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Optimizing Market Scenarios for Battery Electric Vehicles through a Machine Learning based Manufacturer Agent

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Executive Summary

The automotive industry is transitioning to electromobility to meet the global climate goals by 2050. This shift is changing people's purchasing priorities and the composition of the vehicle market. The manufacturers are therefore at a critical point in terms of product development and resource and supply chain management, requiring a deeper understanding of future vehicle design. To analyze possible upcoming vehicle models, a machine learning based manufacturer agent was developed, incorporating a comprehensive technology database and historical vehicle data. Over 3,000 new battery electric vehicle models are generated and evaluated according to their possible year of market entry. The most relevant models are then integrated into the VECTOR21 vehicle technology scenario model to assess their market potential against competing drivetrain types. The results of the battery diversification scenario show a market share for vehicles with lithium iron phosphate cell chemistry of more than 18% in 2030, while nickel rich cells will remain competitive especially in the long-range vehicle variants with up to 53% market potential by 2035. Vehicles that feature sodium-ion batteries could capture a market share of around 9% by 2030, with a potential to increase to more than 17% if cell prices would fall below 50 EUR/kWh. As long as there is no disruptive increase in energy density or a noticeable reduction in expected production costs, the market potential for solid state batteries in the German passenger vehicle market would only be 2% in 2035.

1 Introduction

The shift towards electromobility presents a significant challenge for the automotive industry. For decades, internal combustion engines have been the dominant powertrain technology in the global passenger vehicle market due to their high energy density, cost-effectiveness and widespread fuel availability. However, as environmental concerns and stricter EU emissions regulations mount, manufacturers are accelerating their transition to battery electric vehicles (BEVs) in order to meet the EU's goal of achieving climate neutrality by 2050. By 2035 at the latest [1], the European Union plans to ban new registrations of combustion engine-powered passenger cars and light commercial vehicles. Furthermore, scenario analyses suggest that over 55% of the new passenger vehicle registrations could already be battery electric by 2030, underscoring the rapid growth of electric mobility [2].

With the shift to BEVs, vehicle requirements are also changing. Customers are now focusing on different key performance indicators (KPIs) such as range, charging speed, and vehicle weight, but also factors like carbon footprint, specific resource needs, and supply chain dependencies are becoming more important. As a result, the industry is facing a critical juncture in terms of vehicle design and supply chain management. To recognize and assess potential risks such as battery capacity shortages early on, detailed scenario analyses are needed for future vehicle and material demand. However, due to the fast-developing battery technologies [3], these scenarios can only make meaningful predictions if they also consider possible future vehicle models.

In order to analyze and project future vehicle models, a machine-learning-based manufacturer agent was developed whose neural network was trained using historical vehicle data and an extensive technology data base. This enables the extrapolation of current trends through a regression analysis, considering the technological advancements of various battery chemistries with a specific focus on different automotive manufacturer clusters. As a result, over 3,000 new bottom-up calculated vehicle models are generated, with the manufacturer agent assessing their probability of market entry for different market entry years in 5-yearly increments. The most relevant models are then being implemented in our DLR-internal vehicle technology scenario model VECTOR21.

2 Implementation of the manufacturer agent

The high amount of technological options and components available presents a multitude of design possibilities for future battery-electric vehicles. Figure 2 illustrates the diverse configurations across various vehicle segments, battery chemistries, pack technologies, electric motor types, and potential market entry years. Current ongoing research in inverters utilizing advanced materials like silicon carbide or gallium nitride [4] will further expand this matrix, resulting in over 3,000 unique vehicle combinations with distinct characteristics that need to be evaluated in terms of their probability of market entry.

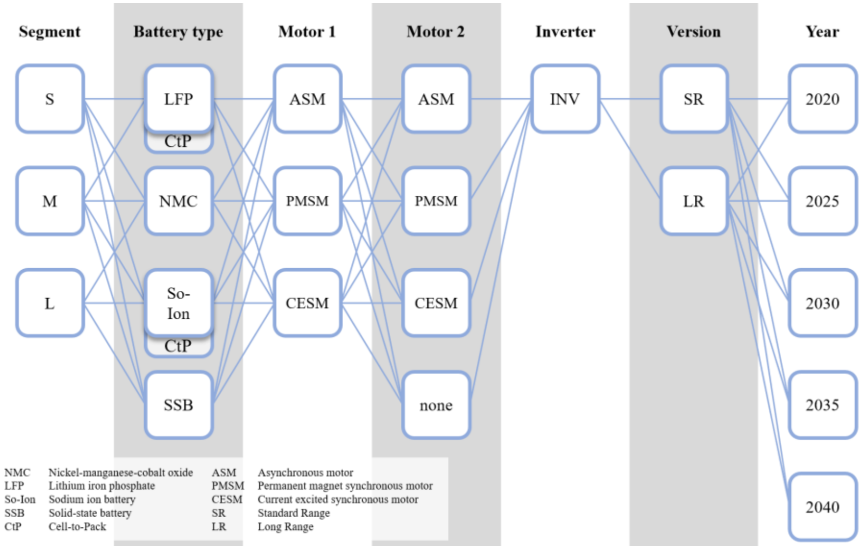

Figure 1: Automized dimensioning of future vehicle models by manufacturer agent [5]

This is why we developed the manufacturer agent which combines these extensive datasets of bottom-up developed possible vehicle configurations and evaluates them with regard to current, historically available vehicle models in Germany [5]. As shown in Figure 1, the possible vehicle configurations are combined on the basis of a technology database covering the years 2020 to 2040 and corresponding key performance indicators such as energy consumption, range and vehicle costs are calculated automatically. Over 3,000 different vehicle variants with varying cell chemistries, battery technologies, electric motor types and quantities as well as different segments and range classes (short and long range) are taken into account. These are then combined with the identified historical trends from the processed historic vehicle data and transferred to the multi-layer, feedforward neural network for training as shown in Figure 2 and described in further detail in [5]. The following input parameters are currently being used: vehicle segment, weight, capacity, range and price. Different variables can be chosen as output parameters. In this case, the selected output is the potential year of market entry. The output layer then uses a sigmoid activation function to calculate the probability of market entry for the various years under consideration.

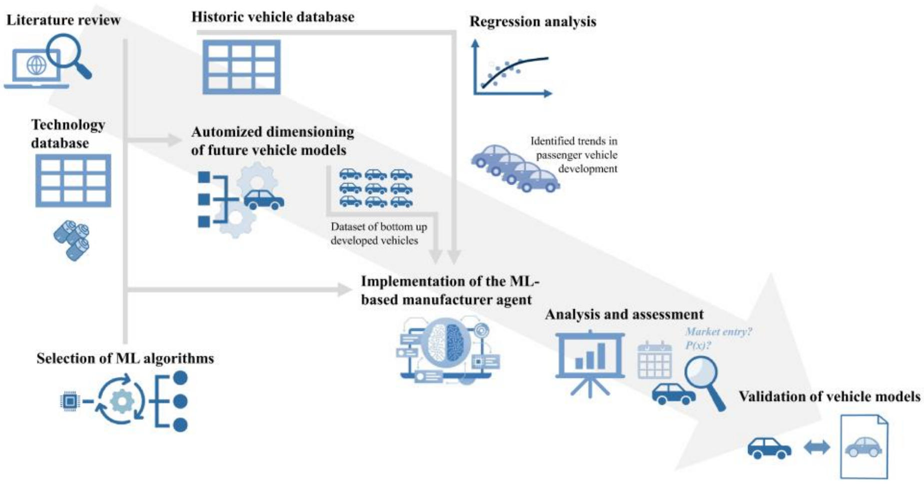

Figure 2: Methodology of machine-learning (ML) based manufacturer agent model [5]

Model training on this combined dataset achieves a 64% classification accuracy with regard to the estimated year of potential market entry, with improved accuracy for future vehicles over current models. This is mainly due to the greater model diversity of current vehicle models. However, a possible misclassification of 1-2 years is not considered critical, as the corresponding vehicle models are still correctly identified as current models.

3 Modelling of newly identified relevant future vehicle models

The results of the manufacturer agent's assessments indicate, that vehicle models with different cell chemistries and battery technologies will be relevant to the market in the future. Lithium iron phosphate (LFP) and lithium nickel manganese cobalt (NMC) batteries are highly relevant to the market across all vehicle segments. Vehicles with LFP cells benefit from the possibility of using them in the Cell-to-Pack (CtP) configuration. Sodium-Ion (So-Ion) cells offer high potential in the medium term, but their market relevance is mainly in the small vehicle segment due to their short range. Assuming that solid state batteries (SSB) are ready for the market from 2030, this battery option is a relevant option for long-range versions in particular. In general, a look at the results show that the future market potential for different cell chemistries depends heavily on market dynamics: If the technology development does not increase as strongly as the trends from the regression analysis fed to the agent, the market potential for all cell chemistries will decrease as the assumed future market requirements would no longer be possible with these technologies.

Figure 3 shows exemplary results for future standard-range vehicle models in the small vehicle segment for the scenario years 2025 and 2030. The range and the probability of market entry determined by the manufacturer agent for the model year under consideration are shown. The latter should only be compared within the same year due to the effect of the changing market dynamics described above. It can be seen that So-Ion and LFP cells are currently highly relevant to the market due to their low costs and (today) sufficient range. However, if the development of corresponding vehicles is considered in the light of the changing vehicle market in 2030, the probability of market entry for cell chemistries with low energy density is reduced. Instead, LFP CtP and Ni-rich cell chemistries appear to be gaining in relevance, as will all solid state batteries, assuming that they reach technological maturity and can be manufactured at competitive prices [6].

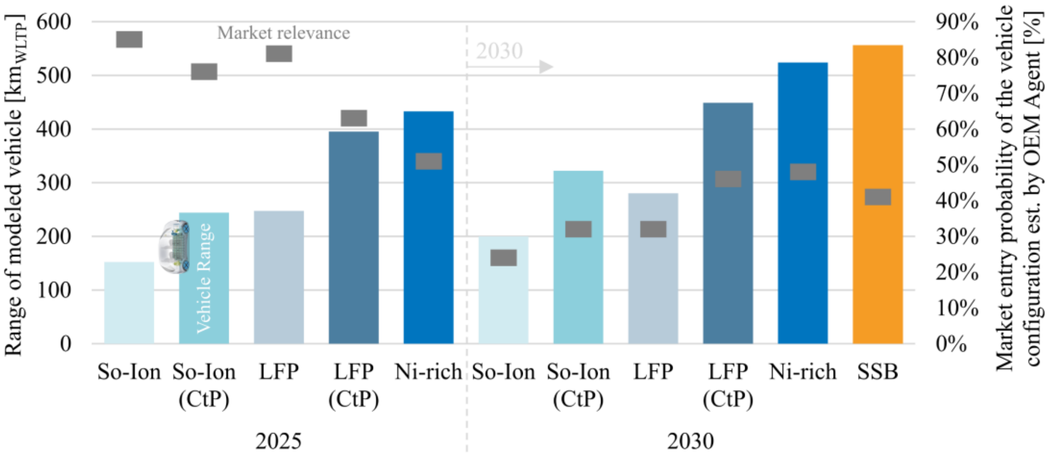

Figure 3: Range and market relevance of different bottom-up calculated vehicle configurations in the small vehicle segment estimated by the manufacturer agent

For subsequent segments and the other baseline years, possible future vehicle configurations were also generated and assessed by the manufacturer agent as described in further detail in [5]. These serve as an input for the market potential analysis utilizing the vehicle technology scenario model VECTOR21.

4 Assessment of market potential

To enhance our analysis, we integrate the most promising of the estimated BEV models into the VECTOR21 framework. This integration allows us to assess the market potential of these models compared to other powertrain types, like conventional vehicles or hybrids.

4.1 Vehicle technology scenario model: VECTOR21

VECTOR21 [7], a technology scenario model, was designed to simulate the purchasing behavior of customers (agents) in the context of new vehicle acquisitions, considering complex market conditions in Germany and Europe [8]. The model aims to capture the details of agent decision-making processes by creating personalized profiles that incorporate factors such as annual mileage, location, income, vehicle size, and other specific requirements. Agents are categorized into different adopter groups based on their inclination to embrace innovation and willingness to pay for environmentally friendly vehicles. The model weights purchase price, operational cost as well as performance-relevant factors like acceleration or range requirements differently for each agent based on their specific customer group (e.g. private or company vehicle) and personalized profile.

As shown in Figure 4, VECTOR21 includes multiple vehicle options that differentiate by segment and powertrain concept, assigning specific energy consumption and component costs to each vehicle. Within this project we focused on passenger vehicles which are modeled in three different vehicle segments (small, medium, and large) for various powertrain concepts:

- Internal combustion engine vehicle (ICEV)
- (Full-)hybrid electric vehicle (HEV)
- Plug-in-hybrid electric vehicle (PHEV)
- Battery electric vehicle (BEV)
- Fuel cell electric vehicle (FCEV)

The model also allows for differentiation between various fuel types, including conventional fossil fuels (gasoline, diesel, compressed natural gas) and synthetic fuels [9]. Furthermore, VECTOR21 now features the possibility to differentiate between different battery chemistries. As shown in [6] and [10], we have included NMC_{622}, NMC_{811} and NCA as Nickel-rich (Ni-rich) chemistries, as well as LFP, So-Ion and even featured solid state batteries with the assumption that they are market-ready from 2030 at cell costs of 120 EUR_{2020}/kWh [3]. Based on the estimations of the manufacturer agent, as shown exemplarily in Figure *3*, more than 30 new battery electric vehicle model variants have been included. For future LFP and So-Ion vehicle models, due to their higher received market entry probability estimated by the manufacturer agent, only cell-to-pack vehicle variants were implemented.

For each agent, the model generates vehicles with these different powertrain configurations and fuel or battery chemistry types on an annual basis, taking into account technological and cost-related developments. The purchase decision of each agent is then uniquely simulated based on a maximization of their individual utility values for each vehicle in an environment characterized by political decisions (e.g., fuel taxation, CO_2 fleet limits, purchase subsidies) and global developments (e.g. energy costs). As the utility calculation also considers factors such as range, CO_2-emissions and acceleration in addition to the purchase price and operational costs, this approach enables the identification of market potential even for vehicles with higher total costs of ownership but better CO_2-emissions, such as hybrid or electric vehicles.

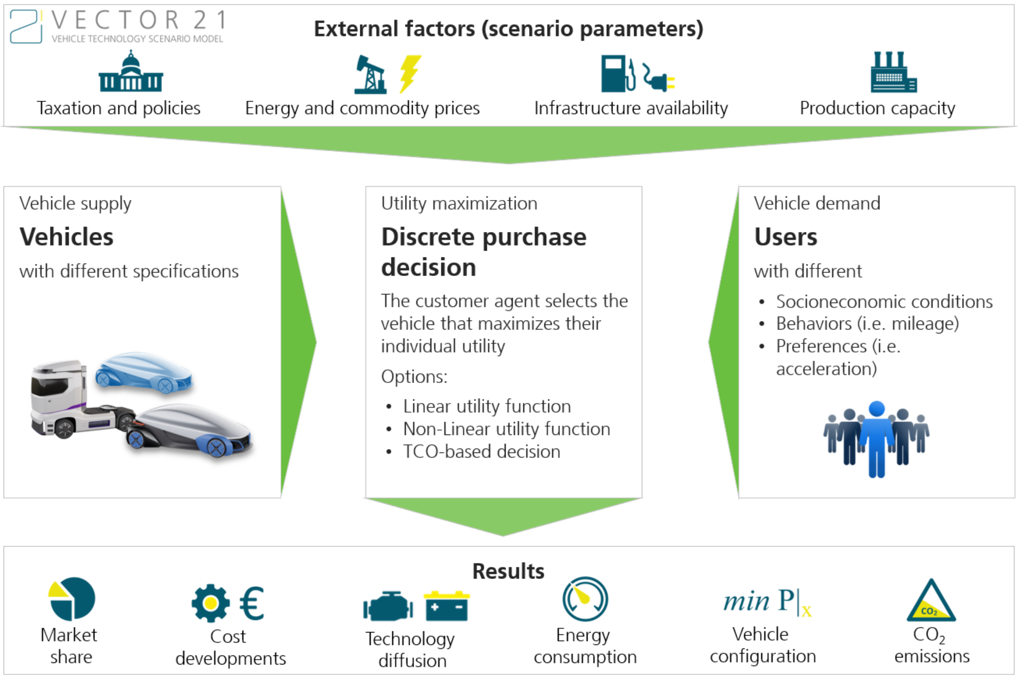

Figure 4: Structure of the VECTOR21 vehicle technology scenario model [7]

4.2 Key scenario assumptions of the battery diversification scenario

Due to better comparability, we based the battery diversification scenario presented in this study on similar framework conditions as used in previous studies: With regard to the political framework such as the CO_2 fleet reduction quota and infrastructure assumptions this paper builds on the “Structural Study BW 2023” [2], whilst the assumptions of the battery price development are based on our own techno-economic analysis [3] and the first developed battery diversification scenario as described in [6]. CO_2- and energy prices are taken from the Ariadne Project [11]. Here, the authors focus on how Germany can reach climate neutrality and also model the interactions between the energy and the transport system. An increase in the CO_2 price and a necessary drop-in of synthetic fuels is assumed, which means that the price of gasoline at the fuel station, as shown in Table 1, will rise by up to 55% until 2035.

Table 1: Main assumptions and inputs for the passenger car BEV diversification scenario simulated with VECTOR21

Scenario parameter	Unit	2022	2025	2030	2035	Source
EU CO_2 fleet reduction quota compared to 2021	%	0	15	55	100	[1]
CO_2 price	EUR/t_{CO2}	69	111	207	312	[11]
Gasoline price at fuel station	EUR/l	1.86	2.25	2.57	2.89	[11]
Diesel price at fuel station	EUR/l	1.95	2.48	2.84	3.19	[11]
H_2 price at fuel station	EUR/kg	9.6	10.9	10.9	10.1	[11]
Electricity price	EUR/kWh	0.34	0.31	0.31	0.28	[11]
H_2 infrastructure	%	1	1	4	6	[2]
Charging infrastructure	%	20	63	100	100	[2]
Fuel cell cost	EUR/kW	151	124	76	61	[12]
H_2 storage cost	EUR/kg_{H2}	1,105	1,048	916	801	[13]
Battery cell cost	EUR/kWh	Shown in Figure 5 [3, 6, 14, 15]				

These parameters describe a progressive development of the passenger vehicle market in line with the European Fit-for-55 policy target [1]. Consequently, a 100% CO_2 emission reduction target for new passenger cars by 2035 and a stricter 55% target by 2030 are implemented. Between these base years, the model assumes a linear decrease in CO_2 fleet targets. If these targets cannot be achieved with the resulting vehicle fleet of that year, VECTOR21 calculates a CO_2 penalty of 95 Euro per gram of CO_2/km above the fleet emission target, which is added to the vehicle's purchase price and therefore passed on to the customer. As a result, vehicles with internal combustion engines may incur additional costs, making them more expensive and less attractive for customer agents.

Vehicle costs are calculated bottom-up, incorporating the costs of individual components. For BEVs, this starts with the different battery cells and costs as specified in Figure 5 which were derived through an in-house techno-economic analysis based on literature review, product datasheets, expert interviews, and teardown reviews reports as described in [3]. In comparison to the previous battery diversification scenario shown in [10], slightly higher battery cell costs were assumed due to the increased raw material prices which have led to an increase in recent battery prices [14]. This is followed by the other relevant parts of the battery assembly, the battery management system, the thermal management system, DC/DC converter, electric motor, power electronics, vehicle chassis, the manufacturer's contribution margin and OEM as well as dealer margins (cf. Table 2 in [6]). A high-energy to high-power factor of 1.65 is assumed for high-power HEV-, PHEV-, and FCEV-batteries, as corresponding batteries have different cell and pack designs and requirements. The cost of fuel cells and hydrogen storage is derived from a US Department of Energy study by James et al. [12, 13].

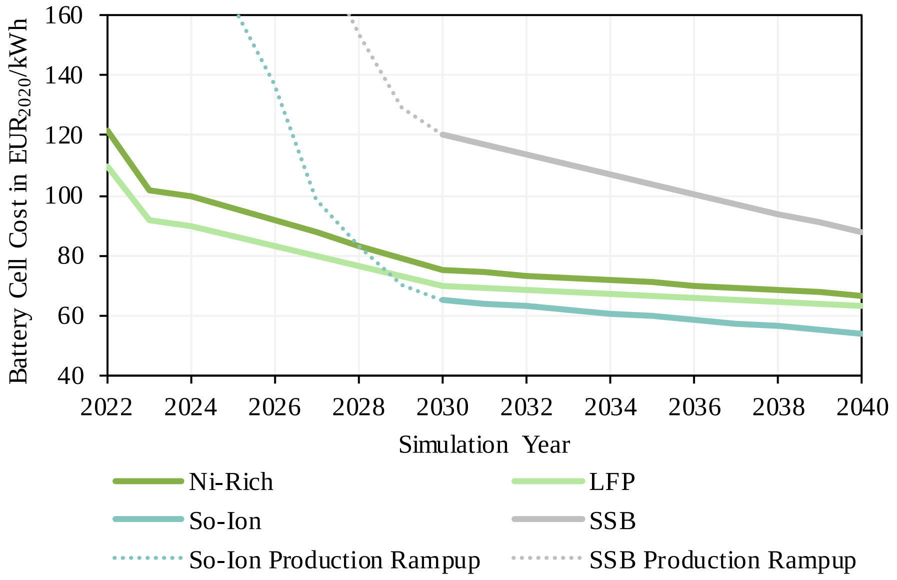

Figure 5: Battery cell costs assumed in the battery diversification scenario (based on [3, 6, 14, 15])

When modeling the passenger vehicle market with VECTOR21, the charging infrastructure is taken into account by comparing the needs of customer agents with the defined availability of infrastructure in their different residential situations. Customer agents with sufficient infrastructure, such as private parking with the possibility to install a wallbox, are compared with those that rely heavily on public charging station expansion. Leaning on the “Master Plan Charging Infrastructure II” of the German government, the expansion of the infrastructure is assumed to occur at a sufficient rate by 2030, based on the various clusters as described in [2].

As indicated in the results presented in Figure 3 for the small vehicle segment, the manufacturer agent identified approximately 30 promising vehicle model variants out of over 3,000 options analyzed, which were subsequently implemented in detail as powertrain options within the VECTOR21 vehicle technology model. The model range does not only distinguish between different cell chemistries but also between standard- and long-range vehicles and vehicles with two- or four-wheel-drive. Notably, only one electric motor was considered for small vehicles, while a performance-oriented version was applied to medium and large vehicle models, which results in better acceleration. Furthermore, a gradual rollout of model availability is assumed, which means that even if certain models, such as those with sodium-ion batteries, become available in 2025, the initial market potential remains limited due to a initial low number of available vehicle models in comparison to existing gasoline vehicle models or other battery electric alternatives. However, based on the historical development of the availability of LFP vehicle models, it is assumed that a comparable range of available models will be on the market within 5 years.

Please note that the scenario results presented in the following chapter are based on several assumptions, including unlimited production capacity of new technologies and unrestricted access to raw materials. As such, these results should be viewed as a simulation of market potential rather than a reflection of actual market expectations in the real world.

4.3 Results of VECTOR21 battery diversification scenario

The battery diversification scenario results show, that there is a growing market potential for all currently available and partly also for future cell chemistries. Generally, a trend towards the electrification of the new passenger vehicles can be observed as shown in Figure 6. However, due to slightly higher battery prices assumed, the transition to purely electric vehicles in this scenario occurs slightly later than in the previous one described in [10]. Instead, the market potential for PHEVs is higher, particularly among agents in the large vehicle segment with high range and also environmental requirements.

In the short term, vehicles with Ni-Rich and LFP cells continue to dominate the battery electric vehicle market. However, agents with high range requirements tend to prefer vehicles with Ni-Rich cell technology, while agents who are environmental-conscious and more purchase price sensitive tend to opt for LFP vehicle models. What is also apparent, particularly for the transition years up to 2030, is that the long-range option of plug-in hybrids will take market share away from long-range Ni-Rich vehicle models, resulting in greater market potential for LFP in the near future. But this will change as the CO_2 fleet limits are being tightened, which will make PHEVs more expensive allowing long-range BEV models to gain market share.

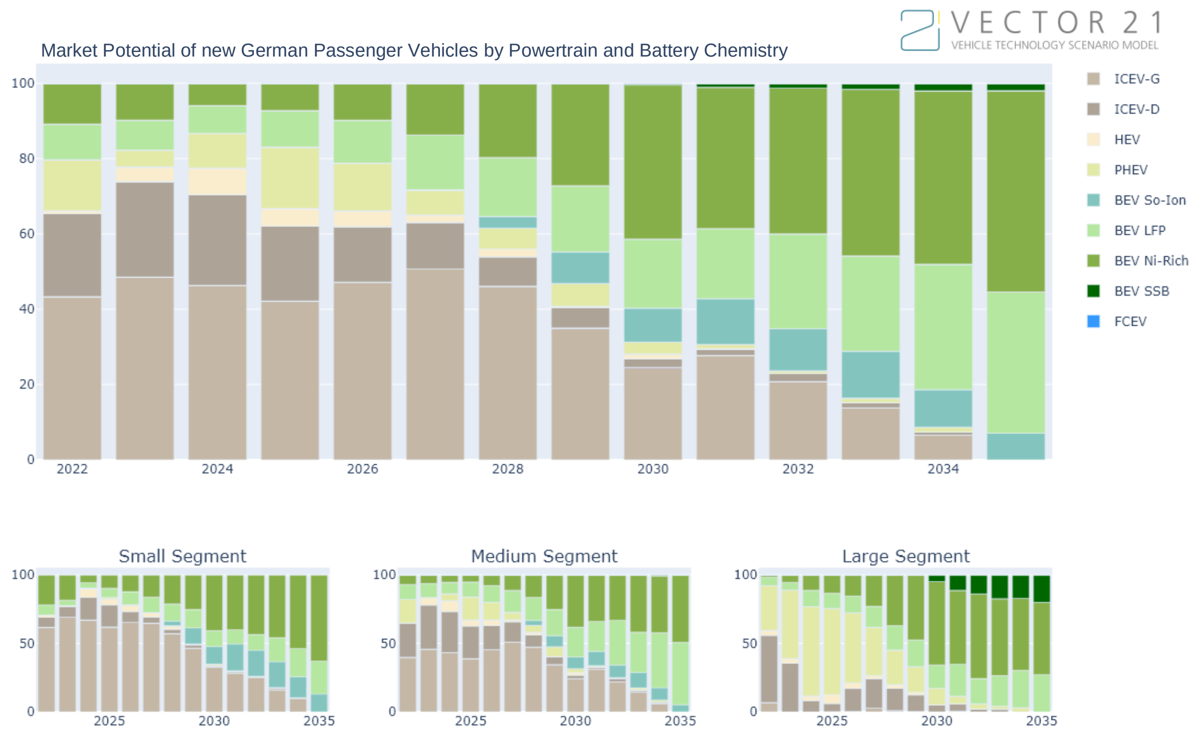

Figure 6: Market potential of different powertrain options as part of the battery diversification scenario done with VECTOR21 for the German passenger vehicle market until 2035

As soon as the costs for So-Ion production cells fall below or equal those of automotive Li-Ion cells (as shown in Figure 5), they will also gain market shares. In contrast to the scenario described in [10], So-Ion vehicles in the medium vehicle segment were also assumed in this case due to the positive assessment of the manufacturer agent. If there is sufficient model availability, this results in a market potential of 9% in 2030. In the small vehicle segment, however, the market potential is even higher at 13%. Should the prices for So-Ion cells fall below the 65 EUR/kWh assumed for 2030, this would result in an even higher market potential. In fact, a decrease to 50 EUR/kWh in 2030 could lead to a market share of over 17%. This would primarily take market share away from LFP technology which, assuming unchanged price development as shown in Figure 5 (70 EUR/kWh in 2030), would then only end up at 14.7% instead of 18,4% overall market share.

Due to the high vehicle ranges that are possible with Ni-Rich cell chemistries, which are sufficient for everyday use, there is continued market potential exceeding 40% in 2030, up to more than 53% when the combustion engine is being phased out in 2035. For vehicles with all solid state batteries, due to the high purchase prices, there is only relevant market potential in the large vehicle segment with agents that are less purchase price sensitive but have a higher focus on vehicle performance like acceleration. However, with target prices of around 104 EUR/kWh in 2035, this could even amount to around 20% market share in the large vehicle segment. Overall, within the VECTOR21 battery diversification scenario, as long as there is no disruptive increase in energy density or a noticeable reduction in production costs, the market potential for solid state batteries in the German passenger car market as a whole is only 2% in 2035.

5 Conclusions

The automotive industry is shifting its focus towards electric mobility due to stricter CO_2 emissions regulations and the planned phase-out of vehicles with internal combustion engine by 2035. As vehicle prices and range are key factors in purchasing decisions, manufacturers are investing heavily in optimizing and developing future battery technologies and cell chemistries.

Our vehicle technology scenario model, VECTOR21, assesses various BEV model variants based on purchase price, operating costs, range, CO_2 emissions, and acceleration. With the help of the developed manufacturer agent we could reduce the more than 3,000 different possible battery electric vehicle variants in the future to around 30 which have been implemented in the model based on the estimations of the manufacturer agent. In the small segment specially vehicles with just one electric motor are considered relevant, while we also implemented performance models for the medium and large vehicle segment that feature an all-wheel drive system. With regard to future possible cell chemistries, as indicated in Figure 3, especially Ni-Rich and LFP cell-to-pack vehicle models show a high market entry probability, followed by SSBs and So-Ion batteries. Considering these vehicles within the VECTOR21 scenario model environment, the results show, that the cheaper cell chemistries like LFP or So-Ion can get a reasonable market share particularly in the small and medium vehicle segment. In contrast, Ni-rich cell chemistries like NMC or NCA will be more competitive in the larger vehicle segments or for long-range vehicle variants within the small and medium segment. Their market share is showing a positive trend up to 2035 due to the tightening of the CO_2 fleet limits as long-range vehicle alternatives such as plug-in hybrids are gradually being pushed out of the market.

Major OEMs like Volkswagen, Stellantis, Tesla, and Mercedes-Benz are already adopting a diversified market strategy, featuring lower cost, less energy dense cell chemistries like LFP for the small and entry level segments specially with the option to package the cells with higher density by using cell-to-pack technology [3]. However, it's crucial to consider the environmental impact of these developments, including reduced repairability and recyclability due to strong bonding within the packs. For this reason, the development of battery electric vehicles should not only focus on reducing costs and increasing range, but also on ecological factors.

Acknowledgments

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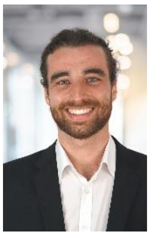
Presenter Biography



Samuel Hasselwander holds a Master's degree in Mechanical Engineering from the University of Stuttgart and is currently working at the Institute of Vehicle Concepts of the German Aerospace Center (DLR). Since 2020, he is evaluating vehicle propulsion technologies for future passenger cars, focusing on hybridized and fully-electrified systems, as well as synthetic fuels. Additionally, he plays an integral role in the analysis of vehicle technology scenarios within the context of climate change, particularly in terms of different cell chemistries, energy efficiency, and the sustainability of future vehicles.