum of 20 equivalent full cycles as stated by [17]. Considering additional costs of 900 Euro for bidirectional wallboxes, the bottom-up modeled vehicle fleet of the PowerForecastMapper reference scenario reaches up to 18.3 million bidirectional-capable BEVs by 2045, representing nearly 1300 GWh of total battery capacity available to increase grid flexibility.

This scale indicates the significant potential of V2G technology for Germany's energy transition and grid stability, with the passenger vehicle fleet representing a substantial distributed storage resource compared to conventional storage technologies. To translate this theoretical potential into practical applications, the PowerForecastMapper utilizes this vehicle fleet data as input for the charging demand model, which incorporates vehicle usage patterns, charging behavior, and available charging infrastructure to assess realistic V2G flexibility and interactions within the German electricity network. This detailed modeling approach will provide stakeholders such as energy providers, vehicle manufacturers and municipalities with more precise information for infrastructure planning and grid integration strategies.

CRediT authorship contribution statement

Samuel Hasselwander: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Data curation, Conceptualization. **Murat Senzeybek:** Writing – review & editing, Visualization, Software, Methodology. **Gabriel Möring-Martínez:** Writing – review & editing, Software, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was funded by the MoDa project of the German Aerospace Center.

Data availability

Data will be made available on request.

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