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"Capturing car market dynamics in the transition towards electric mobility in an agent-based simulation model"

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“Capturing car market dynamics in the transition towards electric mobility in an agent-based simulation model”

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Abstract

The transportation sector plays a significant role in greenhouse gas (GHG) emissions. Over the last decades, GHG emissions have increased dramatically, which brings the need to transform the transportation sector and replace Internal Combustion Engines (ICE) with low and zero-emission vehicles.

The agent-based simulation that has been created, Adoption Dynamics Analysis Model for Electric Vehicles (**"Adam & EV"**), offers an overview of the dynamics and influences between different elements in the electric vehicle (EV) market. Its primary goal is to accelerate the transition towards EVs to reduce emissions while minimizing the cost of incentives. It is mainly focused on the decision-making process for EV consumers and shows trends and relations of various parameters, as they are presented in Figure 1. Finally, it supports stakeholders in decision making regarding EVs by functioning as a validation tool for future scenarios.

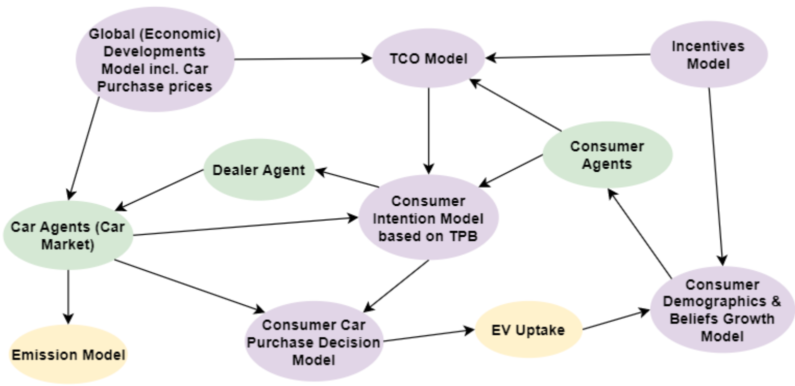


Figure 1. Model structure of original version of the model (modified by the author:) [1]

In this report, the developed car market dynamics of three different original equipment manufacturers (OEMs) are investigated using "Adam & EV". The three selected OEMs are "Volkswagen", "Toyota" and "Tesla". The choice of these OEMs is based on the goals and strategies that they want to follow, while further details about the selection are given in the report.

After the introduction of the research methodology, an extensive literature review is done with the identification and analysis of the most important stakeholders that participate in the car market. Next, the factors that govern these stakeholders are collected and investigated so that a concept map will be designed. The stakeholders that were chosen for the design of the concept map were the "Auto manufacturers - OEMs", "Government", "Oil companies and utilities" and "Consumers". Next, the most important factors were collected, based on the author's judgment, that would describe best the car market. The concept map will also be followed so that the necessary relations to be added in the model for the description and analysis of the OEMs.

With the aid of the new version of the model, car market dynamics of selected OEMs can be investigated in the transition towards electric mobility. Depending on consumers' demand and which OEM and powertrain they prefer, the investments and profits of each OEM are shaped. Finally, the relations of the selected OEMs can be seen and how much one OEM can affect the other according to the sales of each vehicle, ICE or EV. Finally, different options have been added to the model so that the user has more flexibility investigating car market dynamics. In Figure 2, an example of the average share of profits of the three OEMs per powertrain is presented. The developed dynamics can be observed regarding the profits of the OEMs.

As can be seen, when the profits emerging from BEV sales start increasing, the profits of ICE sales start decreasing. This is also correlated with the number of vehicles sold and the demand of the consumers for a particular powertrain. In this work, more details are given regarding the demand and the number of sales made for each OEM, as well as the total investments that have to be made so that the consumers' demand to be met.

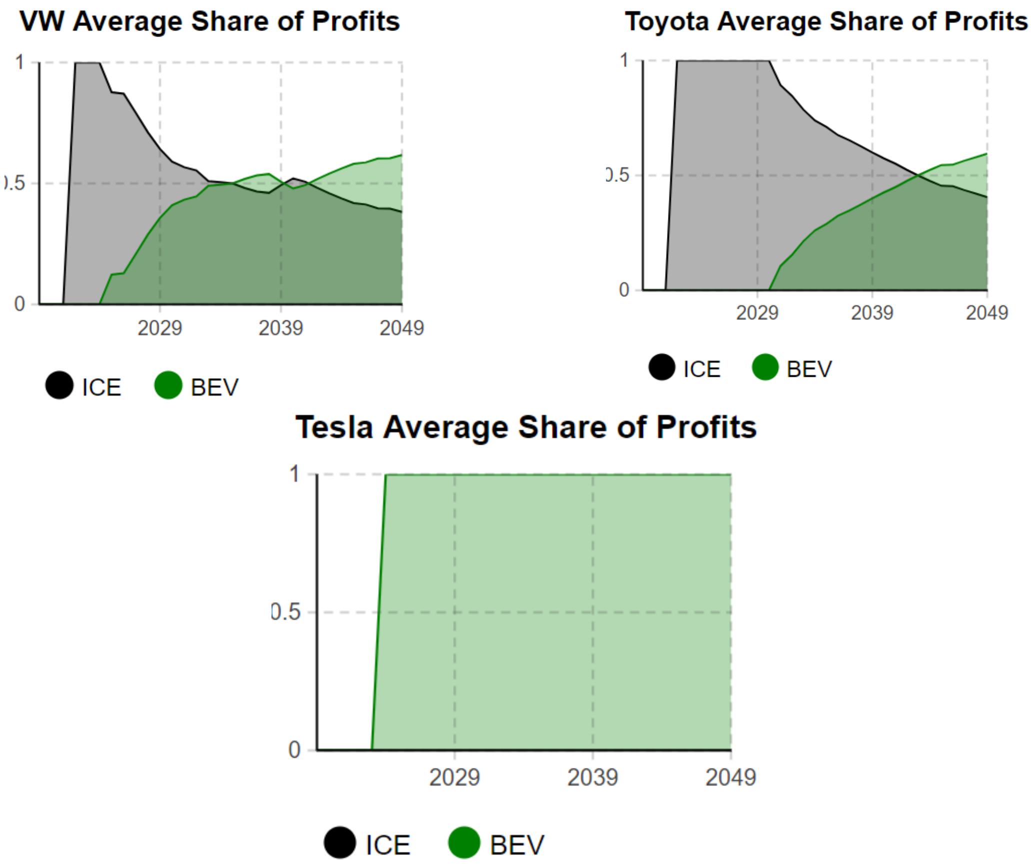


Figure 2. Average share of profits per OEM and per powertrain

Table of Contents

Table of Figures

List of Tables

Abbreviations

Adoption Dynamics Analysis Model for Electric Vehicles	**ADAM & EV**
Agent-Based Modeling	**ABM**
Agent-Based System	**ABS**
Battery Electric Vehicle	**BEV**
Battery Pack	**B.P**
Carbon Dioxide	**CO_2**
Carbon Oxides	**CO**
Compressed Natural Gas	**CNG**
Design Science Research Methodology	**DSRM**
Electric Vehicle	**EV**
European Commission	**EC**
European Union	**EU**
Fuel Cell Electric Vehicle	**FCEV**
Fuel Cell Hybrid Electric Vehicle	**FCHEV**
Greenhouse Gas	**GHG**
Hybrid Electric Vehicle	**HEV**
Internal Combustion Vehicle	**ICE**
Liquified Petroleum Gas	**LPG**
Modular Electric Drive Matrix (German: Modularer E-Antriebs-Baukasten)	**MEB**
Nitrogen Dioxide	**NO_2**
Nitrogen Oxide	**NOx**
Non-Methane Hydrocarbons	**NMHC**
Original Equipment Manufacturer	**OEM**
Nitric Oxides	**NO**
Particulate Matters	**PMs**
Plug-in Hybrid Electric Vehicle	**PHEV**
"Promoting Electric Mobility in Europe"	**proEME**
Renewable Energy Source	**RES**
Research and Development	**R&D**
Research Question	**RQ**
Sulfur Dioxide	**SO_2**
Total Cost of Ownership	**TCO**
Value Added Tax	**VAT**
Volkswagen	**VW**
Zero- and Low-Emission Vehicles	**ZLEV**

1. Introduction

Sectors such as the electric power and construction industry, traffic, transport, agriculture and land use are the leading causes of the various environmental problems that have arisen over the last decades. Global warming, air pollution and ozone layer depletion are only some of the main issues that have come up rapidly over the last years while health problems tend to increase year after year. More specifically, the transportation sector is mostly reliant on fossil fuels. In order for environmental and health problems to be minimized, alternative transportation means were developed with low and zero-emission air pollutants. Automobile manufacturers are investing vast amounts of money towards the electrification of the transportation sector [2].

The goal of the establishment of EVs is not linked just with a healthy and clean environment but also with a reduction of the vehicles operating costs compared to gas and oil-powered vehicles [3]. Electric mobility offers various environmental benefits, which also depend on the kind of the EV technology. EVs are divided into four categories that will be further analysed in Chapter 2. These are the Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Fuel Cell Electric Vehicles (FCEVs), Fuel Cell Hybrid Electric Vehicles (FCHEVs) and Battery Electric Vehicles (BEVs) [4].

The real environmental benefits, though, depend not only on the increase of the global market share of the EVs but on several factors like the energy mix used to charge the electric vehicle and the quantity of air pollutants that are emitted. According to Requia et al. [5], even if the electricity comes from non-renewable sources, the overall CO_2 emissions of EVs are less than the ICE vehicles'. Even though more carbon emissions are emitted during the manufacturing phase of EVs, the overall lifecycle analysis shows that the environmental benefits of EVs are more than ICE vehicles'. Moreover, there have been scenarios stating that by 2030, CO_2 emissions can be reduced four-fold if the electricity generation comes from a larger share of renewable energy sources [6]. On the other hand, some surveys support the opposite. Huo et al. [7] state that in China, where coal is the primary source of electricity generation, EVs increase the sulfur dioxide (SO_2) emissions by 3-10 times and double nitrogen oxides (NOx) emissions compared to ICE vehicles.

Over the last years, there have been various efforts towards the development of EVs. Automotive industries invest considerable budgets in their research and development (R&D) department that will help them take the lead in the race towards electrifying mobility [2]. The implementation of various policies from the European Union and local governments, such as financial or immaterial incentives and technology advances regarding the battery chemistry and capacity result in substantial cost cuts that enable the further uptake of EVs [8].

1.1 Context

The current assignment is situated at the University of Twente in the context of the "proEME Project" [9]. The main goal of the proEME project is to accelerate the transition to electric mobility. Moreover, it researches decision-making processes regarding electric mobility by providing potential stakeholders with the applicable information regarding the electric mobility ecosystem.

''ADAM & EV'' (Adoption Dynamics Analysis Model for Electric Vehicles) is considered as a discussion and knowledge generation tool that shows relations and trends but do not predict exact outcomes. It is an agent-based simulation model developed in Anylogic [10], [11]. The reason why Anylogic was chosen for the development of ''ADAM & EV'' is because it offers a visually attractive agent-based modeling environment, where the dynamics of a system can be explored and analysed.

According to the authors [1],the so-far developed version of "ADAM & EV" should be able to answer questions such as:

- *What are the possible effects of removing or adding an incentive regarding the development of electric vehicles in the coming years?*
- *To what extent will the implementation of a zero-emission zone policy for 2030 affect consumers that are relied mostly on the second-hand market?*
- *To what extent does a policymaker have an actual effect on the EV transition?*

1.2 Research scope

Since the context of the "proEME Project" is focused on the increase of the uptake of electric mobility in Europe, the current assignment's research scope is also focused on Europe. Furthermore, it was decided to highlight the car market dynamics of one country, the Netherlands; else, the research would be excessively broad by examining each country separately. Moreover, the modelled dynamics were decided based on a list of factors that are categorized based on the involved stakeholders. These factors influence the uptake of electric vehicles directly or indirectly. Finally, it was decided to more attention to be given on light-duty electric vehicles, due to their large share of fleet new registrations every year [12].

1.3 Objectives and research questions

The main objective of the current assignment is to capture the car market dynamics of different OEMs towards electric mobility in an agent-based simulation model. Due to the continuing electrification of the transportation sector, most of car manufacturers have changed their policy towards electric mobility or have immediate plans of changing it. The market of electric mobility is new, while huge investments are made from the OEMs so that they will follow this trend, complying, at the same time, with the regulations that are implemented by the European Union and local governments. Moreover, there is significant uncertainty on the pace, at which the shares of electric vehicles will rise, which has an impact on the OEMs strategies.

"ADAM & EV" model offers a simulation environment that exhibits the consumers' behaviour towards electric mobility. However, the model lacks the investigation of dynamics of different OEMs towards electric mobility. As has been stated above, OEMs play a major role in the electrification of transportation sector as they are forced to shift their strategies and provide options with electric powertrains. Hence, in the current assignment the developed dynamics between the OEMs towards electric mobility will be investigated by adding this part to the so-far developed model. The main research question (RQ) of the assignment:

"How can car market dynamics in the transition towards electric mobility be captured in an agent-based simulation model?"

In order for the main research question to be able to be answered, the problem has been decomposed in smaller parts that result in several sub-research questions. These will assist in answering the central one. Below, the sub-research questions are presented.

- **Introduction of electric mobility**

Firstly, a clear definition regarding electric mobility will be given, regarding different kinds of EVs that have been developed so far, and their market penetration in Europe and the Netherlands. Finally, the involved stakeholders are identified and are evaluated based on the "Power/Interest Grid" method [13].

RQ 1: *What is the current status of electric mobility regarding technological trends and market penetration?*
RQ 2: *Which are the stakeholders of the car market considering the transition towards electric mobility?*
RQ 3: *Which are the key factors that affect the uptake of the EVs?*
RQ 4: *What are the relations among the* analysed *factors?*

- **Introduction to agent-based models and ADAM & EV model**

Here, an investigation is conducted regarding the definition of agent-based models and more in-depth insight is given for "ADAM & EV".

RQ 5: *How can an agent-based model help the detailed analysis of system dynamics?*
RQ 6: *To what extent does the Adam & EV model achieve its goals in its current version?*

- **Problem analysis**

The problems that are detected after the investigation of the "ADAM & EV" model are analysed.

RQ 7: *What are the limitations of the current version of* "ADAM & EV" *regarding car market dynamics that were described in the first section?*

- **Solution design**

A concept map is designed, which will be used to implement the required relations in the model.

RQ 8: *Given the limitations of the model and the scope of the assignment, what are the car market dynamics that can be explored so that the quality of the model to be upgraded?*
RQ 9: *How are these elements related to each other?*
RQ 10: *How can this map be concretized into the "ADAM & EV" model so that the modelled car market dynamics can be explored appropriately?*

- **Verification / Validation**

The verification and validation process takes place.

RQ 11: How can the relations of the model be verified?
RQ 12: *How can be validated whether the car market dynamics are modelled correctly?*

- **Conclusions**

The answer to the main research question is given after the answer to all the sub-questions.

RQ 13: *Do the observed outcomes and behaviour of the model describe and explain accurately the modelled car market dynamics?*

1.4 Research methodology

The methodology of the research that is followed is based on the Design Science Research Methodology (DSRM) [14]. It provides a commonly accepted framework for successfully carrying out design science research, that should help researchers to present their research based on that commonly understood framework. It is also a very comprehensible and structured framework, that was judged ideal for the current assignment by the author. In Figure 3 [14], the overview of this approach is presented. Below Figure 3, a short definition is given regarding structure and content of the DSRM.

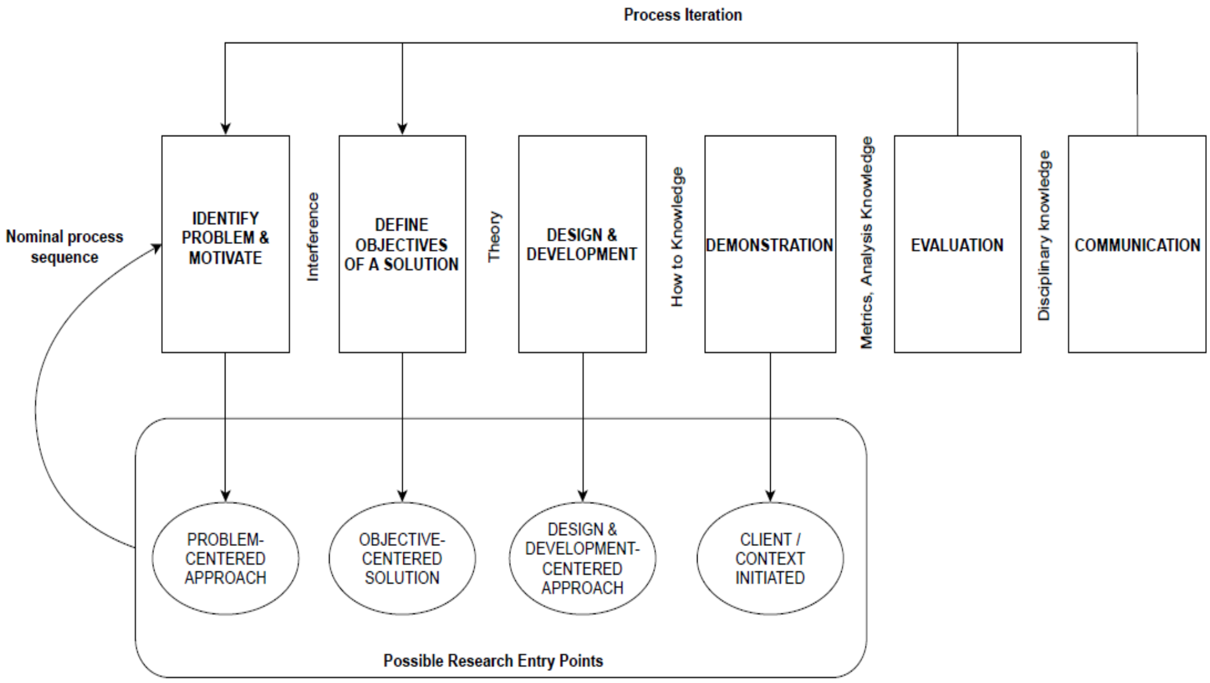


Figure 3. Overview of the DSRM approach [14]

- **Problem identification and motivation**

At this part of the research, the problem is identified and the value of the solution is justified. This way, the problem and the scope of the research is clear, while the solution obtains high value, as the reader has obtained knowledge about the problem.

- **Objectives definition for a solution**

Based on the problem definition, the objectives of a solution can be inferred. They can be either quantitative either qualitative.

- **Design and development**

During this phase of the research, the new artifact is designed that is linked directly with the objectives.

- **Demonstration**

The demonstration of the new artifact takes place in this part of the research. This involves the simulation part that displays the results that tackle the described problems.

- **Evaluation**

During the evaluation process, observations are made on how well the newly designed artifact supports the solution to the problem.

- **Communication**

The last part of the research is the presentation of the artifact to any involved parties and audience that could be interested in the new artifact and can share their opinions.

1.5 Thesis structure and reading guide

The research has been structured such that the answers to the sub-research questions lead to the answer to the main RQ. Hence, Chapter 1 introduces the current research and motivations that led to the completion of the current project. Chapter 2 analyzes the current state of electric mobility regarding the so far developed technologies of EVs, its market penetration and the main involved car market stakeholders. In Chapter 3, the factors that affect electric mobility are collected investigating the main stakeholders that are involved in electric mobility, having been evaluated in Chapter 2. In Chapter 4, the main factors affecting the strategy of OEMs are considered and a concept map is designed that will be implemented later on in the model. Chapter 5 gives an introduction of agent-based models and a more in-depth explanation of the so-far developed version of the “ADAM & EV” model regarding its goals and limitations. In Chapter 6, the process during the implementation of the OEM agent in the model is described and explained. The selected OEMs are presented and the model’s structure is analysed. In Chapters 7 and 8, the verification and validation of the model are taken place, respectively, with the main results of the new version of the model being presented in Chapter 8. Finally, in Chapters 9 and 10, the conclusions from the research are drawn and some recommendations for future work and improvements are proposed, respectively.

It should be noted that by mentioning electric vehicles, any kind of technology that contains an electric motor is meant. More information regarding the various technologies of electric vehicles is given in Appendix A. In Table 1, the link between the DSRM described in subsection 1.4 and the chapters mentioned above is described along with the corresponding research questions so that a more precise overview of the thesis structure to be given.

Chapter number	Chapter title	DSRM	Research questions (RQ)
1	Introduction	Problem identification and motivation	-
2	Background of electric mobility	Problem identification and motivation	1-2
3	Stakeholder analysis	Problem identification and motivation	3
4	Design of the concept map	Define the objectives for a solution /Design and development	4
5	"ADAM & EV" model	Problem identification and motivation / Define the objectives for a solution	5-7
6	Implementation of OEM agent in "Adam & EV"	Design and development / Demonstration	8-10
7	Verification of the model's behaviour	Evaluation	12
8	Validation of the model's behaviour	Evaluation	11
9	Conclusions	Evaluation	13
10	Recommendations and improvements	-	-

Table 1. Overview of the DSRM, the corresponding chapters and the research questions

Finally, a graphical representation of the link between the chapters and the research questions is given in Figure 4. As can be seen, the process has been divided in four boxes with different colours. The first one is the introduction and the research methodology that is followed in the assignment. The second one with the light blue colour represents the literature review that has been conducted in order the solution to be designed (pink coloured box). Finally, the box with the blue colour represents the process that was followed and implementation of the concept map in the model.

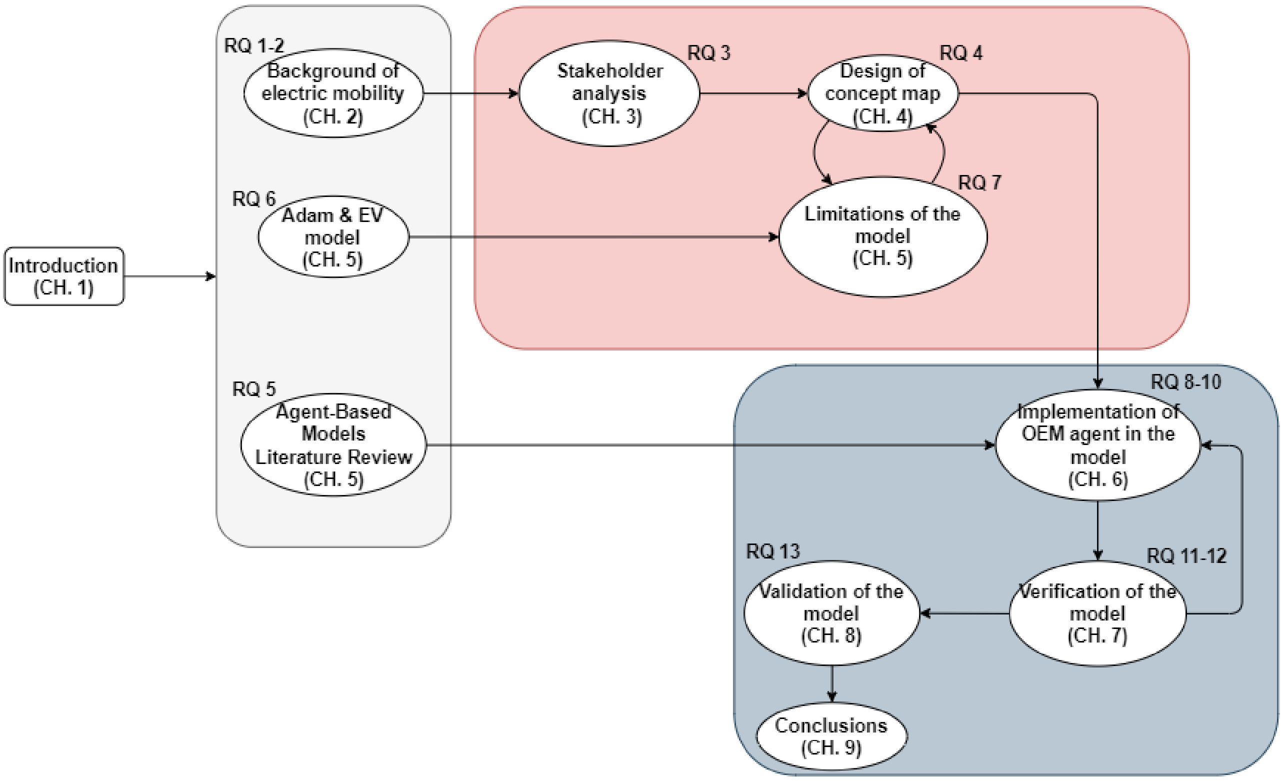


Figure 4. Graphical representation of the link between the chapters of the assignment and the research questions

2. Background of electric mobility

In this chapter, an introduction to electric mobility is given. Section 2.1 provides information about greenhouse gas emissions and the impact the transportation sector has on them, pointing out the need of electric mobility. Section 2.2 analyzes the so-far market penetration of electric mobility in Europe, giving more attention to the Netherlands. Finally, in Section 2.3, stakeholder identification regarding electric mobility is taken place, while stakeholders are categorized using the Power/Interest Grid method [13].

2.1 Transportation emissions

The need to the shift to electric mobility becomes apparent by looking at the share of GHG emissions coming from various sectors. According to the European Commission (EC), in 2014, the road transport accounted for almost 73% of the total GHG emissions [15]. Compared to the rest of the transportation sector, this share is much higher, as it is depicted in Figure 5.

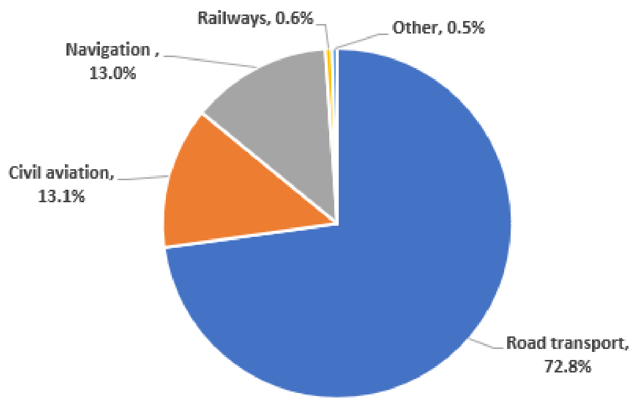


Figure 5. Greenhouse gas emissions from transport by mode in 2014 [15]

More specifically, globally, the emissions coming from the transportation sector account for 30% of nitric oxides (NO) and nitrogen dioxides (NO_2) combined (altogether: NO_x), 10% of particulate matters (PMs), 54% of carbon oxides (CO), 14% of carbon dioxides (CO_2) and 47% of non-methane hydrocarbons (NMHC) [5]. Airborne toxics originating from motor vehicle emissions can cause both carcinogens and non-cancerous health effects, such as neurological, cardiovascular, respiratory, reproductive and immune damage [16]. The health problems that are caused over the years are severe and can even cause death to both humans and animals.

Thus, the need for a drastic change in the transportation sector is imminent. The percentage of GHG emissions coming from this sector is vast and the health problems that are caused because of it are plenty. Electric vehicles could reduce the air pollutants dramatically and eventually, health issues could be prevented [17].

2.2 Market penetration

According to Bloomberg research [18], electric vehicles are going to account for 33% of all vehicles globally by 2050. The percentagewise increase is displayed in Figure 6, where the increase is exponential. So far, electric vehicles account just for around 1% of the total global light-duty fleet, but this is expected to change in the coming years.

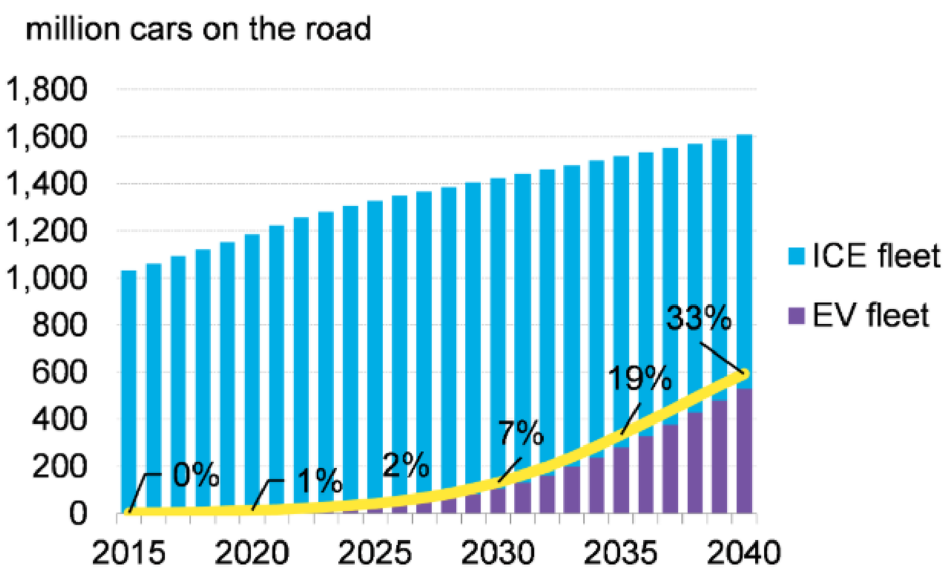


Figure 6. Global light-duty vehicle fleet [18]

Among the alternative fuel vehicles, BEVs and PHEVs have shown a significant increase over the last decade. In Figure 7 [12], the market shares of new registrations of various powertrain vehicles in Europe are presented. While the share of BEVs and PHEVs keeps increasing, liquified petroleum gas (LPG) and compressed natural gas (CNG) vehicles follow the opposite direction.

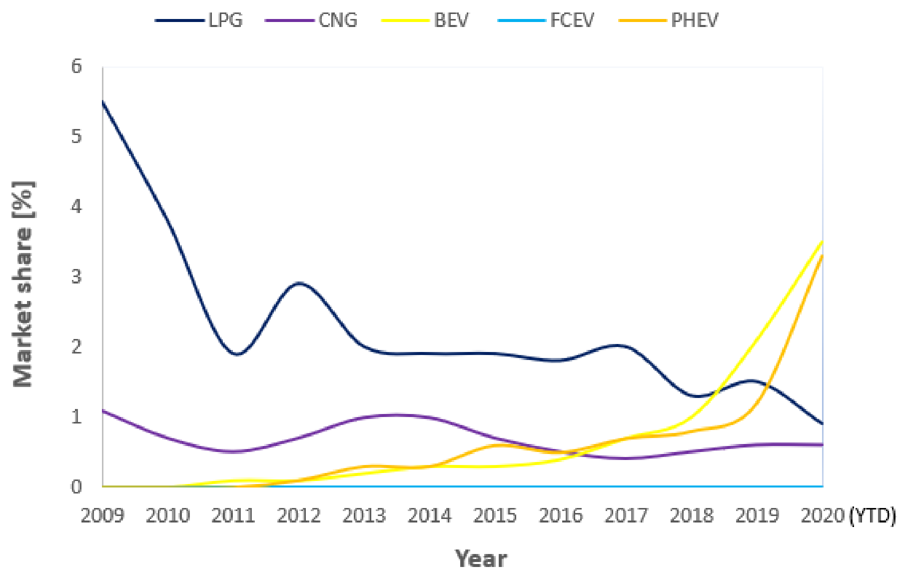


Figure 7. Market share of new registrations of alternative fuel vehicles in Europe (modified by the author: bar chart was turned into line graph) [12]

Electric vehicles are also booming in the Netherlands. The Netherlands is considered a flat country [19] and thus, the slope does not affect battery performance of an EV to a large degree [20]. Moreover, traveling within the Netherlands is usually within the range of an EV due to short distances. Lastly, the weather conditions are not that sharp, which favours battery performance [21]. In Figure 8 [12], the development of all kinds of electric vehicles can be seen. Based on the graph, the sales of the electric vehicle in the Netherlands increase more and more over the nine-year period. Over the last three years of the graph (2016-2019), a slight decrease is noticed for PHEVs, while an exponential growth of BEVs has started. The year to date (YTD) sales for the year 2020 are also worth noticing. Even though half of the year has passed, the decrease in new registrations is evident. This has to do, probably, with the Covid-19 crisis and the financial impacts that it has on the majority of population and companies [22]. On the other hand, the number of FCEVs is still low due to their high cost and lack of charging infrastructure [23].

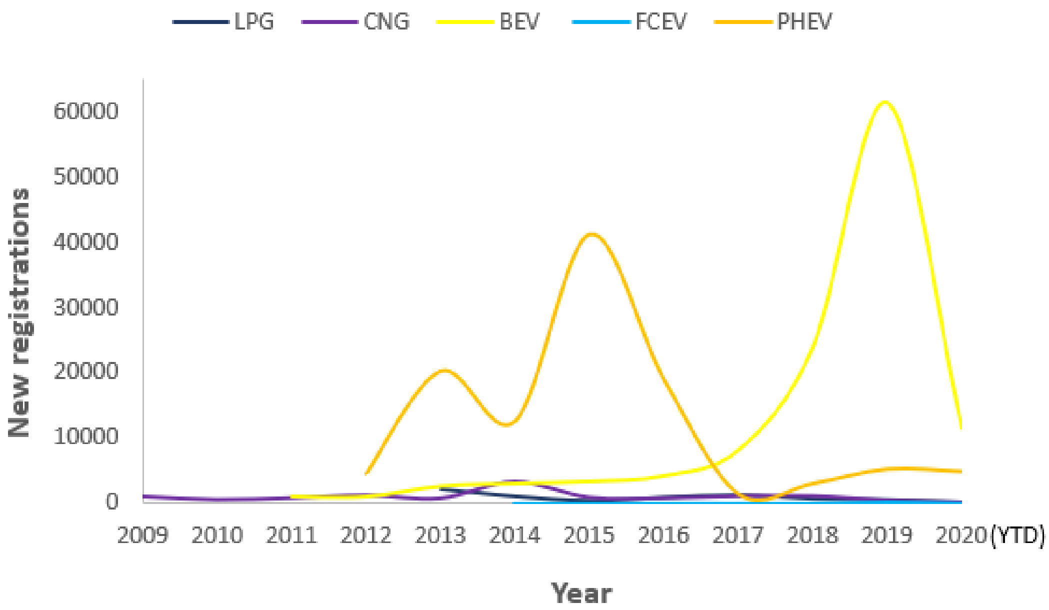


Figure 8. New registrations of electric vehicles in the Netherlands (modified by the author: bar chart turned into line graph) [12]

2.3 Stakeholder identification

In this section, the identification of the various involved stakeholders takes place concerning the car market as a whole, considering the transition towards electric mobility. Next, the stakeholders are evaluated using the "Power/Interest Grid" method [13]. In the car market, the various stakeholders influence one another. This way, a new market can be developed, charging infrastructure and affordable electric vehicles. Below, a short overview is given for each one of the 12 stakeholders that were found during a literature review.

The evaluation and the allocation of the stakeholders in the grid is subjective, as the stakeholders are influenced by many parameters, such as the time or the geographical scope they are investigated. This way, many different scenarios can be developed. Therefore, these kinds of grids can be useful as a tool of discussion. The particular allocation was made based on the author's judgment, the time that the assignment was written and, finally, using the European Union and the Netherlands as geographical scope. The scale for both power and interest was based from 1 to 10.

- **Government**

National and local governments and the European Union (EU) have high interest regarding car market dynamics due to the influence of the vehicles' emission to the environment as also described in Section 2.2. Furthermore, they have to follow the European regulations for the protection of the environment. Therefore, they are more interested in alternative modes of transportation, such as the deployment of electric vehicles. To achieve these kinds of ambitions, financial and immaterial incentives have been offered to early adopters of EVs. This way, the interest of more potential buyers is enhanced and the EV market share is increased. *(Power: 9, Interest: 10)*

- **OEMs**

Following the strict EU regulations to lower their fleet average carbon emissions, most of the car manufacturers have changed their policy and created a path toward the electrification of their fleet. As it will be described more thoroughly later in Section 3.1, almost all of the OEMs have invested in electric mobility. They have already made public their plans by developing new electrified models that they will put on the market in the coming years. This way, they try to achieve long-term viability of their business. The increase of the EV market share is dependent mainly on the product portfolio of the various OEMs to satisfy the needs and requirements of every potential consumer. *(Power: 10, Interest: 10)*

- **Consumers**

Consumers can have the power by either adopting or neglecting electric vehicles to determine what will happen in the coming years regarding the car market. EVs can offer various advantages to the potential customer; the feeling contributing to the protection of the environment and the lower operational costs compared to an ICE vehicle lead to increased interest towards EVs. The more interested customers exist, the higher the demand for the EVs. On the other hand, decreased sales of ICEs can lead to more OEMs to produce more EVs and design more models. The degree of power that customers have is subjective, as it is influenced by their wish buying an EV. If customers have a strong will power, then they can also have high power. On the other hand, if various market parties manipulate customers, they can be perceived as a lower power instrument. As it will be described in later chapters, the "Adam & EV" model is a simulation model based on the consumers' decisions. That is why, for the purpose of the current assignment, consumers were chosen to have high power shaping the car market. *(Power: 9, Interest: 9)*

- **Oil companies and utilities**

As far as oil companies are concerned, it is evident that due to the electrification of the transportation sector, the demand for fossil fuels will be reduced, if the share of renewable energy sources will be further increased. Nevertheless, the EV market share is still limited and they do not expect electric vehicles to go mainstream any time soon [24]. Even if they do, this will not prevent them from participating in the electric mobility system. While this transition may have various drawbacks for this kind of companies, some of the biggest oil companies and utilities have already entered the EV transition by acquiring charging start-ups. In Europe, 79% of the public charging infrastructure belongs to these utilities and oil companies [25]. Finally, lower prices of oil can affect consumers searching for a vehicle, as this will have an impact on their disposable income [26]. *(Power: 8, Interest: 9)*

- **Electricity producers**

The large production and usage of EVs could pose a threat to the balance between electricity production and use. It is worth mentioning that the share of Europe's total electricity consumption from EVs will rise from around 0.03% in 2014 to 4-5% by 2030 and 9.5% by 2050, when a share of 80% of EVs is projected [27]. Hence, additional energy generation will be required that has to be coordinated with, if present, renewable energy sources. Thus, one major issue that is created is the coordination of highly fluctuating renewable energy supplies so that the demand from EVs is covered [27]. Therefore, electricity producers are very interested in the situation of the car market and the degree to which this will change in the coming years. Finally, they provide EV drivers with more flexibility in charging rates and offer them incentives to charge their vehicles at favourable times [24]. *(Power: 3, Interest: 8)*

- **Electricity grid operators**

The uptake of electric vehicles poses a threat to grid operators due to the finite capacity of the local electricity grid [24]. This way, just a limited number of EVs can charge at the same time without overloading the network. The grid has to be reinforced and smart-charging systems have to be implemented so that it can handle all of the EVs [24]. When considering the car market as a whole, electricity grid operators do not have high power over it, but they are still interested in the changes in market shares of EVs and ICEs. *(Power: 2, Interest: 9)*

- **Raw materials suppliers**

Suppliers that are not ready to meet the demands of the OEMs that are focused on EVs may cause them problems in the supply phase. In an electric vehicle battery, there is a complex chemistry of various metals, such as lithium, cobalt, nickel and more. Due to the rise of EVs, the demand and supply of battery raw materials have been transformed. According to G. Montgomery [28], a supply shortage may be faced by the mid-2020s. Until now, though, meeting the demand has not been a challenge for the suppliers. *(Power: 7, Interest: 9)*

- **Charging infrastructure companies**

Charging companies are interested in the transition towards electric mobility as the more EVs on the road, the more charging points have to be installed. Nevertheless, they do not have much power shaping the car market as a whole as the number of EVs is still low and ICE vehicles' market share will still be dominant for the next few decades. *(Power: 5, Interest: 10)*

- **Car dealers**

Car dealers have a unique position in the car market since they are the first point of contact with the consumer [29]. Nevertheless, according to M. Karwa [27] and H. Le [28], car dealers do not look keen on promoting EVs as they have to hire more sales persons, who know about that kind of technology, invest in maintenance network and on advertising to promote them. On the other hand, by selling EVs, car dealers promote sustainability and offer more powertrain choices to the potential customers. Nevertheless, they can adapt in the car market alterations and sell vehicles with any powertrain meeting, this way, consumers' preferences. *(Power: 10, Interest: 4)*

- **Leasing companies**

Leasing companies play a major role in the car market, as customers get more accustomed to not owning a vehicle themselves. More specifically, the leasing market in the Netherlands is the sixth largest in Europe having the most leasing contracts in 2019 compared to previous years. Moreover, the private market has suffered as just one out of five vehicles were bought by private owners in 2019 [32]. As far as leasing companies promoting electric vehicles are concerned, they have some benefits like encouraging sustainability and having more models in their portfolio, meeting all of the customers' demands [32]. Nevertheless, same as described for the car dealers, leasing companies can adapt in car market alterations in order to meet consumers' preferences. *(Power: 10, Interest: 4)*

- **Scientists & Researchers**

The automotive industry is moving fast to new technologies, regarding low emissions and safety, developing continuously. Various research programs and universities are focused on these kinds of technologies and try to have an impact on making the vehicles greener and safer. Even though they may have a significant interest in that sector, their research programs are often funded by highly power stakeholders like the OEMs themselves, governments or the European Union. Hence, for the scope of this assignment, they are not considered as a lower power instrument since they are guided and financed by other stakeholders. *(Power: 1 , Interest: 9)*

- **Fuel distributors**

Fuel distributors deliver and distribute fuel across the countries to the end-users that require fuels. In that sense, they have relatively high power as without them, there will be a shortage of vehicles' fuel. Nevertheless, they do not have much power regarding the car market as a whole, especially when considering the transition towards electric mobility. On the other hand, it is a sector that is also interested in how the car market will be in the coming years, as transportation is mainly based on internal combustion engines. However, for the coming years, ICE vehicles are still going to be the primary vehicle on the market, so the transition towards electric mobility may not affect them a lot after all. *(Power: 4, Interest: 5)*

In Figure 9, the Power/Interest Grid is displayed by allocating the involved stakeholders based on their interests and power in the car market at the current time. Many different versions can be developed regarding the allocation of the stakeholders in the grid due to various predictions that have been made. For example, there is no shortage of raw materials at the moment until five years from now affecting the car market more drastically. Another case with a potential higher power stakeholder is the charging companies. In the future, when more EVs will be on the road these companies will have a more considerable impact on the car market. Moreover, lack of charging infrastructure is of the problems that hinder the EV uptake, but right now is not the primary one, as TCO and range dominate [33]. Considering that TCO keeps decreasing due to battery pack decreasing prices and all-electric range keeps increasing [8], charging companies will have a more deciding role in the car market.

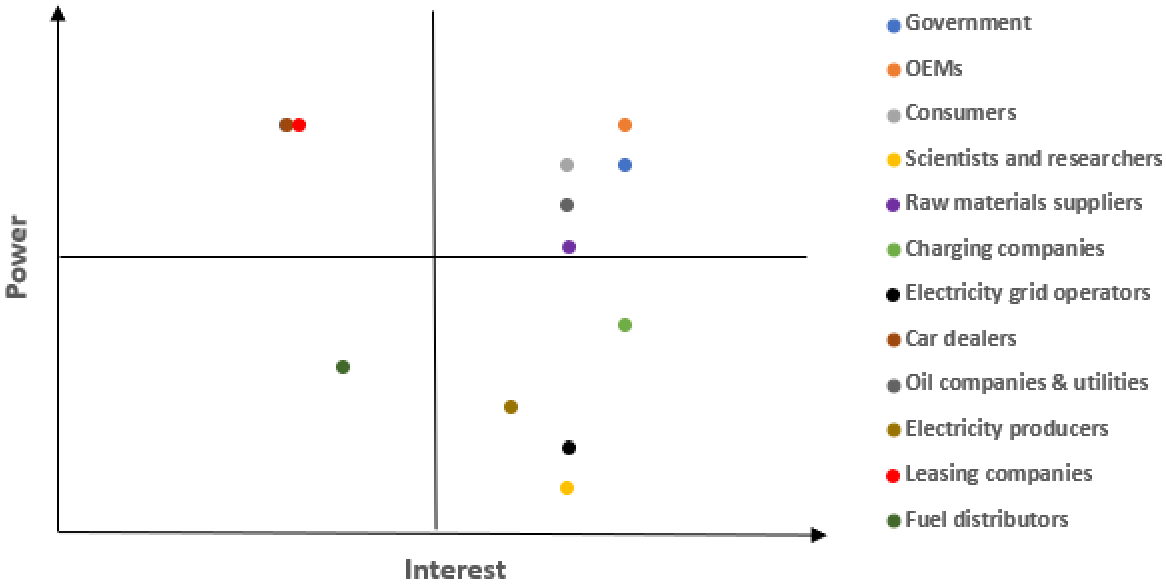


Figure 9. Power/Interest Grid of the involved stakeholders in the car market considering the transition towards electric mobility

In this chapter, the background of electric mobility has been given. It can be seen that given the transportation emissions described in the 2.1, the need for electric mobility is eminent. According to the research made in Section 2.2, the number of electric vehicles on the road is increasing over the years and, more specifically, the BEVs, with PHEVs coming next. Lastly, the stakeholders in the car market have been identified based on a literature review and allocated in the Power/Interest Grid. It can be concluded that the government, the customers, the car manufacturers, and the oil companies are the ones with the highest power and interest in the car market, with raw material suppliers being very close, too.

3. Stakeholder analysis

In this chapter, the stakeholders with the highest position in the Power/Interest Grid are analysed more thoroughly. These are the automotive manufacturers, the customers, the government and the oil companies.

After each section, the factors that are influential for the transition towards electric mobility are presented for the given stakeholder. These factors were identified through a literature review and were grouped into several types. These can be various incentives, specific technological developments, regulations and legislations and even concerns regarding the electric vehicles. Moreover, they are accompanied by their corresponding references explaining them and, in some cases, presenting test-cases, in which they are applied. In Figure 10, a graphical representation of the process that took place during the literature review and the collection of the factors regarding car market.

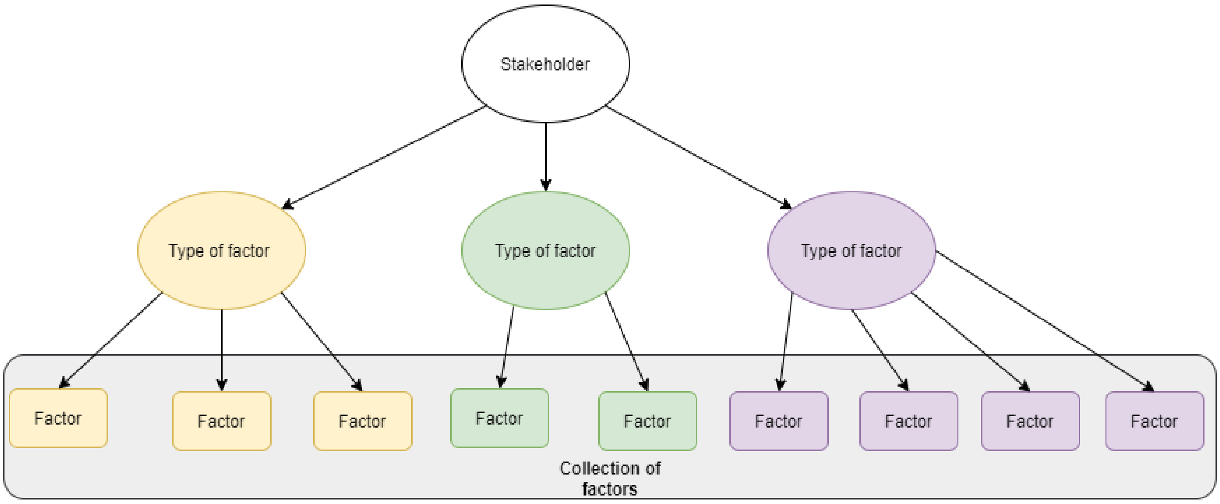


Figure 10. Graphical representation of the process taken place for each stakeholder

3.1 Auto manufacturers – OEM

In this section, an overview is given regarding the OEMs that are dominant in Europe, their market share based on the vehicles' powertrain and their future goals and ambitions towards electric mobility. More intense attention is given to the sector of OEMs, as by now, nearly all of them have announced their plans and intentions to develop electric cars in the near future [34].

In Table 2 [35], the top-selling car brands in Europe in 2019 are presented. As can be figured out, the "Volkswagen Group" leads the race by far, with 27% of the market share with the following brands lagging behind. The average market share of electric vehicles in the European Union is 3% [36]. Tesla is an OEM that provides only BEVs, so it makes sense that its market share will be meager. In 2019, Tesla had 111,728 sales in Europe, with a market share reaching <1% [37].

Brand	2019	Market share
Volkswagen Group	3,866,779	25%
PSA Group	2,467,258	16%
Renault-Nissan-Mitsubishi Alliance (RNMA)	2,197,226	14%
Hyundai Group	1,065,859	7%
BMW Group	1,048,047	7%
Daimler	1,016,655	7%
Ford	965,070	6%
FCA Group	946,571	6%
Toyota Group	797,397	5%
Volvo Car Corporation	342,579	2%
Mazda	256,562	2%
Jaguar Land Rover Group	228,626	1%
Honda	122,080	1%
Tesla	111,728	< 1%

Table 2. Top selling car brands in Europe in 2019 [35]

Below, the goals and ambitions regarding each OEM are presented regarding their transition towards electric mobility, while in Table 3, a summary is provided regarding the electrifications strategies of the presented OEMs. In Appendix A, the different technologies that concern electric vehicles are presented so that a better understanding will be provided, reading the goals and ambitions of the examined OEMs.

i. Volkswagen Group

The Volkswagen Group has already started preparing for the transition to fully BEVs. It is going to invest more than €30 billion in electromobility as it is going to launch more than 50 pure electric vehicles by 2025 compared to the current 6 [38]. Starting in 2020, Volkswagen Group will build its BEVs on the new modular electric drive matrix (German: Modularer E-Antriebs-Baukasten; MEB), a standardized platform that can be used for all of the brands under the group [39].

MEB platform offers a variety of benefits such as reduction of the manufacturing process as all of the models will be based on the same platform, less maintenance costs and is suitable for various models as each brand can place their models on the MEB [40]. At the same time, its architecture is such that the platform is aligned with the high-voltage battery, providing, this way, more space in the interior of the vehicle [41].

ii. PSA Group

PSA Group, under which Peugeot, Opel/Vauxhall, Citroen and DS are found, have also been preparing for the transition to electrification since 2019 [42]. However, they are not going to go fully electric yet. Peugeot and Citroen are planning to have electrified versions of all their models by 2025, while DS is planning to develop just pure electric vehicles after that year [43]. Just like Volkswagen, PSA Group is focusing on building its vehicles on two platforms that could be able to integrate any powertrain of its line-up. These platforms could support internal combustion, electric, or hybrid powertrain covering all of the needs of potential customers [42].

iii. Renault-Nissan-Mitsubishi Alliance (RNMA)

Since 2017, RNMA has published a strategic plan to follow until 2022, which is called Alliance 2022 [44]. The alliance is comprised of ten brands and is the leader in sales of electric vehicles. The target of Renault Group is to reach 5 million units globally with 8 BEVs and 12 electrified models. On the other hand, Nissan's strategy is to reach 1 million electrified Nissan and Infinity vehicles by 2022 using various electrification technologies [45].

iv. Hyundai Group

The Hyundai Group has presented its goals for its electrification strategy called Strategy 2025. It aims to become one of the three largest EV manufacturers in the world [46]. By 2025, 44 electrified models will come out on the market, from which 13 will be hybrids, 6 plug-in hybrids, 23 BEVs and 2 hydrogen fuel cell vehicles [47].

v. BMW Group

BMW Group has announced that all of its models can be electrified, either with a fully electric or hybrid powertrain, while after 2020, more models that can be fully electric will come out [48]. By 2025 BMW Group expects that electric vehicles will account for around 15-25% of its sales globally with 25 electrified models until then, of which the 12 will be pure electric [49].

vi. Daimler

Daimler Group relies its future on different technologies to coexist. Even though it is planning to bring more than ten all-electric vehicles, both battery and fuel cell electric vehicles by 2022, it is also focusing on high-tech combustion engines and systematic hybridization [50].

vii. Ford

Compared to other auto manufacturers, Ford delayed the massive production of electric vehicles. Even though it brought some electric vehicles in the previous years, they lacked acceptance due to, mainly their short-range [51]. The key to Ford's strategy is to electrify first their well-known vehicles so that potential customers will be more familiar with these models. By 2022, 16 BEVs are scheduled to be introduced to the market [52] and 24 PHEVs [53].

viii. FCA Group

In 2018, the FCA Group announced its strategy into the transition to electric vehicles for the future. The goal of the company is to electrify over 34 of its models by 2022, offering 24 BEVs and 10 PHEVs [53]. Moreover, FCA Group has made a deal with Tesla to pool their fleets so that FCA will meet the EU regulations for CO_2 that will be described more thoroughly in Section 6.2.4 [54]. The fleet average emission target for new registered vehicles will 95 g CO_2/km from 2021 and on [55].

ix. Toyota Group

Even though Toyota Group has developed hybrid electric vehicles since 1997, it has never produced battery electric vehicles. However, it is planning to change its strategy starting in 2020 with 10 new models ready to come out, while it also aims to have electric versions of all of its models by 2025 [56]. Moreover, it plans to sell more than 5.5 million electrified vehicles, of which more than 1 million will be zero-emissions vehicles (BEVs or FCEVs) [57].

x. Volvo Car Corporation

Volvo Car Corporation has committed to putting one million electrified vehicles on the road by 2025, with 50% of the cars being fully electric and the rest plug-in hybrid [58].

xi. Mazda

Mazda's electrification strategy will bank mainly on the hybrid motor systems. By 2030, 95% of the vehicles will be hybrid and just 5% will be BEVs [59].

xii. Jaguar Land Rover Group

By 2020, the group is planning to offer electrified versions for all the Jaguar and Land Rover models embracing fully electric, plug-in hybrid and mild hybrid vehicles [60].

xiii. Honda

The ambition of Honda is to achieve two-thirds of its global sales to be electrified by 2030, 15% BEVs and FCVs and 50% of HEVs and PHEVs. Moreover, by 2025 all of the models sold in Europe will be electrified [61].

iv. Tesla

Tesla was always concentrating on electric vehicles, and more specifically on BEVs. Based on "Global EV Outlook 2020" [53], Tesla was planning to have a production capacity of 0.5 million new BEV models by the 2020s, having also announced plans for a future with lower, and if possible, zero accidents [62].

OEM	OEM Announcement
VW Group	0.3 million EVs sold by summer 2020, 1 million EVs produced by 2023, up to 3 million electric car sales in 2025, 25% of the group's sales in 2025, 75 new EV models and about 26 million cumulative sales by 2029.
PSA Group	0.9 million sales in 2022. 14 new EV models by 2021 (7 BEV models and 7 PHEV models).
RNMA	Renault plans 12 new EV models by 2022 and 20% of the brand's sales in 2022 to be fully electric. Nissan targets eight new BEV models by end 2022. Infiniti plans to have all models electric by 2021.
Hyundai Group	44 EV models by 2025 (23 BEV models, 6 PHEV models, 13 HEV models and 2 FCEV modes.). 560 000 BEV sales by 2025.
BMW Group	15-25% of the BMW Group sales in 2025 and 13 new EV models by 2023 (out of 25 electrified models).
Daimler	0.1 million sales in 2020, 10 new EV models by 2022 and 25% of group sales in 2025. More than 50% of sales will be PHEV and BEV by 2030.
Ford	40 new EV models by 2022 (16 BEV models, 24 PHEV models).

FCA Group	34 new EV models by 2022 (10 BEV models, 24 PHEV models).
Toyota Group	10 new BEV models by the early 2020s and more than 1 million BEV and FCEV sales in 2030.
Volvo Car Corporation	50% of group's sales to be fully electric by 2025. A new EV model will be launched every year until 2025. 50% of Volvo sales will be fully electric by 2025.
Mazda	One new EV model in 2020 and 5% of Mazda sales to be fully electric by 2030.
Jaguar Land Rover Group	Offer electrified versions for all of the Jaguar-Land Rover vehicles embracing BEVs, PHEVs and MHEVs.
Honda	15% EV sales share in 2030 (part of two-thirds of electrified vehicles by 2030 globally and 100% of electrified vehicles by 2022 in Europe).
Tesla	0.5 million annual production capacity for Model 3 by 2020.

Table 3. Summary of OEMs' electrification strategies as described in Section 3.1 and based on "Global EV Outlook 2020" [53]

Having summarized the goals of the OEMs, the projected number of new BEV models coming to the market in Europe from 2012 to 2025 is displayed. In Figure 11 [63], the projected total number of BEV models on the market for each car manufacturer is presented. Furthermore, in Figure 12 [63], the corresponding findings for PHEVs are displayed for each car manufacturer.

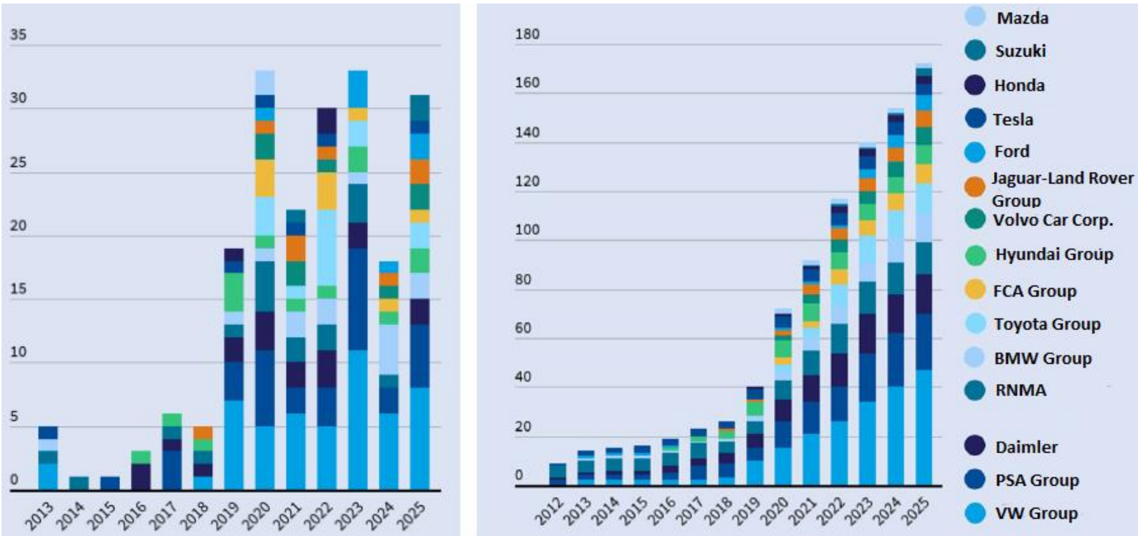


Figure 11. Number of BEV models of each car manufacturer at every year (left), the cumulative number of BEV models of each car manufacturer (right) (The Y-axis represents the number of models), (modified by the author: the OEMs' names were modified to match the way they were presented above) [63]

Figure 12. Number of PHEV models of each car manufacturer at every year (left), the cumulative number of PHEV models of each car manufacturer (right) (The Y-axis represents the number of models),) (modified by the author: the OEMs' names were modified to match the way they were presented above) [63]

It can be concluded that for both types of technologies, 2020 appears to be a milestone year for the car manufacturers as new models start coming out from that year and onwards. Volkswagen leads the race for both BEVs and PHEVs, justifying its large market share displayed in Table 2 and its ambitious goals, as described above. Moreover, the BEV's models exhibit a higher increase showing at the same time, the intentions of OEMs to focus on this specific technology.

Lastly, in Figure 13 [63], the projected models regarding the FCEVs are presented. Toyota seems to be the leader on this occasion as it is also the OEM, which first came out FCEVs.

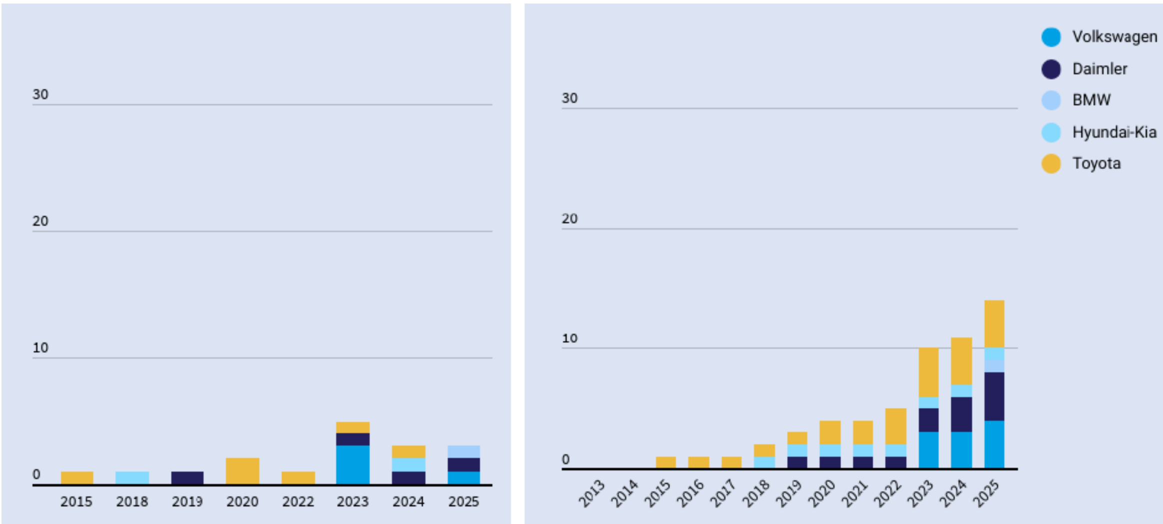


Figure 13. Number of FCEV models of each car manufacturer at every year (left), the cumulative number of FCHEV models of each car manufacturer (right) (The Y-axis represents the number of models) [63]

Combining Figure 11-Figure 13, the total number of models coming out to the market in Europe for each technology can be derived and is displayed in Figure 14 [63]. 53% of the models are BEVs, 43% PHEVs and 4% FCEVs.

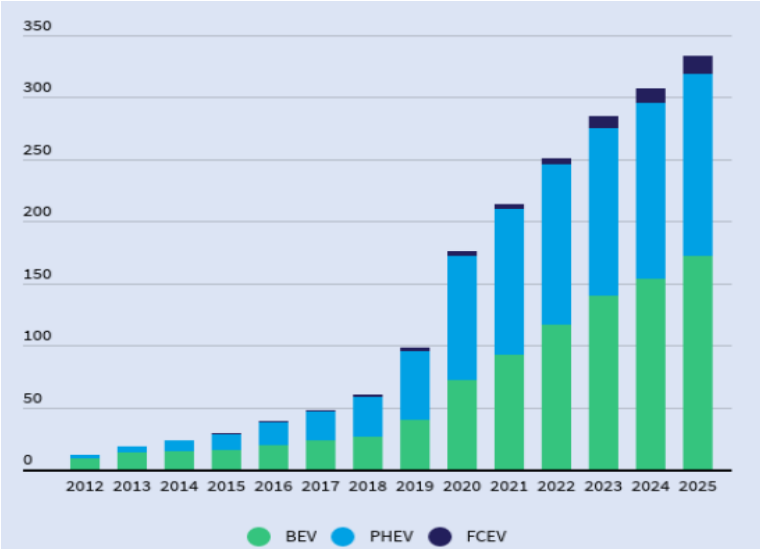


Figure 14. Total number of available EV models on the market in Europe [63]

In Table 4 [64], the share of electric vehicles by the manufacturer is presented during the first quarter of 2020 and 2019. It is worth noticing that even though VW Group has the most models coming out in 2020, its share in the market is below the average, with other OEMs with fewer models being more successful in that sector. The FCA-Tesla cooperation has to do with the compliance of FCA under the EU emissions rules that the CO2 emissions of an OEM's fleet should be under standard limits. In order to avoid paying hefty fines for breaking these rules, FCA has agreed to pay Tesla hundreds of millions of euros so that a share of Tesla's EVs to be counted in FCA's fleet [65].

Finally, in Table 5, a list of factors is presented that govern the different OEMs and contributes to the electric vehicle market dynamics.

Share of electric vehicles			
	March 2020	**YTD 2020**	**YTD 2019**
FCA-Tesla	39%	12%	7%
Volvo	22%	22%	11%
BMW	14%	13%	8%
Other	12%	10%	7%
Kia	12%	12%	7%
Nissan	11%	10%	9%
AVERAGE	***10%***	***7%***	***3%***
Daimler	10%	7%	2%
VW Group	8%	6%	1%
Renault	7%	8%	3%
PSA-Opel	5%	6%	0%
Ford	2%	1%	0%
Toyota-Mazda	0%	0%	0%

Table 4. Share of electric vehicles by manufacturer (modified by the author) [64]

Stakeholder	Type of factor	Factor	Reference
OEM	**Vehicle technical characteristics**	Cooling systems	[66]
		Regenerative braking	[67]
		Weight	[68]
		Powertrain	[69]
		Tank to wheel efficiency	[70]
		Well to wheel efficiency	
		Towing capability	[71]
	Battery technology	Lithium-ion, Lead-acid, Solid-state etc.	[72]
		Battery energy density	
		Range	[73]
		Raw materials	[74]
		Cathode chemistry	[75]
		Battery pack cost	[76]
		Production capacity	[77]
	Technological developments	Lane-keeping system	[78]
		Standardized platform	[79]
		Vehicle functions	[80]
		Vehicle quality	[73] - [74]
		Battery thermal management system	[83]
		Autonomous driving	[84]
		Vehicle platooning	[85]
	Strategy	Production cost	[79],[86]
		Base price	
		Models diversity	
		Designs	
		New business models (fleet sales, battery leasing)	
		Various EV technologies	[4]
		Pooling	[87]
		Investment budget	[88]
		Newly-added investment	[89]
		Willingness to invest	
		Basic investment	
		EV market share	[90]
		Profit from EVs	[91]
		Profit rate	
		Production capacity	[92]–[94]
	Own charging infrastructure	Availability	[95]
	ICE developments	Thermal efficiency	[96]
		Multifuel solutions	[97], [98]
		Turbochargers	[99]
		Advanced injection systems	[100], [101]
		Variable valve timing	[102]
		Catalytic converters	
		Exhaust gas recirculation	
		Crankcase emission control system	
		Powertrain technologies	
		Standardized platform	[103]

OEM	**ICE developments**	Friction reduction	[104]
		Real-world performance monitoring	
		Driveline control systems	
		Platooning	[105]
		ICE sales price development	[106]

Table 5. Factors that govern various OEMs

The more models are available in the electric vehicle market, the more active the sales will be. While in the early 2020s, car manufacturers may rely on various incentives, when price parity is achieved with the ICE vehicles, the electric vehicle market will mature and the sales will continue rising [63].

3.2 Government

As far as politics is concerned, there have been many regulations and adjustments from many parties. Thus, efforts have been made for the transition towards electric mobility from the European Union to national and local governments. The European Union (EU) acted and set targets that would ensure the reduction of GHG. The first target was aiming that by 2020 the GHG emissions would decrease 20% compared to 1990 levels, 20% of EU energy would come from renewable energy sources (RES) and there would be a 20% improvement in energy efficiency [107]. Moreover, the next target that was set was that by 2030 there would be at least a 40% reduction in GHG compared to 1990 levels, at least a 32% share will come from RES and there will be an improvement in the energy efficiency of at least 32.5% [108].

The government of the Netherlands has set its own goals according to the Climate Act and the National Climate Agreement. More specifically, the Climate Act calls for a reduction of 49% of the GHG emissions by 2030 and 95% by 2050. The sectors that will help to achieve these goals are: electricity, industry, built environment, traffic, transport, agriculture and land use. Some measures within the transportation sector are that all of the new passenger cars should emission-free by 2030, implementation of incentives that would enhance the EV uptake and 1.8 million charging points by 2030 [109]. Furthermore, it has been decided by the Dutch national government and more specifically, the ministries of Economic Affairs and Infrastructure and the Environment, that 250,000 electric vehicles to be on the road in the Netherlands by 2025 [110]. In order for these ambitions to be accomplished, several financial and other incentives have been provided, such as tax exemptions for BEVs and PHEVs.

On the other hand, local governments have also invested in the acceleration of electric mobility, by providing incentives to citizens and local businesses to adopt EVs [110], or by banning the access of high-emission vehicles into the city centres. Table 6 presents the various factors that concern politics, such as the different incentives and any regulations regarding the protection of the environment and electric vehicles.

Stakeholder	Type of factor	Factor	Reference
Government	**Financial support**	Financial incentives	[111]–[116]
	Immaterial support	Immaterial incentives	[117]–[119]
	Environment	Paris Agreement	[120]
		European fleet regulations	[121]
		Energy sources	[122]
		Exhaust emissions	[123], [124]
		Environmental awareness	[125]

Table 6. Factors concerning government as a stakeholder

3.3 Oil companies and utilities

Oil companies and utilities are another kind of stakeholder that participate drastically in the transition towards electric mobility as the market dynamics related to EV growth have a significant impact on the energy industry as well. As has been stated in Section 2.3, oil companies have already started investing in charging infrastructure start-ups, having in their possession 79% of the publicly available charging points [25]. Shell, for example, one of the leading oil companies, provides charging points by investing in charging infrastructure and acquiring charging companies [126].

Regarding the oil prices on oil companies, when they are lower they can help reduce the cost of living, especially if a household owns a car or uses transport reliant on oil [127]. The price fall in March-April 2020 has pushed oil to its lowest prices for many years, due to the COVID-19 crisis and the economic recession. Nevertheless, this fall is expected to be only temporary and will not affect people's income to a large degree considering that they may also be out of work due to the pandemic Therefore, oil prices have a severe impact on the users' decision on which kind of vehicle technology he will choose [127].

Moreover, depending on the country, oil prices have different effects. Oil importing countries benefit from lower oil prices compared to oil exporting countries [127]. Hence, it can be understood that oil prices can be volatile and they depend to a large degree to the period of time and the geographical scope. Therefore, oil prices may have serious impact on the users' decision on which kind of vehicle technology he will choose as oil prices affect the vehicle's operational costs.

Furthermore, there are oil companies that have invested in alternative energy projects. These are related to the production of biodiesel and ethanol that can be substituted for petroleum [128]. Oil companies recognize the effect that fossil fuels have on the environment and that is why they are willing to invest in cleaner and greener fuels as substitutes. Moreover, prices of renewable energy sources keep decreasing and get cheaper than conventional energy sources [129].

Nevertheless, there are still "greenwashing" complaints and accusations as oil companies keep investing more than 90% of their capital expenditure in oil and gas, even though they promote "green" strategies and plans [130], [131]. People push these companies to shift their strategy to "greener" and friendlier to the environment. So, changes remain to be seen in the near future.

In Table 7, a list is presented, with the influential factors of oil companies towards the transition of electric mobility.

Stakeholder	Type of factor	Factor	Reference
Oil companies & utilities	**Financial**	Fuel price	[127]
		Uncertainty @ fuel price	[26]
		Electricity price	[132]
	Alternative fuels	Ethanol	[133]
		Biodiesel	
	Environment	Production pollution	[134]
	Investments	Charging infrastructure	[25]
		Renewable energy sources	[128]
	Societal	"Greenwashing" complaints	[130], [131]

Table 7 Factors concerning oil companies as a stakeholder

3.4 Consumers

Another crucial stakeholder involved in the uptake of the EVs is the potential customers, those who are going to buy a vehicle. Some prefer buying an EV because they want to live the experience of driving one. Others are only interested in financial reasons, or they wish to contribute to the improvement of the environment. Finally, the choice for an EV is influenced by the daily commutes and the weather and geographical conditions, as they were also explained in Section 2.2.

Z. Shahan conducted a survey based in Europe, analysing the reasons why EV drivers choose an EV as their vehicle [135]. Environmental contribution seems to be the primary reason for all the countries, with the convenience of instant torque and fast acceleration and smooth and quiet drive coming next [135]. In Table 8, the factors concerning the reasons behind the acquisition of an EV are presented.

Stakeholder	Type of factor	Factor	Reference
Consumers	**EV experience**	Range anxiety	[136]
		Ride quality	[137]
		Dashboard touchscreen	[138]
		Noise level	[139]
		Autonomous driving	[140]
		Acceleration behaviour	[141]
		Regenerative braking	[142]
		Convenience of charging (home, work)	[135]
		Waiting time to receive EV	[143]
		Social network	[144]
		Environmental contribution	[135]
	Travel characteristics	Road elevation	[145]
		Distance traveled	[146]
		Charging infrastructure	[147]
		Weather conditions	[148]
	TCO	Sales price	[149]–[151]
		Leasing cost	
		Maintenance cost	
		Depreciation	
		Discretionary income	
		Financial incentives	
		Fuel/energy consumption	
		Car tax	
		Residual value	
		Car insurance	
		Charging rates	[152]
		Depreciation	[89]

Table 8. Relations that affect the purchase decision of a potential vehicle customer

4. Design of the concept map

In this chapter, the factors that will be included in the design process are gathered. Section 4.1 explains the process during which the selected factors were considered. In Section 4.2, the designed concept map is presented. The concept map demonstrates the design solution that is implemented in the model, in Chapter 6, and will investigate the car market dynamics of various OEMs.

4.1 Framework of the model

In order to identify the factors included in the concept-map, a literature review was conducted in Sections 3.1-3.4. Creating a map containing all of the relations that exist among these factors is a complex task. Moreover, a map like that would not be able to capture the complex. EV market. Therefore, certain types of factors were selected that would simplify the analysis of the model and would represent the EV market in the best possible way based on the author's judgment. The scope of the assignment is the investigation of car market dynamics among various OEMs towards the transition to electric mobility. The approach that was followed was based on Liu et al. [89], who divided their concept map in four major subsystems in order to explore the development of electric vehicles under policy incentives. In the current assignment, in order for the developed dynamics of different OEMs to be explored, two major subsystems were created, the "EV subsystem" and the "ICE subsystem". These should describe the behaviour of each OEM towards electric mobility. The two subsystems will be included in the model and the OEMs will be comprised of them.

Furthermore, there are five more subsystems that are described with a more superficial way, the "Financial support", "Total Cost of Ownership (TCO)", "Regulations", "Decision making" and "Charging" subsystems. The reason behind their short description and investigation was to keep the model simple, concentrating on the OEMs strategies. In order to avoid further complications, the factors concerning the EV market were collected in Table 5 - Table 8 and those, which represent better each subsystem, based on the author's judgement, were used for the design of the concept map. Hence, the concept represents only a part of the car market as not all of the factors were included for simplicity reasons. Following the logic behind Figure 10, in Figure 15, it is displayed what was followed after the collection of the factors influencing car market. As it is shown, the concept map is comprised of some of the collected factors. As it has been mentioned, it would be really complex to include all of the factors in the concept map and later on, in the model.

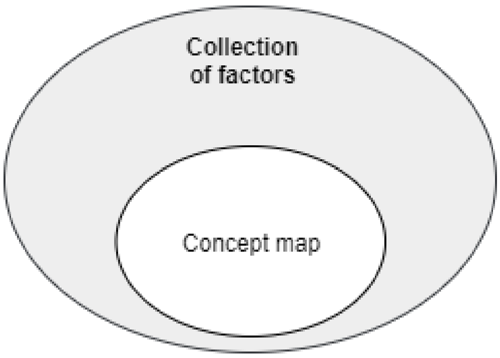


Figure 15. Graphical representation showing that the concept map is comprised of the collected factors

The factors that were chosen are presented in the concept map in Section 4.2. More attention was given to the EV and ICE subsystems as they represent the OEMs and their strategies. According to the powertrain they produce and the demand that exists in the market, the OEMs make investments, produce vehicles and improve their vehicles. Moreover, the sales and the profits come from the sales for each powertrain technology. As it was mentioned, the other subsystems are explained in a more superficial way as they are already mentioned in the current version of the "Adam & EV" model. Nevertheless, since many alterations had to be done in the model and these factors were also influenced, they are included and presented in the designed concept map.

4.2 Design of concept map

As displayed in Figure 15, the concept map contains selected factors after they were identified. All of them influence the uptake of electric mobility directly or indirectly, to a larger or slighter degree. Lastly, the factors are illustrated in different colours so that they will be distinguished based on the subsystem that they belong to.

It was necessary to represent the main variables and show the causality relationship among these variables. Hence, in order for these critical factors to be able to be explored, a causal loop diagram was built, as shown in Figure 17. This diagram displays all of the mutual influences and interactional relationships between the main variables, while the arrows indicate the direct influence that one variable has on another.

As it was mentioned in Section 4.1, more attention was given to the EV and ICE subsystems as it can also be verified by Figure 17. For example, looking at the "Consumers buying EVs" and the developed relations around them as presented in Figure 16 many other factors are also influenced by them. The more consumers buy EVs, the more are sold which has an impact on the profits of the OEM. When the demand is also high, more EVs have to be produced in order to meet the demand, which requires higher production budget and, eventually, higher investments. On the other hand, the higher the models' diversity is, the higher is assumed that the willingness of the consumers buying an EV will be, due to the more choices they have in type or design. The electric vehicle's quality functions and range anxiety also affect the decision of consumers buying an EV, affecting at the same time the rest of the factors. Hence, it can be realized that if all of the factors were included, the concept map would be even larger and more complex than it already is. That is why, the initial intention was to keep the concept map simple, representing with more details just the two major subsystems representing the OEMs.

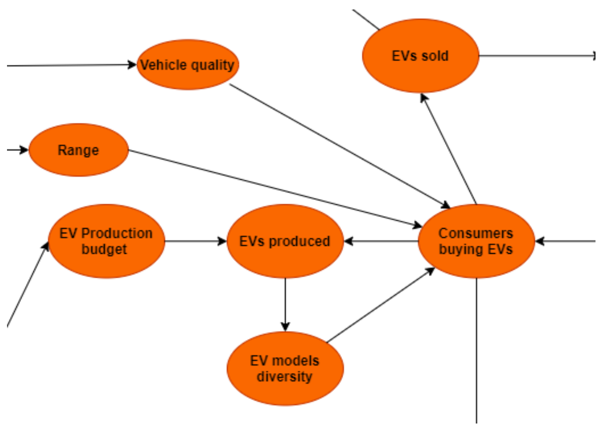


Figure 16. Developed relations among the "Consumers buying EVs" factor

The “Consumers buying EVs” factor is the most important in the concept map as is the factor that will increase the demand and, eventually, the sales, profits and investments. As can be seen from Figure 17, the “Decision making” factors lead to the consumers’ decision to buy an EV. Moreover, one of the decision-making factors is the discretionary income which is affected by many “TCO” factors. Finally, the discretionary income is also influenced by financial incentives given by the governments. All of these relations show the causalities relations that exist in the model, affecting each other.

In Chapter 6, a clearer representation of the model will be given regarding the relation developed as presented in the concept map, the equations that were used to describe some of the factors and the way the model it was structured.

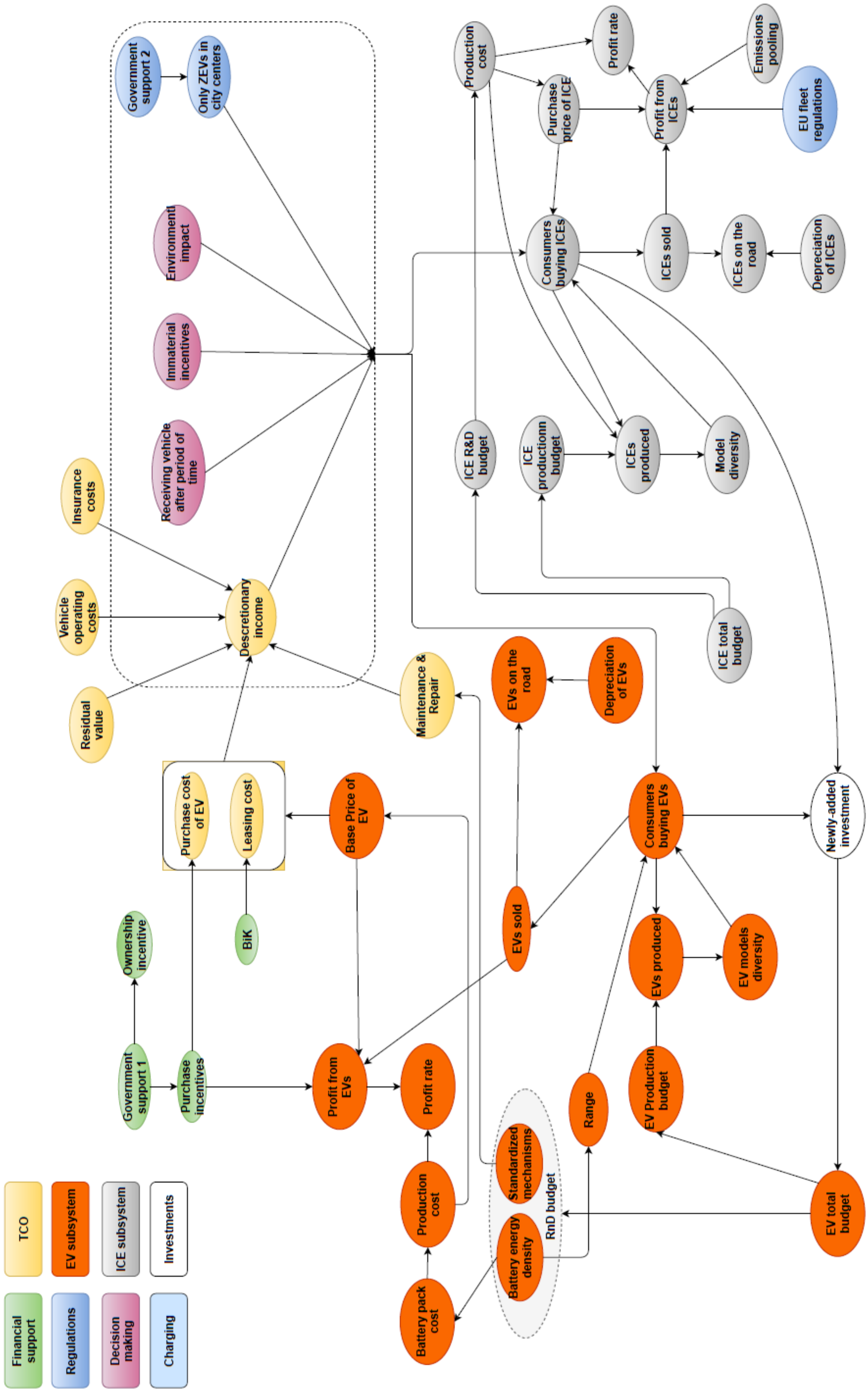


Figure 17. Concept map

5. “ADAM & EV” model

In this chapter, a more in-depth insight into the “ADAM & EV” model is given. Before a more depth in the new version of the “Adam & EV” model is given, the model should be explained so that readers coming from any scientific field have an insight of the model. In section 5.1, a brief introduction is provided for agent-based modeling (ABM) so that the reader has a more precise conception about the Anylogic platform, where “ADAM & EV” was developed. Section 5.2 describes the goals of “ADAM & EV”, given the original version of the model, while some limitations are also described.

5.1 Introduction to agent-based models

ABM is a method of simulation where a virtual environment is created to model the interactions between agents [10]. It is a method that has already been used in many different sectors. Some of these are in social sciences [153], economics [154], medicine [155], to simulate population dynamics [156], geographical systems [157], land-use changes [158] and processes in archeology [159]. It has also been used to model vehicle technology adoption with agents such as consumers, automakers, policymakers, fuel suppliers etc., interacting with each other in a virtual environment [10].

Moreover, ABM deals with complex individual behaviour, including learning and adaptation of individuals, captures emergent phenomena, is flexible and provides a natural description of a system [160]. Decisions are made by these agents individually based on a set of rules. Thus, what makes ABM unique is its ability to simulate the interactions among the agents, which creates a path for the model users to better comprehend their nature. An agent-based system (ABS) can be very simple, with no complicated agent architecture or tangled interaction rules. Nevertheless, various emergent behaviours can be produced due to the interactions of these simple agents [161].

The virtual environment with which the agents interact can have different forms such as that of a lattice or a ring, or random networks and 2D or 3D space or based on a geographic information system (GIS). The agents can have the opportunity to move freely in that environment, something that makes it applicable for modeling and visualizing complex behaviours in physical systems [161].

The reason behind the selection of an ABM to support “ADAM & EV” is that in order to understand the effects of market developments and the changing mobility landscape on individual consumers, a more disaggregated modeling approach is required. Furthermore, the model should give meaning and act as a tool for discussion support for what the simulated world looks like and what are (if there are) the capabilities and possibilities that arise [1]. As it is referred to in [162], the agent-based approach is uniquely suited for the complex adaptive socio-technical system that must be modelled. Given the fact that “ADAM & EV” is a consumer behaviour focused model, ABM was considered as the best solution by the developer. Lastly, a comparison among different models that have already been made regarding the EVs uptake is presented in [1]. The comparison is made among System Dynamics, Equilibrium and Agent-Based Models. It is concluded that the effects of changes in the systems towards consumers should be modelled more explicitly.

The developer of the “ADAM & EV” model chose Anylogic as the software environment for the development of the model as it offers a visually attractive environment and can be extended with other modeling paradigms such as System Dynamics [1]. Finally, Anylogic appears to be a stable and modern tool to use.

5.2 Model structure of original version

The agent-based simulation that has been created, “Adam & EV” offers an overview of the car market dynamics among various elements in the EV market [1]. Its primary goal is to accelerate the EV transition so that emissions to be reduced while minimizing the cost of incentives. It supports involved stakeholders in the decision-making process regarding EVs by functioning as a validation tool for future scenarios.

The scenarios concern plenty parameters that affect EVs’ development, such as the sales price of ICEs and BEVs over the years, the financial or non-financial incentives that may exist and the factors that influence decision-making of all consumers. By selecting a specific scenario, the user has the opportunity to investigate different outcomes like people's behaviour regarding their mobility situation, the development of BEVs and ICEs on the road as well as their sales percentage and the total avoided emissions. All of the covered subjects that were used for the development of the model can be found in [1].

Next, a summary is given regarding the degree to which each agent is explained and developed. Agents are living within the model, which are the consumers, the cars and the dealer. Below, a short description of each agent’s role is given and the extent to which they are modelled.

- **Consumer agent**

The consumer agent is an agent representing a population, the number of which can be varied according to the user’s wish. Like in real life, each consumer has a gender, an age and can get born and die. Moreover, they gain an income, the amount of which depends on their job situation. Consumers have a BEV attitude, which is randomly distributed with a score between 0 and 1 and can gradually increase over time. There is also societal attitude, which is the average over all consumers. Finally, with the aid of a state transition diagram, the car ownership situation is modelled. Once a consumer has a positive intention of buying a car, he will look for one. Hence, he will consider all of the available vehicles based on their powertrain, purchase cost and TCO. To this point, after he checks these vehicles, he will buy the cheapest one. In general, consumers' agents are modelled in high detail.

- **Car agent**

Compared to consumer agents, car agents are modelled with fewer details. Currently, there are just two vehicles in the model. “Volkswagen Golf 1.0 TSI 85pk Trendline” [163], which is a petrol vehicle representing the ICE vehicles in the model and “Volkswagen e-Golf” [164], a BEV representing the BEV vehicles in the model. Same as in real life, vehicles have an age and their own technical characteristics, such as fuel or energy efficiency, that also define their operational costs, including depreciation.

- **Dealer agent**

The dealer, on the other hand, is a single agent that is modelled very superficially. The role of the dealer in the model is to check the demand of the vehicles from the consumers. Then, he provides the model with new vehicles, or with vehicles that are already in stock.

There are also various global economic developments for the base prices of ICEs and BEVs and the fuel and energy costs, incentive options that stimulate the preference of the consumers towards the BEVs, calculation of total and avoided emissions and more. All of them interact with each other in order for the results for the EV uptake and the emissions to be obtained. The structure of the original version of the simulation model is presented in Figure 18 [1]. That figure has been modified as in the described source, the Dealer Agent is also presented as the OEM Agent. In the current assignment, the OEMs will be presented separately. Therefore, Figure 18 displays just this model part.

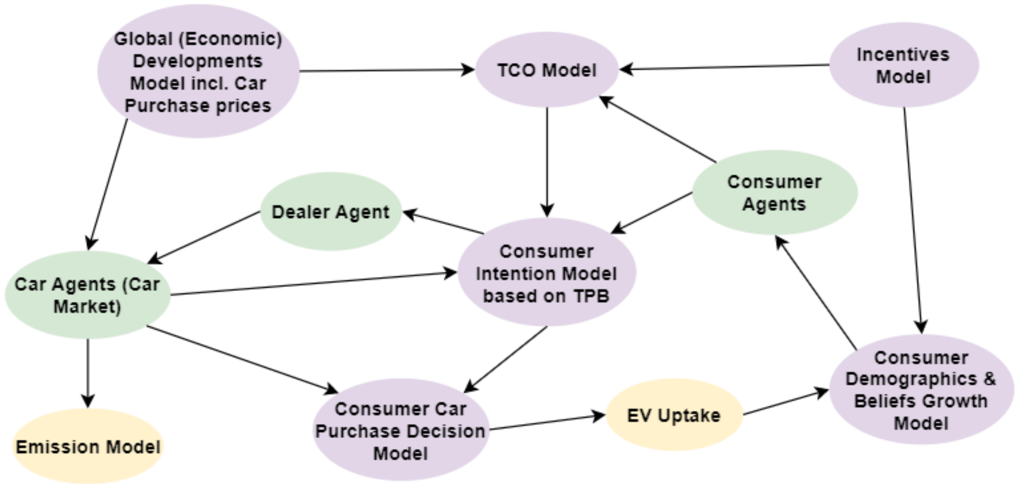


Figure 18. Model structure of original version of the model (modified by the author:) [1]

As has been mentioned before, the “ADAM & EV” model is a tool promoting discussion regarding the EV uptake and to what extent this can be achieved. Considering the main questions of section 1.1, the model provides the user with results and user-friendly graphs that should be able to answer these questions. Some of the most interesting results that can be extracted during the runtime of the simulation are:

Main outcomes:	New sales BEV percentage [%] Total cars on the road (by type)
Economics & Emissions:	Total monthly emissions (by type) [t CO_2] Total avoided emissions [t CO_2] Total government expenditure [k€] Expenditure per avoided ton CO_2 [k€]
Key performance indicators:	Actual BEV sales percentage last month [%] Percentage of BEV on the road [%] Total emissions [t CO_2] Total avoided emissions [t CO_2] CO_2 emissions reduction [%] Total expenditure on incentives [k€] Incentive expenditure per evaded ton CO_2 [k€]

Moreover, by altering the amount of incentives, or their duration, or even removing them, one can see the impacts that this factor has on the EV uptake and the emissions. Hence, it could be said that the original version of the model serves to a decent degree its goal, serving as a discussion tool exhibiting trends and influencing factors.

Nevertheless, there are still some windows of improvement that could reflect real life to a more substantial degree. The causal loop diagram, displayed in Figure 19 [165], emphasizes the different focus areas that should be linked to the focus area “soft factors” (consumers behaviour) which will ultimately determine EV uptake.

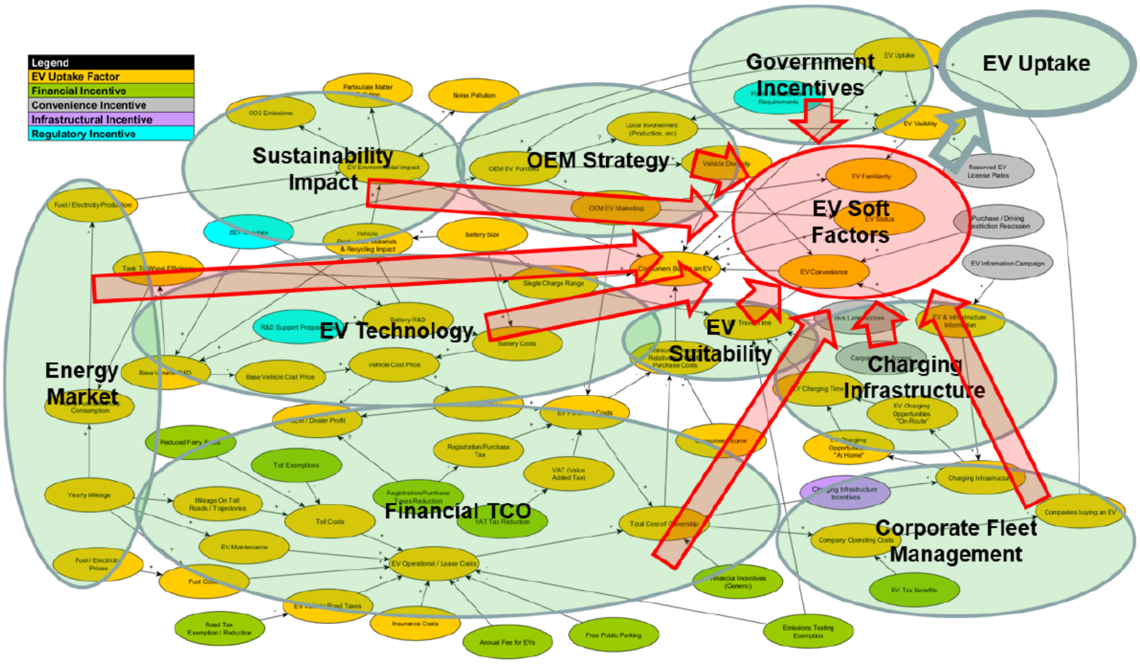


Figure 19. Relational Model of different Focus Areas determining EV Uptake – the visualization shows that effects of the different focus areas should be analysed against their impact on EV soft factors (i.e., consumer attitude and behaviour) as the ultimate determinant of EV uptake [165]

One of the limitations of the model is the limited modelling of the dealer. The “Dealer Agent” operates as a dealer and as an OEM at the same time, checks the demand and generates new vehicles. In real life, new vehicles are manufactured by the OEMs and the dealer orders vehicles from them based on their reading of the marketplace and how well certain models have been sold in the past [166]. For example, VW and Toyota are two OEMs that have their own dealers and provide their vehicles exclusively. Tesla does not have its own dealer and provides its vehicles directly from its production facility. Hence, two dealers could exist in the model that would also read the demand from the consumers.

Furthermore, modelling various OEMs in the model can be very interesting due to the different strategies that each one of them follows. As can be seen from Figure 19, “OEM Strategy” is not described analytically in the original version of the model, even though OEMs can have large power over car market, as it has been described in 2.3

Moreover, the final step before a potential customer selects a vehicle is not modelled with the best possible way. To this time, after several criteria like powertrain preference, purchase cost and TCO, the consumer will select the cheapest one. However, this does not reflect what happens in real life. For instance, people with high incomes will be financial fit for any vehicle, but still, their choice is constrained to the cheapest one. So, the model does not give them the option to buy a more expensive vehicle yet.

It is realized that electric mobility as a whole is a vast market with many parameters and features that could be considered in order for market dynamics to be captured. In the following chapters, an approach is presented in order for some of these problems to be tackled and minimized.

6. Implementation of OEM agent in "Adam & EV"

In this chapter, the new version of the model is presented. Section 6.1 describes the OEMs that were selected and explain the reasons behind that selection. In Section 6.2, the new approach that was followed is presented, the equations that were used for the calculations and the main algorithm that was used, along with visual examples for better understanding. In Figure 20, the structure of the new version of the model is presented with the implementation of the OEM agent in the model. The new structure is in accordance with the one of Figure 18, where the key modelled areas and the relations between them are presented.

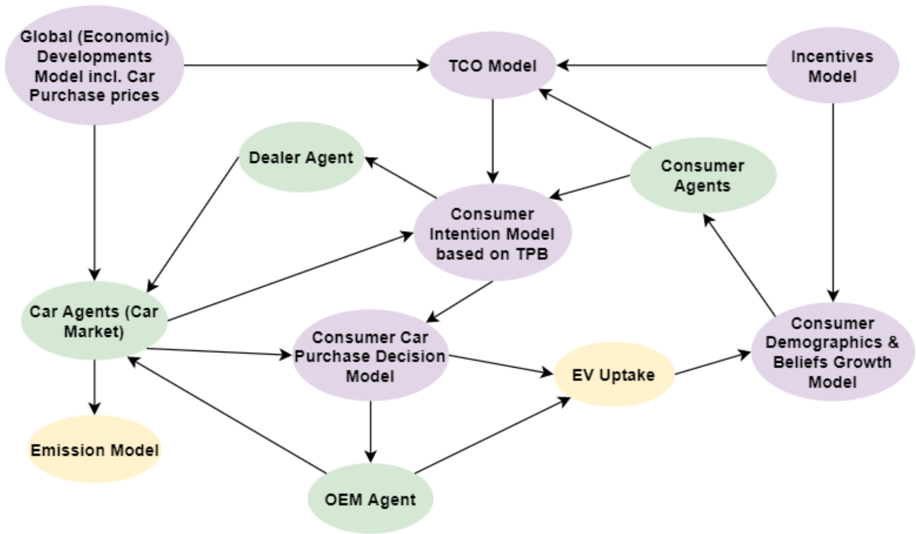


Figure 20. Model structure of new version of the model

6.1 OEMs selection

The first step for the capture and investigation of car market dynamics of different OEMs towards electric mobility is the selection of the OEMs. The goal was the selected OEMs to follow different electrification strategies so that the differences will be more apparent based on the consumers' preferences. The strategy of each OEM is also presented in Table 3. The selected OEMs are:

- **Volkswagen**
- **Toyota**
- **Tesla**

These three were selected as they have presented different electrification plans for the upcoming years. Volkswagen has entered in electric mobility dynamically as it has invested, as a group, billions of euros, planning to launch almost 70 new electric models in the next ten years, which will be built on the Group's MEB [167].

Tesla was selected as the OEM investing solely in electric mobility and the results that this strategy has on its profits as an OEM. It is also worth noting that Tesla's vehicle "Model 3" is the most sold BEV in Europe in 2019, topping other OEMs, as well [37]. Lastly, Toyota was selected as it is an OEM, which is a laggard to the transition to electric mobility as it was planning to produce its first electric vehicles models by the end of 2020, compared to the rest of OEMs that have just started penetrating the market. Both Volkswagen and Toyota have their own alliances; Volkswagen Group is comprised of Volkswagen, Audi, SEAT, ŠKODA, Bentley, Bugatti, Lamborghini, Porsche, Ducati, Scania and MAN [168], while Toyota Group by Toyota and Lexus [35].

Concluding, the selected OEMs have different characteristics regarding their electrification strategies; one OEM that has entered actively into the electric mobility market, one that is concentrated only on electric vehicles and one that has just entered the market. These three OEMs will allow investigating the car market dynamics towards electric mobility, which is the primary goal of the current assignment. In order for a more valid comparison to be made within the simulation, the referred OEMs were not selected as a group. Hence, Volkswagen was selected from the Volkswagen Group and Toyota from the Toyota Group. In Appendix E and Table 22, the number of models that the three OEMs have already produced is presented and the number of models that are about to produce in the coming years. The number of future models emerging from the information about the projected number of BEVs of Figure 11, the percentagewise sales of VW Group [35] and the current models in the market [169]. The results and calculations are also explained in Appendix E.

6.2 Model structure

In this section, an overview of the new version of the model is given, concentrating mostly on the new methods that have been used compared to the original version. In the following sections a clearer presentation regarding the new version of the model is given, following the relations given by the designed concept map in 4.2. Subsection 6.2.1 presents the vehicles and the OEMs that have been used in the model, as well as some important technical and financial characteristics of the vehicles. In subsection 6.2.2, the way the base price developments of the vehicles over the years are presented, while subsection 6.2.3 introduces the equations used for the calculation of the production cost of the vehicles. In subsection 6.2.4, the European fleet regulations are given, so that possible fines to be determined and in 6.2.5, the equations are given for the calculation of the budgets and profits of the OEMs. Next, in 6.2.6, the OEM scoring system that has been implemented is presented and, finally, 6.2.7 analyses the new algorithm for consumers searching a vehicle.

6.2.1 Selected vehicles

In order for the dynamics to be captured, representative vehicles were chosen for the selected OEMs and the powertrains they offer. However, Toyota has not produced any BEVs yet. Hence, one BEV from Lexus was selected, as Lexus is part of the Toyota Group. In Table 9 and Table 10, the characteristics of each vehicle selected are presented.

OEM	Volkswagen	Toyota
Car Name	Volkswagen Golf TSI (Petrol)	Toyota Corolla 1.2 Turbo Comfort
Powertrain	ICE	ICE
Fuel Efficiency [L/km]	6.82	5.6
Fuel Cost [€]	1.55	1.55
Monthly Tax Cost (MRB) [€]	38	45
Monthly Insurance Cost [€]	50	53
Monthly Maintenance Cost [€]	48	48

Table 9. Main characteristics of selected ICE vehicles [170]–[172]

OEM	Volkswagen	Toyota	Tesla
Car Name	Volkswagen eGolf	Lexus UX 300E Electric	Tesla Model 3 Standard Range Plus
Powertrain	BEV	BEV	BEV
Energy Efficiency [kWh/km]	16.8	19.3	15.3
Battery Capacity [kWh]	35.8	54.3	75
Range [km]	230	400	415
Electricity Cost [€/kWh]	0.13	0.13	0.13
Monthly Tax Cost (MRB) [€]	0	0	0
Monthly Insurance Cost [€]	79	97	94
Monthly Maintenance Cost [€]	39	44	52

Table 10. Main characteristics of selected BEV vehicles [169], [132], [173]–[175]

The characteristics presented in Table 9 and Table 10 are used to determine various financial parameters, like the variable and fixed costs, and help the consumer to decide his preference on, initially, the powertrain and later on, on a specific OEM. More details will be given in the next subsections.

6.2.2 Base price development

In order for the yearly sales prices, until 2050 to be decided, some projections have been made regarding the base prices of the vehicles. The base prices of both Volkswagen's vehicles had already been projected for the previous version of the model. The way it was projected was that inflation was added for the ICE and deflation for the BEV in such a way that they reach cost parity in 2030. After that year, inflation is also added to the BEV.

	Base price [€]				
Year	**Volkswagen Golf TSI** [176]	**Toyota Corolla 1.2 Turbo Comfort** [177]	**Volkswagen eGolf** [178]	**Lexus UX 300E Electric**	**Tesla Model 3 Standard Range Plus**
2020	17,890	15,638	27,257	39,992	40,817

For the vehicles of Tesla and Toyota, the base price was calculated based on the value-added tax (VAT) of the Netherlands, which is 21%, and their sales price [174], [175]. In Appendix B and Table 19, the base price developments are presented for each vehicle that was selected, while Figure 21 displays schematically the base price development over the years.

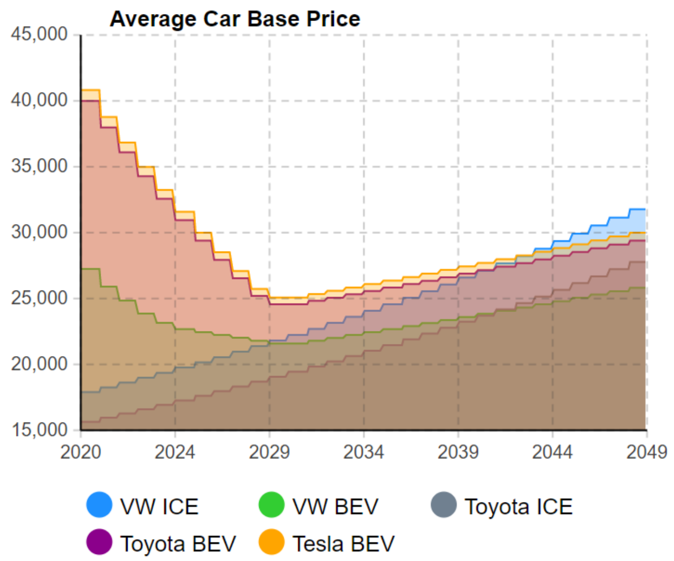


Figure 21. Average car base price development of the selected vehicles

6.2.3 Production cost of ICE/BEV

As far as the calculation of the production cost of ICEs and BEVs, different approaches were followed. The ICE production cost was calculated in a more arbitrary way compared to the BEV's, following the approach of Liu et al. [89], where the ICE production cost is 85% of its sales price. Hence, the production cost of the ICE vehicles is calculated as in Eq. (1), while the profit of one ICE is calculated based on Eq. (2). It is also assumed, that in the ICE production cost all of the factors involved in the cost of manufacturing an ICE vehicle are included. These can be raw materials and auto parts, direct labor and advertising charges, sales tax and other factors such as logistics, overheads or dealership markups [179].

$$\text{ICE production cost [€]} = 0.85 * \text{ICE sales price [€]} \tag{1}$$

$$\text{Profit of one ICE [€]} = \text{ICE sales price [€]} - \text{ICE production cost [€]} \tag{2}$$

For the calculation of the BEV production cost, a more thorough approach was followed. It is mostly based on the battery pack (B.P) production cost, as it is considered as the most expensive part of an EV affecting the total cost to a large degree. The battery pack accounts for 35% of the total BEV production cost, where 25% has to do with the battery cells and the rest 10% with the battery pack integration [180]. Considering that the cost of integration of the battery pack will not change much in the future, the remaining 25% was used for the calculations. In Eq. (3) the price of the production cost is calculated without the battery pack by deducting 25% of the total cost.

$$\text{BEV cost without B.P [€]} = \text{BEV base price [€]} * 0.75 \tag{3}$$

The deduction of the battery pack from the base price was made so that the decreasing price of the battery pack to be included for every year. There are many projections in the literature, average values or OEM statements. Since it was impossible to find official data for each OEM regarding their prices, average values were used from a study conducted by Bloomberg [76]. Bloomberg has forecasted that by 2024, battery pack cost will be around 84 €/kWh and 55 €/kWh by 2030. In Figure

22, the prices that were calculated are displayed up to the year 2050. In Appendix C and Table 20, the costs for the battery pack for the next 30 years are displayed.

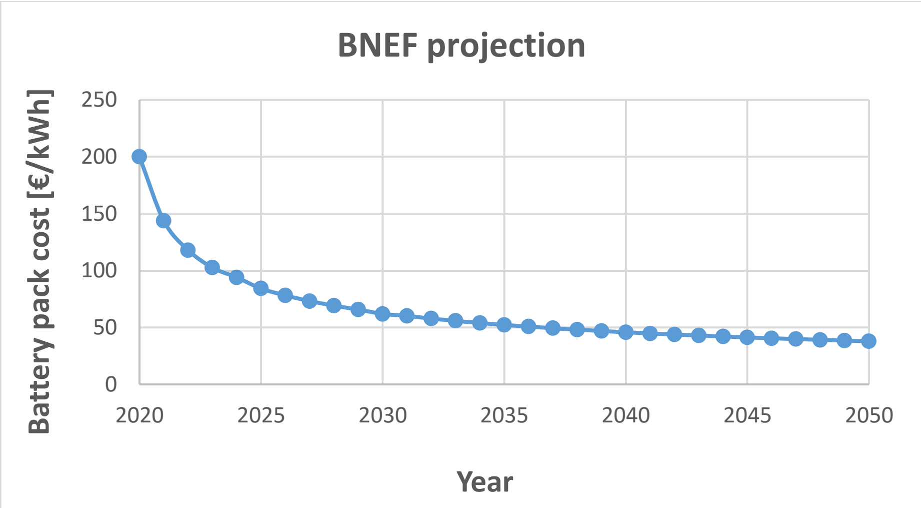


Figure 22. Bloomberg's battery pack price projections

Later, the production cost of the battery pack alone is calculated according to the battery capacity of each selected vehicle, as in Eq. (4).

$$\text{B.P cost [€]} = \text{B.P cost [€/kWh]} + \text{Battery capacity [kWh]} \tag{4}$$

Having information for the vehicle's production cost without the battery pack and the price developments of the battery pack over the years, the final production cost of the vehicle can be calculated according to Eq. (5). The profit of each BEV for each OEM can later be calculated as the difference in the sales price and the BEV production cost at that point of time plus the amount of subsidy given by the government to the consumer, as shown by Eq. (6).

$$\text{BEV production cost [€]} = \text{BEV cost without B.P [€]} + \text{B.P cost [€]} \tag{5}$$

$$\text{Profit of one BEV [€]} = \text{BEV sales price [€]} - \text{BEV production cost [€]} + \text{BEV purchase bonus [€]} \tag{6}$$

Finally, the profit rate of all of the vehicles can also be calculated based on Eqs. (7) and (8), according to the vehicle's powertrain.

$$\text{BEV profit rate [\%]} = (\text{ Profit of one BEV [€] / BEV production cost [€] }) * 100 \tag{7}$$

$$\text{ICE profit rate [\%]} = (\text{ Profit of one ICE [€] / ICE production cost [€] }) * 100 \tag{8}$$

6.2.4 European fleet regulations

In order for the electrification of the transportation sector to be more quickly achieved and, thus, the EU's commitments under the Paris Agreement to be fulfilled, some regulations and targets have been implemented. These regulations concern newly registered passenger vehicles and the non-achievement of those induce fines to the OEMs.

More specifically, the 15% from 2025 and the 35% from 2030 on of the newly registered vehicles should be zero- and low-emission vehicles (ZLEV) [121], while the emission target from 2021 on will be 95 g CO_2/km. If the average CO_2 emissions of the OEMs' fleet do not reach the mentioned percentages of newly registered ZLVEVs, they have to pay 95 € for each g/km of target exceedance for each newly registered vehicle [55].

Manufacturers are also given incentives to produce and offer ZLEVs of less than 50 g CO_2/km with a "super-credits" system. It has already been announced that this system will apply for the period 2020-2022, as shown in Table 11. For the simulation, it was assumed that the "super-credits" system will continue until 2030 with the number of vehicles accounting, also, for 1.33 vehicles and after 2030, they will account for 1.

Year	Number of ZLEVs
2020	1 ZLEV = 2 vehicles
2021	1 ZLEV = 1.67 vehicles
2022	1 ZLEV = 1.33 vehicles

Table 11. "Super-credits" system for newly-registered ZLEVs

In Appendix D and Table 21, the exact values that were used for the simulation are presented. The fine of 95 € per g/km of exceedance was considered the same for the rest of the coming years.

6.2.5 OEM investment budgets

In this subsection, the way the production and R&D budgets are calculated is explained. In order to avoid any harsh assumptions, initial or were avoided as the simulation represents a microworld and the demand for new vehicles, both ICEs and BEVs, is much smaller. Hence, it was decided to determine how much was spent on production and R&D when the running year ends. This way, the demand for new vehicles is known, while the production cost has already been calculated, see 6.2.3. The production budget or the amount of money that was spent during the previous year of the simulation is calculated in Eqs. (9) - (11).

$$\text{ICE production budget} = \text{ICE production cost} * \text{ICE demand} \tag{9}$$

$$\text{BEV production budget} = \text{BEV production cost} * \text{BEV demand} \tag{10}$$

$$\text{Production budget} = \text{ICE production budget} + \text{BEV production budget} \tag{11}$$

As far as the profits of the OEMs are concerned, they are calculated according to the production cost, the sales price and the possible fine (see 6.2.4) and subsidies that the OEMs receive. If the user selects a purchase bonus to be given to the consumer, the purchase price for the consumer is decreased, while the government gives that amount of money back to the OEMs. In the Eqs. (12) - (16),

$$\text{Profit of one ICE} = \text{ICE sales price} - \text{ICE production cost} \tag{12}$$

$$\text{Total ICE profit} = \text{Profit of one ICE} * \text{ICE demand} \tag{13}$$

$$\text{Profit of one BEV} = \text{BEV sales price} - \text{BEV production cost} + \text{Purchase Bonus} \tag{14}$$

Total BEV profit = Profit of one BEV * BEV demand (15)

Total profit = Total ICE profit + Total BEV profit – EU fine (16)

Regarding the R&D investments, according to S. Schwartz [181] and [182], it was found that the R&D expenses for Tesla are about 6% of the total revenues. Hence, that percentage was considered for the other OEMs, too, as no accurate enough literature was able to be found in the literature. What was found was the amount of money that is spent, on average, for each vehicle [183]. Though, this would be very difficult to quantify it due to the microworld of the simulation.

Collection of profits (t) = Total profit (t) + Collection of profits (t-1) (17)

R&D budget = 6% * Collection of profits (t) (18)

Total investment = Production budget + R&D budget (19)

In Figure 23, a schematic representation of the timeline, under which the OEM budgets and profits are calculated. As has been mentioned, the budgets and profits are calculated at the end of each running year for that year.

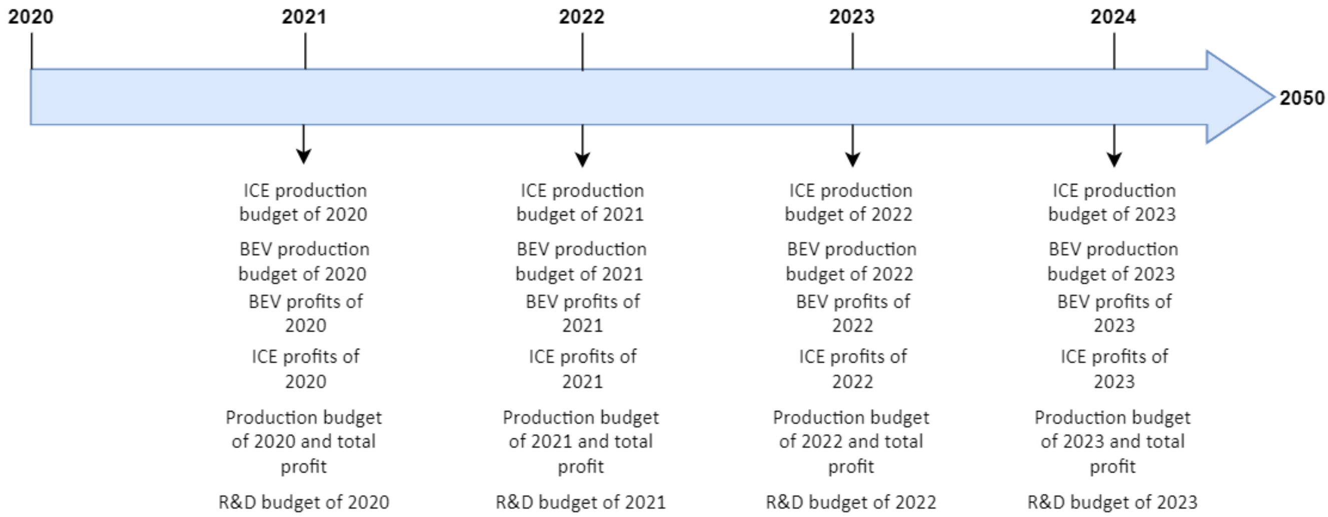


Figure 23. Schematic representation of the timeline, under which the OEM budgets and profits are calculated

Of course, production and R&D budgets are not the only budgets that an OEM invests money in. There are many departments in an automobile company, such as marketing, logistics, raw material suppliers etc. However, these two were considered as the most important ones for the current assignment, as the production determines the profits and the R&D determines the technical characteristics scores, as described above.

6.2.6 OEM scoring system for BEVs

The scoring system is used for the consumers to be able to judge and select, based on specific criteria, their preferred OEM and eventually their preferred vehicle. This system was implemented so that the search criteria, under which a consumer searches for a vehicle to buy, to be expanded. This comes in accordance with the limitations of the original version of the model that have been described in Section

5.2. In the original version of the model, the consumers were able to select a vehicle based only on financial criteria. First, they were looking for cars that they were able to purchase and maintain and later on, they were selecting the cheapest vehicle.

6.2.6.1 Consumer relative weights

The first step for the new approach was to select some characteristics that will be attributed to the consumers in the form of relative weights. The ones selected were chosen based on Figure 24, which comes from a transnational survey in the Netherlands that was executed within the "proEME Project" [184]. As can be observed, the primary attribute that people consider before buying an EV is the purchase cost by far, with the range of the electric vehicle coming second. Next with relatively same percentages, operational costs, model diversity, driving economy etc., are found.

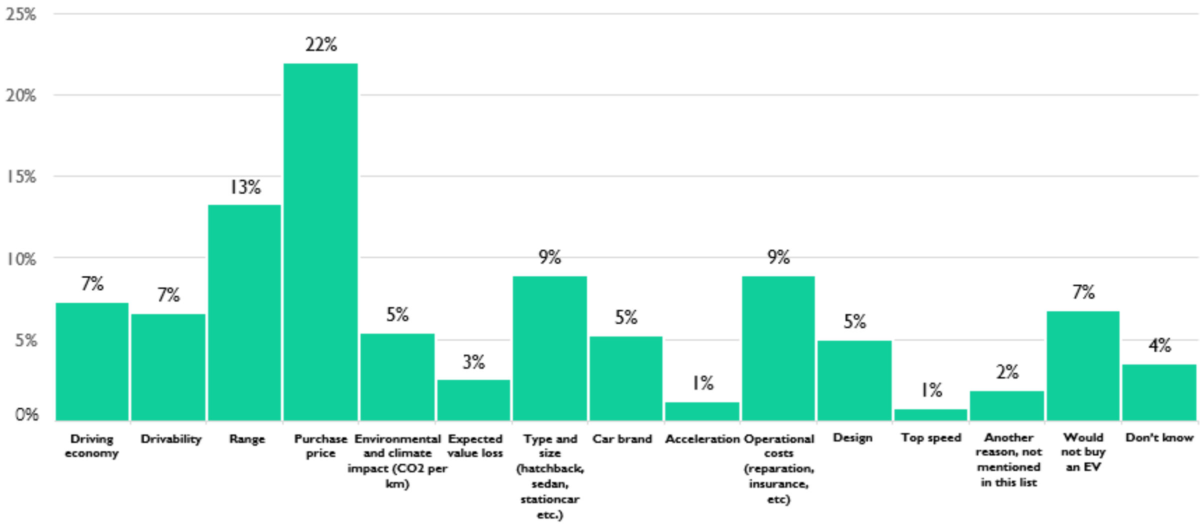


Figure 24. Factors that potential consumers consider before buying an EV in the Netherlands [184]

Although the financial part of the vehicle is already covered during the decision-making process (see, for example, Figure 31), there are still those who insist on concentrating on the economy of the BEV. Therefore, maintenance costs, as part of the operational costs, were selected as the first attribute for the consumers. In the model, the monthly costs of a vehicle are calculated as a function of fixed and variable costs, as presented by Eqs. (20)-(22). As can be seen by these equations, the only factor that is directly related with the OEMs is the maintenance costs. This can be clearer explained by the MEB platform of VW and the reduced maintenance costs that are expected [40]. On the other hand, the rest of the described factors are mostly government-related or have to do with the driving behaviour of each consumer. Therefore, more attention was given to the maintenance costs.

$$\text{Total monthly cost} = \text{Fixed monthly cost} + \text{Variable monthly cost} \tag{20}$$

$$\text{Fixed monthly cost} = \text{Monthly tax cost} + \text{monthly insurance cost} + \text{monthly maintenance cost} - \text{Operational incentive} \tag{21}$$

$$\text{Variable monthly cost} = \text{Monthly energy cost} + \text{Monthly depreciation} \tag{22}$$

Range is another one that could not be missing from the distributed relative weights due to the high place it has in Figure 24. Finally, model diversity is the last one that was chosen. Model diversity can be translated as different types and sizes of the vehicle (hatchback, sedan etc), as well as varying designs. Another reason that these three attributes were selected is that they are linked with the technical characteristics of an EV. The range is linked with battery capacity, maintenance costs with standardized mechanisms, like the MEB platform of VW [41], while model diversity has to do with the number of BEV models that OEMs put on the market.

Hence, three relative weights are distributed to the consumers by the time the simulation starts running. Moreover, different cases were developed regarding the way the relative weights are distributed. The cases are presented with the form of radio buttons so that the user will have the opportunity to observe the dynamics behind the consumers' concerns. In Figure 25, the cases regarding the distribution of the mentioned relative weights are presented for a random consumer. The sum of the relative weights should be 1 and the values of each one of them depend on the option of the radio button. These are shown in Table 12.

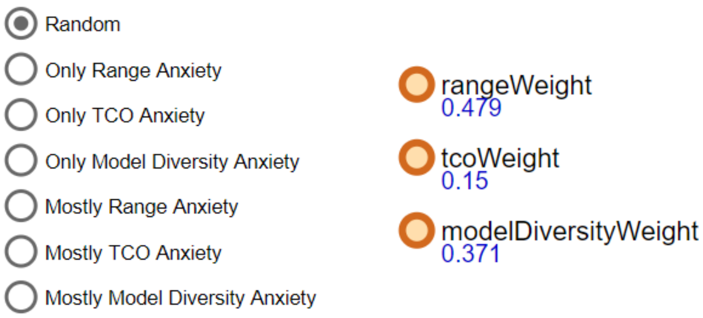


Figure 25. Relative weights distribution cases for a random consumer

Options / Attributes	Random	Only Range Anxiety	Only TCO Anxiety	Only Model Diversity Anxiety	Mostly Range Anxiety	Mostly TCO Anxiety	Mostly Model Diversity Anxiety
Range	0-1	1	0	0	0.5-0.6	0.2-0.3	0.2-0.3
Maintenance	0-1	0	1	0	remainder	0.5-0.6	remainder
Model Diversity	0-1	0	0	1	0.2-0.3	remainder	0.5-0.6
Sum	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Table 12. Possible values for each of the relative weights' values

6.2.6.2 R&D technical characteristics

The higher the battery energy density is achieved, the higher the all-electric range an EV has [72]. The standardized mechanisms and, more importantly, the standardized platforms that are put on the market reduce the TCO, as they also require less routine maintenance [8], [63]. Evaluating the range of each selected vehicle, their maintenance costs and the future production plans regarding new BEVs, initial scores were given to each one of the OEMs. The scores of each attribute are presented in Appendices E and F, as well as the way they were calculated.

It was also assumed that when an OEM invests in battery energy density developments and standardized mechanisms, these characteristics are improved year by year. Moreover, the more money is invested, the more rapid these improvements will be achieved. Hence, two sliders have been added in the simulation so that the user will be able to choose what percentage of the OEM's R&D budget will be invested in each one of the two technical characteristics. The default values of the percentages are set based on the needs of each OEM, according to their pre-defined scores. For example, if VW's battery energy density does not provide adequate range but also has low TCO, more money will be invested in the battery energy density. In Figure 26, the sliders with the allocation of R&D budget are presented, determining, this way, the technical characteristics' scores of each OEM at random period of time. In Table 13, the relative weights of a random consumer are presented along with the OEM scores that are also displayed in Figure 26. The relative weights of this random consumer are multiplied with the OEM scores and, thus, a final score for each OEM is calculated.

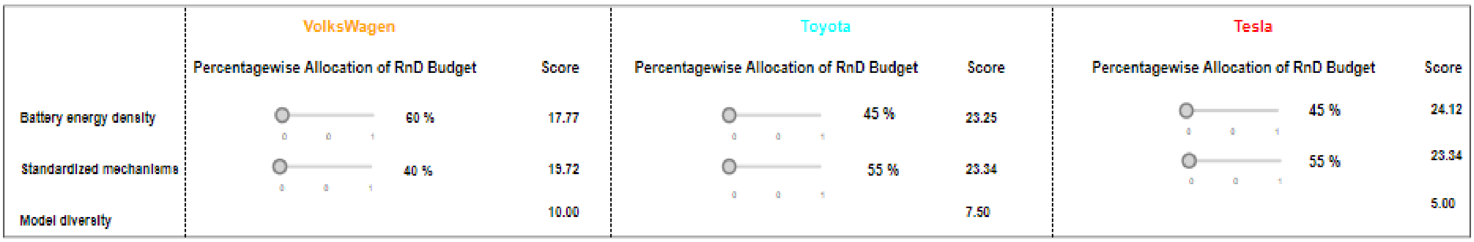


Figure 26. Allocation of R&D budget

Selected Consumer	Relative weights		OEM technical characteristics	VW	Toyota	Tesla
Range weight	0.573		**Battery energy density**	17.77	23.25	24.12
TCO weight	0.215		**Standardized mechanisms**	19.72	23.34	23.34
Model diversity weight	0.212		**Model diversity**	10	7.5	5
Final scores				**16.54**	**19.93**	**19.90**

Table 13. Example of a selected consumer with his own relative weights

As can be seen from Table 13, Toyota has the highest score for this consumer with 19.93 points. The result is also shown in Figure 27, as displayed within the simulation.

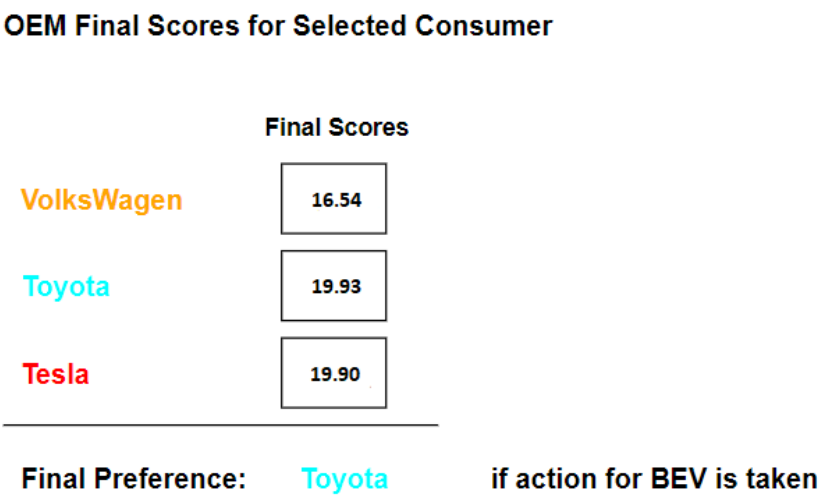


Figure 27. Final scores of a random consumer

6.2.7 Searching for a vehicle

In this subsection, the code behind the process of consumers searching for a vehicle is analysed, along with the differences with the original version of the model. The consumer searches a vehicle based on his intention to buy a vehicle. There are two kinds of intentions, “Intention to buy an ICE” and “Intention to buy a BEV”. The two described intentions are calculated based on three decision-making factors, which are also weighted based on user preferences.

1. **Personal EV Attitude**

The Personal BEV attitude is distributed randomly among the people living in the simulation with a score between 0 and 1. This BEV attitude grows gradually over time and the ICE attitude is the inverse number of the BEV attitude.

2. **Societal BEV Attitude**

Societal BEV attitude is the average of the Personal BEV attitude of all the people of the simulation. The societal ICE attitude is also the inverse of the societal BEV attitude.

3. **Behavioural Control**

Behavioural control consists of three other factors: whether or not a potential consumer is “purchase- and TCO-fit” for the available vehicles, and whether or not a zero-emission zone has been implemented. By the term “purchase and TCO-fit” it is meant that the potential consumer has the required budget to purchase the vehicle and take care of its operational cost, respectively. These two factors are determined by looking at which portion of available vehicles fit the financial requirements of the consumer and each one of them get a value from 0 to 1. Regarding the last one, this factor is 0 if a zero-emission zone is active and 1 if it is not. Finally, the three factors are also weighted individually based on the user. Hence, the final value of the Behavioural Control results in being from 0 to 1.

The three decision making factors are summed based also on the relative weights of each consumer and a total score is calculated that reflects the intention of a consumer buying a vehicle. If the intention of each powertrain is larger than 0.5, then the potential consumer has a positive intention over that vehicle with that powertrain. In Figure 28, an example is presented with the decision-making factors, which are weighted based on the user preferences. As can be seen, the total score for both BEVs and ICEs is greater than 0.5 and, eventually, the intention of this random consumer is positive to buy any of these vehicles.

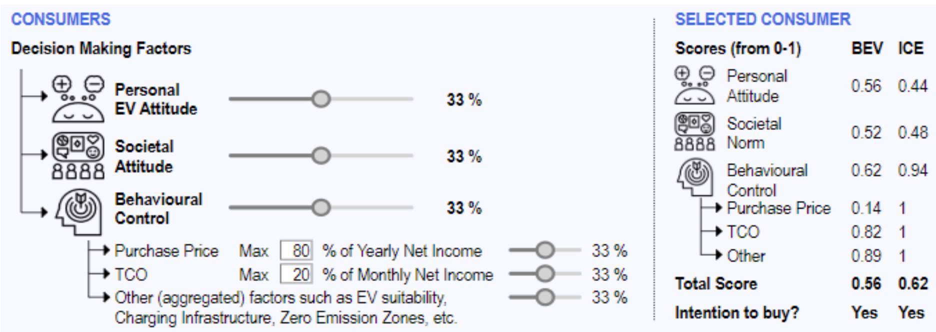


Figure 28. Decision making factors and intention of a random consumer buying a vehicle

6.2.7.1 The original version of the model

The original version of the model follows a different approach regarding the intention of buying an ICE/BEV compared to the new one. In the original version, by the time the potential consumer wants a vehicle, either a new one or a replacement one, depending on his intention to buy an ICE or BEV, he will select the cheapest vehicle.

This is also one of the limitations of the original version of the model that was addressed in section 5.2, as there may be consumers that want a more expensive vehicle. Since they have already checked if they can purchase or maintain the potential cars based on their income and the vehicle characteristics, nothing is preventing them from choosing any vehicle, powertrain-based, they want. In Figure 29, the whole process of the consumer searching a vehicle is presented as it has been coded in the original version of the model.

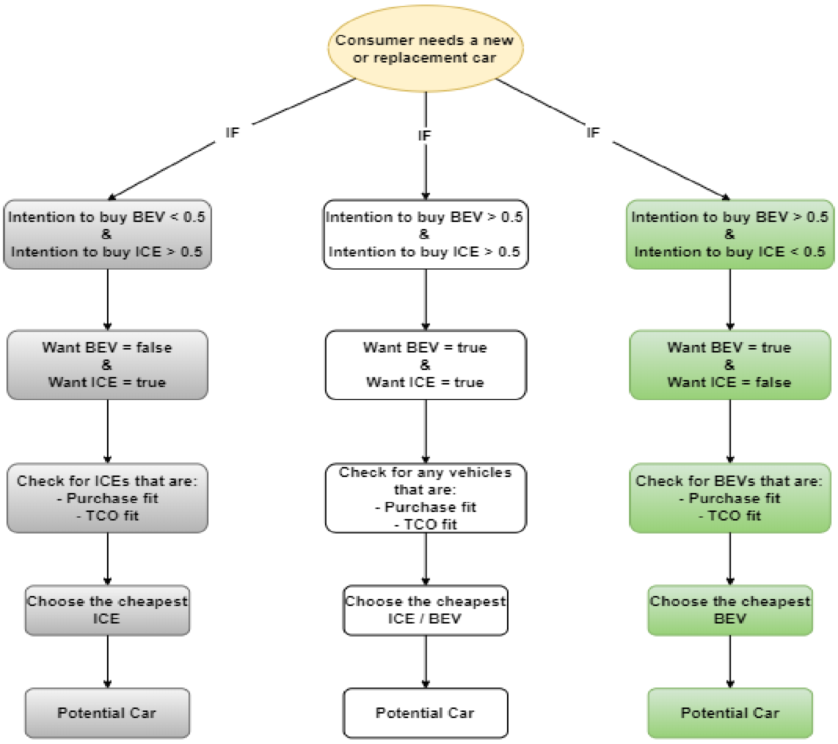


Figure 29. Process of a consumer searching a vehicle based on the original version of the model

6.2.7.2 The current version of the model

As far as the current version of the model is concerned, some modifications were made. The new approach that was followed is displayed in Figure 30 and Figure 31 where the way that the consumer chooses a potential vehicle to buy is described schematically. In Figure 30, two different cases are described; the first one (left) is the case, where the consumer intents to buy just an ICE and the second one just a BEV. These changes were based on the limitations of the model that have been described in Section 5.2 and are intended to improve the quality of the original version of "Adam & EV".

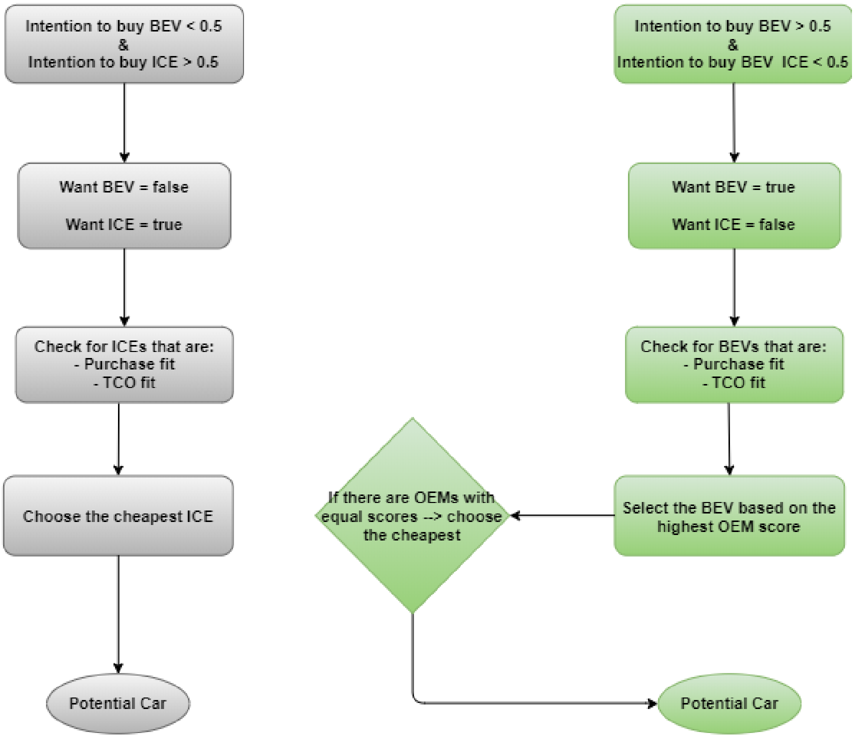


Figure 30. Schematic representation of a consumer searching just an ICE (left) and just a BEV (right)

More specifically, when a consumer intends to buy just ICEs, he follows the same approach with the original version of the model. After he checks all of the ICE vehicles that he can purchase and maintain, he chooses the cheapest one.

Regarding the second case and when the consumer intends to buy just a BEV, a new approach is followed. The consumer first checks the BEVs that he can purchase and maintain. After that, he chooses to buy the vehicle that belongs to the OEM with the highest score. In the case that two or more OEMs have the same highest scores, he chooses the cheapest BEV. The method that was followed to determine the scores of each OEM over the years is presented in the next subsection.

In Figure 31, the consumer searches for any vehicles, ICEs and BEVs, as the intention for both powertrains is larger than 0.5. This case is divided into three subcases. If the intention of the consumer to buy a BEV is larger than the ICE's and also both of them are larger than 0.5, then the approach for the intention of BEVs that was mentioned above will be followed. On the other hand, if the ICE intention is larger the BEV's and both of them have an intention of larger than 0.5, the approach for the intention for the ICEs will be followed. Lastly, if both of the intentions are greater than 0.5 and also equal, the consumer will look for any vehicle, regarding the powertrain, and he will select the cheapest.

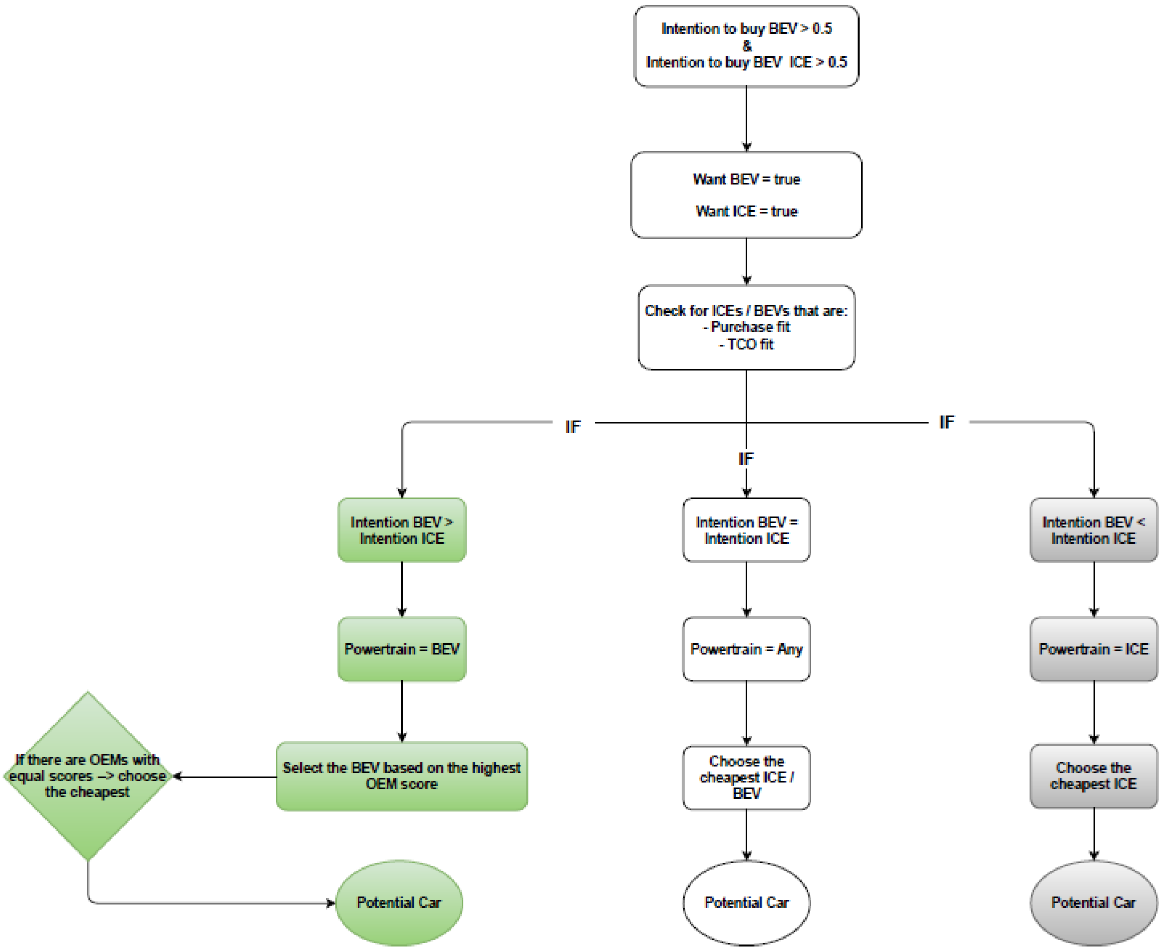


Figure 31. Schematic representation of the consumers searching both ICEs and BEVs

It is worth noticing that the values of the intentions of a consumer buying an ICE or BEV keep changing as the simulation runs. So, the vehicle that he will look for depends on the values of his intentions at the point of time he acts like buying a vehicle.

As far as the vehicles that are in stock, the potential consumer checks the OEM scores according to the year that they were manufactured. This happens due to the R&D developments that take place for each OEM that have as a result the increase of their technical characteristics' scores. Hence, when a vehicle is in stock because they remain unsold or they are considered as used, these vehicles have an age which is known. By looking at the OEM scores at the manufacturing year, the consumer can decide which vehicle he will choose. So, the same approach is followed as in Figure 30 and Figure 31, but this time the OEM scores are based on the manufacturing year of the unsold or used vehicle. This approach takes place if no potential car is found for the specific consumer as far as the new vehicles are concerned.

7. Verification of the model's behaviour

In this chapter, the verification of the model takes place. Several simulations are made by changing essential variables so that the relations and behaviour of the model to be explained. At the same time, the results are explained and whether or not they were expected. Through verification, it is confirmed if the relations described are correctly implemented concerning the conceptual model. Three cases were chosen so that the verification to be taken place. The cases were selected such that as many parts of the concept as possible to be verified regarding the EV and ICE subsystems. Hence, in the following sections, the concept map is presented for each case having highlighting elements, so that it will be clearer which parts are verified. In 7.1, the values of the relative weights have experimented through the options list that has been implemented and the results in the BEV/ICE sales are investigated. In 7.2, it is examined the impact that the percentagewise allocation of the R&D budget has on the consumers' OEM preference for the BEVs. Finally, the EU fines were decided to be examined concerning the relative weight's distribution option.

7.1 Consumers' relative weights

One of the most crucial, if not the most, parameter influencing the decision of a consumer selecting a BEV is the way the relative weights are distributed. As it will be explained later in this section and looking in Figure 32, depending on the consumers' factors that they find the most important, such as range, maintenance cost or model diversity, other factors are influenced, as well. The sales of each OEM depend on the consumers' preferences, as each OEM has vehicles with different technical characteristics and, eventually, the profits are influenced too.

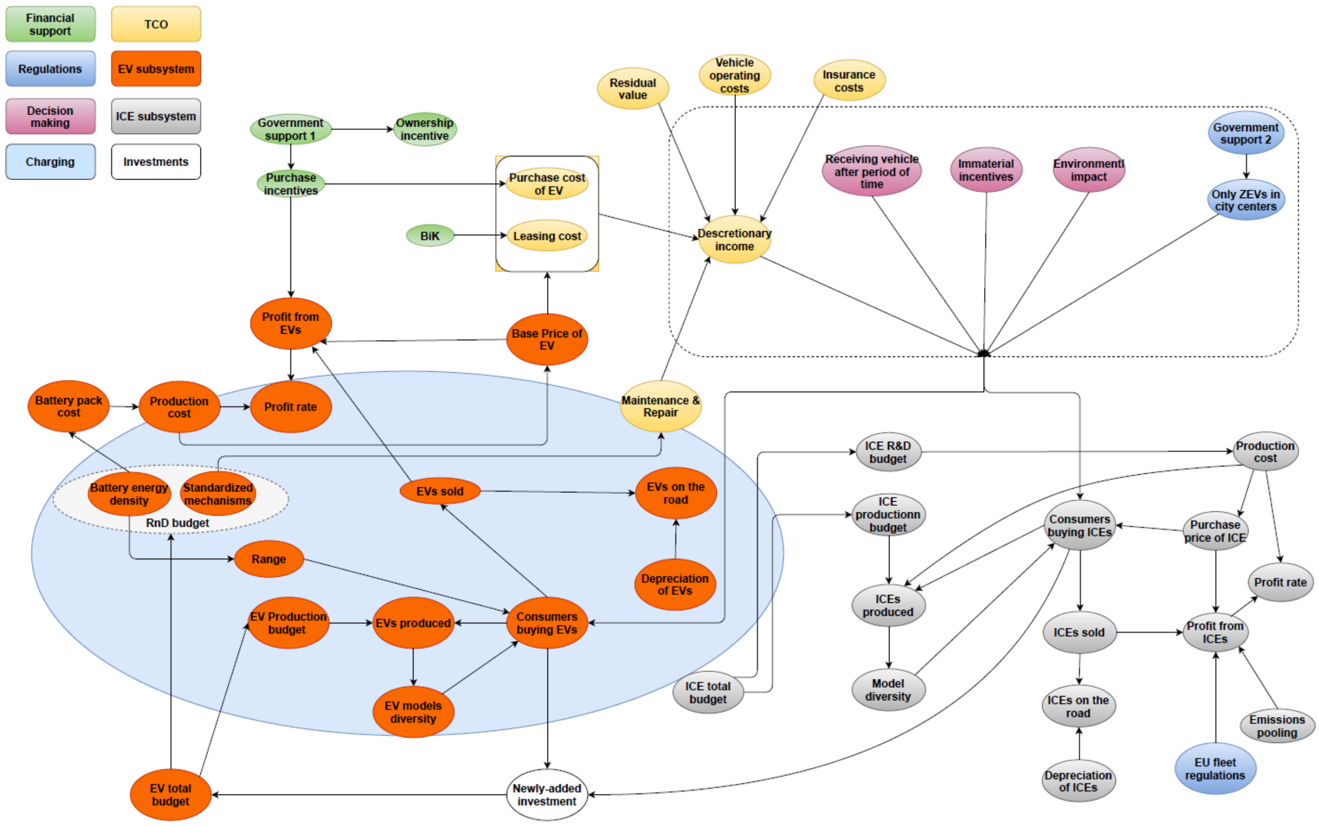


Figure 32. Concept map with highlighting elements for the verification of consumers' relative weights

There are many surveys regarding the factors that consumers consider before buying an EV. However, these can change over time or may not even be trustworthy to such a degree that these behaviours cannot be captured in a simulation model. This way, an option list was created, shown in Figure 25, with different options and behaviours. Choosing an option before the start of the simulation, different behaviours are set based on relative weights described in Table 12. The obtained results regarding the new vehicles sold per OEM and per powertrain are presented in Figure 33 - Figure 39, while keeping the allocation of R&D budget constant as presented in Table 14.

	Volkswagen [%]	Toyota [%]	Tesla [%]
Battery energy density	60	45	45
Standardized mechanisms	40	55	55

Table 14. Default values of percentagewise allocation of the R&D budget

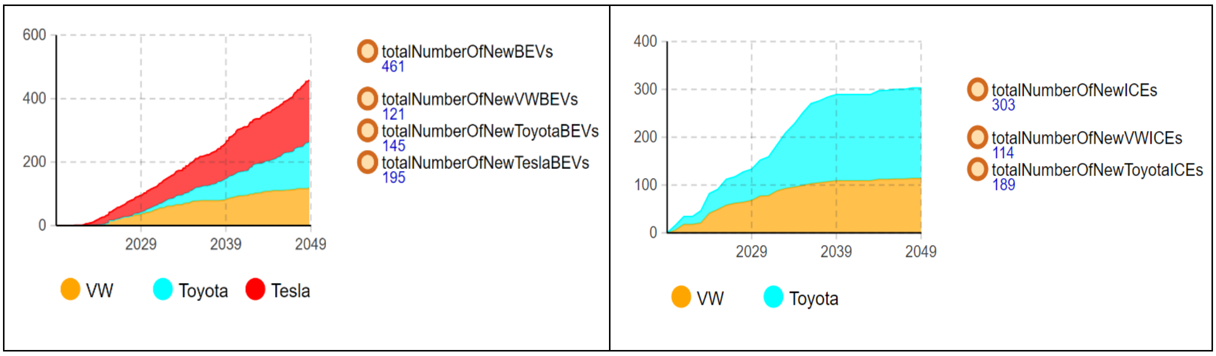


Figure 33. "Random" relative weight distribution – Cumulative sales of BEV/ICE vehicles

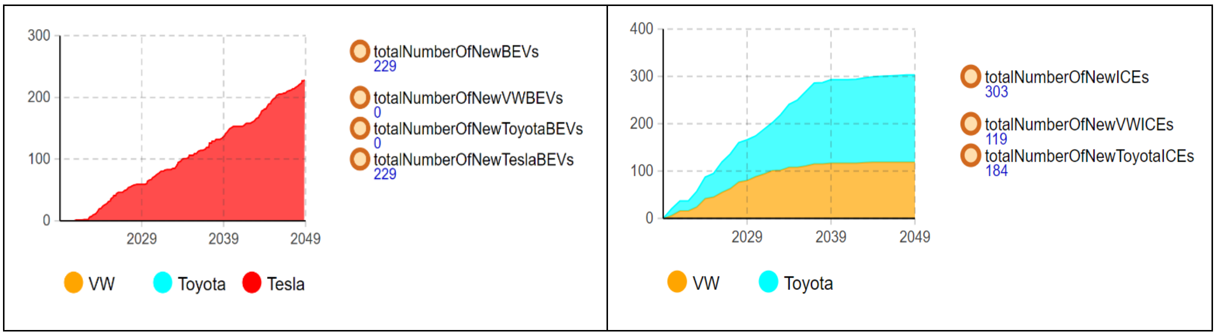


Figure 34. "Only range anxiety" relative weight distribution - Cumulative sales of BEV/ICE vehicles

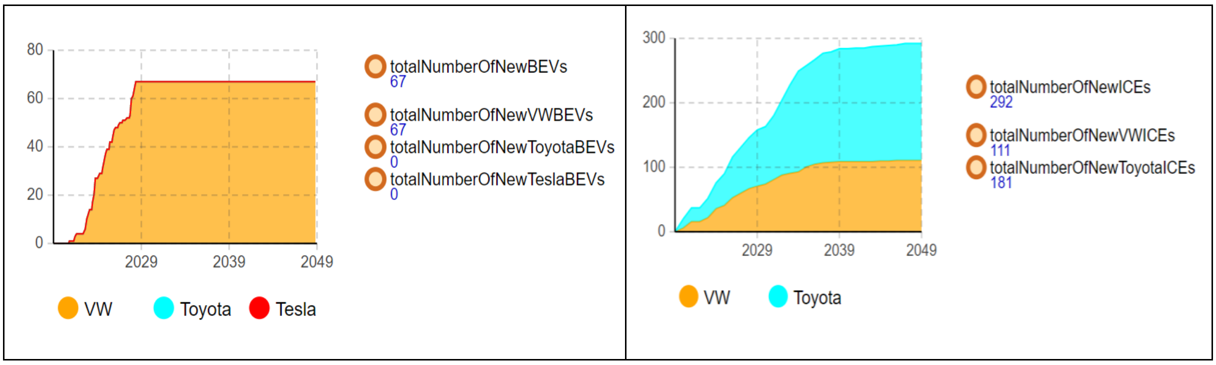


Figure 35. "Only TCO" relative weight distribution - Cumulative sales of BEV/ICE vehicles

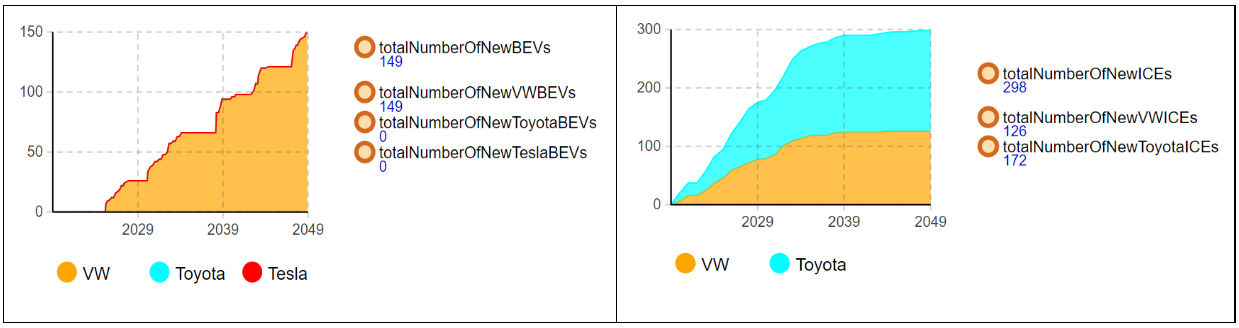


Figure 36. "Only model diversity" relative weight distribution - Cumulative sales of BEV/ICE vehicles

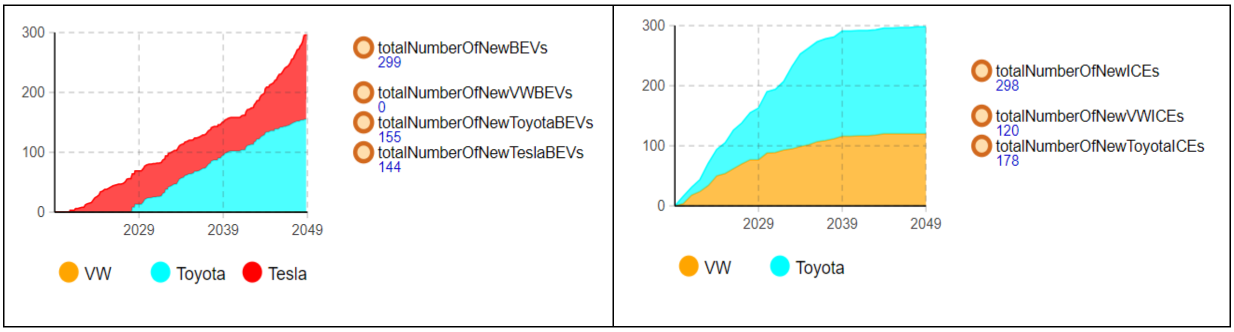


Figure 37. "Mostly range anxiety" relative weight distribution - Cumulative sales of BEV/ICE vehicles

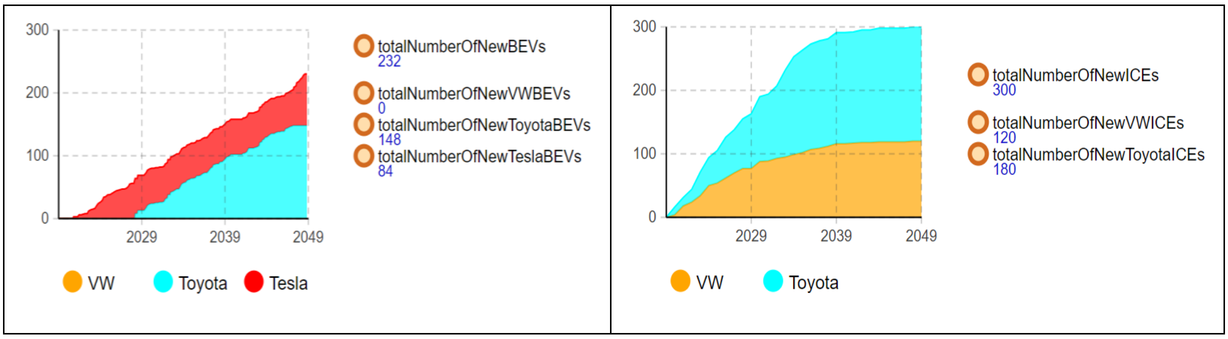


Figure 38. "Mostly TCO" relative weight distribution - Cumulative sales of BEV/ICE vehicles

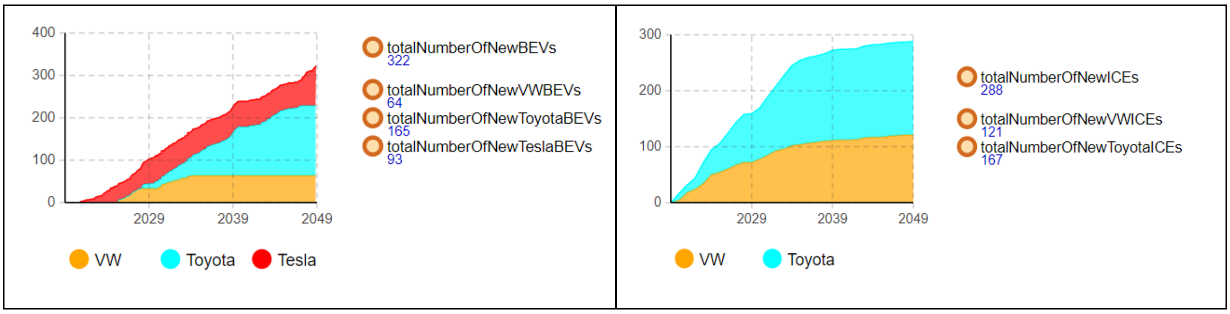


Figure 39. "Mostly model diversity" relative weight distribution - Cumulative sales of BEV/ICE vehicles

	VW BEV	Toyota BEV	Tesla	VW ICE	Toyota ICE
Random	121	145	195	114	189
Only range	0	0	229	119	184
Only TCO	67	0	0	111	181
Only model diversity	149	0	0	126	172
Mostly range	0	155	144	120	178
Mostly TCO	0	148	84	120	180
Mostly model diversity	64	165	93	121	167

Table 15. New BEV/ICE vehicles sold for every option of relative weight distribution

In the figures above, different cases are presented regarding the relative weights and the way they have been distributed. Figure 34 shows that just Tesla vehicles are sold, which makes sense since the relative weight of the consumers for the range of the vehicle is 1. The same stands for Figure 35 and Figure 36, where the consumers give "attention" just to TCO and model diversity, respectively. That is why there just consumers buying from VW and not the rest of the OEMs.

In Figure 38, the case, where more attention is given in TCO by consumers, is presented. Even though more VW sales would have been expected due to lower maintenance costs, this does not occur. Instead, Toyota and Tesla dominate. This is probably due to the OEM's R&D developments investing more in standardized mechanisms than VW does, as can also be seen in Table 14. Similar behaviour is presented in Figure 37, where Toyota and Tesla also dominate, something that makes sense since their battery energy density score is very close. Hence, the final score of each consumer depends on the exact values of the relative weights and the other attributes, as well.

Regarding the case where the distribution of the relative weight favours mostly model diversity, it can be observed that during almost all of the 30 years Toyota leads the market. This can be explained due to the models that Toyota puts on the market (for exact values look in Table 22 in Appendix E). Nevertheless, for this case, range and TCO anxiety are also weighted and that is why Toyota seems to have the most sales, as it has lower maintenance costs than Tesla's vehicle and higher range than VW's vehicle.

Finally, the outcome of the random distribution presented in Figure 33 on page 24 has to do mostly with the initial scores given as presented in Table 22 and Table 23 and the R&D developments. All of the OEMs increase their sales over the years because of the final scores being pretty close. In the end, Tesla ends up with the highest sales due to a higher range, improved TCO and not much less new BEV models.

For all of the cases, it can be noted that the sales of BEVs start growing after some years. This has to do, probably, with the intention of consumers buying a BEV. In 6.2.7.1 was mentioned that the BEV attitude and the BEV societal attitude grow over time. Hence, consumers buy only ICEs during that period.

Another result that needs to be pointed out is the few sales achieved by VW for the case of Figure 35. There are just 67 sales achieved during the first decade because people are interested only in TCO and which vehicle has the lowest maintenance costs. So, for the first ten years VW leads the market but after that, sales appear to stop. This can be explained due to the R&D developments that have been achieved by the other two OEMs having obtained higher score in standardized mechanisms. These OEMs, though, provide more expensive vehicles and the consumers in the model may not be able to purchase them, which can explain why the sales stopped occurring. Another reason why the sales stopped could be that the consumers could not find a BEV that would fit their financial requirements and they ended up buying an ICE vehicle.

The same can happen for the case of Figure 34, where the preference is only the Tesla vehicles. Tesla, though, is an expensive vehicle too. Hence, people with relatively low income will not buy a Tesla even though they want to. Hence, they will just have to wait until the price of Tesla will decrease and they are "purchase fit" and "TCO fit".

The results for the sales of the ICE vehicles are relatively the same. The algorithm regarding the consumers searching for a vehicle did not change to large degree compared to the original version of the model. The only change occurred at the point where a consumer searches for any vehicle. In this case, he will prefer a powertrain based on the highest intention. For all of the cases for new ICEs sold, Figure 33 - Figure 39, no sales are observed during the decade 2040-2050, which is expected due to high shares of BEV sales.

7.2 Allocation of the R&D budget

The percentagewise allocation of the R&D budget is another essential factor that can affect the final OEM preference of the consumers. By allocating the percentages of the technical characteristics that have been described and depending on their values, their individual scores will change more or less rapidly and, eventually, the final score. In Figure 40, the highlighting area of the concept map is presented that is about to be verified. Next, three test cases are presented with different R&D budgets keeping the relative weight distribution constant, choosing, for example, the "random" option.

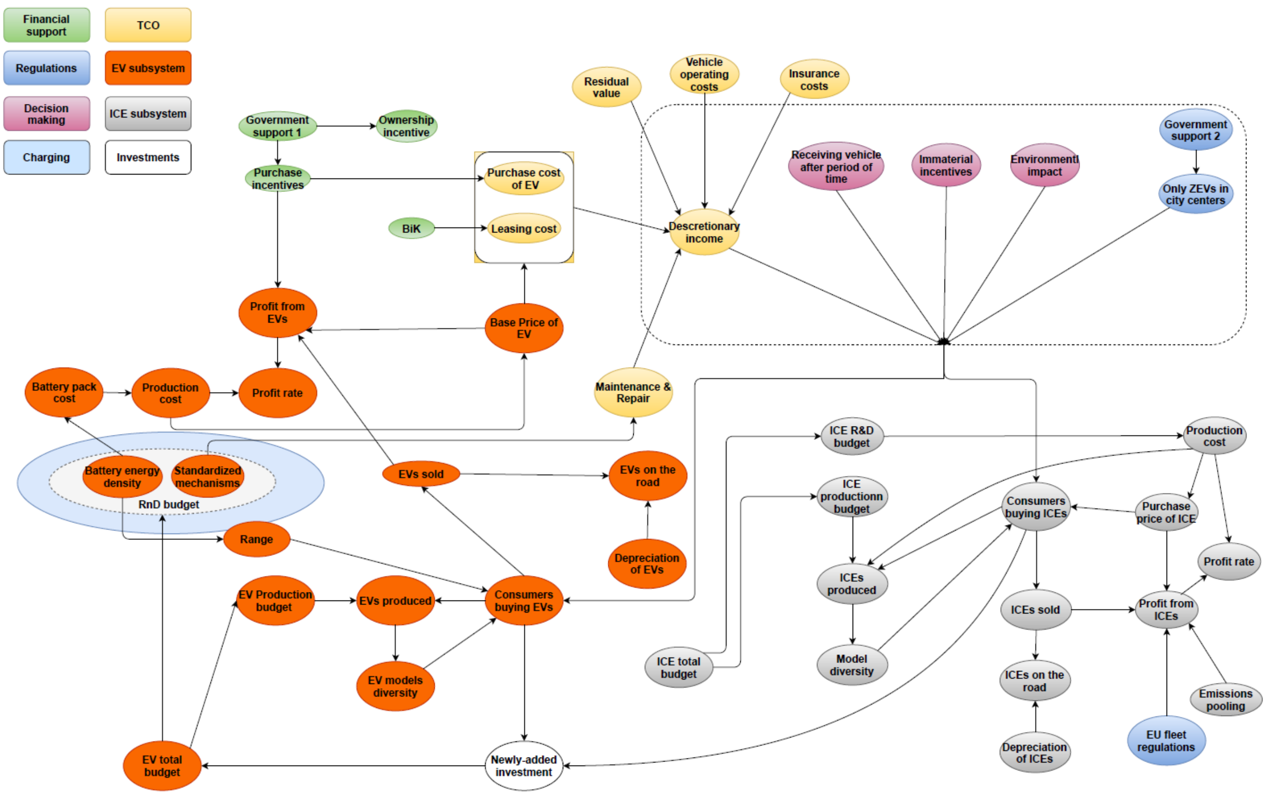


Figure 40. Concept map with highlighting elements for the verification of allocation of R&D budget

i. Volkswagen

By altering the VW's R&D budget, the changes in the sales of VW can be observed and, as a result, the changes in the rest of the sales. In Figure 41, the exact values of the R&D budget percentages are presented.

By the end of the simulation of the first test case, the model has been developed such that the sales of BEVs coming from VW would increase. The reason behind this logic is that the main differences among the OEMs are found in the battery energy density. Hence, by investing more in this kind of technology, higher individual scores are achieved, and eventually higher VW final scores. Indeed, in Figure 42, this is confirmed with the new BEVs coming from VW increasing by about 40 sales.

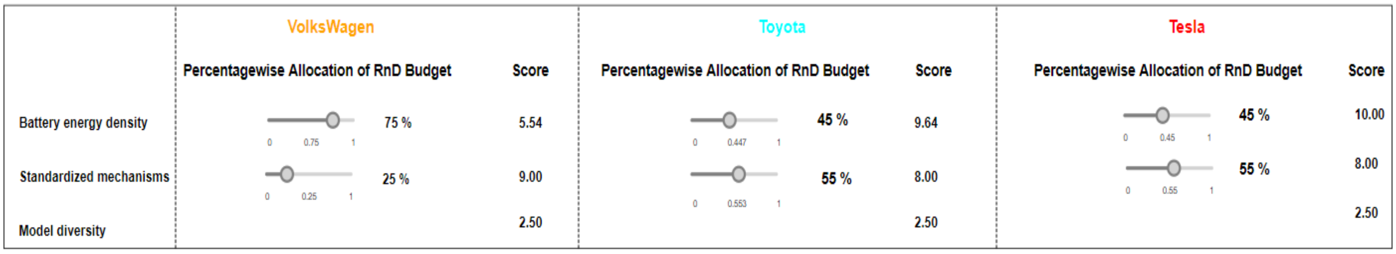


Figure 41. Volkswagen investing more in battery energy density technology

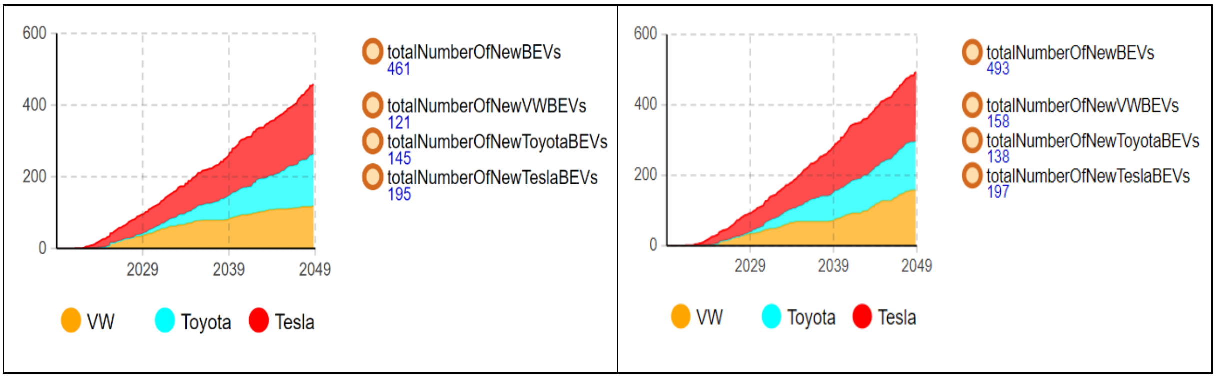


Figure 42. Cumulative sales of BEVs per OEM based on default R&D % allocation (left) and new R&D % allocation (right)

ii. Toyota

Following the same approach as with Volkswagen, the percentages of allocation of R&D budget was altered for Toyota and are presented in Figure 43. Similarly, with the first test case, the model has been developed such that Toyota sales will increase due to the higher individual score of battery energy density. Indeed, and by observing the results of the OEM sales in Figure 44, Toyota's BEV sales have increased, while Tesla's decreased.

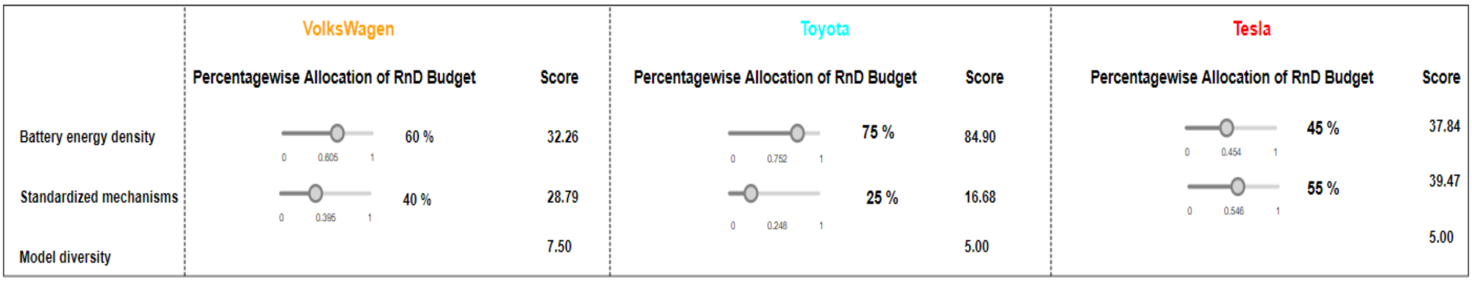


Figure 43. Toyota investing more in battery energy density technology

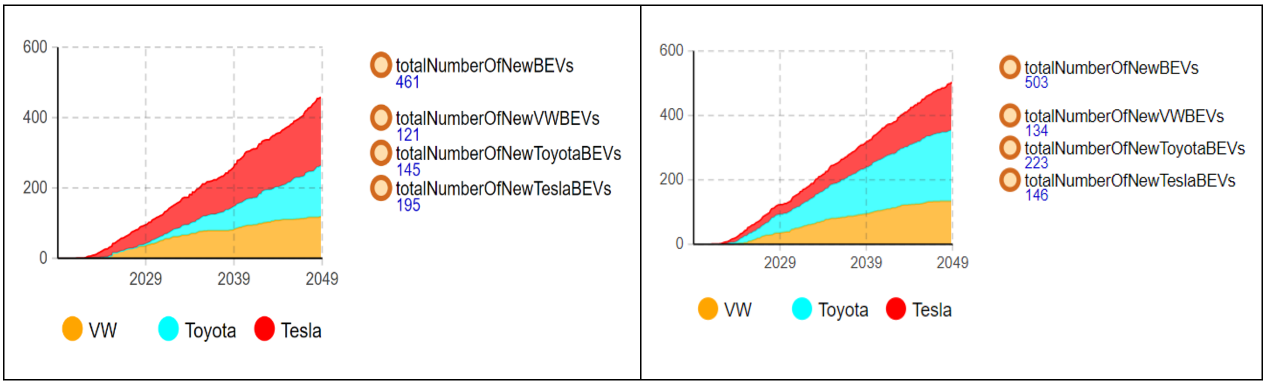
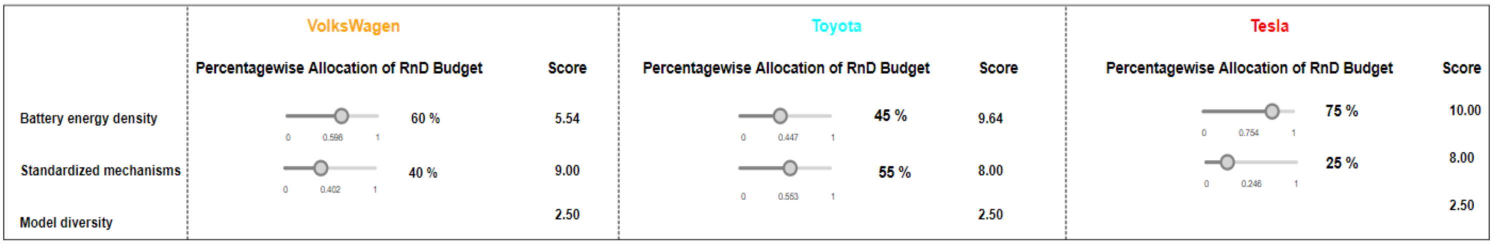


Figure 44. Cumulative sales of BEVs per OEM based on default R&D % allocation (left) and new R&D % allocation (right)

iii. Tesla

The last case to investigate is Tesla's percentagewise allocation of the R&D budget. In Figure 45, the percentages are shown, while in Figure 46, the final results are presented. As can be seen, the difference in Tesla's sales is not that apparent compared to the default case. This can be explained by the fact that Tesla had already higher battery energy density score (for exact values see Table 23 in Appendix F). Hence, by investing more in that sector would not have much impact in sales as it would continue having the highest score among the OEMs. On the other hand, Toyota's sales have had a significant increase which is explained by the investments that Toyota has made achieving, this way, high scores in both standardized mechanisms and battery energy density.



	VolksWagen		Toyota		Tesla	
	Percentagewise Allocation of RnD Budget	Score	Percentagewise Allocation of RnD Budget	Score	Percentagewise Allocation of RnD Budget	Score
Battery energy density	60 % (0.598)	5.54	45 % (0.447)	9.64	75 % (0.754)	10.00
Standardized mechanisms	40 % (0.402)	9.00	55 % (0.553)	8.00	25 % (0.246)	8.00
Model diversity		2.50		2.50		2.50

Figure 45. Tesla investing more in battery energy density technology

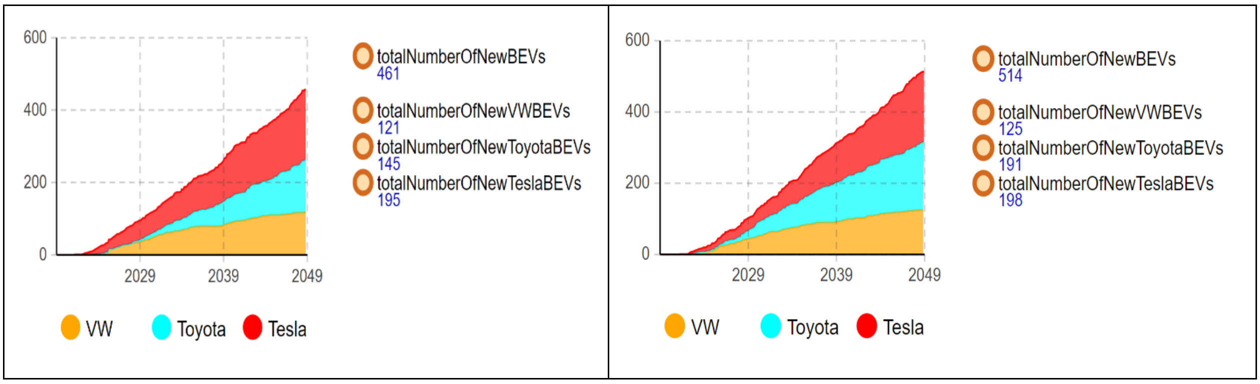


Figure 46. Cumulative sales of BEVs per OEM based on default R&D % allocation (left) and new R&D % allocation (right)

7.3 European Union fines

Modelling EU fines is also relevant factor that can influence the profits of the OEMs. As it has already been described in 6.2.4, the OEMs are subjected to fines if their share of new BEVs sold is under some thresholds. Hence it would be expected that when the sales of BEVs were low compared to the ICE's for the OEMs, then there would be fines that would decrease their total profits. In this section, the EU fines are verified. It was decided "extreme" scenarios to be investigated so that the differences in fines and sales to be more apparent. By extreme, it is meant that the BEV sales come from just one OEM. Of course, these scenarios are not realistic and serve but serve the purpose of the model's verification. Hence, three cases are examined below, for each OEM.

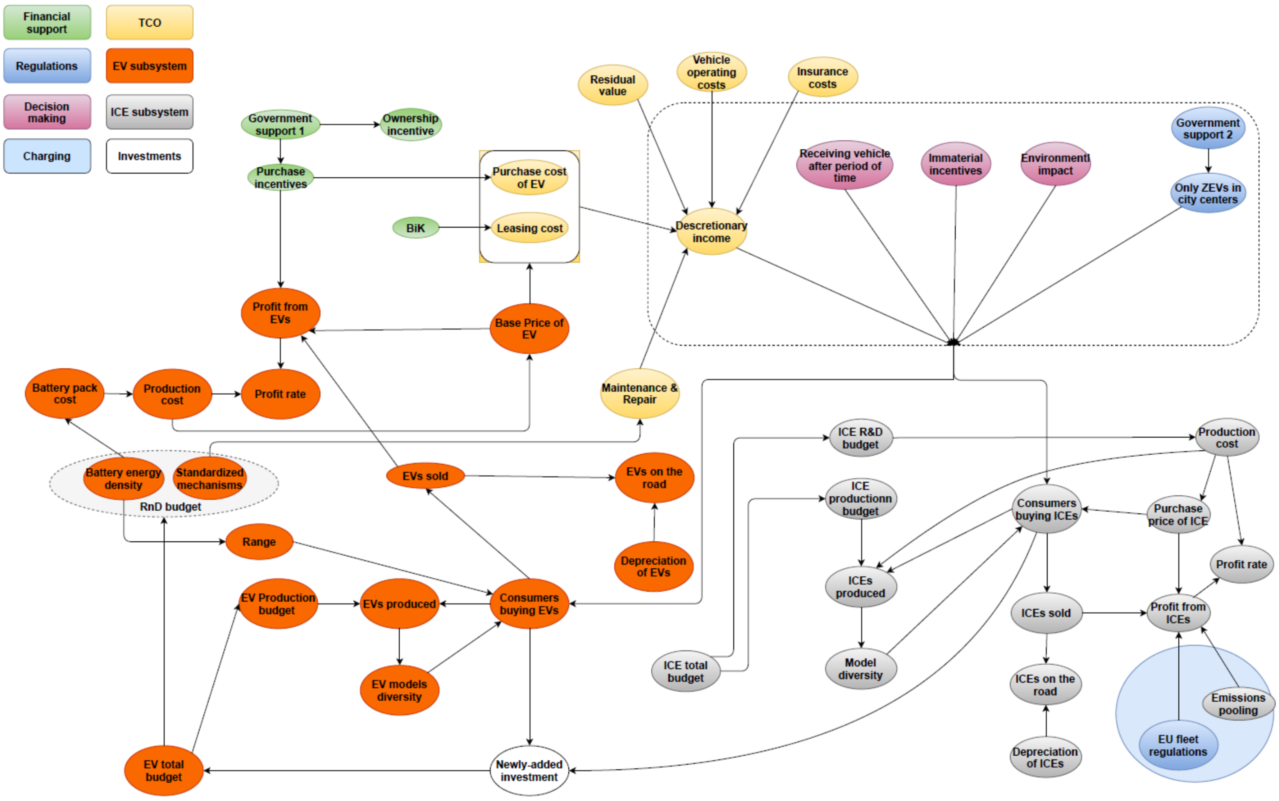


Figure 47. Concept map with highlighting elements for the verification of EU fines

i. Only VW BEV sales

In this case, all of the BEV sales that occur during the 30-year period of the simulation come from VW. This can be achieved by choosing the option "Only TCO Anxiety" and investing all of the R&D budget of VW in the standardized mechanisms. As can be seen by Figure 48, the only time that a fine is implemented to VW by EU is when no BEV sales have taken place at that year, compared to the ICE sales. On the other hand, Toyota get fines in most of the years due to the fact that they do not sell BEVs, but just ICE vehicles.

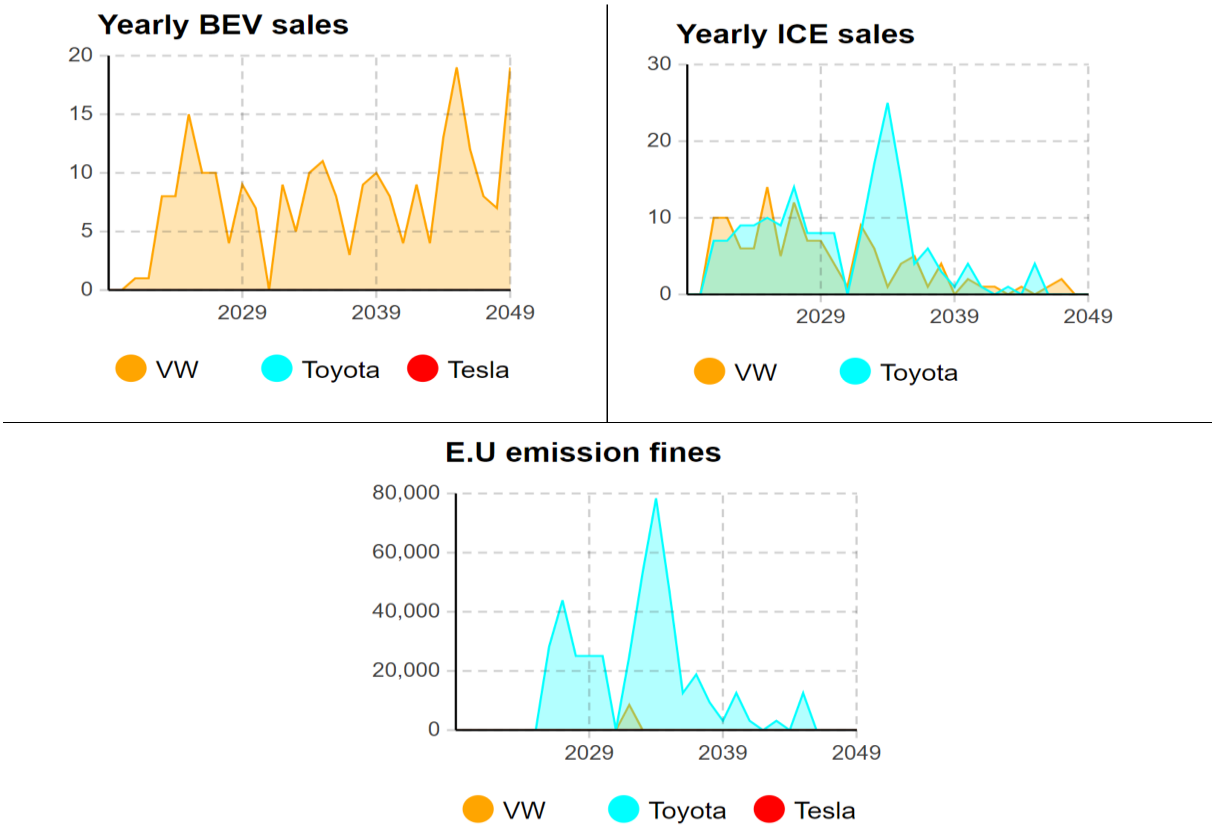


Figure 48. Yearly sales of BEV/ICE vehicles per OEM (up) and EU emission fines (down) when all of the BEV sales come from VW

ii. Only Toyota BEV sales

The second case that is examined is the scenario that all of the BEV sales come from Toyota, except from one sale taking place in the beginning of the model, as Tesla initially, has higher battery energy density score. This was achieved by selecting the option “Only range anxiety” and investing the total R&D budget of Toyota on the “Battery energy density”. This way, Toyota will always have the highest score among the three OEMs and will be consumers’ top preference. Hence, the variables of the model were set, this time, so that all of the BEV sales come from Toyota and there will be no EU fines in most years. The only case that there may be fines at some years is when Toyota’s ICE sales exceed the BEV’s in no small degree.

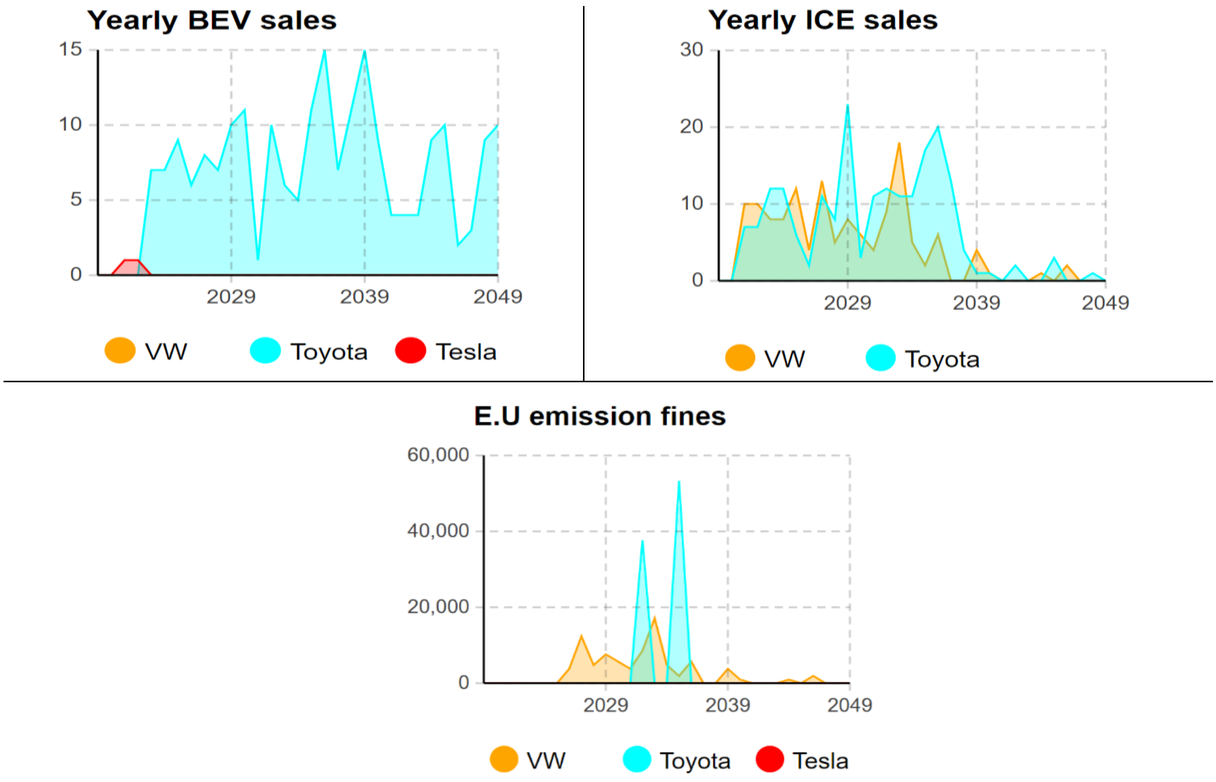


Figure 49. Yearly sales of BEV/ICE vehicles per OEM (up) and EU emission fines (down) when all of the BEV sales come from Toyota

Analysing Figure 49, it is confirmed that all of the BEV sales come from Toyota. At the same time, though, the sales of Toyota's ICE vehicles also increase. As far as the EU emission fines, it can be seen that they are occurred only in specific years, which is justified due to higher sales of ICEs at these specific years. On the other hand, since there are no VW BEV sales during the simulation, it is expected that VW will get fines for all of the running years. Indeed, looking in Figure 49, there are fines all over the years apart from the years that there are no ICE sales. A plateau of new ICE sales emerged during the last years of the simulation, justifying the no-fine incident for the final years. Finally, it should also be noted that the OEMs start getting fines from the EU after 2025 when this legislation will start being active, as described in 6.2.4.

iii. Only Tesla BEV sales

The second "extreme" scenario is the BEV sales coming just from Tesla. This is achieved by selecting the option "Only range anxiety" distribution. This way, VW and Toyota will only have profits from ICE sales, but it is also expected to receive significant fines for most of the years of the simulation. Just like in the first case, the only years that these two OEMs will not get a fine will be when they will not sell any ICE vehicles. Observing Figure 50, it is verified that because VW and Toyota do not have any BEV sales, fines are implemented by the EU after the year 2025. Moreover, as was mentioned, the only years that fines are not implemented are the years that no ICE sales take place, too, which is verified by the plateaus created in the ICE sales for both VW and Toyota.

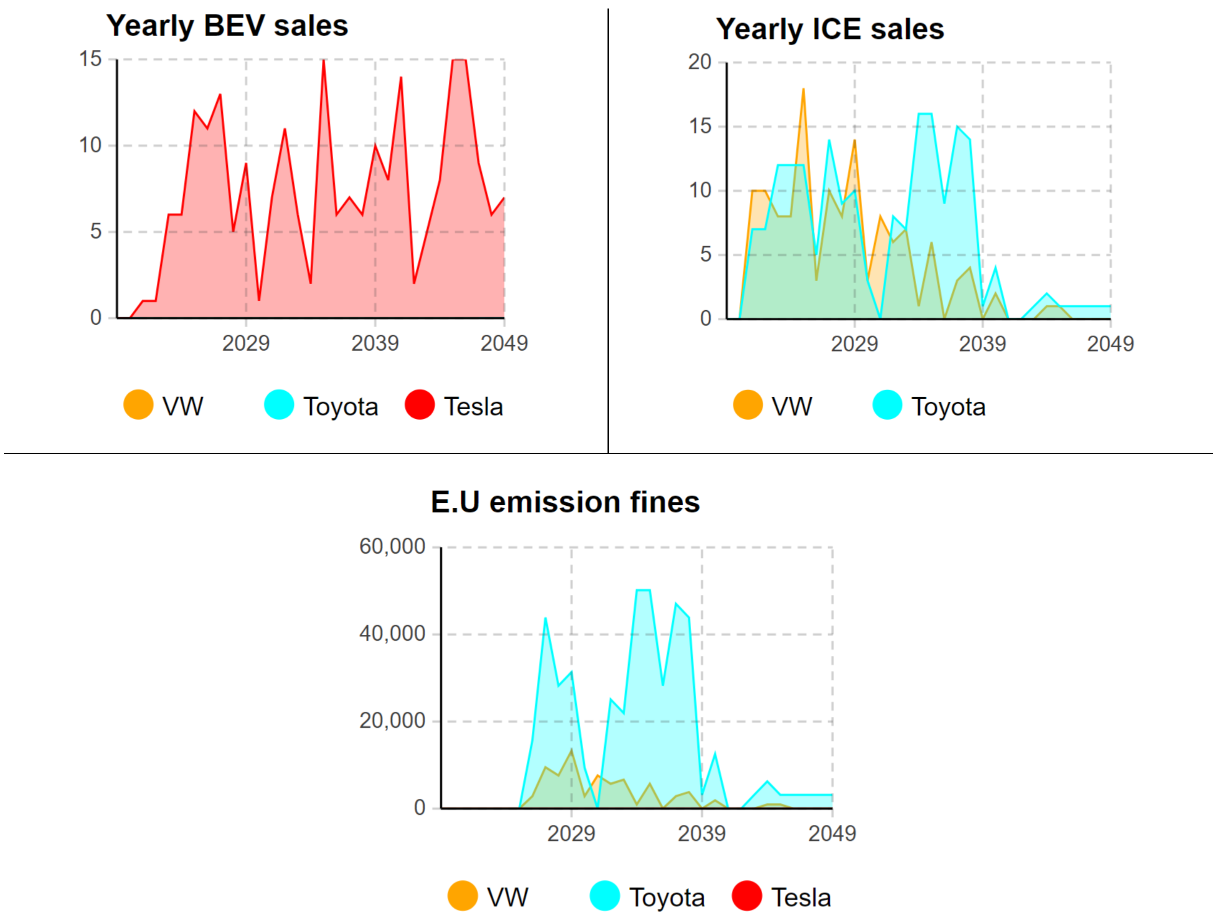


Figure 50. Yearly sales of BEV/ICE vehicles per OEM (up) and EU emission fines (down) when all of the BEV sales come from Tesla

7.4 OEM profits

By changing all of these variables and experimenting with the different options that are provided, the sales of each OEM are influenced and, hence, its profits. The profits of each OEM are linked with the ICE and BEV vehicles production and the sales price of the vehicles. All of these equations are described more thoroughly in 6.2.5. The same "extreme" scenarios will be investigated, but this time regarding the profits of the OEMs.

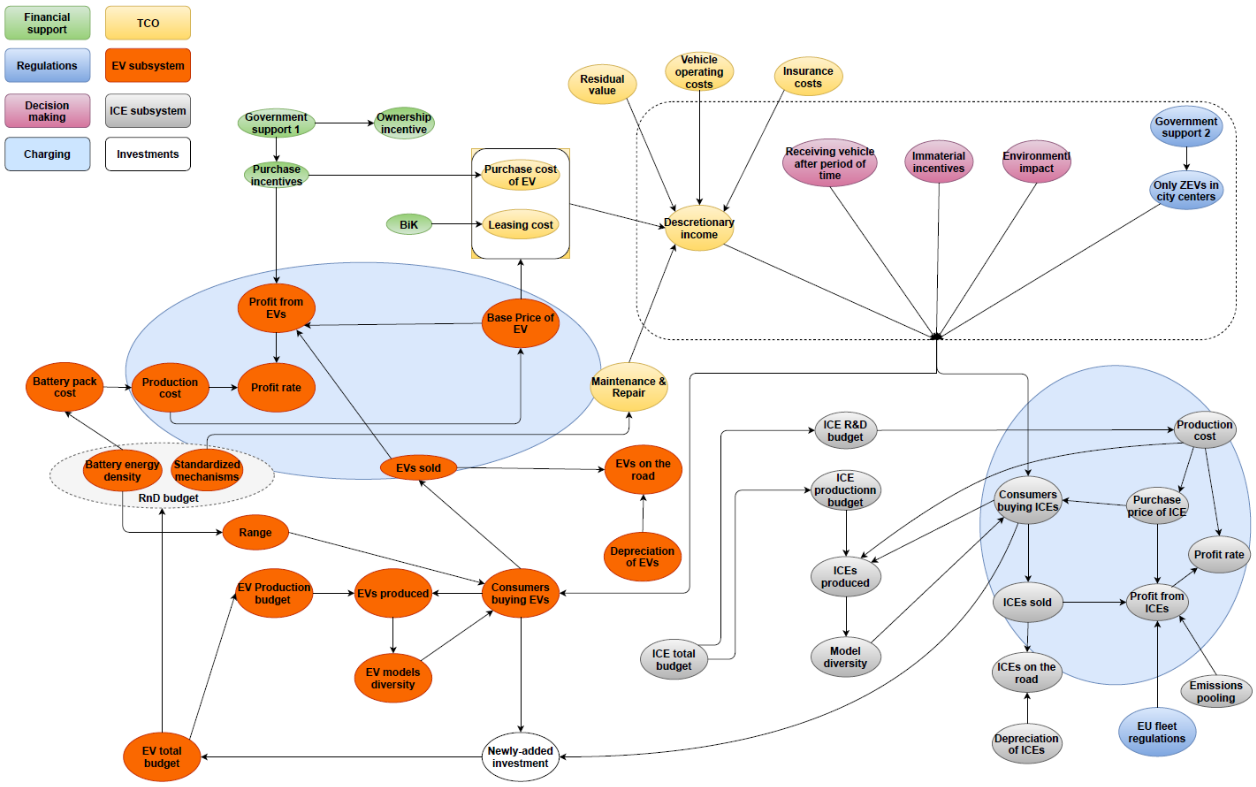
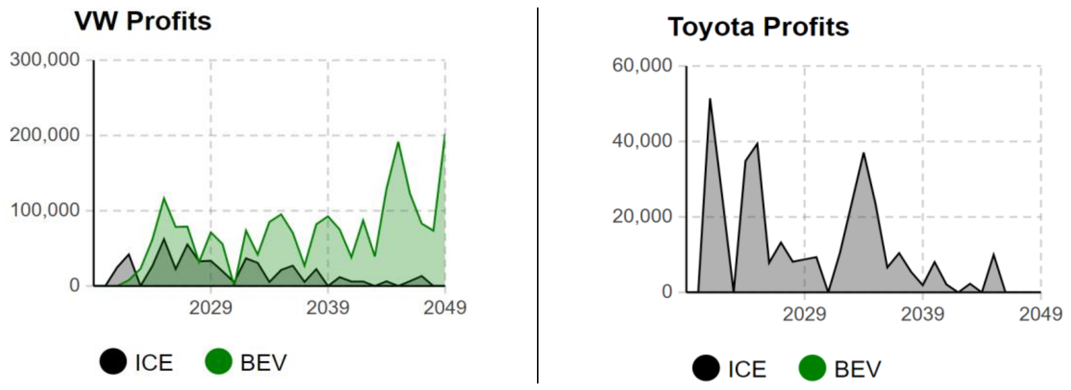


Figure 51. Concept map with highlighting elements for the verification of OEM profits

i. Only VW BEV sales

The first scenario that is under investigation is the case where the BEV sales come from just the VW. Indeed, analysing Figure 52 and the profits of each OEM per powertrain, it can be seen that VW has profits coming from both powertrains compared to Toyota. Toyota does not have any BEV sales and that is why all of its profits emerge from ICE vehicles.



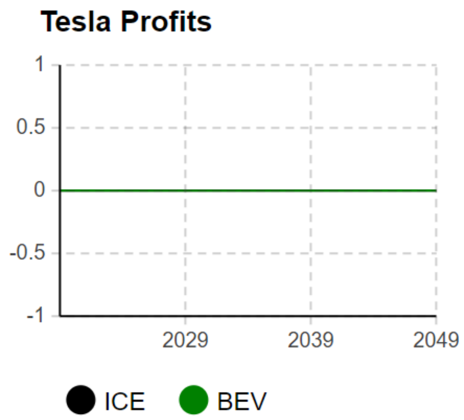


Figure 52. OEMs profits for both powertrains when there are only VW BEVs sales

In Figure 55, the average share of profits of the OEMs per powertrain are presented. As it would have been expected, the average share of BEV profit of VW increases due to the increase of sales of its BEVs. On the contrary, as it can be seen by Figure 52, the sales of the ICE vehicles have a slight decrease over the years resulting in decreasing average share of ICE profits.

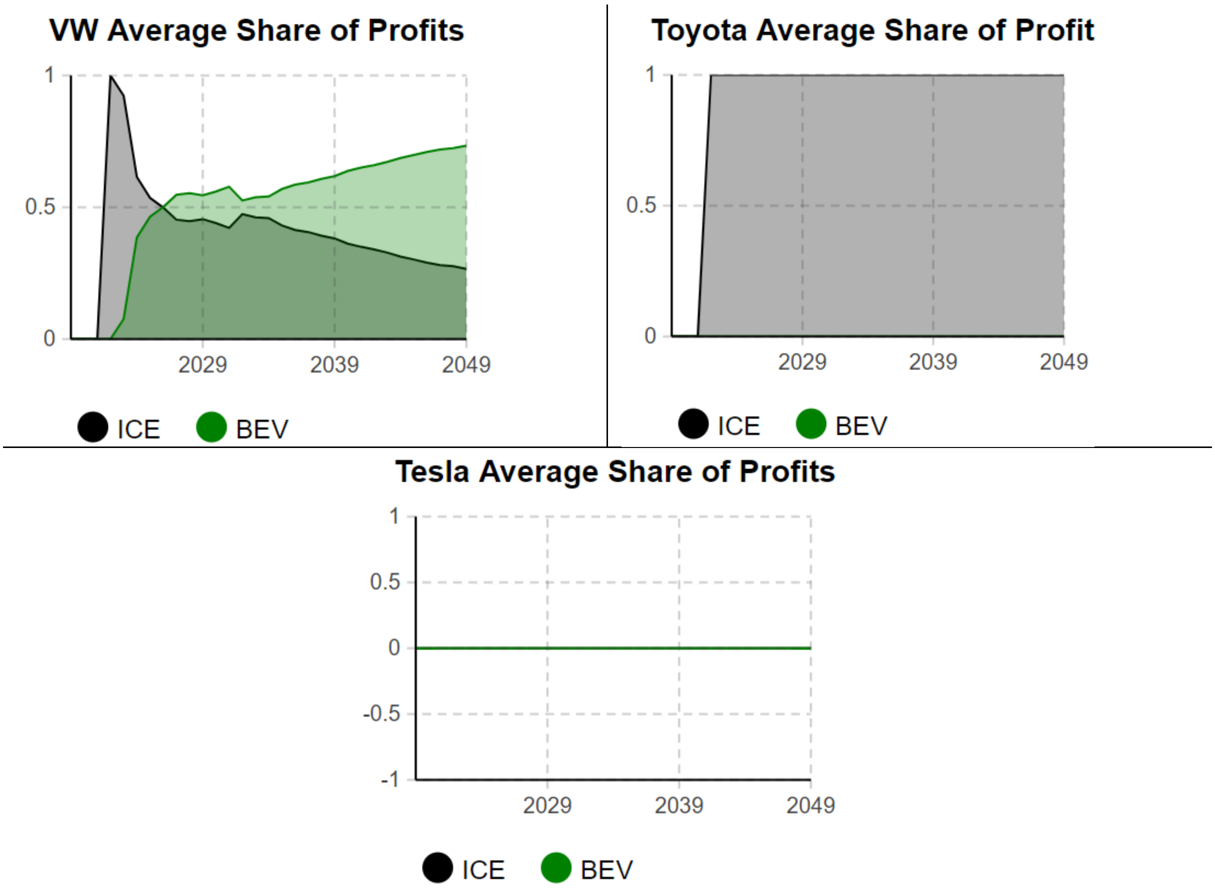


Figure 53. Average share of profits of the examined OEMs when there are only VW BEVs sales

ii. Only Toyota BEV sales

In Figure 49, the total sales of Toyota's ICEs and BEVs are presented with its corresponding EU fines. In Figure 54, the total profits are presented for each powertrain investigated, based on the scenario of just Toyota's BEV sales taking place. As far as Toyota is concerned, it can be seen that most of its profits come from BEVs sold, while a share in the profits have also the ICE vehicles as they keep getting sold, as well. VW, on the other hand, has no profits coming from BEVs, which makes sense since there are no BEVs sold from VW. Finally, Tesla has profits only from one sale that took place in the beginning of the simulation, as it has already been mentioned in Section 7.3. Finally, in order to give a more comprehensible overview, the average shares of profits of the OEMs are presented in Figure 55, where the profits of each OEM come from or which powertrain of each OEM is responsible for the profits in every year.

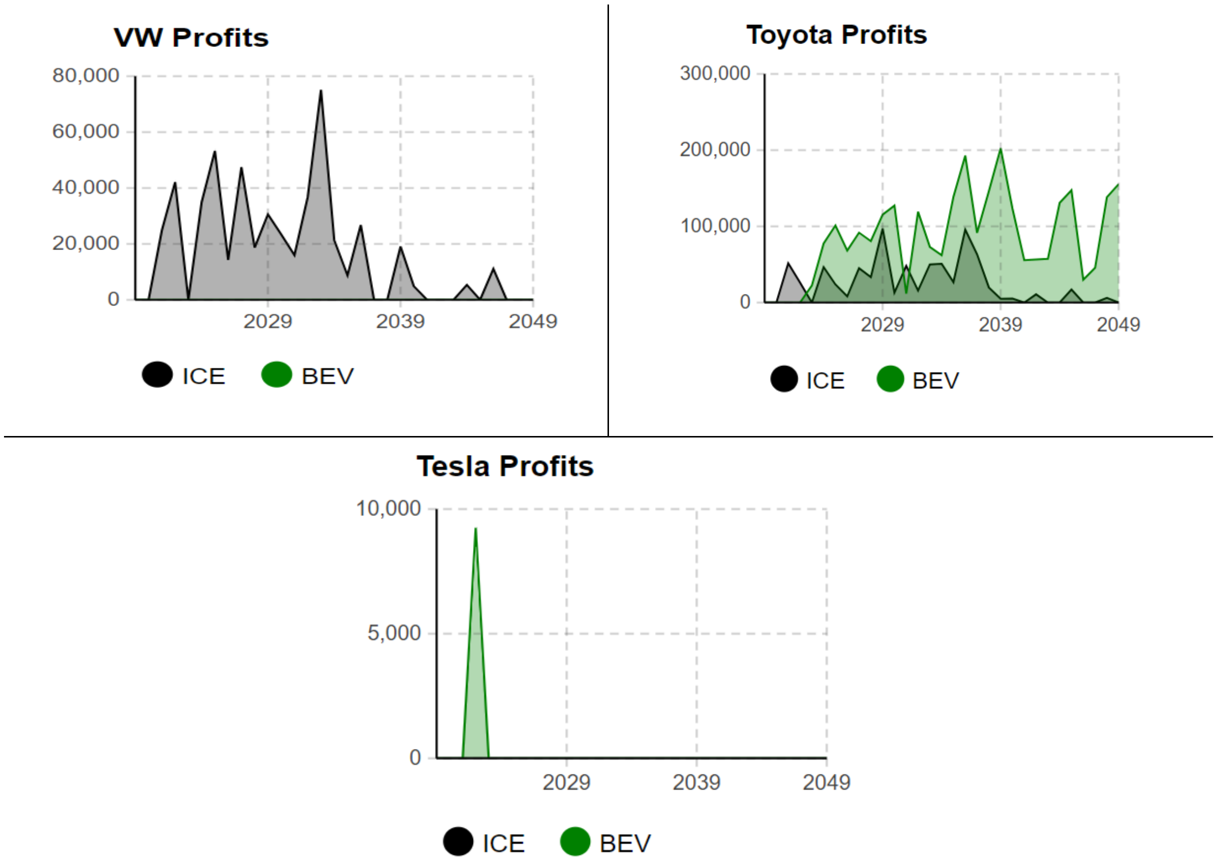
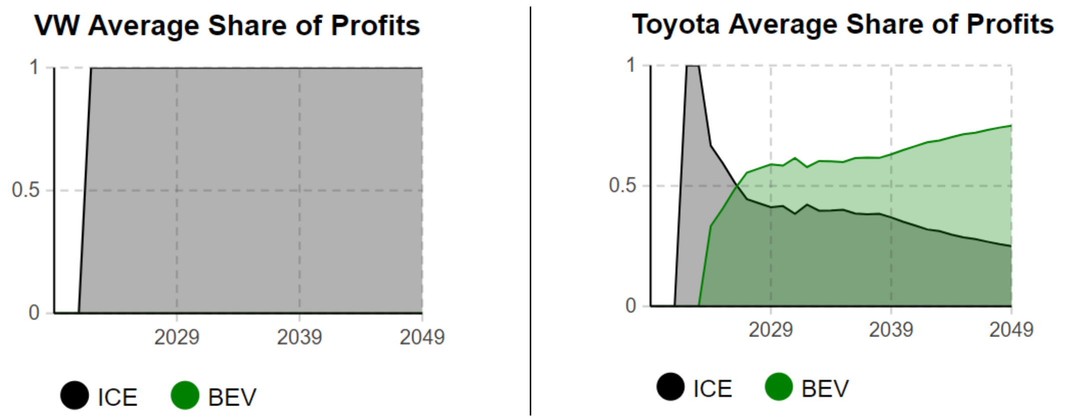


Figure 54. OEMs profits for both powertrains when there are only Toyota BEVs sales



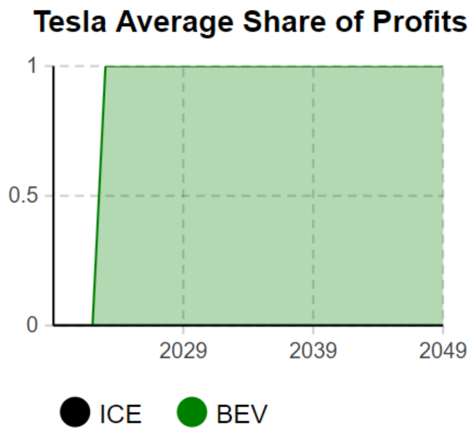


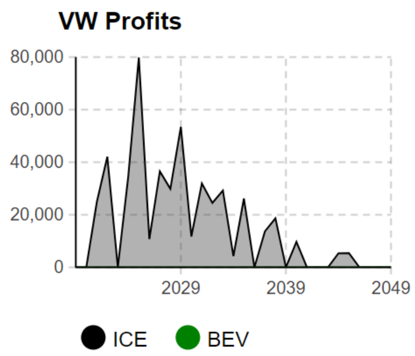
Figure 55. Average share of profits of the examined OEMs when there are only Toyota BEVs sales

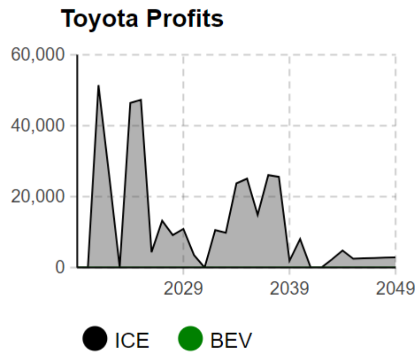
Tesla has an average share of profit of 100% because in order to calculate the share of profits all of the non-zero values had to be collected. Since, Tesla has made just one sale, according to the model, it has an average share of profit of 100%, even though after this first sale, it has not achieved more.

iii. Only Tesla BEV sales

As far as the second case is concerned, all of the BEV sales come from Tesla, as it can also be seen from Figure 50. Hence, it would be expected that since VW and Toyota have no BEV sales, all of their profits would come from ICE sales. On the other hand, since Tesla has many BEV sales, it would be expected to have high BEV profits.

Indeed, looking in Figure 56 and Figure 57, it is seen that the profits of VW and Toyota come from just ICE sales, while Tesla's only from BEVs. The years when there are no profits for VW and Toyota are the years when no sales take place in the simulation. In Figure 57, the average shares of profits for each OEM and per powertrain are presented. In this figure, just the years that sales have taken place are included and that is why no "gap" years are shown (when no sales take place). Hence, following the sales' results, the shares of profits for VW and Toyota are 100% for ICE sales for both OEMs, while for Tesla, which realizes just BEV sales, is 100% for BEV sales.





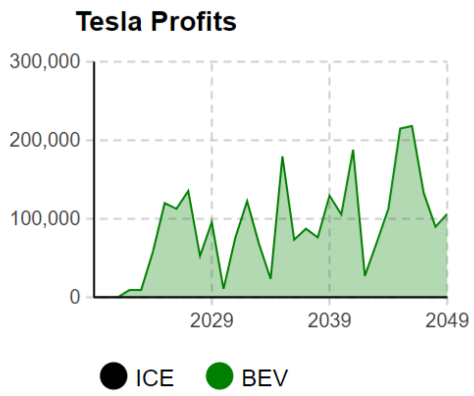


Figure 56. OEMs profits for both powertrains when there only Tesla BEV sales

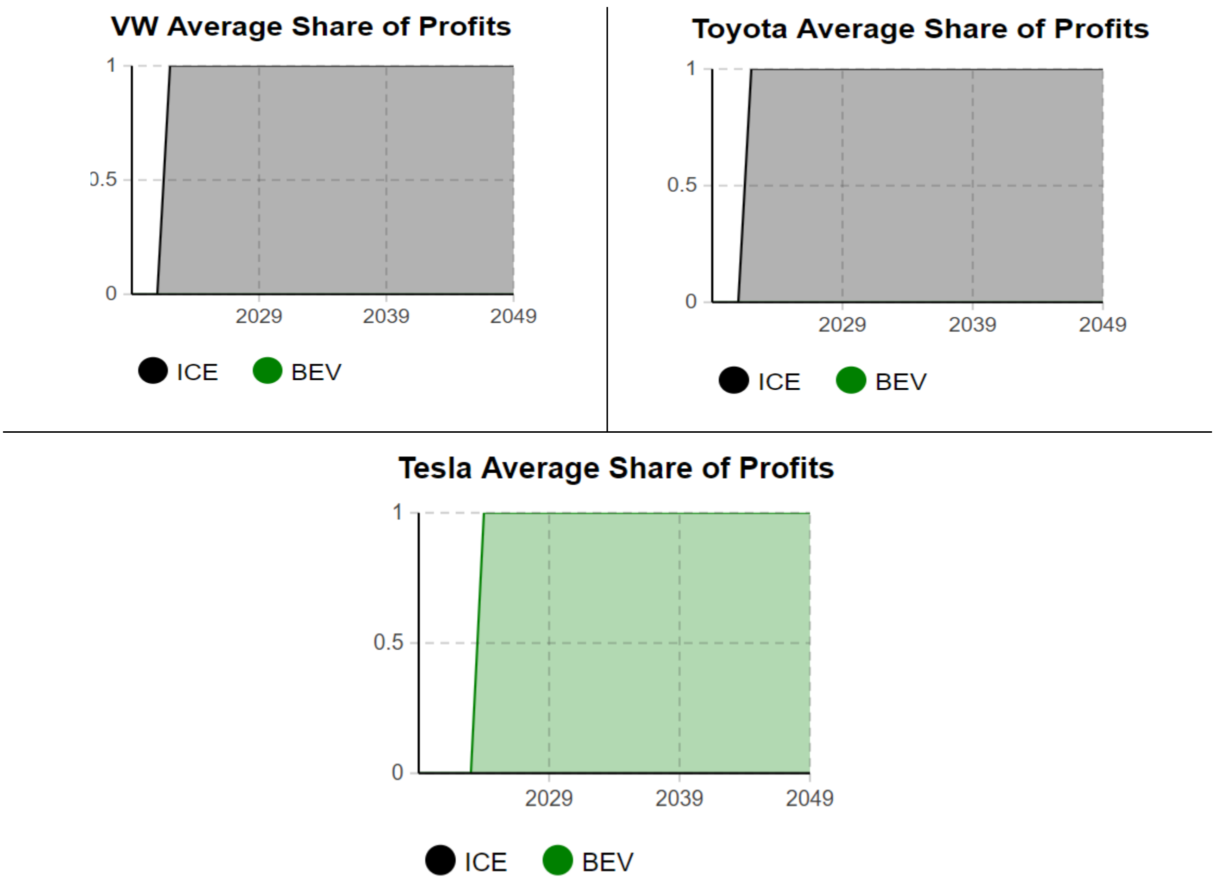


Figure 57. Average share of profits of the examined OEMs when there are only Tesla BEVs sales

8. Validation of the model's behaviour

In this chapter, an approach is followed so that the validation of the model to be made by comparing the model's behaviour with knowledge of how the real-world operates. It is discussed whether the car market dynamics are captured based on the assumptions that have been made from the beginning. It is also vital to highlight whether the end-result behaviour matches what would have been expected and whether it reflects the real world. Hence, in Section 8.1, published forecasts are presented about the shape of electric mobility in the coming years, while in Section 8.2 the main results of the new version of the model are analysed.

8.1 Future expectations and projections

The logic behind the approach that was followed during the implementation of the OEMs in the model was based on the consumers' decision-making process. It was assumed that each produced vehicle is also sold. European carmakers and other foreign carmakers that sell in the EU, like Toyota, dedicate their production to the market of the EU so that the OEMs comply with the CO_2 regulations. This approach was also followed by [63], which made projections regarding the EV market shares, as well.

In Figure 58 [63], the shares of vehicles produced are presented until 2025. It can be seen that the share of ICE vehicles keeps dropping, while the share of BEVs increases. The drop of the ICE vehicles would be offset by the increase in EV production [63]. For the year 2025, the exact shares of the different types of vehicles are presented in Figure 59 [63].

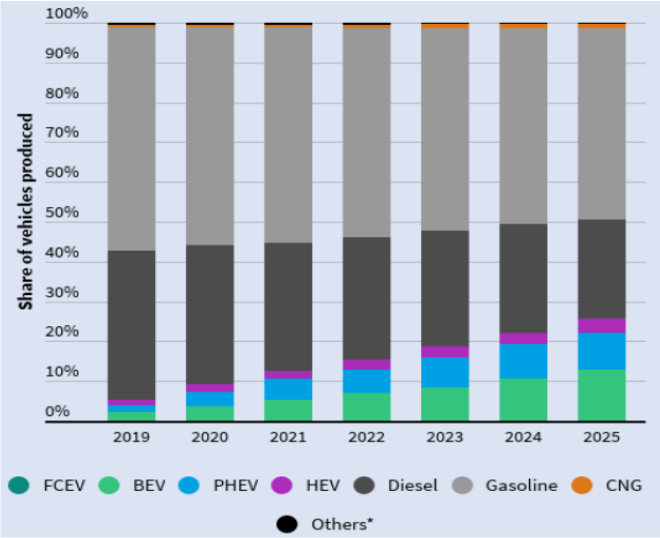


Figure 58. EU production of vehicles per type in 2025, in the share of total production (*Others include: E100, E85, LPG) [63]

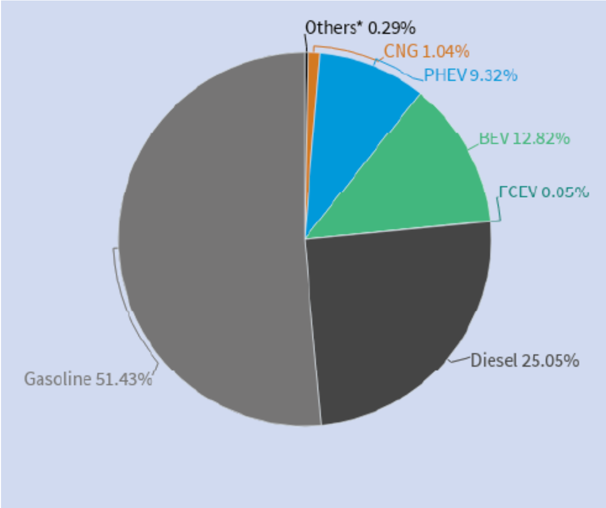


Figure 59. Forecasted European production of vehicles per type in 2025 (*Others include: E100, E85, LPG) [63]

As far as the shares of vehicles per OEM for the year 2025 are concerned, they are presented in Figure 60. As can be observed, BEVs of VW Group account for over 10% of its vehicles produced, while the Toyota-Lexus alliance is still behind compared to the rest of OEMs.

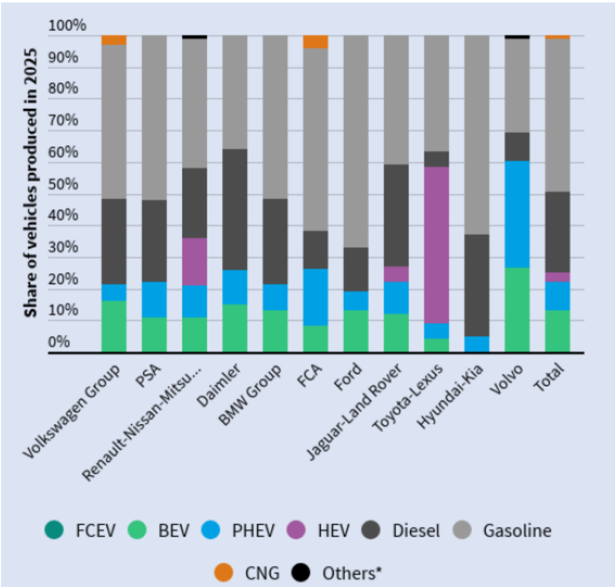


Figure 60. Share of vehicles produced in 2025 per OEM (*Others include: E100, E85, LPG) [63]

Finally, “Transport & Environment” developed different scenarios investigating EV market shares based on the extent of ICE improvements and whether or not OEMs are focused on selling EVs to comply with the CO2 emission standards. In Figure 61 [63], the EV market shares for the years 2025 and 2030 are presented. An increase is noticed for all of the developed scenarios for both of these years.

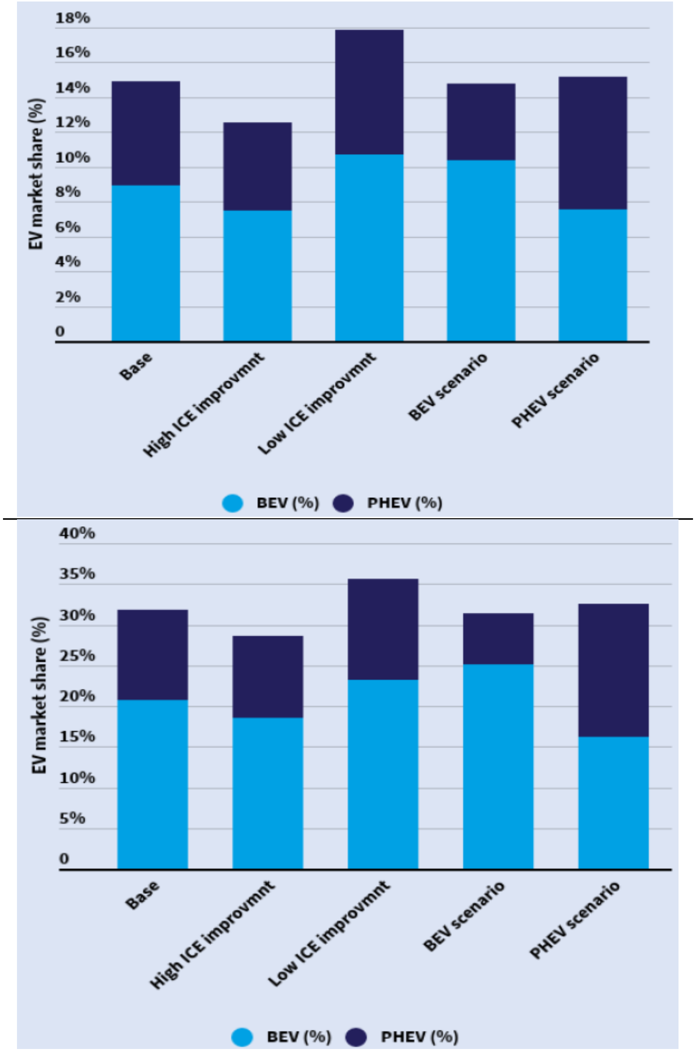


Figure 61. Expected minimum EV share in 2025 (up) and in 2030 (down) for CO_2 compliance [63]

As can be observed by Figure 62, VW as a group has reached the first place of sales during the first third of 2020 in terms of BEVs, while Toyota Group has not produced and sold any BEVs yet. Since the difference of new registrations among Tesla and VW Group is not that great, it can be assumed that Tesla tops all of the other OEMs if they are considered as stand-alone OEMs and not as alliances. This is noted because, in the current simulation, VW is considered as a single OEM instead of its group. Hence, it would be expected that Tesla would have the most sales for the first few years, VW would be the main competitor and Toyota would start having actual sales after some years.

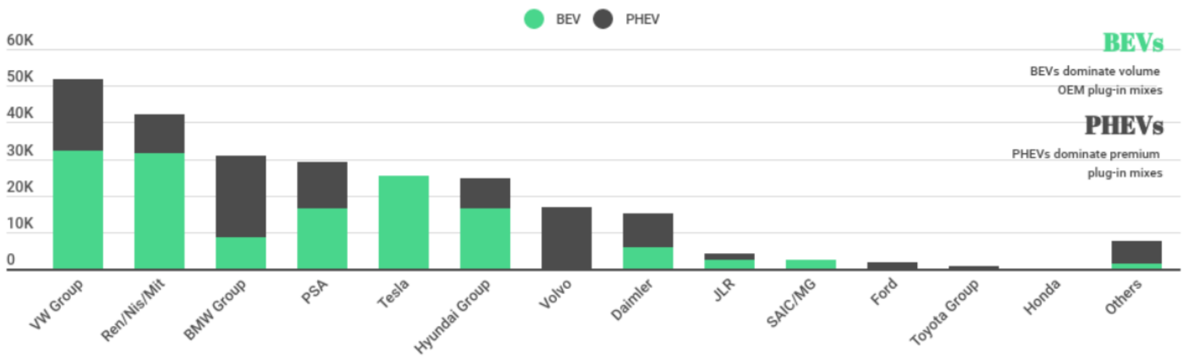


Figure 62. BEV and PHEV new registrations during the opening third of 2020 [185]

8.2 Model's behaviour

In this section, the behaviour and the developed relations of the new version of the model are made clearer, while some main outcomes are presented and compared to the EV market shares of section 8.1. Random relative weights distribution with the default percentages of R&D budget allocation were chosen for the investigation of the model's behaviour, as also described in Section 7.1 on page 48. These options give an adequate number of sales for all of the OEMs allowing further analysis.

The way the new version of the model has been developed and because of the specific vehicles that have been selected, it is expected Tesla will have the highest number of sales due to its high individual scores. It is also expected that VW will also have many sales due to the high "standardized mechanism scores" even though its "battery energy score" is not high enough and, lastly, because of the lower vehicle sales price.

On the other hand, Toyota's representative vehicle is expensive and has lower scores in battery energy density than Tesla and a lower standardized mechanism score than VW. Toyota can become more competitive when its scores increase due to R&D developments and the decrease in the battery pack cost. That is why Toyota sales are noticed after the first decade and influence the BEV market to a large extent, affecting the other OEMs' sales. In Figure 63 and Table 16, the differences between the first five and ten years are presented regarding the BEV sales of the selected OEMs.

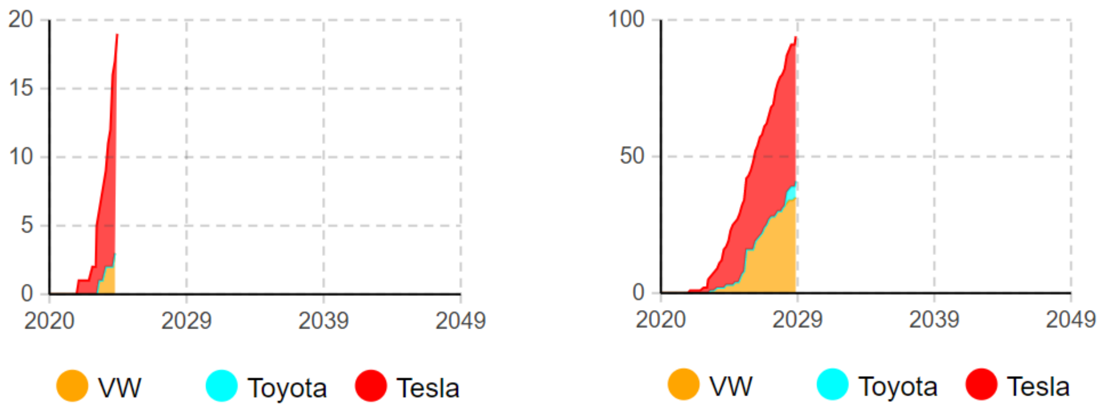


Figure 63. Number of new BEVs sold in 2025 (left) and in 2030 (right)

	2025				2030			
	VW	Toyota	Tesla	Total	VW	Toyota	Tesla	Total
Number of new BEV sales [#]	3	0	16	19	35	6	53	94
Number of new ICE sales [#]	41	41	-	82	68	65	-	13
Share of BEV sales vs total sales [%]	3	0	15.8	18.8	32.7	5	49.5	56.1
Share of BEV sales vs total sales from T&E [%][63]	-	-	-	~9	-	-	-	~20
Share of OEM BEV sales vs OEM total sales [%]	6.8	0	100	-	34	8.5	100	-
Share of OEM BEV sales vs OEM total sales from T&E [%][63]	~10	~4	100		N/A	N/A	N/A	N/A

Table 16. Detailed values for the BEV market for years 2025 and 2030

The numbers of the sales of VW and Tesla may be small but this is a simulation with consumers living in a microworld. The simulation has an initial population of 1000 consumers, who can also give birth and die. Therefore, more attention will be given to market shares as they can be more representative. The small numbers are justified due to the not so developed BEV attitude of consumers during the first 5 years of the simulation. Toyota's sales, on the other hand, are zero as the selected vehicle is expensive and Toyota as an OEM has low scores compared to the rest of the OEMs.

Observing Figure 60 and the share of BEVs produced by the VW Group, it can be concluded that the simulated results are not that far from "Transport & Environment's" projections. In Figure 60, the VW Group has a share of BEVs of around 15%. However, in the current assignment, VW is investigated as a single OEM. Considering that VW has the most sales among the VW Group, that share will be lower than 15%. Assuming that it will be at around 10%, it is comparable to the simulated 6% for the year 2025. The results follow the trend of Figure 62, as well, with Tesla leading the sales, considering VW as a single OEM. Finally, it should be noted that the projections made by "Transport & Environment" are based on their forecasts and assumptions. Different research methodologies can be followed obtaining different results. Hence, it very difficult to have same results with other projections that have been made. The most important thing is to capture similar behaviour and the results to follow the market trends and OEMs strategies and future plans.

More conclusions can be drawn as the years go by and Toyota starts playing a significant role in EV uptake too. Due to R&D developments, Toyota is improved in terms of its technical characteristics and combined with the increased BEV intention of consumers, more of them prefer buying a BEV and, eventually, from Toyota. Tesla, on the other hand, continues increasing its sales as it is the most established OEM in the EV market with the highest scores and the most preferred vehicle.

In Figure 64, the shares of the sales of each OEM per powertrain are presented. As can be observed from the OEMs that sell both powertrains, VW and Toyota, the share of ICE sales decreases by the time the BEV share of sales increases. On the other hand, Tesla has always a share of 100%, which is expected as it sells only BEVs. It can also be noticed that VW's shares of sales of the two powertrains reach to an equilibrium in the mid-2040s, while Toyota being a laggard to the transition to electric mobility needs more years to reach this state.

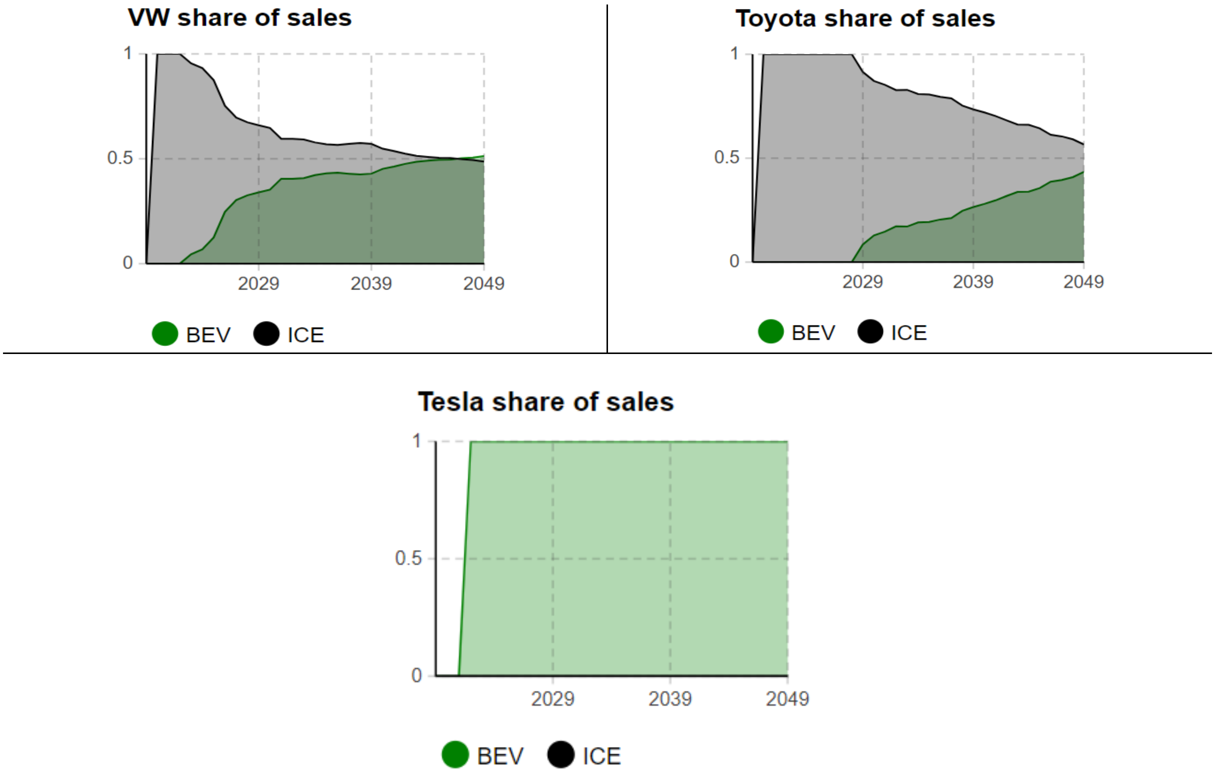


Figure 64. OEM share of sales per powertrain

The influence that one OEM has on the other is shown clearer in Figure 65, where the shares of BEV sales of each OEM are presented. As is displayed, when the VW BEV sales start increasing, Tesla's BEV sales start dropping by almost a half showing the considerable impact that one OEM has on the other. As the years go by and Toyota is penetrating the BEV market, the sales of both VW and Tesla are influenced. A slight decreasing slope is noticed in Tesla's share of BEV sales, while a more noticeable is the one of VW. In the mid-2040s, Toyota has achieved taking the second place in BEV sales over the VW.

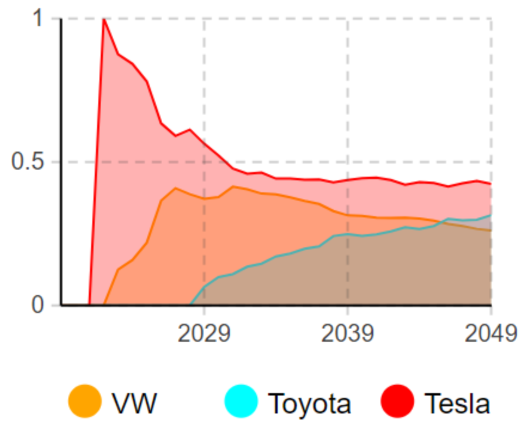


Figure 65. Share of BEV sales of each OEM over the total BEV sales

Along with the sales, similar behaviour follows the average share of profits per powertrain of the three OEMs. In Figure 66, the yearly BEV sales of the OEMs are presented, while in Figure 67, the average shares of profits per powertrain are displayed. As far as VW is concerned, it is observed that by the time BEV sales keep increasing, the ICE sales have a decreasing trend. This results in falling share of ICE profits and increasing BEV profits. The profits can be influenced by the number of vehicles sold per powertrain and by the profit rate of each vehicle. Figure 67 shows that after the mid-2030s, the sales of BEVs are more profitable than the ones of ICEs.

Toyota has similar behaviour with VW. As can be seen from Figure 66, BEVs start being sold after the second decade of the simulation, which results in increasing share of BEV profits. Regarding ICE sales, they are drastically decreased after the year 2040. These two behaviours affect the average share of profits of Toyota, as can be observed in Figure 67, with BEVs being more profitable for Toyota, as well. Finally, Tesla's average share of profits emerges just from BEVs since it does not offer any ICE vehicles.

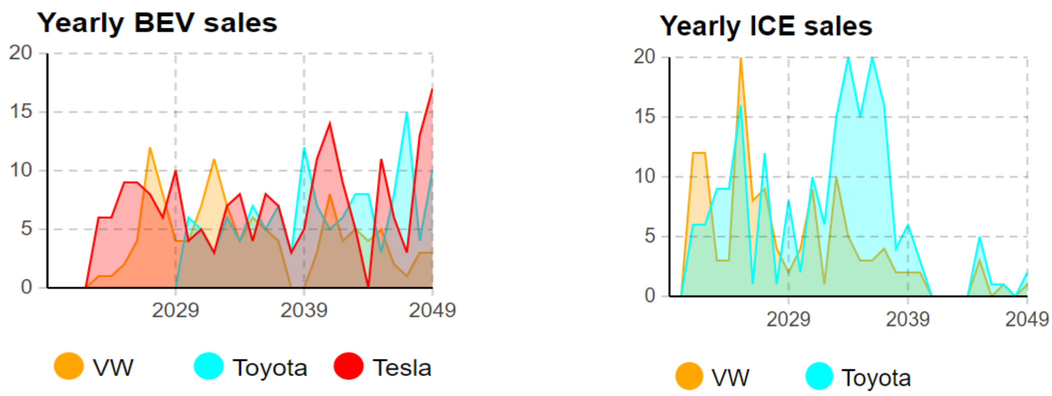


Figure 66. Yearly BEV and ICE sales of the three OEMs

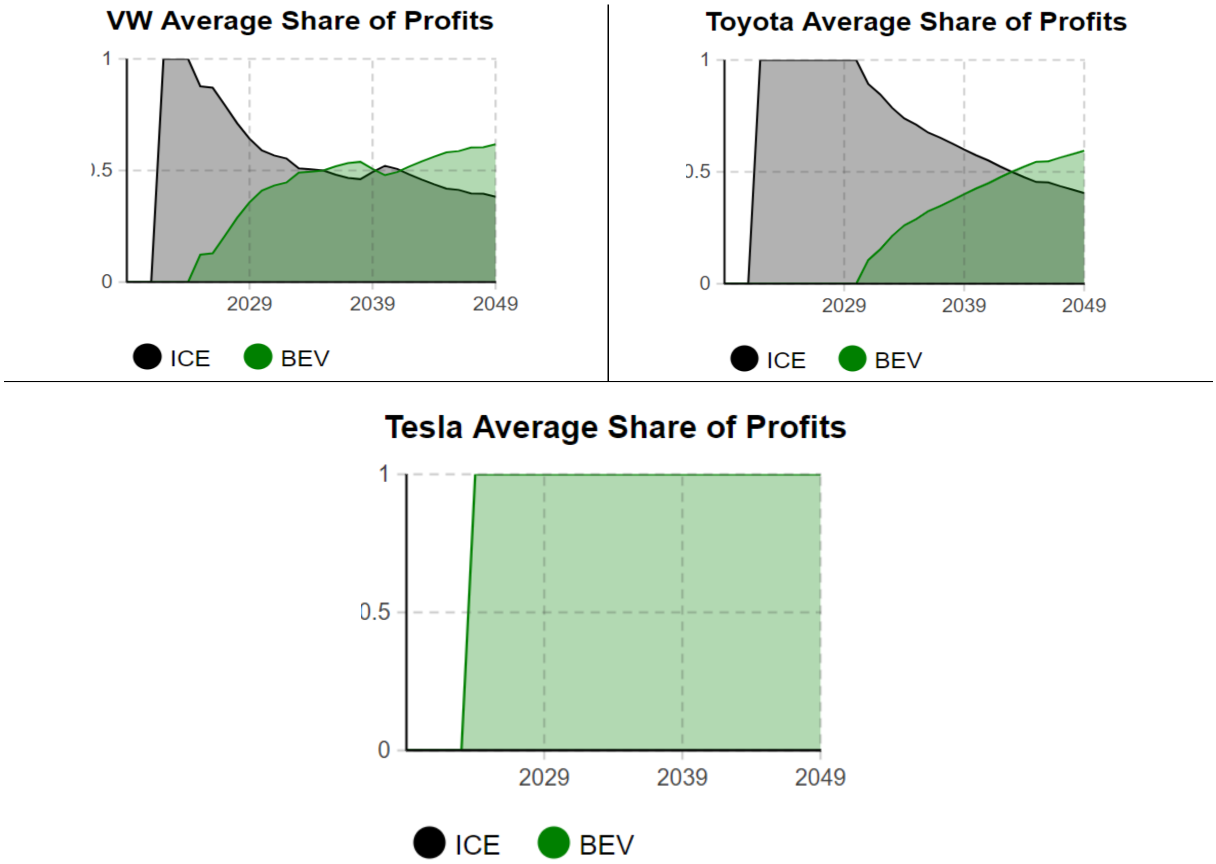


Figure 67. Average share of profits per OEM and per powertrain

The shares of the newly registered BEVs for the EU are shown in Table 17 [12]. In Appendix G, the extrapolated BEV market shares are presented until the year 2050. As shown in Table 24 and Figure 75 on pages 95-96, in 2050, the market share of the newly registered BEVs will be 94.64%. This means that almost all of the newly registered vehicles in the EU will be BEVs, which also leads, eventually, to large share of BEVs on the road.

Year	EU BEV market shares [%]
2011	0.1
2012	0.1
2013	0.2
2014	0.3
2015	0.4
2016	0.4
2017	0.7
2018	1.0
2019	2.1
2020	3.5

Table 17. BEV market share of newly registered vehicles in EU [12]

In Figure 68 and Table 18, the simulated behaviour and values are presented, respectively, regarding the new vehicles sold during the simulation. The simulated results are not in accordance with the extrapolated values, as the BEV sales are less rapid. However, an increasing trend is shown, which favours the BEV sales. Moreover, according to "Global EV Outlook", many European countries have already set objectives for the EV deployment and pursue the objective of "*EV30@30 Campaign*" by pledging to actively pursue the objective of 30% EV sales by 2030 [8]. The simulated value is at 41.4% of the new sales, which is pretty close to the goals that have been set by these countries.

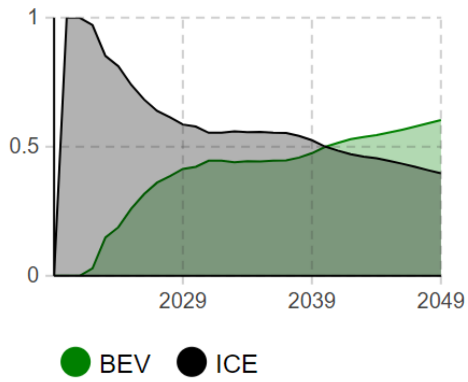


Figure 68. Share of new vehicles sold per powertrain

	BEVs new sales [%]	ICEs new sales [%]
2025	18.8	81.2
2030	41.4	58.6
2035	44.4	55.6
2040	47.5	52.5
2045	54.5	45.5
2050	60.3	39.7

Table 18. Share of new vehicles sold per powertrain

9. Conclusions

The main research question of the graduation assignment that has been set in Section 1.3 was: "*How can car market dynamics in the transition towards electric mobility be captured in an agent-based simulation model*?". Reflecting back on the main research questions and the sub-research questions that have been developed on page 2, a research methodology was followed taking into consideration the most important involved stakeholders in the car market and gathering any factors that concern car market and emerge from these stakeholders. This way, the first three research questions were able to be answered through a literature review regarding car markets.

Many assumptions and simplifications were made in order a concept map to be designed and the fourth research question to be answered. The concept map is used as a guidance tool for the implementation of the OEM agent in the "Adam & EV" model, while the relations among the analyzed factors are also visible.

The next part of the research was a literature review for agent-based models to be conducted since "Adam & EV" is an agent-based model and a better and more thorough insight should be given. Hence, the answer about the definition and the usage of agent-based models was given for RQ 5, followed by the goals and limitations of the original version of the "Adam & EV" model and RQ 6-7.

The following research questions that have been developed are related to the implementation of the OEM agent in the model and what can be explored within the model. Hence, the answer of RQs 8-10 give useful information to the reader about the way the OEM agent was implemented and the developed dynamics among the OEMs.

More specifically, the research was conducted using an agent-based simulation model that included the consumers, a dealer, the cars and the OEMs. The relationship among the OEMs was examined regarding the EV uptake and how they influence each other. Depending on consumers' demand and powertrain preference, the market is shaped affecting the OEMs directly, while, at the same time, the OEMs affect each other.

Moreover, the investments and the profits coming from the OEM's sales were modelled, linking them with sales price and production cost developments for both ICEs and BEVs. A scoring system was introduced so that the OEM preference of a consumer buying a BEV to be shaped. The preference can change over the years based on R&D investments on certain technical characteristics of the BEVs and model diversity.

Seven options were added regarding the relative weight distribution or the importance that a potential consumer gives to specific BEV attributes, representing, this way, seven different scenarios. The user has the opportunity to select each one of the options so that he will investigate more efficiently the developed dynamics. Car market dynamics of different OEMs can also be examined with more flexibility with the installed sliders of the R&D investments.

Research questions 11-12 are related with the verification and validation of the model. As far as verification is concerned, different test-cases were examined in Chapter 7 by altering various variables and analysing the results compared to what would have been expected. This way, it is confirmed if the relations described in the designed concept map are correctly implemented concerning the conceptual model. Lastly, the validation part is achieved by comparing the model's behaviour with knowledge of how the real-world operates. Moreover, by examining other published projections, the behaviour of the "Adam & EV" model is investigated compared to these forecasts.

Concluding, by answering the above research questions, the car market dynamics in the transition towards electric mobility can be captured using an agent-based simulation model. The uptake of EV mobility has serious effect on the OEM strategies and the investments they are going to make in the following years as well as their profits.

10. Recommendations and improvements

The approach that was followed to model car market dynamics for different OEMs towards electric mobility was based on the consumers' behaviour due to the fact that consumers are modelled with a more analytical way. Following the consumers' demand, the production of the vehicles was set as it was assumed that by the time the consumer asks for a vehicle, that vehicle is produced and sold. Another approach would be two different dealers to be created, one for VW and one Toyota. Tesla does not have a dealer in the real world. Hence, these vehicles could be produced by the OEMs and for the cases of VW and Toyota to be given to their corresponding dealer. The dealer, having known the demand, supplies the vehicles to the consumers. Tesla, on the other hand, could provide its vehicles directly from its agent (in real life: factory) to the consumers. This way, the model would be more representative of real life. This way the dealer representing each OEM could read the demand only for this specific OEM and order vehicles based on that demand. The created stock can also be analyzed more accurately watching the developed dynamics between BEVs and ICEs.

Another point that could improve the quality of the model and bring it closer to real-life would be the addition of more vehicles with different powertrains. In Appendix A, the different technologies of electric vehicles are presented. ICE vehicles could be separated to diesel, petrol and CNG. This, combined with more OEMs, would give the consumers more options to select a vehicle with a specific powertrain. Hence, the results would also reflect other technologies' sales regarding electric mobility. This, more comparisons can be made with other published projections, such as the one from "Transport & Environment", which includes more powertrain options too.

Furthermore, projections that have been made with extrapolation or not, like the battery pack cost or the base price development of the vehicles, need further validation. The more realistic these values are, the more valid the outcomes of the model will be.

As far as the scoring system is concerned, three attributes were selected that are linked with the consumers' concerns regarding electric vehicles and some technical characteristics of the electric vehicle. However, this approach is based on assumptions and simplifications that were made in order the consumer preference to be shaped on which OEM he will select. This approach was selected due to lack of literature in R&D developments and the investments that are made by each OEM. If more information will be given about the R&D strategy of each OEM and the pace, in which they expect to improve their vehicles in the coming years, more representative data could be used.

Finally, several OEMs have made considerable investments to improve ICE vehicles. Making them friendlier to the environment will help the OEMs complying with the EU CO_2 regulations and prevent them from getting fined. Because of this regulation, which has also been described in 6.2.4, OEMs have started shifting their strategy to the production of electric vehicles. Nevertheless, these huge ICE investments have not brought the anticipated profits yet. Hence, it would be interesting to model that factor, too, and exploring the dynamics that are developed.

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Appendix

A. Electric vehicle technologies

The development of electric vehicles has been proved as the primary solution to the decrease of GHG emissions [186]. Vehicles that primarily move with one or more electric motors are the key to the electrification of transportation. Below, the various categories of the so-far developed technologies regarding electric vehicles are presented. They are divided based on the powertrain of each technology and the fuel that provides the vehicles with power.

1. Hybrid Electric Vehicles

Over the last two decades, Hybrid Electric Vehicles (HEVs) have been developed as a potential solution to the problems mentioned above. These vehicles use ICEs in combination with electric motors that are connected to a battery pack. This way, propulsion is provided to the wheels either combined or separately. What makes this technology challenging is the management of the power flow between the fuel and the energy storage source (ESS). There are three different configurations regarding the power flow: i. Series HEV, ii. Parallel HEVs and iii. Series-Parallel HEVs.

i. Series HEV

In that kind of configuration, Figure 69, the ICE is not connected directly to the transmission system. Firstly, the ICE will turn on the generator to generate electricity, which will be stored later in the ESS. The electric motor is powered by the ESS, making the vehicle move. Having such configuration, the ICE always operates at its highest efficiency achieving high fuel economy.

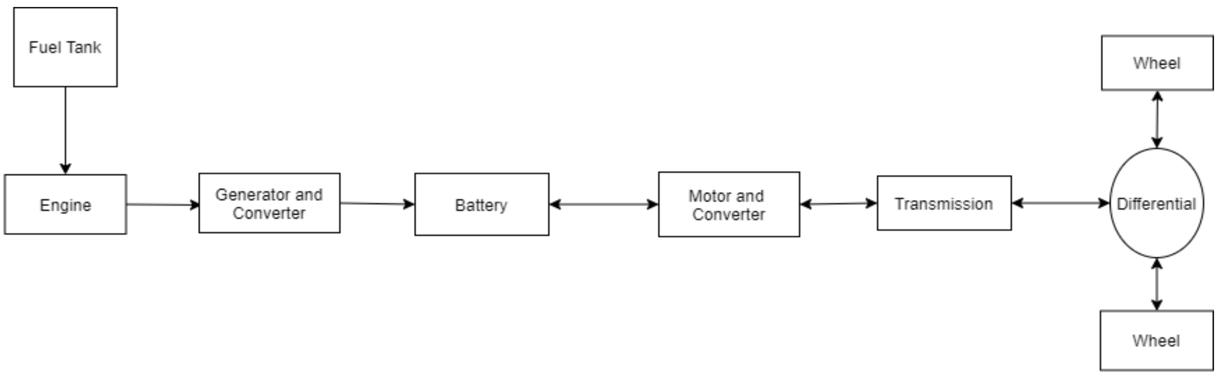

Figure 69. Series HEV configuration

ii. Parallel HEV

On the other hand, with a parallel configuration, the power flows via two paths from the ESS to the transmission, as can be seen in Figure 70. The path coming from the ICE is called the mechanical path, while the path coming from the ESS is called the electrical path. It is also worth referring that the power flow in the electrical path goes in both directions.

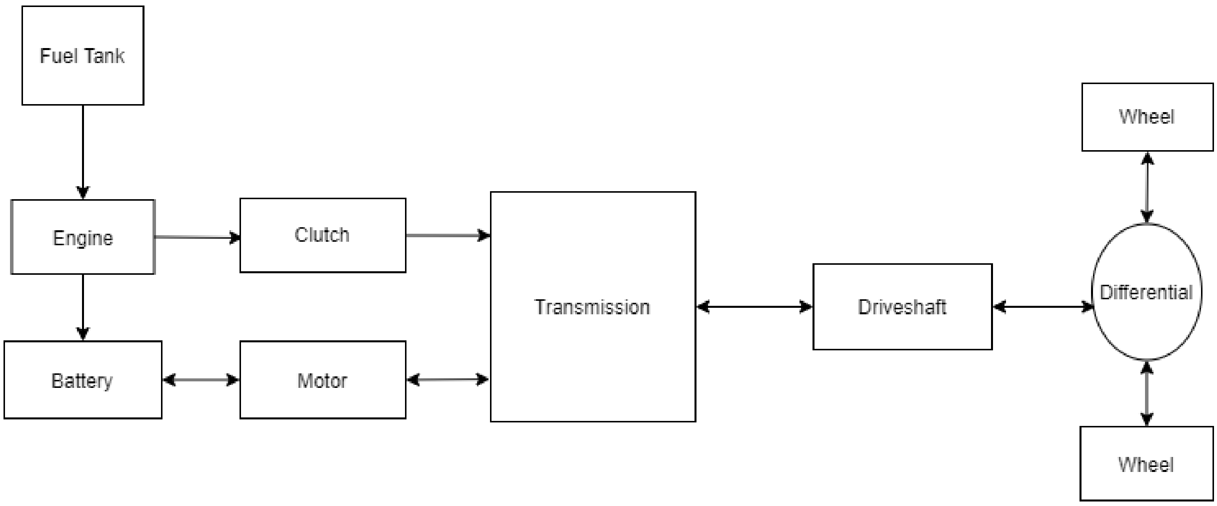

Figure 70. Parallel HEV configuration

iii. Series-Parallel HEV

As far as the series-parallel configuration is concerned, it is a combination of the previous two technologies. The vehicle can be powered solely by the ICE or the ESS or both operating at the same time as in the parallel configuration. Moreover, a power splitter is used so that the ICE can run in its optimum operating range as much as possible. The configuration of the series-parallel HEV is displayed in Figure 71.

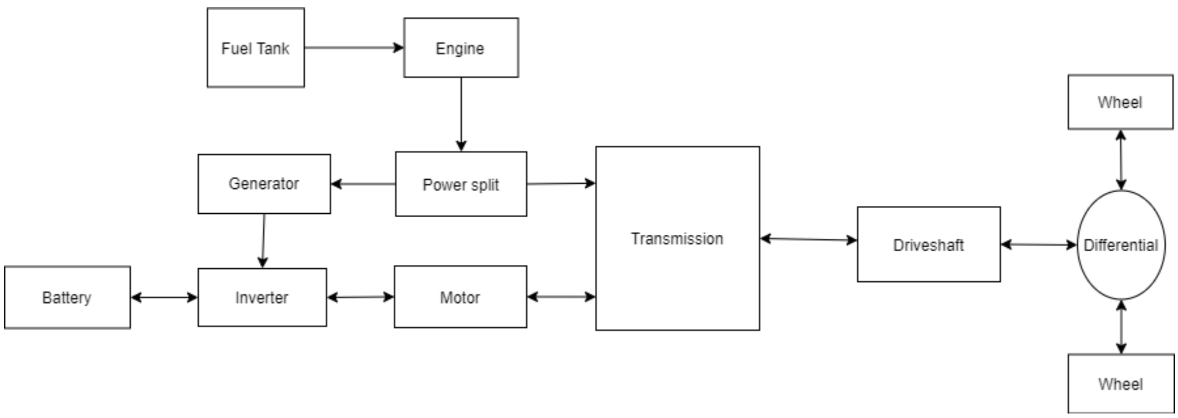

Figure 71. Series-Parallel configuration

2. Plug-in Hybrid Electric Vehicles

The most recent breakthrough of the HEVs is the plug-in hybrid electric vehicles (PHEV). The advantage of PHEVs is the ability to run all-electric for the first couple kilometers before using the ICE engine. The ESS of the PHEVs can be charged using outlets from the grids making the drive emission-free for short distances. The range that PHEVs can run all-electric is called all-electric drive range (AER) and after that threshold, the vehicle switches back to the conventional HEV. Finally, the PHEVs permit operational in the charge depleting (CD) mode, allowing the ESS to run out of energy before it turns on the ICE. On the other hand, HEVs can operate just in the charge sustaining (CS) mode, but the margin of the state of charge (SoC) is small that the energy management system can take full advantage of [187].

3. Fuel Cell Electric Vehicles

Fuel cell electric vehicles (FCEVs) use an all-electric powertrain having a fuel cell stack as the energy source. It is fuelled with hydrogen that emits just water and heat and, consequently, is considered as zero-emission vehicles (ZEVs). The hydrogen that is used as a fuel is stored either in a tank or is extracted from a fuel processor, as displayed in Figure 72 [3].

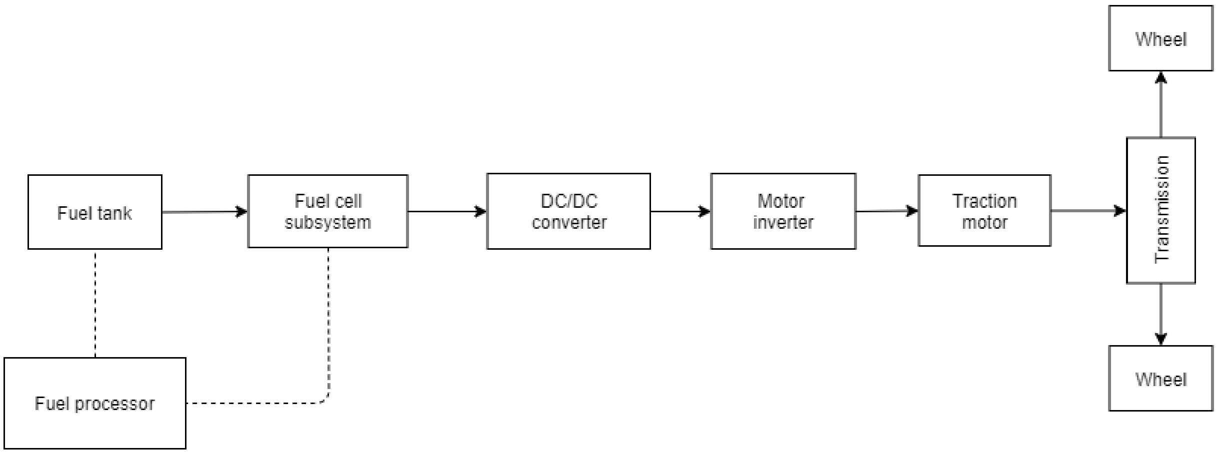

Figure 72. FCEV configuration

4. Fuel Cell Hybrid Electric Vehicles

Fuel cell hybrid electric vehicles (FCHEVs) are similar to the conventional FCEVs, with the only difference that they have an extra ESS. This ESS can be batteries or ultracapacitors and are charged and discharged according to the supply and demand. The configuration of this kind of technology is shown in Figure 73.

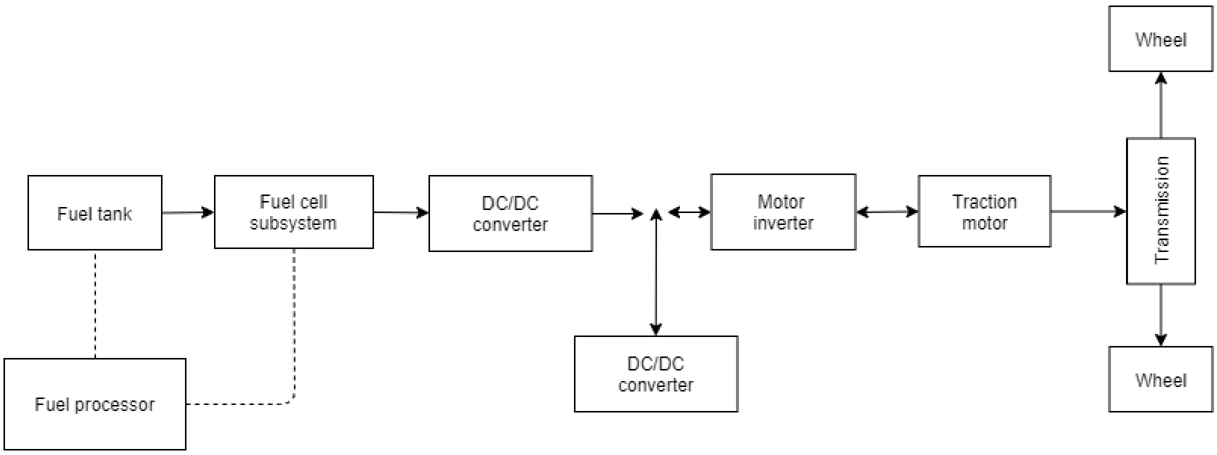

Figure 73. FCHEV configuration

5. Battery Electric Vehicles

Battery electric vehicles (BEVs) are vehicles using batteries as their only power source. Therefore, they are also considered as ZEVs. Their battery can be charged onboard or off-board. Nowadays, the developments for BEVs are done with high speeds concentrating mostly on the battery technology so that the cost to be minimized and the AER to be maximized. The weight of the vehicle is low, as this configuration requires the lowest mechanical drivetrain compared to the other technologies that have been described. The architecture of the basic BEVs is shown in Figure 74.

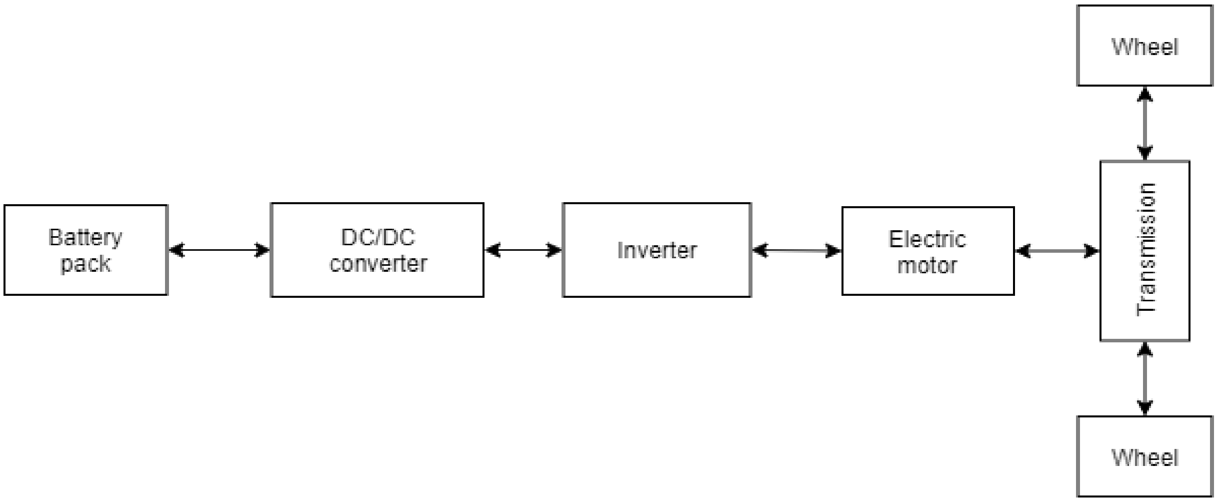

Figure 74. BEVs configuration

B. Base price development projections

Year	Inflation	VW Golf petrol [€]	Toyota Corolla [€]	Inflation / Deflation	VW eGolf [€]	Lexus UX 300e [€]	Tesla Model 3 [€]
2020		17,890	15,638		27,257	39,992	40,817
2021	2%	18,248	15,951	-5%	25,894	37,992	38,776
2022	2%	18,613	16,270	-5%	24,599	36,093	36,837
2023	2%	18,985	16,595	-5%	23,369	34,288	34,995
2024	2%	19,365	16,927	-5%	22,201	32,574	33,246
2025	2%	19,752	17,266	-5%	21,091	30,945	31,583
2026	2%	20,147	17,611	-5%	20,036	29,398	30,004
2027	2%	20,550	17,963	-5%	19,035	27,928	28,504
2028	2%	20,961	18,322	-5%	18,083	26,532	27,079
2029	2%	21,380	18,689	-5%	17,179	25,205	25,725
2030	2%	21,808	19,063	-3%	16,749	24,575	25,082
2031	2%	22,244	19,444	0%	16,749	24,575	25,082
2032	2%	22,689	19,833	1%	16,917	24,821	25,333
2033	2%	23,143	20,229	1%	17,086	25,069	25,586
2034	2%	23,605	20,634	1%	17,257	25,319	25,842
2035	2%	24,078	21,047	1%	17,429	25,573	26,100
2036	2%	24,559	21,468	1%	17,604	25,828	26,361
2037	2%	25,050	21,897	1%	17,780	26,087	26,625
2038	2%	25,551	22,335	1%	17,957	26,348	26,891
2039	2%	26,062	22,782	1%	18,137	26,611	27,160
2040	2%	26,584	23,237	1%	18,318	26,877	27,432
2041	2%	27,115	23,702	1%	18,502	27,146	27,706
2042	2%	27,658	24,176	1%	18,687	27,417	27,983
2043	2%	28,211	24,660	1%	18,873	27,692	28,263
2044	2%	28,775	25,153	1%	19,062	27,968	28,545
2045	2%	29,350	25,656	1%	19,253	28,248	28,831
2046	2%	29,937	26,169	1%	19,445	28,531	29,119
2047	2%	30,536	26,692	1%	19,640	28,816	29,410
2048	2%	31,147	27,226	1%	19,836	29,104	29,704
2049	2%	31,770	27,771	1%	20,035	29,395	30,001
2050	2%	32,405	28,326	1%	20,235	29,689	30,302

Table 19. Base price developments along with inflation/deflation values

C. Bloomberg's battery pack price projections

Year	BNEF Battery prices potential decrease €/kWh
2020	178*
2021	128
2022	105
2023	91
2024	84*
2025	75
2026	70
2027	65
2028	62
2029	59
2030	55*
2031	54
2032	52
2033	50
2034	48
2035	47
2036	45
2037	44
2038	43
2039	42
2040	41
2041	40
2042	39
2043	38
2044	37
2045	37
2046	36
2047	35
2048	35
2049	34
2050	34

Table 20. Bloomberg battery pack price projection values (with the star (*) are the values based on Bloomberg projections; the rest are extrapolated)

D. European fleet regulations

Year	ZLEV credits	ZLEVs target shares
2020	2	0%
2021	1.67	0%
2022	1.33	0%
2023	1.33	0%
2024	1.33	0%
2025	1.33	15%
2026	1.33	15%
2027	1.33	15%
2028	1.33	15%
2029	1.33	15%
2030	1.33	35%
2031	1	35%
2032	1	35%
2033	1	35%
2034	1	35%
2035	1	35%
2036	1	35%
2037	1	35%
2038	1	35%
2039	1	35%
2040	1	35%
2041	1	35%
2042	1	35%
2043	1	35%
2044	1	35%
2045	1	35%
2046	1	35%
2047	1	35%
2048	1	35%
2049	1	35%
2050	1	35%

Table 21. "Super-credits" system and ZLEVs target shares

E. Projected number of models and model diversity scoring

Year	VW Group	VW assumed models (46% of the VW Group)	VW score	Toyota	Toyota score	Tesla	Tesla score
2020	17*	5*	2.5	2*	2.5	7*	2.5
2021	21*	6*	2.5	3*	2.5	9*	2.5
2022	27*	12	5	8*	2.5	13*	5
2023	33*	15	5	10*	2.5	13	5
2024	40*	18	5	11*	5	13	5
2025	48*	22	7.5	12*	5	13	5
2026	55**	25	7.5	16**	5	14	5
2027	62**	29	7.5	19**	5	15	5
2028	70*	32	7.5	21**	7.5	16	5
2029	69	32	7.5	24**	7.5	16	5
2030	68	31	10	27**	7.5	17	5
2031	67	31	10	28	7.5	17	5
2032	66	30	10	29	7.5	17	5
2033	65	30	10	30	7.5	17	5
2034	64	29	10	31	10	18	5
2035	63	29	10	32	10	18	5
2036	62	29	10	31	10	18	5
2037	61	28	10	30	10	17	5
2038	60	28	10	29	7.5	17	5
2039	59	27	10	28	7.5	17	5
2040	58	27	10	27	7.5	17	5
2041	57	26	10	26	7.5	16	5
2042	56	26	10	25	7.5	16	5
2043	55	25	10	24	7.5	16	5
2044	54	25	7.5	23	7.5	16	5
2045	53	24	7.5	22	7.5	16	5
2046	52	24	7.5	21	7.5	16	5
2047	51	23	7.5	20	5	16	5
2048	50	23	7.5	19	5	16	5
2049	49	23	7.5	18	5	16	5
2050	48	22	7.5	17	5	16	5

Table 22. Projected number of models of the three OEMs with their corresponding points (values with one star (*) are based on the literature; values with two stars (**) are extrapolated values.

Volkswagen number of models:

In Figure 11, the number of models of VW Group is presented. Since just Volkswagen is considered in the current simulation model, an estimation about this specific OEM has been made regarding its number of models. Hence, considering that 46% of the VW Group sales are due to Volkswagen, it was considered that the number of models of VW would also be 46%. However, the information in Figure 11 is limited, as the last projected year is 2025. For the next few years, the values were extrapolated until 2028, when an upper limit of the model was set [168]. From 2029 until 2050, it assumed that VW Group is withdrawing some of its models. It can also produce new, but the assumption is that, on average, it is down one model after the year 2029. The same stands for VW as it has been assumed that its models are the 46% of the Group. In Table 22, the total number of models are presented for VW. The number of models in the year 2020 is based on the current data taken from [169].

Toyota number of models:

The same approach stands for Toyota as well, with the only difference that the values regarding the number of models are taken directly from Figure 11, as the number of sales of Toyota compared to Lexus is way larger [35].

Tesla number of models:

As far as Tesla is concerned, according to [169], it is going to have 13 different models by 2022. From 2023 until 2050, assumptions are made with increases and decreases regarding the number of models.

OEMs score

For the score that each OEM gets for the new BEV models, it was assumed that for every 10 models, 2.5 points are given to each OEM.

F. Battery range and maintenance costs scoring

OEM	VW	Toyota	Tesla
Battery range [km]	230	400	415
Battery energy density score	5.54	9.64	10
Monthly maintenance costs [€]	39	44	52
TCO score	9	8	8

Table 23. Initial scores for battery range and monthly maintenance costs

Battery energy density score

The way the scores were calculated was similar to the OEMs' scores. It was assumed that for 0-20 €, an OEM gets a perfect 10 score, for 21-40 € a score of 9 and so on.

TCO score

As far as the TCO scores are concerned, it was based on the inverse proportion. On this occasion, a perfect 10 score gets the OEM with the lowest maintenance costs. Hence, VW being the cheapest regarding monthly maintenance costs, gets a perfect 10 score, while the rest of the values are calculated based on inverse proportion.

G. BEV market share in EU

Year	BEV Share [%]
2011	0.10
2012	0.10
2013	0.20
2014	0.30
2015	0.40
2016	0.40
2017	0.70
2018	1.00
2019	2.10
2020 YTD	3.50
2021	4.10
2022	5.24
2023	6.53
2024	7.96
2025	9.53
2026	11.25
2027	13.10
2028	15.09
2029	17.23
2030	19.51
2031	21.92
2032	24.48
2033	27.18
2034	30.02
2035	33.00
2036	36.12
2037	39.39
2038	42.79
2039	46.34
2040	50.02
2041	53.85
2042	57.82
2043	61.93
2044	66.18
2045	70.57
2046	75.10
2047	79.78
2048	84.59
2049	89.55
2050	94.64

Table 24. BEV market share projection in EU; the red values are based on** [12]**; the rest are extrapolated

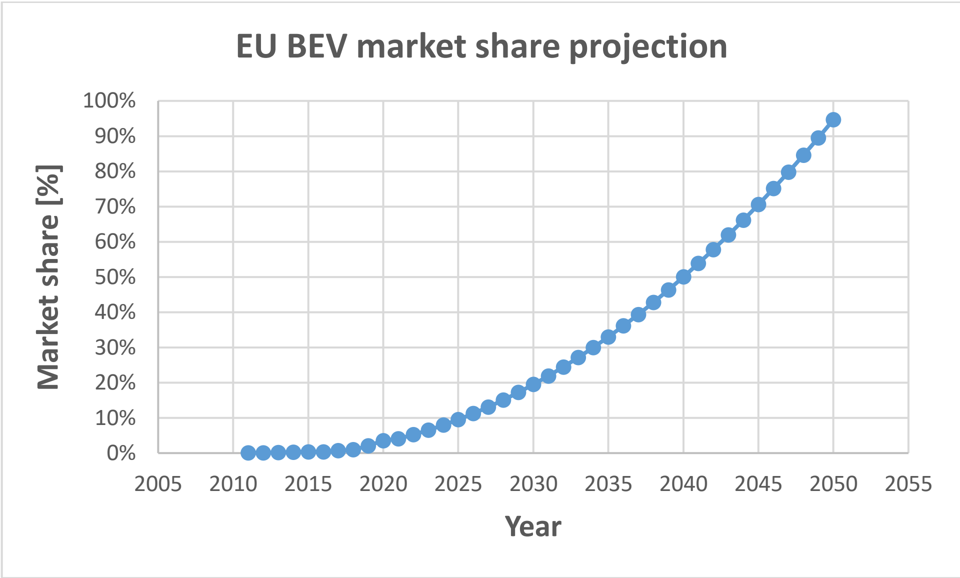

Figure 75. BEV market share projection in EU