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Project portfolio planning under CO_2 fleet emission restrictions in the automotive industry

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Abstract

This paper aims to identify financially and environmentally promising project portfolio decisions under CO_2 fleet emission restrictions in the automotive industry. These decisions are particularly difficult due to uncertain demand, ever-stricter CO_2 fleet emission thresholds, and an increasing number of alternative powertrain technologies that can be integrated into different vehicle projects with high project-specific investments and long product life cycles. We develop a mixed-integer linear programming model that maximizes the net present value of car manufacturers' project portfolios, so-called cycle plans, by selecting specific vehicle projects and by determining the respective production quantities to comply with the given thresholds for the CO_2 fleet emissions. By applying the model to an illustrative European car manufacturer, promising cycle plan decisions are determined and analyzed across six market demand scenarios. The results reveal that compliance with the European emission thresholds until 2035 is generally possible if electric vehicle demand gains momentum, but threshold exceedance and corresponding penalty payments can be financially advantageous in some situations. Long-term compliance with CO_2 regulation and financial success is supported by the fast market introduction of battery electric vehicles and the preparation of fuel cell electric vehicles for a later market introduction in large-sized vehicles.

KEYWORDS
alternative powertrains, CO_2 fleet emissions, electric mobility, industrial ecology, project portfolio planning, strategic management

1 | INTRODUCTION

Car manufacturers are confronted with ever-stricter CO_2 fleet emission thresholds. To comply with these thresholds and to ensure competitiveness, decisions on the future vehicle and powertrain project portfolio need to be made well before the actual market introduction.

Project portfolio planning is a research field studying decisions on the selection of product development projects to be realized from a set of potential projects (Ali et al., 1993; Krishnan & Ulrich, 2001). These decisions are of particular importance in industries with high product-specific investments, interdependencies between individual projects, long development times, and long market life cycles, such as in the automotive industry (Raasch et al., 2007).

Here, several potential vehicle projects compete for scarce development capacity, production capacity, and customer demand. Decisions on the realization of vehicle projects result in so-called cycle plans, which provide an overview of all vehicle models offered and important milestones, such as start of production (SOP) and end of production (EOP). Cycle plans are usually generated annually in a rolling planning process. The main goal is to maximize financial key performance indicators (KPIs) (Hüls et al., 2020; Raasch et al., 2007), but especially environmental KPIs (e.g., fleet emissions) are becoming increasingly important metrics in car manufacturers' annual statements (BMW, 2021) and also strategic KPIs (e.g., market shares) are considered (Busch & Lewandowski, 2018; Kieckhäfer et al., 2012).

Even though cycle planning is a well-established process, new challenges arise from the emission regulations (Fritz et al., 2019; Hüls et al., 2020; Kieckhäfer et al., 2015). Exceeding the legal thresholds would lead to penalty payments and possibly loss of reputation. In Europe in the year 2021, for instance, manufacturers are sanctioned with a penalty of €95 per g/km exceedance and per sold vehicle if their average CO_2 fleet emissions, based on the New European Drive Cycle (NEDC), are above 95 g/km. Compared to the 2021 threshold, further reductions of 15% in the year 2025 and 37.5% in 2030 must be achieved. As the emission thresholds depend on the average weight of the vehicles sold, heavier vehicles are generally favored (EU, 2019).

To comply with the CO_2 thresholds, several basic portfolio strategies are available. First, car manufacturers can implement technological measures, such as hybridization, to reduce the fuel consumption and emissions of internal combustion engine vehicles (ICEVs). Second, they can advance the development and market introduction of alternative fuel vehicles (AFVs), such as battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs) (Hawkins et al., 2012; Muniz & Belzowski, 2017). Both the emission reduction of ICEVs and the market introduction of AFVs lead to higher production costs and at least temporarily lower profits (Cano et al., 2018; Islam et al., 2018; McKinsey & Company, 2019). While the future production costs of alternative powertrains are expected to decrease (Armand et al., 2020; BNEF, 2020; Rahman et al., 2020; Schmuch et al., 2018; Wolfram & Lutsey, 2016), the speed and level of cost reduction are highly uncertain. Additional uncertainties are related to the customers' willingness to pay (Greene et al., 2018; Proff & Fojcik, 2016) and the demand for AFVs (Kieckhäfer, 2018; Kumar & Alok, 2020). All these factors affect the compliance with CO_2 fleet emissions as well as profits.

This study aims to investigate the optimal composition of future vehicle project portfolios under consideration of the technological, environmental, and business-related mechanisms mentioned above. Using a novel mixed-integer linear optimization model for project portfolio planning, we identify promising decisions regarding the realization of vehicle projects, respective production capacities, and production quantities that maximize the net present value of a cycle plan while considering CO_2 fleet emission restrictions. The model is applied to six market scenarios and the resulting cycle plans and related KPIs are analyzed to derive robust recommendations for the automotive industry and regulators.

The contribution of this paper is twofold. First, the portfolio planning literature is expanded by developing a project portfolio planning model that allows for the generation of scenario-based, financially optimal cycle plans restricted by environmental regulations. The model considers the distinct characteristics of the automotive industry and can be used by car manufacturers to identify optimal project portfolios in their rolling planning process. Thereby, car manufacturers can optimize their cycle plan once per planning period taking the decisions of the previous planning period into account. Second, promising project portfolio decisions for car manufacturers are derived by analyzing the optimal cycle plans across the six scenarios.

The remainder of this paper is structured as follows: In Section 2, the existing literature related to vehicle project portfolio planning is discussed. In Section 3, our new model-based approach for project portfolio planning is presented and the underlying assumptions and related data are explained. In Section 4, the model is applied to derive beneficial project portfolio decisions and robust technology strategies, distinguishing between settings with tolerated exceedance of emission thresholds and under strict compliance. In Section 5, the implications of the results for car manufacturers are discussed, and in Section 6, the paper concludes with a summary and prospects for future research.

2 | LITERATURE: APPROACHES TO VEHICLE PROJECT PORTFOLIO PLANNING

The considered planning problem is related to three major literature streams: project portfolio selection, assortment planning, and simulation-based portfolio planning (Hüls et al., 2020).

The literature stream of project portfolio selection (PPS) refers explicitly to the selection of an optimal project portfolio that fulfills strategic and financial objectives in multiple periods, considering the cash flow that results from the project decisions. Reviews on PPS approaches are given in Kornfeld and Kara (2011) and Mohagheghi et al. (2019). Most PPS approaches are principally based on the framework introduced by Archer and Ghasemzadeh (1999) and use different methods to identify beneficial project portfolios with a recent trend towards optimization models. Aspects of uncertainty are considered to an increasing extent (Mohagheghi et al., 2019). While most approaches focus entirely on financial criteria, some approaches also consider environmental or social criteria (Khalili-Damghani et al., 2013; Koppinen & Rosqvist, 2010; Kudratova et al., 2018; Ma et al., 2020). Despite successful PPS applications to other industries (Sampath et al., 2015), no model has been adapted explicitly to the considered problem in the automotive industry yet, to the best of our knowledge. Especially the interdependencies between vehicle project decisions, production capacities, and production quantities have been neglected (Mohagheghi et al., 2019). This limits the utility of these models for the automotive industry, where the financial results are driven by high project-specific investments and quantity-dependent cash flows from sales and production. Moreover, the CO_2 fleet emissions are driven by the production quantities of specific vehicles projects with particular powertrain technologies.

Approaches from the assortment planning literature are already more prevalent in the automotive industry. Assortment planning models seek to find optimal sets of specific products that companies should offer to customers (Umpfenbach et al., 2017). Reviews on assortment planning models are given in Fisher and Vaidyanathan (2014) and Kök et al. (2015). In the context of the automotive industry, Maddulapalli et al. (2013) show that car manufacturers can achieve higher contribution margins through assortment planning while complying with CO_2 fleet emission thresholds. Taghavi and Chinnam (2014) conclude that, in the short term, the increased sale of diesel vehicles and, in the medium term, the market launch of more mature hybrid and battery electric vehicles is necessary to achieve both financial and environmental goals in the US market. Umpfenbach et al. (2017) illustrate the influence of emission thresholds on the characteristics of the optimal product portfolio as well as the resulting sales and profits. While most assortment planning approaches consider important aspects of the planning situation (e.g., multiple vehicle models with different powertrain technologies and size classes that can be offered while demand is limited), they usually focus on a single period and neglect intertemporal interdependencies (e.g., development of vehicle models, investments in production capacity) as well as uncertainties (e.g., regarding vehicle demand).

An overview of market diffusion models that consider portfolio decisions is given in Gómez Vilchez and Jochem (2019). These models particularly address industry- and policy-oriented questions by modeling the market diffusion of new powertrain technologies and focusing on the interactions between market participants, including customers and manufacturers. Walther et al. (2010) focus on decisions regarding the timing of new powertrains' market introduction and the composition of the product portfolio. They illustrate that compliance with CO_2 emission legislation in California requires alternative powertrains to be deployed in almost all market segments. Kieckhäfer et al. (2017) show that the long-term market success of AFVs might necessitate the elimination of conventional powertrain technologies from the product portfolio. Thies et al. (2016) find that pricing decisions are an important lever to steer the market diffusion of AFVs. The same holds for marketing strategies, according to Harrison et al. (2018). These studies show that certain technologies or strategies are beneficial for reducing CO_2 emissions over time. Similar findings are presented by Kellner et al. (2021), who emphasize the trade-offs between profit, market share, and GHG emissions of alternative powertrains using a static multi-criteria decision-making approach. For cycle planning, all these approaches lack detail at the manufacturer level. Here, individual decisions on vehicle projects and cycle plans need to be considered.

Such individual decisions are considered by Raasch et al. (2007) and Hüls et al. (2020). Raasch et al. (2007) develop a controlling tool that supports the evaluation of cycle plans and vehicle project decisions, mainly from a financial perspective. The framework presented by Hüls et al. (2020) additionally allows for the consideration of environmental KPIs. Both approaches, however, rely on a manual procedure, which is hardly applicable to industry-relevant problem sizes.

Overall, the existing approaches only provide limited insights regarding the transformation of powertrain portfolios in the automotive industry. While highly aggregated (simulation) models allow for investigating strategic portfolio measures such as advantageous market introduction strategies and required market shares for electric vehicles, PPS models help to identify optimal project decisions considering demand and strategic targets. What has largely been neglected is the decision-making logic of car manufacturers, including simultaneous decisions on the realization of vehicle projects, their production quantities, and required production resources. Consequently, the existing approaches cannot provide recommendations related to these cycle plan decisions that are crucial in terms of profitability and CO_2 compliance.

3 | METHODS

To facilitate the generation of cycle plans, an optimization model for project portfolio planning in the automotive industry is developed (Section 3.1) and the data basis for its application is specified (Section 3.2). The model can be integrated into the overall planning framework of Hüls et al. (2020), which comprises all relevant decisions and KPIs of the project portfolio planning problem under CO_2 fleet emission restrictions.

3.1 | Optimization model for vehicle project portfolio planning

The overall concept of the optimization model is illustrated in Figure 1. The planning horizon comprises all periods for which the cycle plan can be influenced by the decision-maker. It is a subset of the set of all periods, which also includes periods outside the planning horizon to model already fixed portfolio decisions.

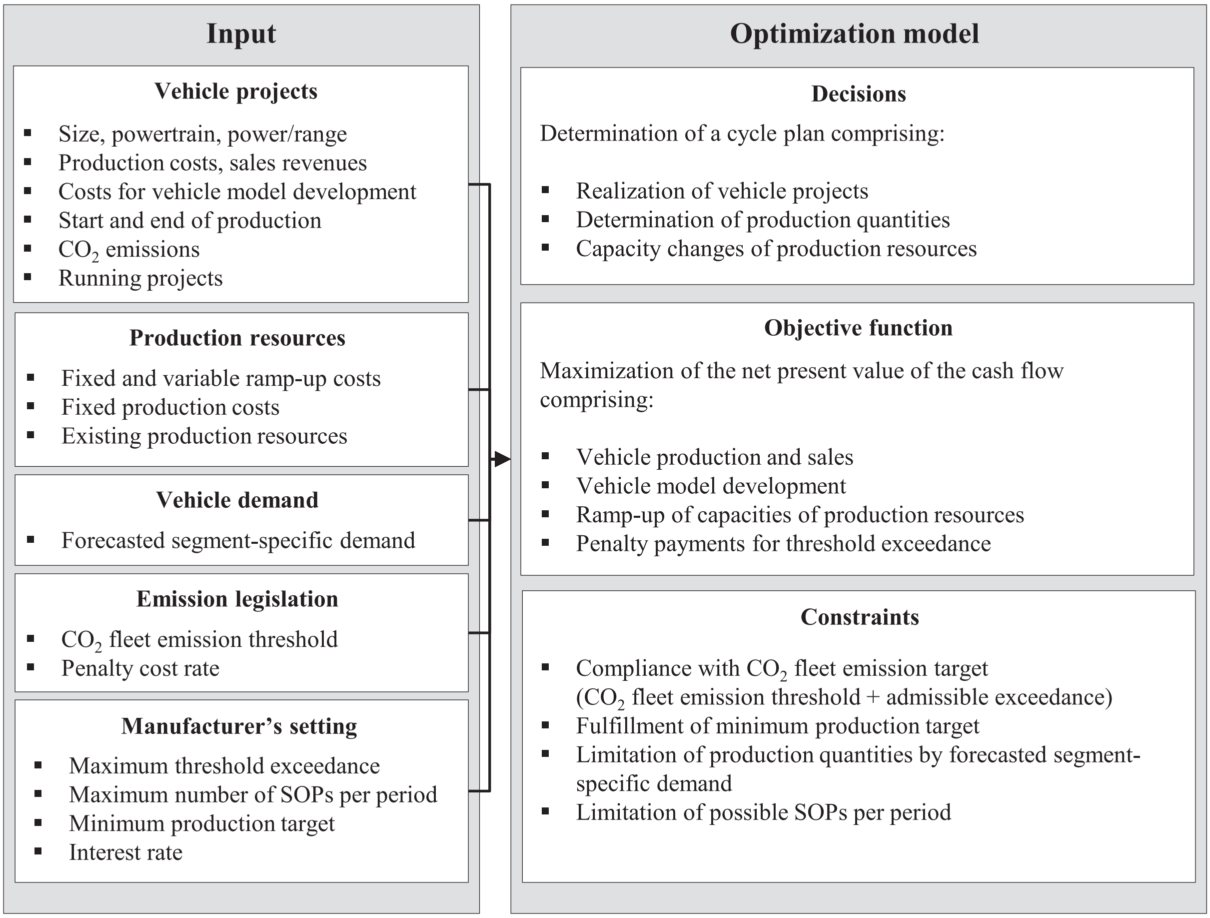

FIGURE 1 Concept of the project portfolio planning model for cycle plan generation

Within the planning horizon, a cycle plan is defined by three types of **decisions**: the decisions on the realization of pre-defined vehicle projects, the decisions on the respective production quantities in every planning period, and the decisions on the capacities of production resources.

The **objective function** of the model maximizes the net present value of the cash flow resulting from vehicle production and sales, vehicle model development, ramp-up of production capacities, and penalty payments for CO_2 fleet emission threshold exceedance. The cash flow comprises all payments within the planning horizon and additionally the payments related to vehicle model development and the ramp-up of production capacities that may be required before the planning horizon starts.

The cycle plan decisions are restricted by **constraints**: The CO_2 fleet emission thresholds, or the extended target, defined by a manufacturer's tolerated maximum thresholds exceedance, must not be exceeded. Additionally, a minimum annual production target of the manufacturer has to be met for reasons of employment protection, securing of market shares, and avoidance of factory closures (Fleischmann et al., 2006). The annual production quantities are limited by the assumed demand in the respective market segment. Limited development and ramp-up capacities are reflected by a maximum number of annual SOPs.

All **vehicle projects** are characterized by the respective vehicle size, powertrain technology, power or range class, and the project-specific SOP. Based on these characteristics, key performance indicators, such as project-specific CO_2 emissions, sales revenues, production costs, and costs for vehicle development, are defined. The payments for vehicle development are allocated to the respective years before the SOP. For all vehicle projects, a maximum market life cycle is assumed. Reflecting the individual setting of a manufacturer, running vehicle projects with SOP before the planning horizon are considered.

Each vehicle project requires a particular type of **production resource**. The production resource is shared with similar vehicle projects that require the same type of resource. Individual decisions to ramp-up or ramp-down capacity of production resources are modeled to determine the corresponding cash flow. Economies of scale regarding production resources are depicted by a fixed and a variable cost term (Rajagopalan, 1992). The payments for capacity ramp-up are allocated to the respective periods before and after the SOP (Fleischmann et al., 2006). Additionally, annual fixed costs for existing production resources, including, for example, energy costs and loan payments, are considered. In the year of vehicle projects'

SOP, the respective capacity utilization cannot exceed a certain level due to the ramp-up process (Gopal et al., 2013). Reflecting the setting of a particular manufacturer, existing production resources at the beginning of the planning horizon are considered. These resources can be used, expanded, or ramped down.

Heterogeneous **vehicle demand** is modeled as a set of mutually exclusive market segments, which represent the demand for specific types of vehicle models (e.g., small BEVs with low range). Every vehicle project serves exactly one market segment, but every market segment can be served by multiple vehicle projects. Unfulfilled demand is considered lost.

Emission legislation is considered in terms of CO_2 fleet emission thresholds and a respective penalty payment rate for threshold exceedance. Furthermore, parameters regarding the **manufacturer's setting**, including the maximum tolerated threshold exceedance, the maximum number of new vehicle product launches per period, the minimum production target, and the target interest rate, are specified.

A detailed formulation of the optimization model is provided in the Supporting Information S1.

3.2 | Data basis and main assumptions

The data basis for model application is related to an illustrative manufacturer serving the European passenger car market. It is based on publicly available data and own assumptions. The main assumptions and data refer to the vehicle projects, the production resources, the vehicle demand, the CO_2 fleet emission legislation, and the specific setting of the manufacturer (Figure 1). The following overview of the key data and assumptions is complemented by detailed tables for all input parameters in Supporting Information S2 as well as more detailed description and visualization in Supporting Information S1.

3.2.1 | Vehicle projects

A set of 264 vehicle projects is defined. The vehicle projects are characterized by cost differences between powertrains, between size classes and between power/range classes as well as different CO_2 emissions (Table S2-1 of Supporting Information S2). All vehicle projects have a market life cycle of seven years. BEVs and FCEVs are considered emission-free during operation. Tailpipe emissions of conventional cars are assumed to decrease over time due to technological improvements, leading to increasing variable production costs. In contrast, the variable production costs of battery systems and fuel cells are assumed to decrease over time (Berckmans et al., 2017; Lutsey & Nicholas, 2019).

Sales revenues from vehicles projects are assumed to be independent of the powertrain but depend on the size class and the power or range class. They vary between €12,000 for small vehicles with low power or range and €40,000 for large vehicles with high power or range. The development costs of a new vehicle model are €420 million. The allocation of investment payments relative to the SOP of a vehicle project is based on Fleischmann et al. (2006) and own estimations.

3.2.2 | Production resources

The parameters of the production system are typical for a volume manufacturer. The capacity ramp-up of production resources leads to fixed costs of €20 million and variable costs of €2,750 per capacity unit. Per installed unit, annual costs of €50 are incurred. In the ramp-up year, production resources can be utilized at 75% of their nominal capacity. Vehicle projects with the same powertrain technology and size class can be produced on the same production resource.

3.2.3 | Vehicle demand

The considered manufacturer is assumed to face a total demand of 2.25 million vehicles per year. The demand is partitioned into 24 market segments. A first segmentation is done by the vehicle size classes small, medium, and large with time-invariant market shares (ACEA, 2019; ICCT, 2019). Within each size class, the demand is segmented according to powertrain technologies (ICEV, PHEV, BEV, and FCEV). These segments are further differentiated by discrete power or range classes, equally divided into the categories "low" and "high".

For each size class, the same development for the powertrain split is assumed, which varies across six distinct scenarios (Figure 2): The "innovative" demand scenarios describe a relatively fast ramp-up of demand for BEVs and FCEV (zero-emission vehicles, ZEVs), together reaching a share of 47% in 2030 and 60% in 2035. The "conservative" scenarios describe a rather slow demand development for ZEVs, reaching a share of 5% in 2030 and 17% in 2035. Additionally, ZEV demand is differentiated by the shares of BEVs (75/50/25%) and FCEVs (25/50/75%).

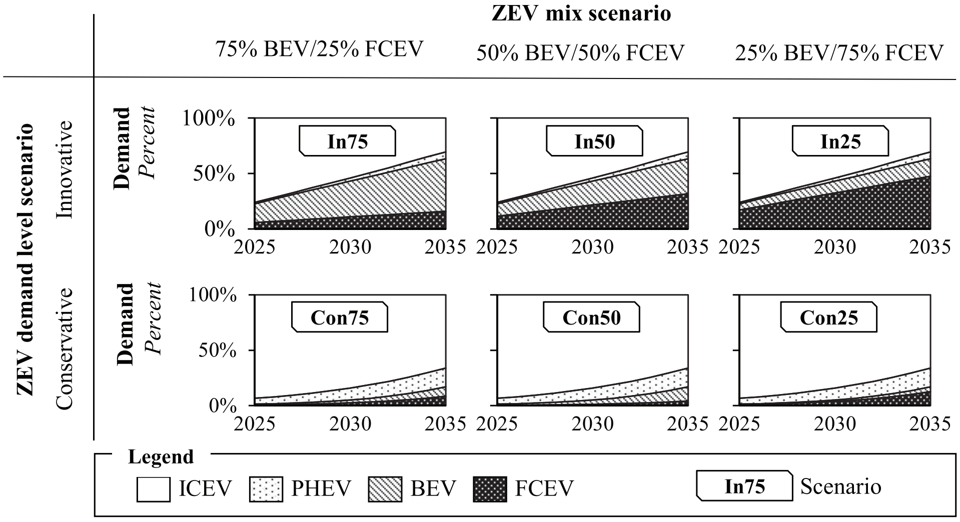

FIGURE 2 Development of powertrain market shares in six demand scenarios (own representation, assumptions based on Higgins et al. (2017), Coffman et al. (2016), and PricewaterhouseCoopers (2019)). Underlying data for this figure can be found in Supporting Information S2

3.2.4 | Emission legislation

The CO_2 fleet emission thresholds are based on the announcements of the EU. They are assumed to be at 80 g/km from 2025 to 2029, 60 g/km from 2030 to 2034, and 45 g/km in 2035. In line with current EU legislation, penalty payments are assumed to be at €95 per gram exceedance and vehicle sold (EU, 2019). A detailed description of Regulation EU 2019/631 and simplifications made within this model can be found in Supporting Information S1.

3.2.5 | Manufacturer's setting

The assumptions on the targets of the considered manufacturer, the initial situation, and the cost structure are plausible for a volume manufacturer (Table S2-2 of Supporting Information S2). The minimum production target is one million vehicles per year and the target interest rate is 5% per year. The set of previously decided vehicle projects and existing capacities in the year 2025 is detailed in Table S2-3 of Supporting Information S2.

4 | RESULTS

To identify beneficial vehicle project portfolio decisions, the optimal cycle plans of an illustrative manufacturer are analyzed for each of the demand scenarios. In the first setting, an exceedance of the fleet emission thresholds is tolerated with respective penalty payments (Section 4.1), and in the second setting, strict compliance with the emission thresholds is presumed (Section 4.2). Finally, the portfolio decisions are analyzed for different types of manufacturers (Section 4.3).

4.1 | Beneficial project portfolio decisions with tolerated threshold exceedance

To identify beneficial project portfolio decisions, optimal cycle plans are determined for each scenario. The essential vehicle project decisions framing these cycle plans and the corresponding production volumes resulting from the optimization are presented in Figure 3. With the tolerated exceedance of the emission thresholds ($\varepsilon = 1$ in Equation (18), S1), ICEVs prevail as the dominant technology across almost all periods, segments, and in all scenarios due to their high contribution margin. BEV projects are mainly realized in the medium and large size class in all scenarios. Small BEV models are either phased out (as soon as the demand for larger BEVs is high enough, cf. scenarios In75, In50), not produced at all (if demand for BEVs is generally low, cf. scenarios In25, Con25), or phased in late (if demand for BEVs is low first and they are needed to avoid penalty payments later, cf. scenarios Con75, Con50). In scenarios In75 and In50, small BEV projects are terminated due to negative contribution margins after 2027. Paradoxically, they are reintroduced again temporarily in 2030 to avoid higher penalty payments, leading to production interruptions and

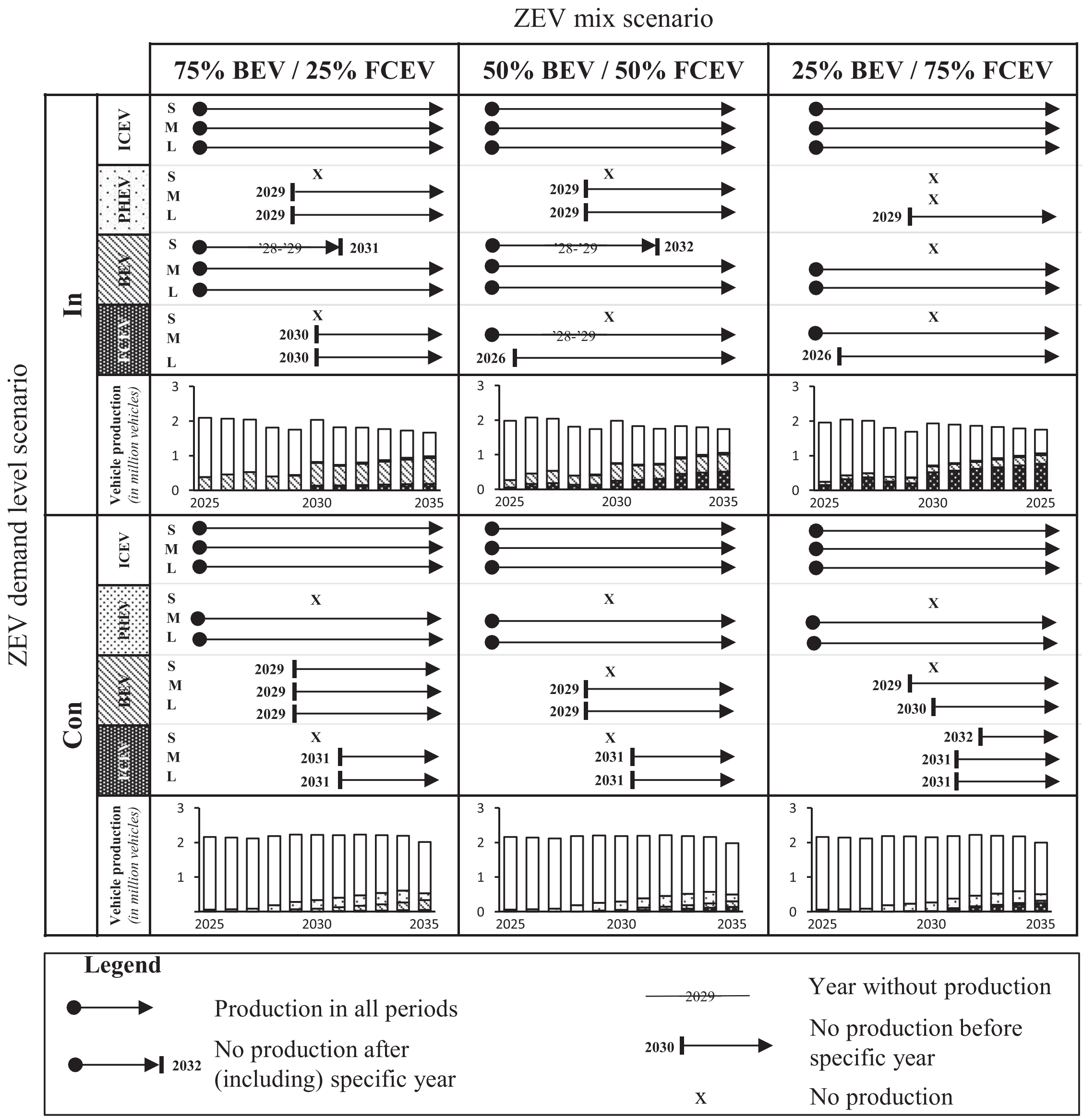

FIGURE 3 Optimal cycle plan decisions and production quantities without with tolerated threshold exceedance. Underlying data for this figure can be found in Supporting Information S2

spare capacity in 2028 and 2029. Projects with large or medium FCEV models are realized in all scenarios but start in different years (2026–2031) and with considerably different volumes, depending on the market demand. Small FCEV projects are solely realized in scenario Con25 from 2032 onwards to avoid penalty payments. PHEVs constitute an important lever of cycle planning just in conservative scenarios. Here, the demand for PHEVs is assumed to be much higher than in the innovative scenarios. As larger PHEVs have a higher contribution margin and a higher or same CO_2 reduction effect than small PHEVs (compared to ICEVs of the same size), especially mid-size and large PHEV projects are realized.

The fleet emissions and NPVs resulting from the vehicle project decisions are presented in Figure 4. Fleet emissions are significantly lower in the innovative scenarios than in the conservative scenarios and comply with the threshold in all periods except 2025, 2026, and 2030. In the conservative scenarios, the threshold is exceeded in all periods, resulting in substantial penalty payments of about €30 billion. The optimal NPV only varies by up to 10% across the considered scenarios. In the conservative scenarios, similar financial results are achieved (Figure 4) and similar vehicle project decisions are made (Figure 3) because BEV and FCEV decisions play a minor role. In the innovative scenarios, financial results and the decisions differ according to the ZEV mix.

Focusing on the cash flow in the innovative scenarios (Figure S1-2 of Supporting Information S1), the annual cash flow is comparably low in 2025 due to high penalty payments. By 2030 investments for the development of new vehicle projects and the expansion of production capacities become necessary to avoid penalty payments afterward. In the conservative scenarios, penalty payments are incurred in all periods and especially pronounced when the threshold is tightened (i.e., 2025, 2030, and 2035). Compared to the innovative scenarios, the cash flow from production and

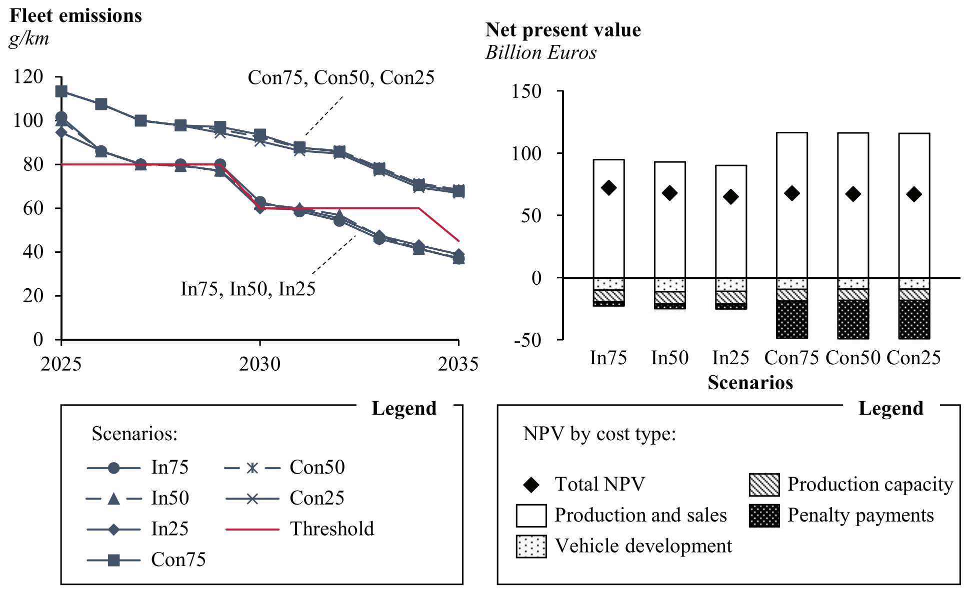

FIGURE 4 Fleet emissions and net present values of optimal cycle plans with tolerated threshold exceedance. Underlying data for this figure can be found in Supporting Information S2

sales is higher (due to the higher ICEV volume) but decreases over time with declining ICEV volume and declining contribution margins (due to the technological improvement of ICEVs). At the end of the planning horizon, the cash flow is higher in the innovative scenarios. Besides, no penalty payments are incurred. Thus, the cycle plans might also form a good basis for periods beyond the planning horizon.

4.2 | Beneficial project portfolio decisions under strict compliance

As exceeding the emission thresholds might be undesired because of non-financial reasons, such as bad reputation or even market exclusion (e.g., in the USA), the analysis is also carried out with a strict compliance constraint ($\varepsilon = 0$). Figure 5 summarizes the cycle plan decisions and the corresponding production volumes resulting from the optimization for this setting.

Ensuring compliance with new fleet emission regulations has a significant influence on cycle planning. With low demand for ZEVs as assumed in the conservative scenarios, no feasible cycle plan can be determined that allows for simultaneous compliance with the minimum required production volume and with the emission threshold. In the innovative scenarios, ongoing ICEV projects are terminated earlier and substituted by ICEV projects with lower CO_2 emissions to comply with the regulation. Specifically in 2025, large ICEVs are not produced at all and the total ICEV volume is reduced by about 50%. Consequently, the market introduction of several unprofitable BEV projects is postponed until 2026 in the scenarios In50 and In25, because a further compensation of emissions from ICEVs is not required earlier. For several FCEV projects, the market introduction starts earlier, which is especially pronounced in the scenario In75. An additional small FCEV project is realized from 2026 until 2031 in the scenario In25.

The cycle plan decisions with strict compliance result in approximately 8% lower NPVs compared to the results without strict compliance (Figure 6). The cash flow is especially lower in the periods 2025, 2026, and 2030 due to the reduced sales volume (Figure S1-3 of Supporting Information S1). The amount of cash flows is similar but structurally different as other vehicle projects are realized. Especially investments in the development of ZEV projects and ICEV projects with improved CO_2 emissions are made earlier.

4.3 | Robustness analysis

Despite the uncertain demand, manufacturers must focus on certain powertrain technologies due to limited financial resources, development capacities, or other restrictions. In the following, three specific technology strategies are investigated that restrict the portfolio options of the manufacturer. Technology strategy A sets the focus on BEVs, which is in line with scenario In75. PHEVs are not available, and the earliest possible phase-in of FCEVs is in 2030. Also, technology strategy B does not consider PHEVs. Based on scenario In25, the strategy centers on FCEVs, and the earliest possible phase-in of BEVs is in 2030. Focusing on scenario Con50, ICEVs and PHEVs are in the center of technology strategy C. Consequently, FCEVs are not considered and the earliest possible phase-in of BEVs is in 2030.

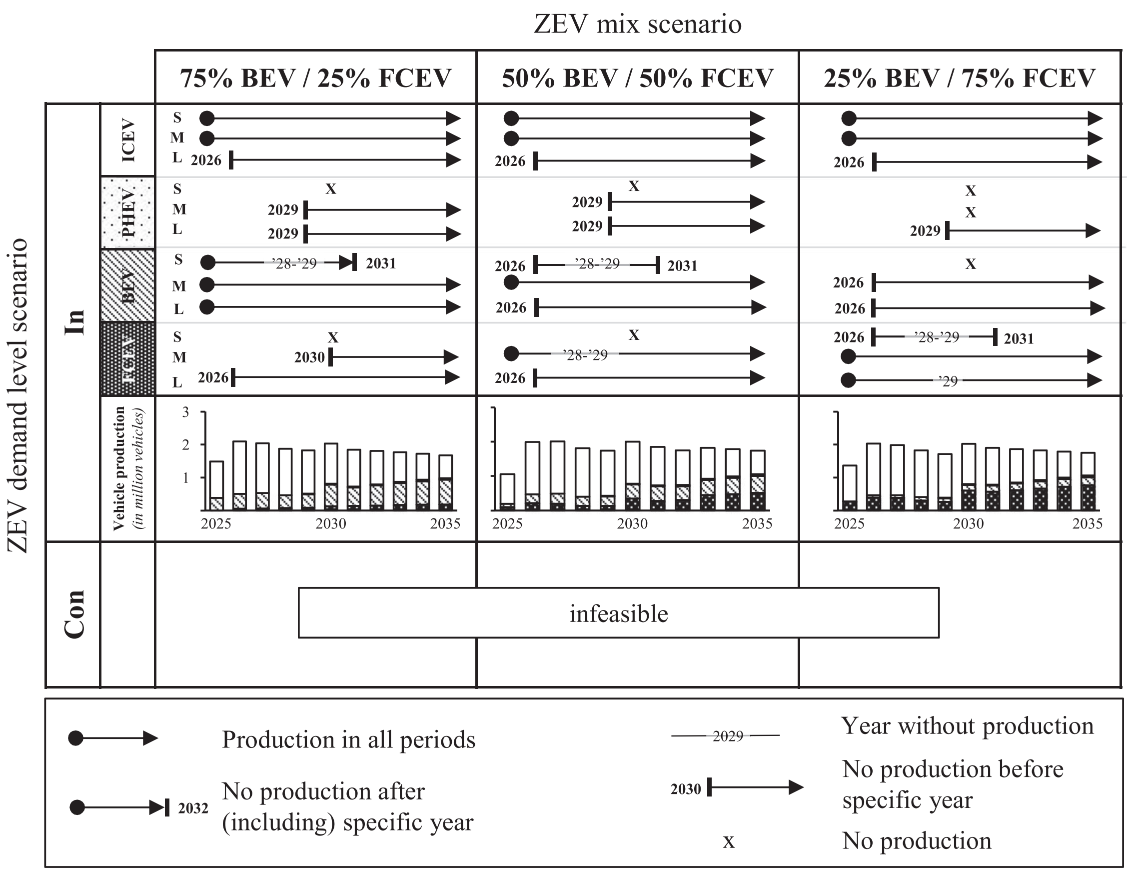

FIGURE 5 Optimal cycle plan decisions and productions quantities with strict compliance. Underlying data for this figure can be found in Supporting Information S2

The optimal cycle plans for the different technology strategies are generated across all scenarios. Thereby, the technology restrictions are fixed for the entire planning horizon and the vehicle project decisions are fixed until 2029. Production capacity adjustments are limited to ± 20% until 2029. Starting in 2030, new vehicle project decisions and unconstrained capacity decisions are possible.

To analyze the robustness of these technology strategies, three alternative decision rules are employed. The maximin rule is a pessimistic decision rule that selects the option with the highest value in the worst case. The maximax rule is an optimistic decision rule that selects the option with the highest value in the best case. The Hurwicz rule is a compromise between the maximax and maximin rule. It weights the best case value with an optimism parameter α and the worst case value with a pessimism parameter $(\alpha - 1)$ (McPhail et al., 2018). Figure 7 shows the resulting NPVs as well as the average NPV and the Hurwicz metric, using an α-value of 0.5 representing a decision-maker who is neither optimistic nor pessimistic, for all strategies across all scenarios. For comparison purposes, also the results of the base case from Section 4.1 are given.

Not very surprisingly, technology strategies A and B outperform strategy C within the innovative demand scenarios. In contrast, technology strategy C leads to good results in each conservative scenario. Across all scenarios, concentrating on BEVs (strategy A) is favorable when following a maximax or the Hurwicz rule ($\alpha = 0.5$). For a risk-averse decision-maker following the maximin rule, strategy B with a focus on FCEV is the best option as it enables decent financial results even in adverse market scenarios. Option C is not favored by any of the analyzed robustness metrics.

The CO_2 fleet emissions resulting from the project decisions are illustrated in Figure 8. For all scenarios, the focus on specific technology strategies leads to higher fleet emissions than in the corresponding base case. These deviations are rather small within the conservative scenarios. In contrast, deviations are much higher for technology strategy C within the innovative scenarios. Thus, sticking to ICEVs and PHEVs when the EV market is on the rise harms CO_2 compliance, which in turn leads to decreasing NPVs due to the high penalty payments.

5 | DISCUSSION

Major incumbent car manufacturers pledged to become carbon-neutral over the next decades (Toyota, 2021; Volkswagen, 2021b). At the heart of those pledges is a transformation of the vehicle portfolio from fossil fuels to renewable electricity. For that reason, ZEVs are introduced to the market to an increasing extent, backed up by a full project pipeline. Moreover, some car manufacturers already announced that the development

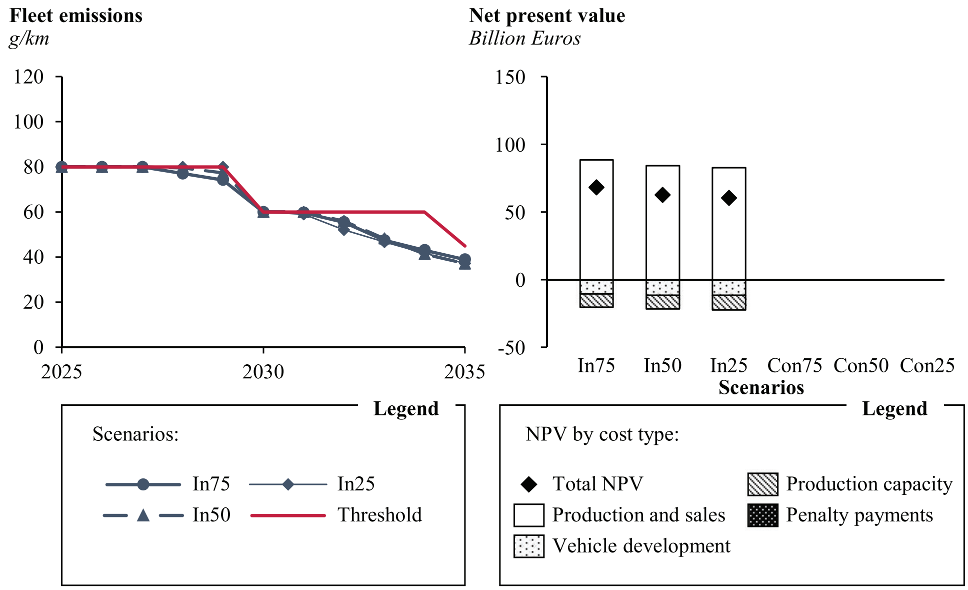

FIGURE 6 Fleet emissions and net present values of optimal cycle plans with strict compliance. Underlying data for this figure can be found in Supporting Information S2

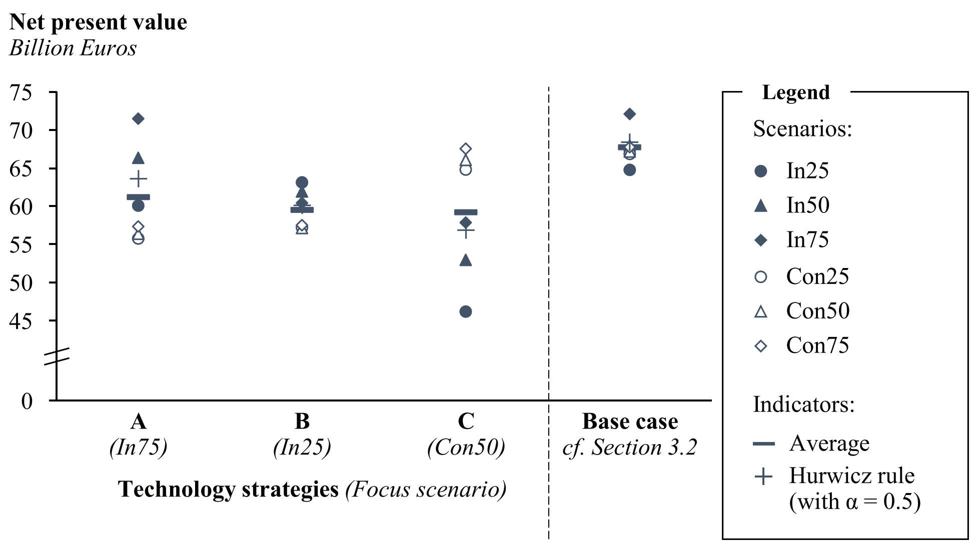

FIGURE 7 Net present value of manufacturer's cycle plans in different scenarios. Underlying data for this figure can be found in Supporting Information S2

and market phase of internal combustion engines will come to an end in the upcoming decades (General Motors, 2021; Volvo, 2021). Evaluating the financial and non-financial consequences of these kinds of decision is anything but straightforward.

The proposed project portfolio planning model can help to guide decision-making in this context. During cycle planning, strategic decisions on the composition of the future vehicle portfolio and important milestones along the lifecycle of vehicle projects are made. By deciding on individual vehicle projects to be integrated into the project portfolio as well as the respective production capacities and production volumes, the model allows determining financially and environmentally promising cycle plans in line with industry practices and with a special emphasis on CO_2 fleet emission regulations.

The illustrative example, which is based on publicly available data and own assumptions, not only reveals the potential of the planning approach but also gives first important hints related to the pending transformation of the vehicle portfolio. First and foremost, setting the focus on ICEV and PHEV projects can be considered a risky decision within cycle planning. These technologies do no longer seem to allow for long-term compliance with CO_2 thresholds nor for high NPVs, particularly if the demand for ZEVs keeps momentum. The results thus strongly support the strategies of several car manufacturers betting on the market success of electric cars (ICCT, 2021).

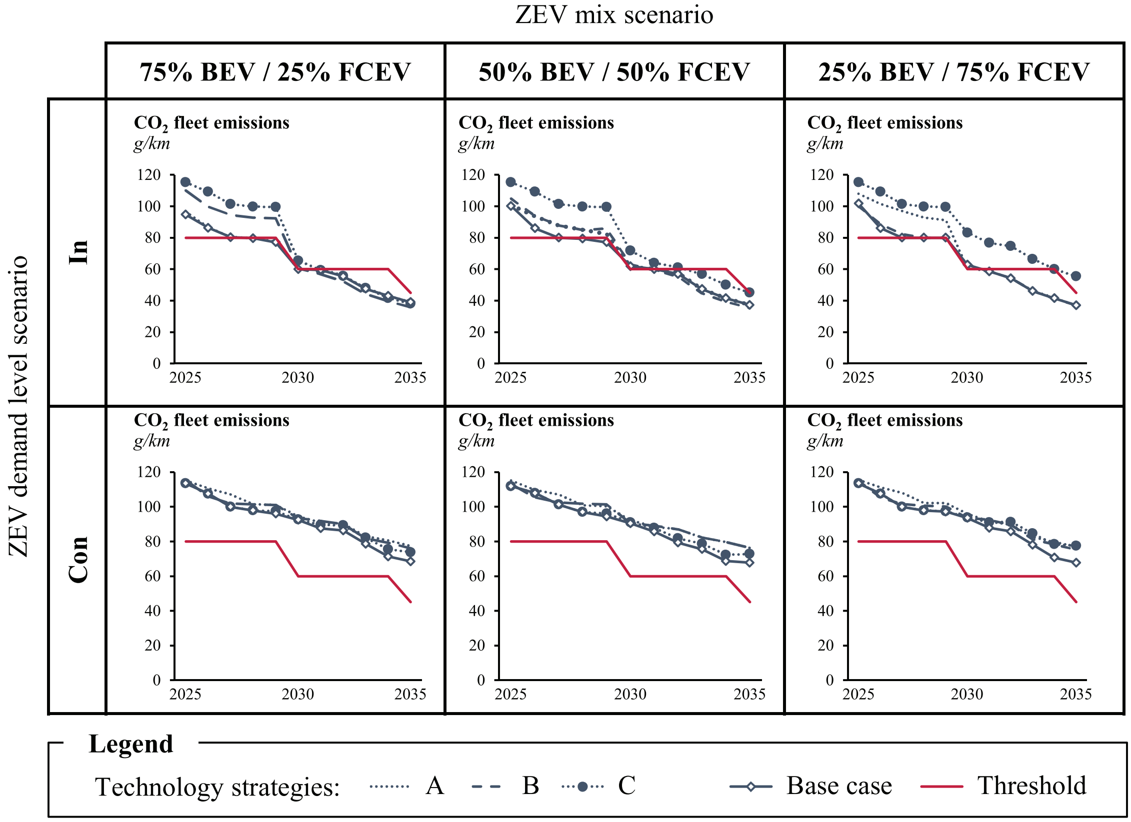

FIGURE 8 CO_2 fleet emissions of different technology strategies in different scenarios. Underlying data for this figure can be found in Supporting Information S2

In scenarios characterized by significant ZEV market shares, our results reveal that compliance with emission thresholds until 2035 is generally possible. Therefore, the identification and reduction of customers' barriers to the adoption of ZEVs can be regarded an important lever (Berkeley et al., 2018). At the same time, our analysis indicates that a complete phase-out of ICEVs should not start before 2035. In all considered scenarios, ICEVs are necessary to guarantee a high NPV due to their relatively high contribution margins, and to maintain a high production volume given the yet high demand shares for conventional cars. Whether either diesel- or petrol-fueled ICEVs play a major role in the future, highly depends on future exhaust emission legislation, the development of fuel subsidies, the development of renewable fuels, and entry bans in cities for certain technologies.

Another ongoing discussion in academia and industry centers around the role of FCEVs in future vehicle portfolios. Due to technological progress and significant cost cuts in battery technology as well as more important applications for green hydrogen, many scientific experts and industry leaders see BEVs to win the race in the automotive industry (Felgenhauer et al., 2016; Ueckerdt et al., 2021; Volkswagen, 2021a). While the competition on green hydrogen between several application areas is out of the scope of our model, expectations on the development of technological characteristics, costs, and market demand for BEVs and FCEVs can be fed directly into it. On that basis, transparent decisions on whether to integrate FCEVs into the vehicle portfolio or not can be made.

Our results confirm that BEVs are an important lever of portfolio planning. Even in the most conservative scenarios, at least three BEV projects are realized, reaching a market share of at least 14.5% in 2035. This calls for an early phase-in of BEVs. Larger BEVs are more favorable than smaller BEVs due to the assumed higher ratio between contribution margin and CO_2 emissions resulting from a lower price sensitivity in larger segments (Hardman et al., 2016; Higgins et al., 2017). FCEVs can additionally support long-term compliance with emission thresholds if the demand develops as assumed in our illustrative example. In these cases, the technology pipeline could be complemented by FCEV projects, which should be ready for new vehicle product launches around 2030.

As an additional feature, our modeling approach sheds light on whether to strive for a strict compliance with emission thresholds or not, which has not been addressed in literature so far. While the reduction targets in Europe until 2025 seem to be less ambitious than the manufacturers' own targets (Fritz et al., 2019), we show that threshold exceedance might be favorable from a purely financial perspective. In essence, this result is due to the interplay between CO_2 emissions, corresponding penalties, and the contribution margins of the individual vehicle projects. Accepting off-limit fleet emissions, however, must be compatible with the manufacturer's non-financial goals, values, and strategies. Those factors are not included in the mechanisms of the optimization model yet.

The discussed results apply to our used data set approximating European legislation (see Supporting Information S1). To adapt the model and results to other markets, further constraints such as fuel economy targets, BEV multipliers, or off-cycle credits for ICEVs, may be integrated. Furthermore, the emission values must be identified based on the respective driving cycles. In our model, we assume a centralized production focusing on the European market. Especially when addressing smaller regulated markets driven by imports (e.g., Saudi Arabia), modeling a decentralized production would be necessary to reflect the interdependencies. The proposed model mainly addresses established volume manufacturers (e.g., Volkswagen, Toyota). Manufacturers with a pure ZEV portfolio (e.g., Tesla) and niche manufacturers serving only a specific market segment face much lower complexity in cycle planning.

6 | CONCLUSION AND OUTLOOK

This article proposes a novel optimization model that supports car manufacturers in planning project portfolios under CO_2 fleet emission restrictions. Considering different market scenarios, portfolio decisions and technology strategies of car manufacturers are analyzed. The results show that compliance with emission thresholds until 2035 is generally possible, given a significant demand for ZEVs. Especially large or medium sized BEVs are important to comply with emission thresholds, while ICEVs substantially contribute to the profitability of car manufacturers until 2035. From a purely financial perspective, threshold exceedance might be favorable.

There are several limitations to our study. The first concerns vehicle demand, which in our approach is considered exogenous. To model demand endogenously, the integration of a choice model might be a promising option, which has already been pursued in assortment planning and product line design models (Umpfenbach et al., 2017). This would also allow to consider the influence of purchase subsidies.

Second, the level of aggregation could be refined even further. In our model, just one car manufacturer is considered, hampering the analysis of competition or cooperation between manufacturers. Regarding the latter, the developed model principally allows for pooling with other manufacturers. To this end, virtual vehicle projects from the other manufacturers could be included in the fleet emissions calculation, associated with a penalty payment (or positive payment if the other manufacturer benefits from the pooling) that would be due if the vehicle projects were included in the emissions pool. Moreover, vehicle model variants and derivates (Raasch et al., 2007) are not considered. The same holds for the dependence of emission thresholds to the vehicle weight. The integration of this dependency could lead to a further realization of heavier vehicles, such as sport utility vehicles (SUVs). To shed light on the car manufacturer's flexibility regarding the shift of vehicle registrations from one period to another in order to reduce fleet emissions in critical periods, self-registration of vehicles and leasing models can be analyzed.

Third, the considered scenarios do not account for all possible developments of uncertain parameters. In a next step, the robustness of the results to further parameter variations such as the assumed market life cycle, penalty level, and the target interest rate can be tested. To allow for the identification of more robust cycle plans the application of robust optimization techniques provides a promising direction for future work.

Additional promising avenues for future research concern the expansion towards a multi-criteria decision-making approach for strategic vehicle portfolio planning, and the transition from the current CO_2 fleet emission targets to a life cycle-oriented perspective that also includes the environmental impacts related to the production and end-of-life of the vehicles as well as the supply chain of energy carriers. In this regard, the various interdependencies between developments in the automotive industry and in the energy sector should be considered. Furthermore, a site-specific disaggregation of the production capacities for vehicles and their key components could be useful to analyze coordination aspects at manufacturer level as well as potential supply constraints.

CONFLICT OF INTEREST

The authors declare no conflict of interest. While Christoph Hüls and Jörg Wansart were employed by the Volkswagen Group when this study was carried out, the analyses and results were not influenced by the company and do not reflect the views of the Volkswagen Group.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Supporting Information.

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