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An analysis of the economic performance of battery electric vehicles in selected EU countries

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Abstract

Conventional vehicles are responsible for more than 17% of the world's total greenhouse gas emissions, which are created by burning fossil fuels in internal combustion vehicles. Electric vehicles are alternative technology which can reduce greenhouse gas emissions in the transport sector. However, their high cost, limited driving range and long charging time are the major challenges for their broader acceptance and use. The core objective of this work is to analyze economic performance of battery electric passenger cars in six selected European countries with different gross domestic product per capita, different development of charging infrastructure as well as different policy framework. It will be analyzed economic performance of electric vehicles in the next ten years. To show how different costs affect the performance and development of electric vehicles on the European Union market, the Net Present Value calculation method is used. Both battery electric vehicles and conventional vehicles are investigated. The calculations are made for three groups of vehicles: small cars, sedans, and sport utility vehicles. For each group of vehicles, three different vehicles, from different manufacturers are analyzed. Regarding the economic comparison of battery electric vehicles and conventional vehicles it has to be considered that some parameters such as fuel consumption, ranges, charging fees, fuel and registration taxes vary considerably between countries and car models. Moreover, battery electric vehicles require more frequent charging to match the range of conventional vehicles. The total charging costs for battery electric vehicles vary based on charger type, with fast direct current chargers incurring the highest costs. Ultimately, the results suggest that battery electric vehicles are less economically viable than conventional vehicles due to their high purchase costs and higher maintenance costs, specifically related to high battery replacement costs. The analysis showed that European Union countries with lower gross domestic product per capita experience a slower increase in the number of battery electric vehicles as well as in development of charging infrastructure. Policymakers should consider targeted incentives to promote battery electric vehicles adoption. While subsidies play a role, high taxes on conventional vehicles (as seen n the Netherlands) can also drive battery electric vehicle profitability. Crafting a balanced approach that encourages battery electric vehicle purchases without compromising revenue is crucial. The investment in charging infrastructure is important. The higher annual costs associated with battery electric vehicles charging highlight the need for accessible and efficient charging stations. Public-private partnerships could facilitate this infrastructure expansion.

Keywords: Battery electric vehicle, conventional vehicle, economic assessment, costs

Kurzfassung

Konventionelle Fahrzeuge sind für mehr als 17 % der weltweiten Treibhausgasemissionen verantwortlich, die durch die Verbrennung fossiler Brennstoffe in Fahrzeugen mit Verbrennungsmotor entstehen. Elektrofahrzeuge sind eine alternative Technologie, mit der die Treibhausgasemissionen im Verkehrssektor gesenkt werden können. Ihre hohen Kosten, die begrenzte Reichweite und die lange Ladezeit sind jedoch die größten Herausforderungen für ihre breitere Akzeptanz und Nutzung. Das Hauptziel dieser Arbeit ist die Analyse der wirtschaftlichen Leistungsfähigkeit von batteriebetriebenen Elektro-Pkw in sechs ausgewählten europäischen Ländern mit unterschiedlichem Bruttoinlandsprodukt pro Kopf, unterschiedlicher Entwicklung der Ladeinfrastruktur sowie unterschiedlichen politischen Rahmenbedingungen. Analysiert wird die wirtschaftliche Leistungsfähigkeit von Elektrofahrzeugen in den nächsten zehn Jahren. Um zu zeigen, wie sich unterschiedliche Kosten auf die Leistungsfähigkeit und Entwicklung von Elektrofahrzeugen auf dem Markt der Europäischen Union auswirken, wird die Berechnungsmethode des Nettogegenwartswerts verwendet. Es werden sowohl batteriebetriebene Elektrofahrzeuge als auch konventionelle Fahrzeuge untersucht. Die Berechnungen werden für drei Fahrzeuggruppen durchgeführt: Kleinwagen, Limousinen und SUVs. Für jede Fahrzeuggruppe werden drei unterschiedliche Fahrzeuge unterschiedlicher Hersteller analysiert. Beim wirtschaftlichen Vergleich von batteriebetriebenen Elektrofahrzeugen und konventionellen Fahrzeugen muss berücksichtigt werden, dass einige Parameter wie Kraftstoffverbrauch, Reichweite, Ladegebühren, Kraftstoff- und Zulassungssteuern je nach Land und Automodell erheblich variieren. Darüber hinaus müssen batteriebetriebene Elektrofahrzeuge häufiger aufgeladen werden, um die Reichweite konventioneller Fahrzeuge zu erreichen. Die Gesamtladekosten für batteriebetriebene Elektrofahrzeuge variieren je nach Ladegerättyp, wobei Schnellladegeräte mit Gleichstrom die höchsten Kosten verursachen. Letztendlich deuten die Ergebnisse darauf hin, dass BEVs aufgrund ihrer hohen Anschaffungskosten und höheren Wartungskosten, insbesondere im Zusammenhang mit den hohen Kosten für den Batterieaustausch, weniger wirtschaftlich sind als konventionelle Fahrzeuge. Die Analyse zeigte, dass in Ländern der Europäischen Union mit einem niedrigeren Bruttoinlandsprodukt pro Kopf die Anzahl batteriebetriebener Elektrofahrzeuge sowie die Entwicklung der Ladeinfrastruktur langsamer steigen. Die politischen Entscheidungsträger sollten gezielte Anreize in Betracht ziehen, um die Einführung batteriebetriebener Elektrofahrzeuge zu fördern. Während Subventionen eine Rolle spielen, können auch hohe Steuern auf konventionelle Fahrzeuge (wie in den

Niederlanden) die Rentabilität batteriebetriebener Elektrofahrzeuge steigern. Die Ausarbeitung eines ausgewogenen Ansatzes, der den Kauf batteriebetriebener Elektrofahrzeuge fördert, ohne die Einnahmen zu beeinträchtigen, ist von entscheidender Bedeutung. Die Investition in die Ladeinfrastruktur ist wichtig. Die höheren jährlichen Kosten für das Laden von batteriebetriebenen Elektrofahrzeugen unterstreichen den Bedarf an zugänglichen und effizienten Ladestationen. Öffentlich-private Partnerschaften könnten diesen Ausbau der Infrastruktur erleichtern.

Schlagwörter: Batteriebetriebenes Elektrofahrzeug, konventionelles Fahrzeug, wirtschaftliche Bewertung, Kosten

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1 Introduction

On January 29, 1886, the German inventor Carl Benz applied for a patent for his "vehicle with gas engine operation" [1]. This date is considered the birth year of the "modern" car with an internal combustion engine. More than 130 years later, it is unimaginable to think of today's modern society without transportation sector.

Transportation of passengers and goods is important, and their availability and mobility costs are important for everyday life [2]. Every day, millions of people use different forms of transport to perform their daily duties, such as work, education, shopping, escorting, leisure, personal or professional business. The number of vehicles grows every year. In 2010, the number of vehicles in the European Union (EU) was around 240 million, while in 2020 that number had grown to almost 290 million, which is an increase of 17% in the last 10 years [3]. Passenger vehicles are responsible for this increase. Every year more people decide to buy a vehicle, and more companies invest in vehicles for their employees, so that they can perform their business duties more easily. All this has resulted in more than 87% of the total number of vehicles in the EU being passenger vehicles [3]. In 2020, there were more passenger vehicles than the total number of vehicles in 2010, including buses, mopeds, motorcycles, and various forms of public passenger transportation. The growth in the number of personal vehicles can be seen in Figure 1.1.

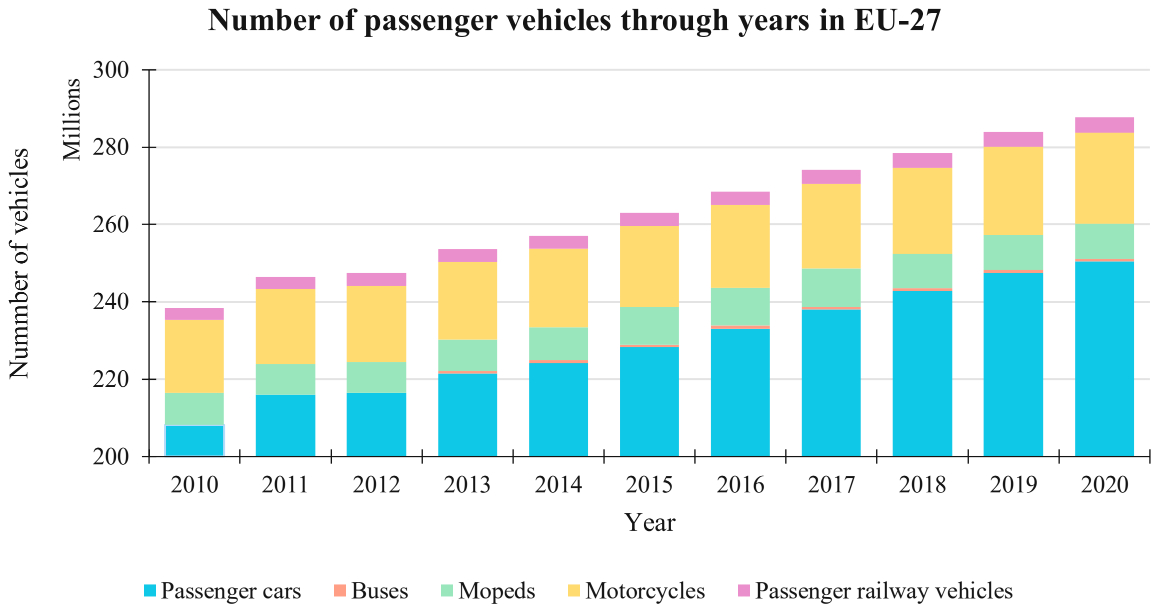


Fig. 1.1 – Development of the number of passenger vehicles at the EU level in the period from 2010 to 2020 [3]

Globally, we are facing the problem of climate change. This problem is caused by the emission of greenhouse gases (GHG) in the earth's atmosphere. Greenhouse gases are gases in the atmosphere that raise the Earth's surface temperature. What differentiates them from other gases is their ability to absorb wavelengths of radiation emitted by the Earth, resulting in the greenhouse effect [4]. The five most common greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide (CO_2), methane, nitrogen oxide (NO_2) and ozone [4].

Conventional vehicles with internal combustion engines use fuel such as diesel, gasoline, and liquefied petroleum gas (LPG) to operate. These gases are obtained from crude oil. During the production and combustion of diesel, gasoline, and LPG, CO_2 is released.

The invention of the internal combustion engine brought many advantages to the world, but also many disadvantages. Among the many disadvantages of the internal combustion engine, such as limited efficiency, noise and vibration, dependence on fossil fuels, maintenance requirements, and safety concerns, one of the main disadvantages is the emission of CO_2 and its negative impact on the environment [5].

Governments around the world are making special efforts to reduce CO_2 emissions and thus prevent further accumulation of CO_2 and further warming of the atmosphere. These efforts that are considered the main driver of the electric vehicle (EV) industry. The EU, as a leader in reducing CO_2 emissions, created a strategic energy technology plan that was adopted in November 2007 [6]. One of the key areas of action of strategic energy technology plan from 2007 is competitiveness in the global battery and e-mobility sector [6]. Two years prior to that, in 2005, the EU emissions trading system [7] was announced. The European Union Emission Trading System (EU ETS) is a carbon emission trading scheme and is intended to lower GHG emissions by the EU countries. This scheme limit emissions of specified pollutants over an area [8]. Since 2005, the EU ETS has helped reduce emissions from power and industrial plants by 37% [9].

Battery electric vehicles (BEV) are one of the solutions for reducing air pollution and CO_2 emissions [2], and the main reason why many political solutions are specifically aimed at BEVs.

Preferences on whether a new passenger car should be powered by a petrol or diesel engine differ between EU member states. Government incentives to encourage the share of cars with lower emissions, the number and variety of alternative fuel car models offered, the prices of such models, as well as Gross Domestic Product (GDP) per capita, all have an impact on consumer preferences [10]. Government incentives include, for example, tax reductions, subsidies, or special benefits such as access to lanes reserved for public transport and free parking [10]. Therefore, the number of BEVs in individual EU member countries varies. Figure 1.2 shows the number of BEVs for individual EU member countries in 2022. Germany, with a share of more than 34% of the total number of BEVs on the EU market, is undoubtedly the leader [11]. However, Cyprus with fewer than 1,000 BEVs in 2022, is in the last place [3].

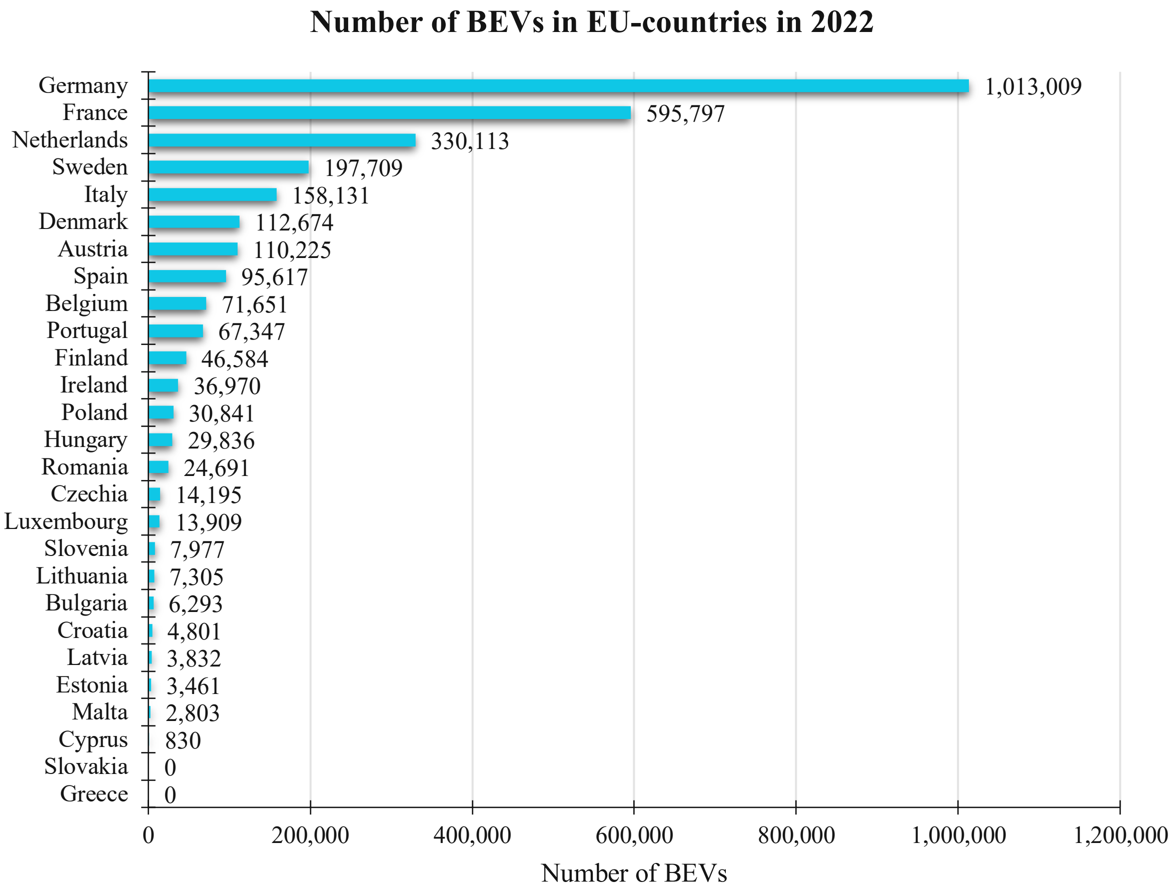


Fig. 1.2 - Number of BEVs in EU-countries in 2022 [3]

Figure 1.3 shows the percentage of BEVs per capita for individual EU member states in 2022. Although Germany has the highest number of BEVs, it ranked sixth in terms of the percentage of BEVs per capita. Luxembourg was the only EU member state with more than 2% BEVs in 2022.

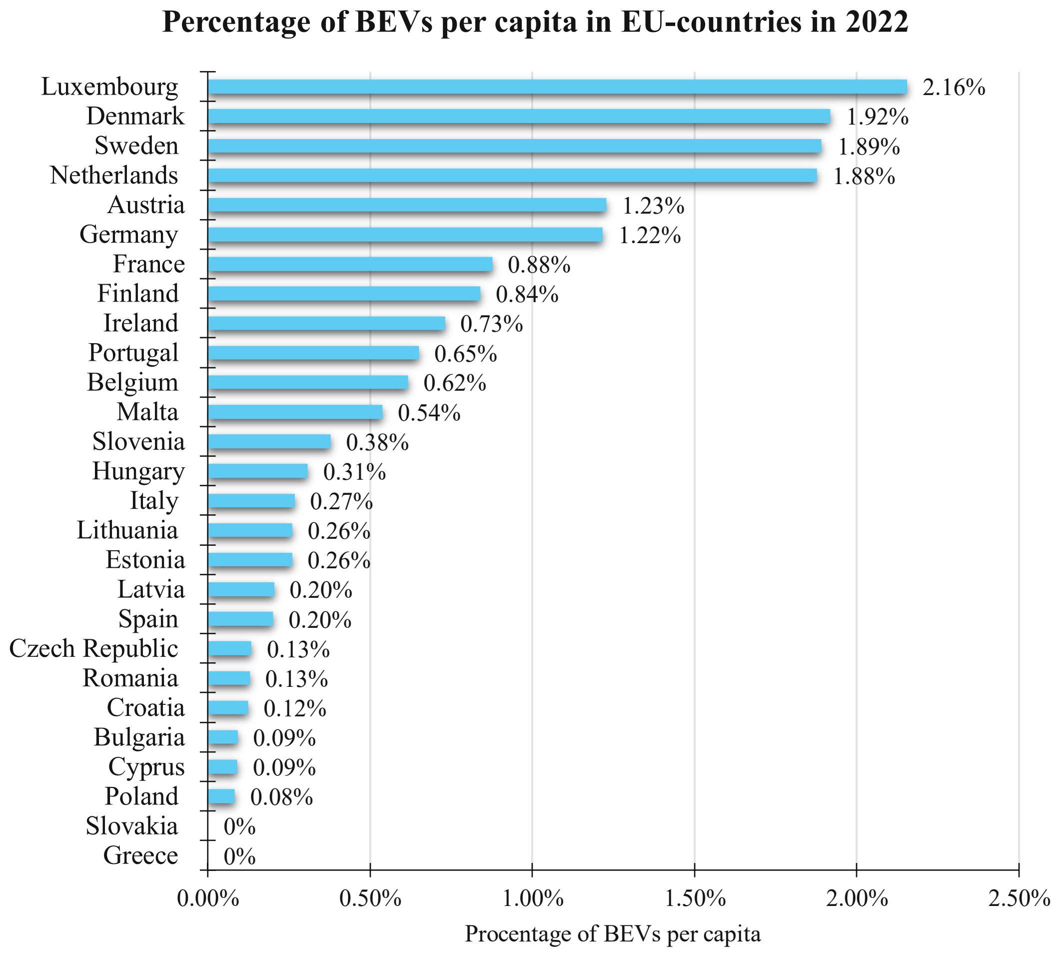


Fig. 1.3 - Percentage of BEVs per capita in EU-countries in 2022 [3]

The share of BEVs in the total number of passenger vehicles in an EU member country depends on the government incentives as well as the GDP per capita of the EU member country. The aim of this thesis is to analyze the economic performance of BEVs in selected countries based on GDP per capita, fix, and variable costs of BEVs in comparison to conventional vehicles (CVs).

Six different EU countries are chosen, depending on their GDP and development of infrastructure for BEVs. The chosen countries are:

- Sweden,
- Germany,
- Netherlands,
- Cyprus,
- Croatia, and
- Lithuania.

A more detailed explanation of the selection of EU countries is described in Chapter 4.

The intention is to show how the European BEV market could look like in the next 10 years. Numerous factors, such as size of the vehicle, purchase costs, maintenance, insurance, recharging/refueling cost, development of the observed country can stimulate the further development of the BEV market. These factors can define the economic performance of the BEV.

A comparison of CVs in relation to BEVs is analyzed. The vehicles are divided into the following three groups: small vehicles, sedans, and Sport Utility Vehicles (SUVs). Within each group, three different vehicles from different manufacturers are analyzed. The Net Present Value (NPV) is calculated for each vehicle. For the calculation of NPV, the following parameters are analyzed:

- Fix costs,
    - Purchase costs,
    - Subsidies
- Variable costs
    - Refueling/recharging costs
    - Maintenance
    - Insurance
    - Vehicle registration
    - Taxes

As the cost of refueling depends on the type of fuel used to drive the CV, the calculation of NPV for different CVs is made for:

- diesel
- petrol.

When it comes to BEVs, a similar calculation is made. The NPV of BEV is compared depending on the speed of the charger and the percentage of charging performed by different chargers. The NPV of a BEV charged:

- exclusively from alternating current (AC) chargers,
- exclusively from direct current (DC) chargers,
- exclusively from private home charging,

- with a ratio of 60% private charging, 40% public charging, of which 24% is from AC chargers and 16% from DC chargers,
- with a ratio of 50% private charging and 50% public charging, of which 25% is from AC chargers and 25% from DC chargers.

In addition to the calculation of NPV for each vehicle, the following factors that may have an impact on the economic performance of BEVs are analyzed:

- charging/refueling time,
- maximal range,
- GDP per capita.

BEVs are an attractive topic for the consideration of many researchers, so the literature dealing with the topic of BEVs is diverse and numerous.

Tuffour (2024) [12] examines the question: "Can EV truly meet the demands of sustainable energy?" His research delves into the long-term planning implications of BEV adoption for modern transportation and energy systems, shaping discussions around sustainability objectives. Challenges related to socio-environmental impacts, including those associated with lithium-ion battery production, social equity considerations, and network infrastructure burdens were identified [12].

In Yu's (2024) [13] study, a comprehensive vehicle energy model was established to simulate BEV performance under varying ambient temperatures and driving conditions. Adhikari (2020) [14] focuses on identifying and analyzing barriers to BEV adoption. The study identifies seventeen distinct barriers, categorized into five main groups. Meanwhile, Pollak (2021) [15] highlights three key obstacles slowing down the growth of BEVs in the EU: affordability, infrastructure availability, and lack of investment. Where Tsiropoulos (2022) [16] assesses the factors influencing investments in EU charging infrastructure.

Littlejohn (2022) [17] uses a stylized two-period model for the automobile manufacturing sector to compare the cost-effectiveness of different policies. The model compares CVs against BEVs [17]. Newbery (2015) [18] estimated the battery costs that would make BEVs cost-competitive by considering efficient transport fuel and electricity prices.

Kemperdick (2024) [19] estimates external costs associated with various BEV emissions using Well-to-Wheel analysis. The results of his analyze show that BEVs tend to have the lowest external costs [19]. On the other hand, Bruke (2024) [20] provides a comprehensive analysis of initial costs and total costs of ownership (TCO) for light-duty BEVs from 2020 to 2040. Figenbaum (2022) [21] analyzes the total cost of ownership (TCO) of BEVs versus CVs in Norway.

In summary, research on BEVs highlights challenges and opportunities for further development.

The work is divided in 10 Chapters. Chapter 2 describes the state of the art, while Chapter 3 explains the methodical procedure. Chapter 4 describes in detail how the countries for analysis were selected. The analyzed EU member states were selected based on GDP per capita and the number of BEVs per capita.

Chapter 5 presents electricity generation at the level of the entire EU. The method of generation and the price of electricity are important parameters for the further development of the BEV market at the EU level.

Chapter 6 focuses on BEV operation and the most important components within a BEV. It also discusses in detail the diverse types of electric motor (EM) used inside a BEV depending on its purpose. Diverse ways of charging the battery are described in more detail. Calculations of BEV-battery charging time, as well as maximum ranges of the observed vehicles, were made.

Chapter 7 focuses on CVs. This Chapter explains how the CV works.

Chapter 8 discusses the various costs of BEVs as well as CVs in more detail. All relevant costs were observed, such as insurance, maintenance, vehicle registration, purchase costs, subsidies, taxes, and charging/refueling costs.

In Chapter 9, a detailed comparison of BEVs and CVs is made, and based on the comparison between BEVs and CVs, an economic assessment of BEVs on the EU market can be made. In Chapter 10 presents the conclusion of the entire thesis.

Charging costs for BEVs could affect the economic assessment of BEVs. This thesis focuses on a scenario where there could be an increase in the price of electricity at the EU level. An increase in the price of electricity could cause an increase in the cost of charging BEVs. This could reduce the economic efficiency of BEVs. In this thesis, the impact of changes in the price of electricity, subsidies, maintenance costs, vehicle purchase costs and vehicle registration on the economic assessment of BEVs at the EU level will be analyzed.

2 State of the Art of Battery Electric Vehicles

Today, BEVs face various challenges and require different strategies. The main problem with BEVs is the battery. Therefore, BEVs are particularly suitable for small BEVs for low-speed communities in short-distance transportation, which only requires a smaller battery [22].

Currently, the main driving force behind BEVs is environmental concerns. The main question to be answered is, "Can BEVs be affordable?" The key factors that make BEVs affordable are range and price. To tackle the range issue, all types of batteries are under development. Lithium-ion (Li-Ion) batteries are the most widely used type of battery in BEVs. Significant efforts are being made to improve various BEV subsystems, such as electric motors, power converters, electronic controllers, power management units, battery chargers, batteries, and other auxiliary devices of BEVs, as well as integration and optimization at the system level [22].

Due to the problem of climate change, efforts have been made globally to reduce CO_2 emissions in recent decades. In 2020, the transport sector was responsible for 7.1 billion tons of CO_2 [23], or 20% of the total CO_2 emissions on a global level [24]. Road vehicles caused 74.5% of the total CO_2 emission from the transport sector [25]. Because of the high share of the transport sector in CO_2 emissions, it was necessary to make some changes. One way to reduce CO_2 emissions is to replace CVs with BEVs. The European Union has an ambitious goal of becoming climate-neutral by 2050. By 2030, the European fleet of BEVs should reach 40 million vehicles [26], which is an increase compared to the last available data from 2022.

In 2018, there were eight times more BEVs compared to 2013, while in 2022 there were eight times more BEVs compared to 2018 [10]. The number of BEVs on the EU market reached almost three million vehicles in 2022, and their share in the total number of passenger cars grew from 0.02% to 1.2% [10]. Figure 2.1 shows the change in the number of passenger vehicles and BEVs in the EU from 2013 to 2022. Compared to 2013, the number conventional of passenger vehicles increased by 13%, while the number of BEVs increased exponentially.

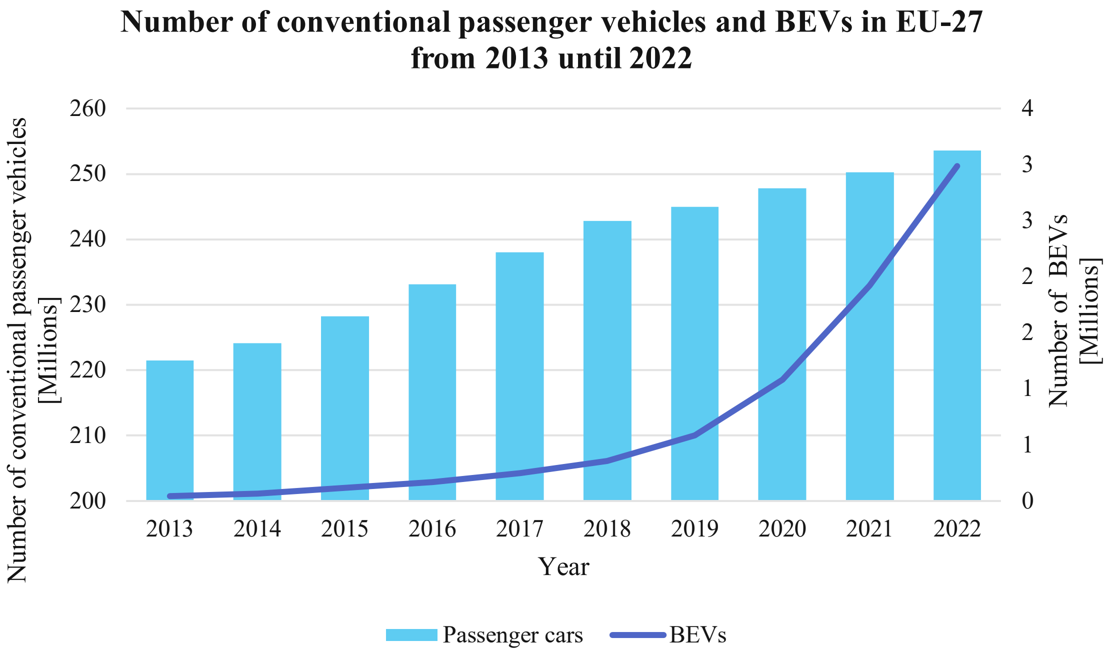
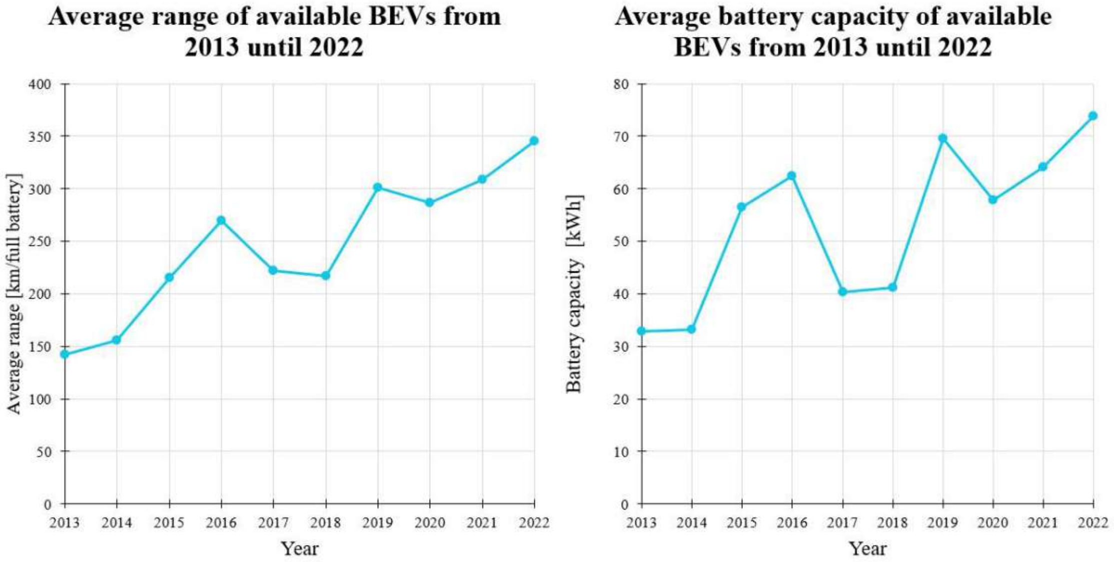


Fig. 2.1 - Number of conventional passenger vehicles and BEVs in EU-27 from 2013 until 2022 [10]

Two particularly important parameters for the further development of the BEV market are the range with a full battery and the BEV battery capacity. Increasing the capacity of the BEV battery also increases the maximum range that the BEV can cover. The short range of BEVs compared to CVs represents one of the major obstacles for their development. However, in the last decade, there has been significant development of the battery and an increase in the range. Figure 2.2 a) shows how the BEV range in 2022 increased by more than double in comparison to 2013. Figure 2.2 b) shows the increase in BEV battery capacity. Looking at these two figures, it is noticeable that the BEV range directly depends on the battery capacity. The battery capacity has increased from approximately 30 kWh in 2013 to about 75 kWh in 2022. This increase in battery capacity has been accompanied by a significant improvement in the average range of BEVs, which has grown from 150 km per full charge in 2013 to 350 km per full charge in 2022. Another indicator of the relationship between battery capacity and BEV range can be observed in the years 2016 and 2017. As shown in Figure 2.2 b), there was a decrease in the average battery capacity from approximately 63 kWh in 2016 to about 40 kWh in 2017. This reduction in battery capacity directly resulted in a decrease in the maximum range of the BEVs. Specifically, the range dropped from approximately 270km per full charge in 2016 to about 225 km per full charge in 2017, see Figure 2.2 a).



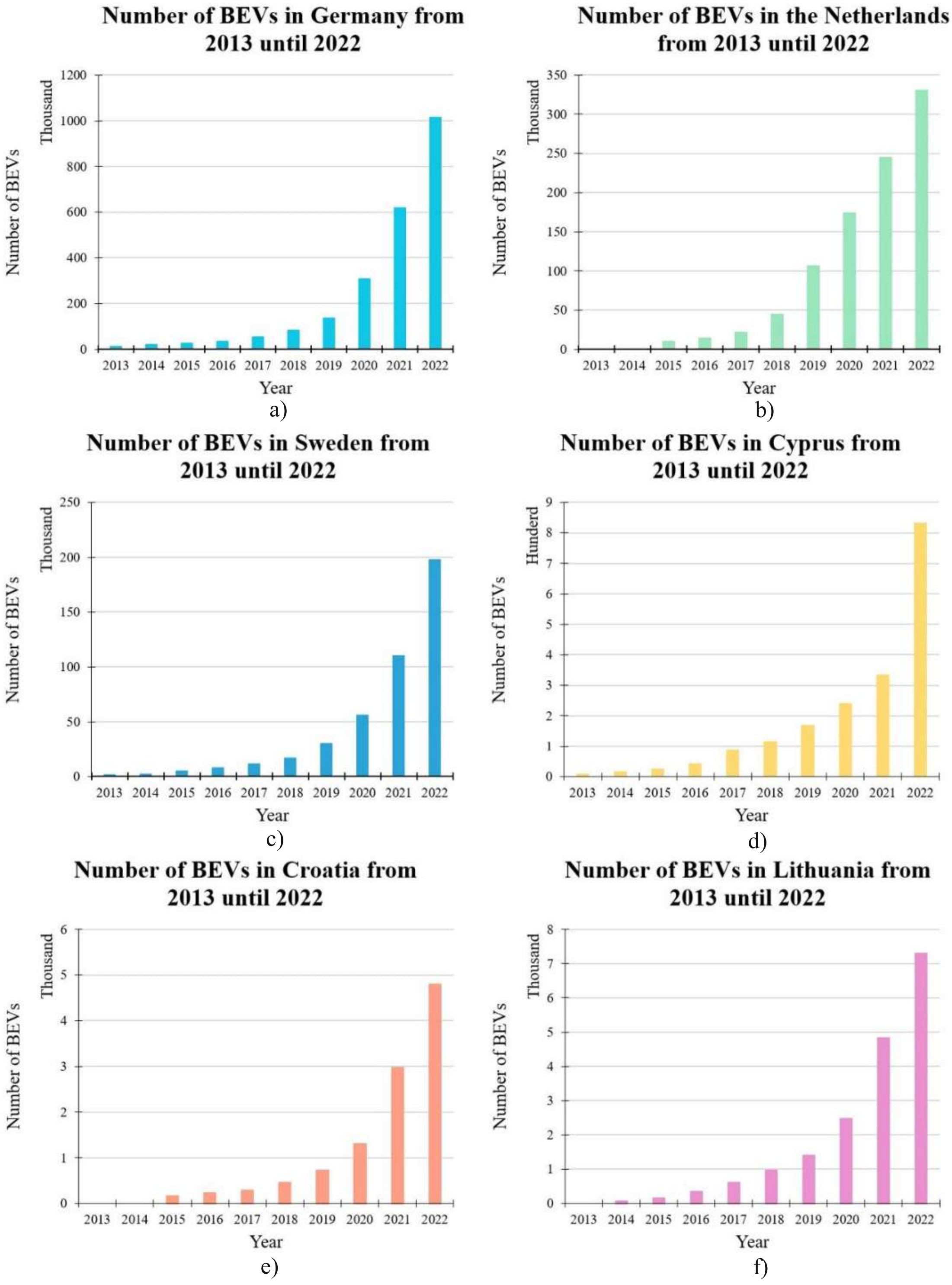
a) b)

Fig. 2.2 - a) Average range and b) average battery capacity of available BEV from 2013 until 2022 [27]

In the introduction, the number of BEVs per EU member state in 2022 is shown. However, how the number of BEVs in the selected countries developed in the previous decade can be seen in Figure 2.3. In all observed countries there is an exponential growth in the number of BEVs. In 2013, 12,000 BEVs were registered in Germany, while there were only six registered BEVs in Cyprus [3]. In 2022, Cyprus had 830 registered BEVs, while Sweden already had over 1,000 BEVs in 2013 [3]. Croatia exceeded the number of 1,000 BEVs in 2020, while Lithuania exceeded the number of 1,000 BEVs one year prior, i.e., in 2019 [3].

If we compare the number of BEVs in 2015 and 2022, Sweden had the largest percentage increase in the number of BEVs. Although Sweden had five times fewer registered BEVs in 2022 compared to Germany, the growth in the number of BEVs is faster compared to Germany. Cause for this growth can be high GDP per capita, more detail in Chapter 4.

All three observed countries with high GDP per capita have more than several hundred thousand registered BEVs, while the three countries with the lowest GDP per capita, Cyprus, Croatia, and Lithuania, have not yet exceeded the figure of 10,000, especially Cyprus.



a) b) c) d) e) f)

Fig. 2.3 - Number of BEV in a) Germany, b) Netherlands, c) Sweden, d) Cyprus, e) Croatia, and f) Lithuania from 2013 until 2022 [3]

In terms of sales of BEVs, Sweden remains the global leader: a sales penetration rate of 60% is second only to Norway [28]. However, Sweden faces the problem of a mismatch between sales of BEVs and charging infrastructure. User satisfaction with charging in Sweden (76%)

is below the world average of 82% [28]. Overall, the country faces an aging grid and is struggling to bring power to its capital cities as demand grows faster than expected.

When it comes to Germany, it is worth mentioning the growth of the charging infrastructure in Germany, which reached a total of more than 97,000 stations [29]. In 2022, the average was 22 cars per point. In 2023, that number decreased to 21 [29].

The Netherlands has more public charging stations per vehicles than any other country, with one station for every five BEVs currently on the road [30]. By September 2021, the total number of regular charging stations increased to 78,279, and fast charging stations to 2,524 [30].

On the other hand, we have Cyprus with only 63 [31], Croatia with 871 [32] and Lithuania with 71 public charging stations [33].

The goal to reach 40 million BEVs by 2023 can be achieved through a series of regulations and targets. There are multiple ways in which the EU encourages the increase in the number of BEVs. Some of the ways are:

- encouraging car manufacturers to produce vehicles with low CO_2 emissions,
- support for the development of a comprehensive charging infrastructure,
- numerous subsidies from individual EU countries, etc. [26].

One of the legislations that stands out among the many introduced legislations is the “Alternative Fuels Infrastructure Regulation” (AFIR) [26]. The main objective of AFIR is to stabilize the EV charging environment in the EU by providing standards and guidelines to all member states.

The most prominent parts of the AFIR regulation are:

- '60 km rule' - member states must install a fast-charging station of at least 150 kW every 60 kilometers along the trans-European transport network (TEN-T) [26]
- charging capacity of at least 1.3 kW per registered BEV [26]
- price transparency - charging stations above 50kW should have prices exclusively based on energy, i.e., per kWh, and clearly indicated to the driver before the start of the charging process [26]
- open data - consumers must have unrestricted access to all information about availability, location, operational status, and price at different charging stations [26]. This

regulation is important to achieve interoperability, and to make the charging system more accessible.

- smart charging - the ability of the BEV charger to communicate with the Charge Point Management System (CPMS) via the cloud. This enables remote monitoring and control of charging devices [26].

There are a lot of other examples of relevant EU legislations, such as:

- Energy Efficiency Directive (EED) - Using energy more efficiently will contribute to reducing the EU's overall energy consumption [34]. Current improvements in energy efficiency should reduce at least 32.5% of total energy consumption in the EU by 2030 [26].
- Renewable Energy Directive (RED) - the legal framework for the development of clean energy across all sectors of the EU economy, supporting cooperation between EU countries towards this goal [35].

3 Method of Approach

In this thesis, parameters such as purchase costs, recharging/refueling costs, insurance, maintenance, and taxes are analyzed to assess the economic performance of BEVs. Six EU member states are analyzed:

- Germany
- Netherlands
- Sweden
- Cyprus
- Croatia
- Lithuania

A comprehensive approach is taken to determine the NPV of BEVs. NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is typically used to analyze the economic assessment of an investment. NPV will help determine if the purchase of BEV is worth undertaking in comparison with purchase of CV. This method can be used to compare BEVs with CVs in the current conditions of the EU [36].

Figure 3.1 shows all the parameters that are analyzed for the calculation of NPV from BEV and CV. Two types of vehicles are primarily observed:

- Battery Electric Vehicle (BEV)
- Conventional Vehicle (CV)

Within each type of vehicle, i.e., BEV and CV, a distinction is made between:

- small vehicles,
- sedans, and
- SUVs.

Within each of the analyzed groups, three vehicles from different manufacturers are observed. Tables 1 and 2 below show which car models are analyzed [37] and which of their technical characteristics are relevant for the analysis.

To take all parameters into account, and to avoid neglecting some of the factors that can have an especially important influence on the result of the analysis, a hierarchical approach is used.

For each of the selected vehicles, the maximum range of BEVs and CVs, the charging/refueling time as well as the costs are calculated. These parameters are shown with yellow color in Figure 3.1.

When it comes to costs, fix and variable costs are considered (shown in light blue in Figure 3.1). The specific parameters that are analyzed are shown in purple Figure 3.1.

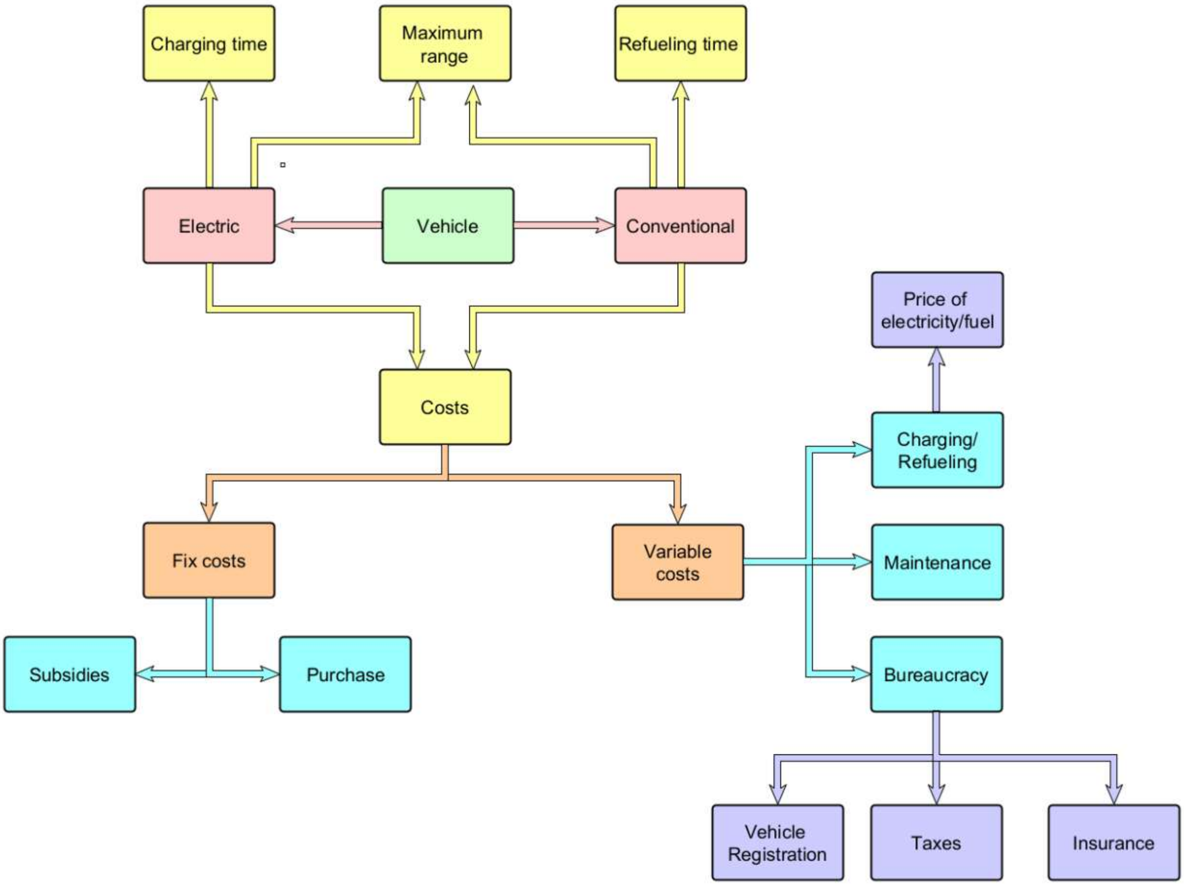


Fig. 3.1 - Structure of all parameters taken into consideration.

Table 1 - Technical parameters of the analyzed BEVs [37] [38]

	Battery Electric Vehicle								
	Small			**Sedan**			**SUV**		
	Peugeot e-208	**Fiat 500e**	**Mini Electric Cooper**	**BMW i5**	**Citroen Ë C4**	**Hyundai Kona Elektro**	**Peugeot e-2008**	**Mazda MX-30**	**BMW iX3**
Complete vehicle curb weight [kg]	1455	1405	1140	2350	1561	1830	1550	1675	2185
Load capacity [kg]	455	400	410	610	459	492	480	444	540
Length [mm]	4055	3632	3850	5060	4355	4355	4304	4395	4734
Width [mm]	1745	1683	1727	1900	1800	1825	1775	1795	1891
Height [mm]	1430	1527	1432	1505	1520	1575	1550	1555	1668
Average electricity consumption [kWh/100km]	16	14.9	17.6	20.8	15.1	16	15.13	19	18.9
Maximum power output [kW]	50	42	32.6	195	54	163	115	50	80
Maximum torque [Nm]	260	220	270	365	270	255	260	271	400
Acceleration to 100km/h [s]	8.1	9	7.3	3.9	10	9.9	9.1	9.7	6.8
Total range [km]	340	303	234	506	420	514	400	200	461

Table 2 - Technical parameters of the analyzed CVs [37]

	Conventional Vehicle								
	Small			**Sedan**			**SUV**		
	Peugeot 208	**Fiat 500**	**Mini Cooper**	**BMW 5**	**Citroen C4**	**Hyundai Kona**	**Peugeot 2008**	**Mazda CX-30**	**BMW X3**
Complete vehicle curb weight [kg]	980	1005	1130	1685	1260	1915	1270	1556	1935
Load capacity [kg]	530	375	540	600	500	555	505	599	615
Length [mm]	4055	3571	3821	4963	4360	4350	4304	4395	4708
Width [mm]	1745	1627	1727	1868	1800	1825	1775	1795	1891
Height [mm]	1430	1488	1415	1479	1525	1585	1550	1540	1676
Average fuel consumption [l/100km]	4.1	3.8	4.9	5.3	4.4	7.5	6.5	5.6	7
Maximum power output [kW]	56	63	100	135	82	152	97	134	213
Maximum torque [Nm]	118	145	220	290	250	265	300	224	650
Acceleration to 100km/h [s]	13.2	11	8.8	8.1	10.5	7.8	9.3	9.2	5.7
Total range [km]	975	920	816	1283	1363	626	676	910	970

4 Gross Domestic Product per Capita of Different European Countries

Gross Domestic Product (GDP) is an important parameter when discussing the development of a country. It is defined as:

“Gross domestic product (GDP) is the total monetary or market value of all the finished goods and services produced within a country's borders in a specific period. As a broad measure of overall domestic production, it functions as a comprehensive scorecard of a given country's economic health. [39] *“*

The higher the GDP, the more developed the country. GDP can be determined using expenditure approach, also known as the consumption approach, which calculates the consumption of diverse groups participating in the economy [39]. This approach can be calculated using the following formula (4.1) [39]:

$$GDP = C + G + I + NX \tag{4.1}$$

where:

- C – consumption
- G – government spending
- I – investment
- NX – net exports

All these activities contribute to the country's GDP. Consumption refers to expenditures for personal consumption or consumer spending [39]. Consumers spend money to buy goods and services. Consumption is the largest component of GDP and accounts for more than two-thirds of GDP [39]. Consumer confidence, therefore, has a significant impact on economic growth. A high level of confidence indicates that consumers are ready to spend, while a low level of confidence reflects uncertainty about the future and unwillingness to spend [39].

Government consumption represents government consumption and gross investments. Governments spend money on equipment, infrastructure, and salaries. Government spending can become more important than other components of a country's GDP when consumer spending and business investment fall sharply [39]. (This can happen after a recession, for example.)

Investment refers to private domestic investment or capital expenditure [39]. Businesses spend money to invest in their business activities. For example, a company may purchase machinery. Business investment is a key component of GDP as it increases the productive capacity of the economy and raises employment levels [39].

The net export formula subtracts total exports from total imports (NX = Exports - Imports) [40]. The goods and services produced by the economy, which are exported to other countries, minus the imports purchased by domestic consumers, represent the country's net exports [39].

However, GDP per capita is the sum of gross value added by all resident producers in the economy plus any product taxes (less subsidies) not included in the valuation of output, divided by mid-year population. Growth is calculated from constant price GDP data in local currency [41].

After the GDP per capita have been defined, the countries are raked according to their GDP per capita so that the development of the BEV market can be compered between the countries with a high GDP per capita and the countries at the bottom of the list. The goal is to determine whether GDP per capita represents one of the important obstacles in the development of BEVs, or whether the situation is different.

Table 3 - Raking of EU countries by annual GDP per capita in €. [42]

	Country	GDP		Country	GDP		Country	GDP
1.	Luxembourg	85,850	10.	France	33,180	19.	Slovakia	16,360
2.	Ireland	77,430	11.	Italy	28,250	20.	Estonia	16,250
3.	Denmark	51,660	12.	Cyprus	27,480	21.	Lithuania	15,100
4.	Sweden	46,170	13.	Spain	24,810	22.	Croatia	14,750
5.	Netherlands	43,800	14.	Malta	24,570	23.	Poland	14,670
6.	Austria	38,080	15.	Slovenia	21,870	24.	Hungary	14,360
7.	Finland	37,560	16.	Portugal	19,310	25.	Latvia	13,220
8.	Belgium	37,050	17.	Greece	18,690	26.	Romania	10,030
9.	Germany	36,010	18.	Czech Republic	18,460	27.	Bulgaria	7,680

To select the countries that will be observed in this thesis, it is necessary to observe GDP per capita with the number of BEVs per 1,000 inhabitants. This is shown in Figure 4.1.

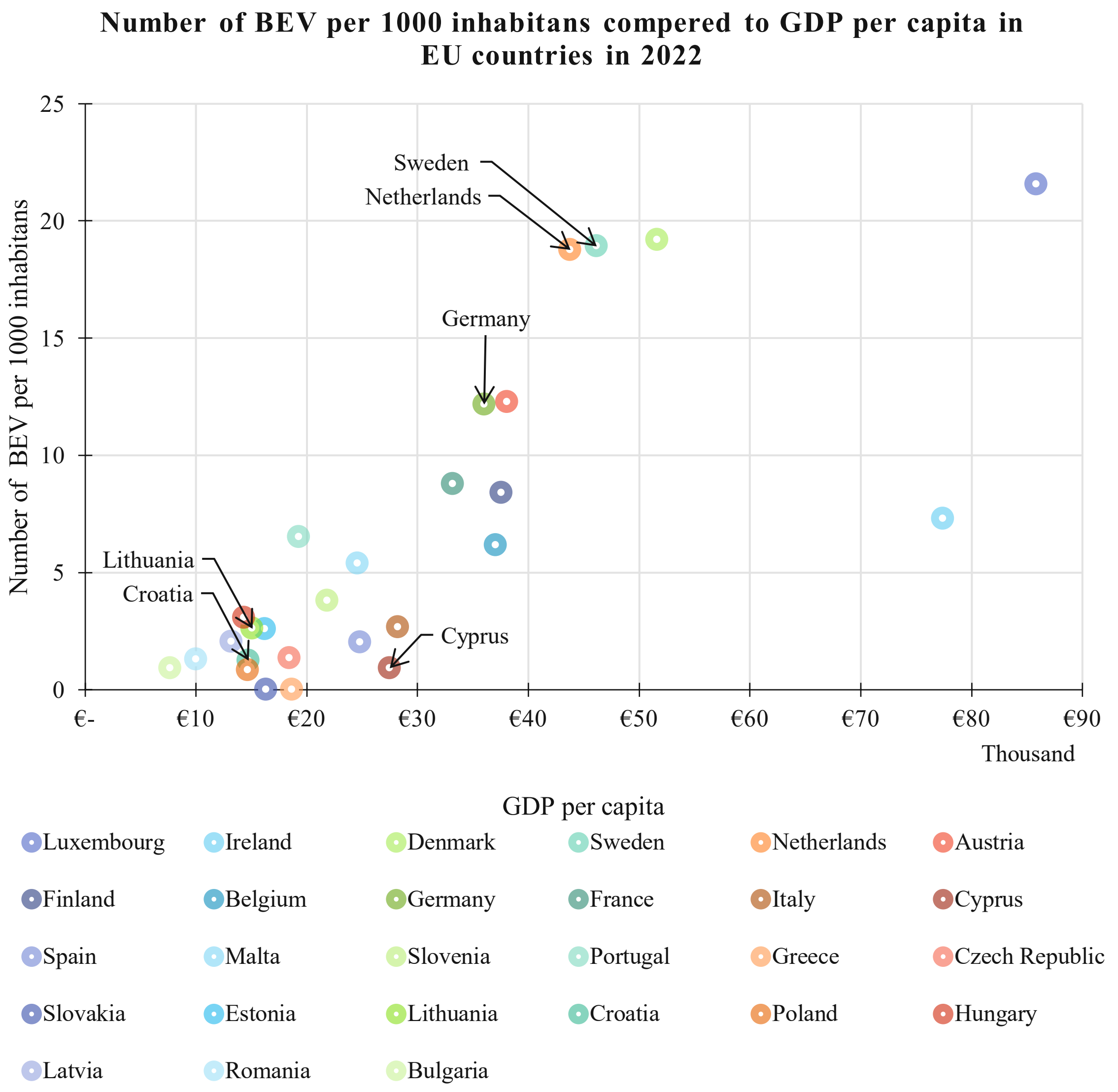


Fig. 4.1 - Number of BEV per 1000 inhabitants compared to GDP per capita in EU countries in 2022 [3] [42]

In Figure 4.1, Cyprus has a small number of BEVs per 1,000 inhabitants compared to a high GDP per capita. Croatia and Lithuania are also countries with one of the lowest GDP per capita and small number of BEVs per 1,000 inhabitants. On the other hand, we have the Netherlands and Sweden with a higher GDP per capita compared to Cyprus, as well as a significantly higher number of BEVs per 1,000 inhabitants. There is also Germany, which has a slightly higher GDP per capita compared to Cyprus, but the number of BEVs is higher. Although Germany has the largest number of registered BEVs at the EU level, it also has a large population, which results in a lower number of BEVs per 1,000 inhabitants compared to the Netherlands and Sweden. These six countries were selected for a more detailed analysis, which will be discussed in Chapter 8.

5 Generation of Electricity in EU-27

In this chapter the possible scenario of the total annual generation of electricity by sources until 2050, as well as the costs of electricity are analyzed.

5.1. Scenario of the Total Annual Generation of Electricity by Source until 2050

The fleet of power plants in Europe has been evolving over many decades. Fossil fuels dominated the sector of electricity generation. The current climate debate is impacting electricity generation. A total of 10 EU countries have decided to phase out the generation of electricity from coal to limit the negative effects of high emissions [43]. Well-known and proven technologies are available for the future: gas-fired power plants, renewable energy sources and nuclear power plants.

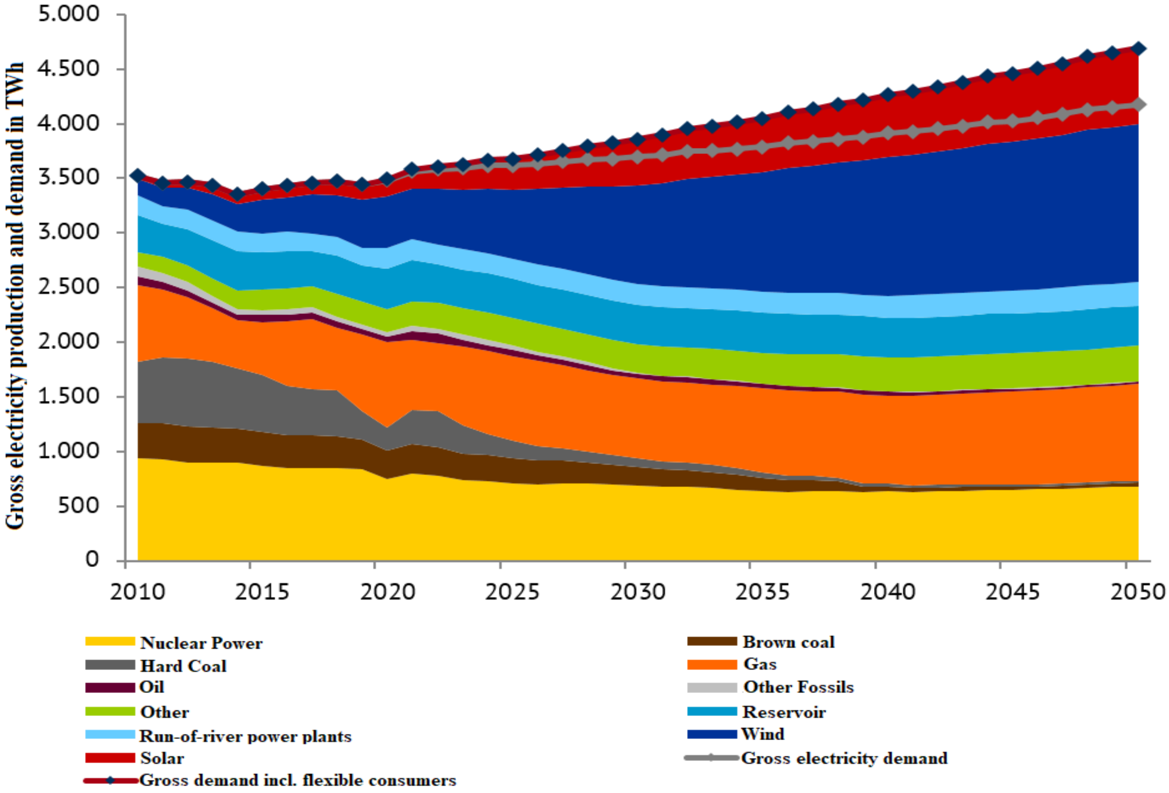


Fig. 5.1 - Gross electricity production and demand for energy sources EU-27 [44]

Figure 5.1 is stacked area chart that represents the gross electricity generation and demand in Terawatt hours (TWh) from 2010 to 2050. The chart is divided into different colored areas, each representing a source of electricity generation.

This chart provides insights into energy strategies and potential shifts towards renewable sources over fossil fuels. It visualizes predictions or plans for how different energy sources will contribute to overall electricity generation over time while also showing expected trends in electricity demand. It is noticeable that the amount of electricity generated from hard coal, as well as brown coal, could be reduced to a minimum at the EU-27 level by 2050. During the same period, considerable progress could take place in the field of wind and solar power plants.

The amount of electricity generated from wind and solar panels could see an increase. This is the consequence of reduced costs in the last 10 years. In the "EU Energy Outlook 2050", the share of renewable energy sources will increase to about 65% of the total supply capacity by 2050 [44], see Figure 5.1.

Gas power plants will primarily be built at the European level in the future. This is due to lower emissions compared to coal-fired power plants [44].

Overall, the share of generation capacity of controllable thermal power plants will decrease from the current 47% to about 24% by 2050 [44]. This significantly affects the structure of electricity prices, which are increasingly characterized by renewable energy sources.

The amount of electricity generated from coal is declining as already seen from 2010 and 2020 and this trend will continue until 2050. Decrease by about 58% by 2030 and by about 91% by 2050 is expected [44]. Generation from gas will increase by about 25% where wind and solar systems will generate about 46% of electricity until 2050 [44]. 80% of electricity will be generated without emissions.

5.2. Costs of Electricity

Electricity costs have a significant impact on the economic assessment of BEVs. To conduct the economic assessment of BEVs, it is necessary to first perform an analysis of the changes in electricity costs.

The prices of primary energy and CO_2 are particularly relevant for the development of electricity prices for the period from 2024 to 2050.

Figure 5.2 is a line graph that represents the forecast of electricity prices and the range of fluctuations in individual markets from 2021 to 2050. The graph has a horizontal axis labeled with years from 2022 to 2050 and a vertical axis labeled with electricity prices marked from 0 to 140€/MWh.

The blue line indicates the Baseload-Price, which shows a sharp decline from just under 120€/MWh in 2022 to around 70€/MWh in 2024. It then gradually decreases, reaching slightly above 60€/MWh by 2030. The calculated electricity prices increase from 60 €/MWh in 2030 to approximately 80 €/MWh between 2030 and 2050, see Figure 5.2. This is an increase of 12.5% compared to 2024. Due to rising CO_2 prices, electricity prices could continue to rise from 2030 [44]. However, due to the large-scale development of photovoltaics and wind power plants, the rise in electricity prices will slow down.

Additionally, there are red error bars at certain points along the blue line representing the range of fluctuation in individual markets; these bars indicate variability within each year's price forecast.

Due to the movement of commodity prices, countries with a weak expansion of renewable energy sources record a higher increase in electricity prices [44].

This graph is interesting as it provides insight into expected trends and uncertainties within the electricity market.

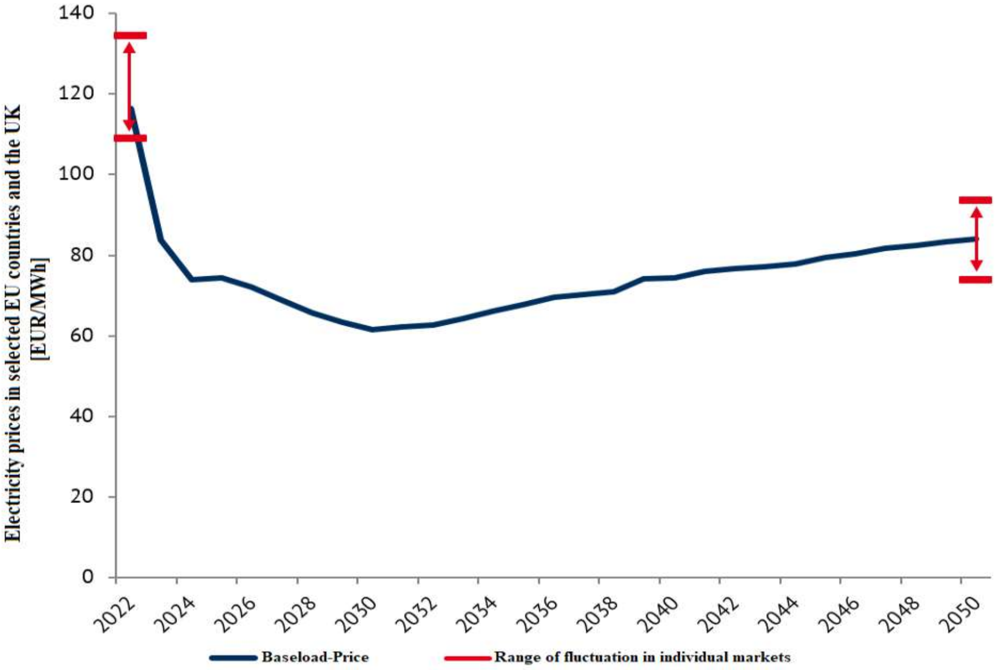


Fig. 5.2 - Annual baseload prices in the day-ahead markets and range of fluctuation in national individual markets of selected countries in Europe on average [44]

6 Battery Electric Vehicles

The changes in the way vehicles are driven is important. Because more than 17% of the total global GHG emissions are caused by transportation. Over the past decade, vehicle manufacturers have introduced many alternative engines to replace CVs. One of these alternative vehicles is battery electric vehicles (BEV). However, BEVs require many specialized parts such as: battery, electric motor (EM), motor controller, regenerative brakes etc. [45].

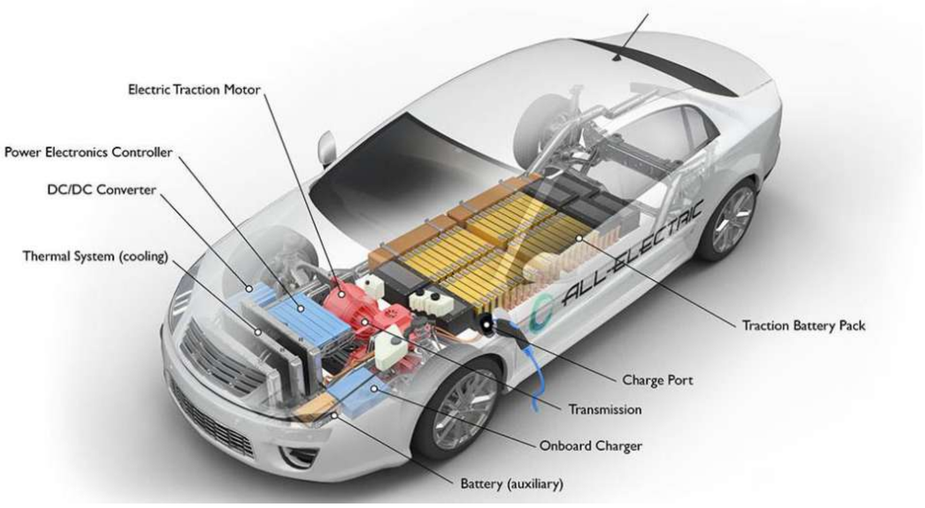


Fig. 6.1– Important parts of BEV [46]

However, how do they work? In BEVs, electrical energy is converted into mechanical rotational energy by EM, where the rotational energy is applied to the wheels of the vehicle via a suitable transmission system [47]. EM powers the vehicle using electrical energy stored in the battery [45]. EM can function as a built-in generator for the battery. EM produces electricity when braking [45]. BEVs have many other advantages. They are more efficient than CVs, BEVs converting about 80% of the energy it uses into usable power, while CV only convert 20% [45]. High durability, minimal maintenance costs, low noise level at low speeds are just some of the advantages.

BEVs also have a regenerative braking system. The regenerative braking system is a system in which part of the energy that would be converted into heat and lost during standard braking is converted into electrical energy and charges the battery [45]. Such systems include a small electrical generator as part of the vehicle's braking system; they must be used in conjunction with conventional friction brakes [45]. In addition to the fact that the energy is used up completely and that they improve the overall energy efficiency of the vehicle, an additional advantage of regenerative brakes is the extension of the service life of the vehicle's braking system because its parts do not wear out so quickly.

As already said, there are no exhaust gas emissions while driving a BEVs. This helps improve local air quality. The environmental benefits occur when BEVs are powered by electricity from renewable sources. What would be an ideal case, however, in 2014, around 30% of the total electricity generation in the EU was from renewable sources. In addition to that, since electricity is mostly generated from non-renewable sources, the amount of GHGs is smaller.

BEVs still have a limited driving range compared to CVs and usually require a long time to recharge the vehicle's batteries.

6.1 Types of Electric Motors

Diverse types of EMs are used in BEVs. What type of motor is used inside a BEV depends on the choice of the design engineer or depending on the purpose of the BEV. Over the years, there has been significant research in the field of EMs and diverse types of AC and DC motors have been developed. This gives BEV manufacturers a wide range of different EMs to choose from according to their requirements. Choosing a specific type of engine for a BEV must be considered because the characteristics of the engine affect the overall performance of the vehicle. What creates the current problem is the high production costs of the EMs themselves. However, it is reasonable to expect their reduction in the future thanks to more efficient production systems, improved design, and smaller engines.

Diverse types of motors have different characteristics, which is why it is important to evaluate motors according to some basic parameters for choosing a specific type of motor for a BEV. EMs used in BEVs should have important attributes such as simple design, high specific power, minimal maintenance costs and good controllability.

Motors widely used by BEV manufacturers are:

- DC brushed motors,
- brushless DC motors,
- induction (asynchronous) motor,
- synchronous motor and
- reluctance motor.

6.1.1. DC Brushed Motor

In the case of a brushed DC motor, the connection between the external supply circuit and the motor's armature is achieved through brushes along with commutators. These brushes are made of carbon, copper, carbon graphite, metal graphite and are mostly rectangular in shape [47]. One of the main disadvantages of this type of motor is the wear of the commutator due to continuous brush cutting. Friction between the brushes and the commutator is a factor that limits the maximum speed of the motor. Brushed DC motors can achieve high torque at low speeds, which makes them suitable for traction systems [47]. Depending on the output power and rated voltage, brushed DC motors can have two, four or six poles, and the field winding can be series or shunt connected. Poor power density compared to a PMSM (Permanent-magnet- synchronous motor) or BLDC (Brushless direct current motor) motor is another disadvantage of a brushed DC motor for use in BEVs [47].

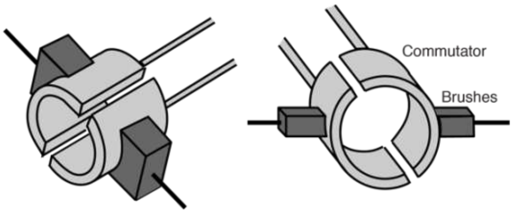


Fig. 6.2 - Bruch and commutator [48]

6.1.2 DC Brushless Motor

A brushless DC motor offers certain advantages over a brushed DC motor, such as less maintenance and higher efficiency. Mechanical commutation as in brushed DC motor is replaced by equivalent electronic commutation (inverter circuit and rotor position sensing element) in brushless DC motor [49]. BLDC motor is defined as a rotating self-synchronous machine with a permanent magnet rotor and known rotor shaft positions for electronic commutation [50]. Figure 6.3 shows the basic arrangement of the stator, rotor, and position sensor in a BLDC motor. The BLDC motor provides higher torque at peak current and voltage values compared to other motors [51]. Due to better working characteristics at higher speeds, these engines are used in compressors, pumps, and ventilation systems [47].

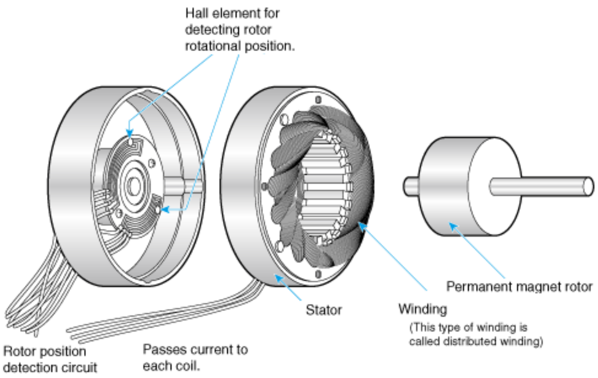


Fig. 6.3 - Basic arrangement of rotor and sensor elements in BLDC motor [52]

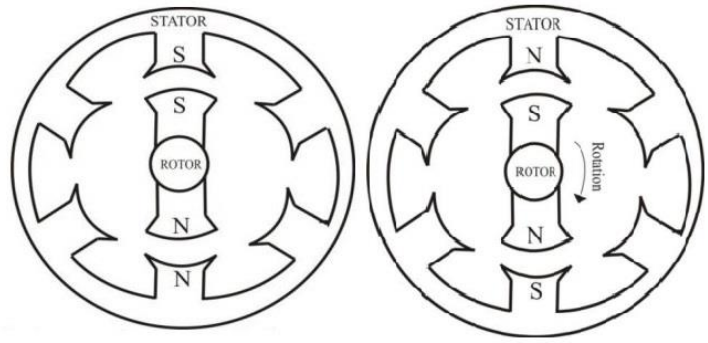
6.1.3 Induction (Asynchronous) Motor

Due to high efficiency, good speed regulation and the absence of a commutator, three-phase induction motors are widely used in BEVs. A three-phase AC power supply is connected to the stator winding, due to which a rotating magnetic field is established. This rotating magnetic field interacts with the stationary rotor conductors, and the induced current flows through the rotor conductors [47]. The induced current establishes its own magnetic field. The interaction between the revolving magnetic field and the field caused by the induced currents gives rise to unidirectional torque. The name asynchronous motors come from the fact that the speed of the rotor is lower than the speed of the rotating field.

6.1.4 Synchronous Motor

The rotor is excited from the DC power supply, while the stator is connected to a three-phase AC supply. Because of this, there is a continuous change in the polarity of the stator poles, while the polarities of the rotor poles are constant. If initially the stator and rotor are positioned so that they have polarities as shown in Figure 6.4 a). At this moment, the S pole of the rotor is repelled from the S pole of the stator. Now, during the second half cycle, the stator poles will change their polarities and now the S-pole of the rotor will be attracted towards the N-pole of the stator. Therefore, the rotor will experience a pulsating torque and will not rotate in any direction due to the inertia of the rotor. Therefore, the synchronous motor has no self-starting torque.

Now, if the rotor is rotated by external means such that the rotor poles are continuously influenced by the stator poles of opposite polarity even with a continuous change in polarity, the rotor will start rotating in one direction [47]. Figure 6.4 b) shows the S-pole rotor and N-pole stator connected to each other and the rotor rotating clockwise. Now, even if the external means are removed, the rotor and stator poles are locked together, and the rotor will rotate at synchronous speed. The rotor should rotate at such a speed that it moves through the tilt distance of the pole within half the power time [47]. Due to its high efficiency and high torque density, the synchronous motor finds its application in servos, wind turbines and EVs.



a) b)

Fig. 6.4 - Rotor and stator poles have a) same polarity b) opposite polarity. [47]

6.1.5 Switched Reluctance Motor (SRM)

A switched reluctance motor produces torque using the variable reluctance method. When the stator coils are energized, a variable resistance is created in the air gap between the stator and the rotor. The rotor tends to move to the position of least reluctance, which causes torque [47]. The switched reluctance motor has characteristics such as high starting torque, wide speed range, and good inherent fault tolerance capability, which makes it suitable for EV applications.

6.2 Battery

Both CV and BEV must have a battery to power the vehicle. Battery is a key component of the BEV. The BEV-battery should be able to power the EM. For the battery to be able to perform this function and all additional functions inside the vehicle, it must have a higher energy storage capacity, which results in them being larger and heavier in a physical sense, and more expensive in a financial sense.

Depending on the type of BEV, batteries have different technical characteristics that determine how much electrical energy is stored as well as how quickly the stored energy can be released and made available to power the vehicle. Battery efficiency can be defined using several measures, including:

Energy density: a measure of how much electrical energy can be stored per unit volume or mass of a battery. This measure is relevant to the range of the vehicle, since batteries with higher energy density can usually power the vehicle over longer distances.

Power density: a measure of power per unit volume, i.e., how quickly a battery can deliver or receive a charge. This measure is more relevant to driving performance, i.e., acceleration and driving speed and charging times [13].

Power-to-Energy ratio (P/E) shows how much power per unit of energy is required for an application, see Figure 6.5. Well, since BEVs use only EM that is powered from the battery, these batteries require more energy capacity due to a longer driving range, so BEVs have the lowest P/E factor compared to other types of vehicles [53].

Also, BEVs require that the battery has a durability of 1,000 deep cycles [53]. The deep cycle means one cycle where the battery is completely discharged and then fully charged [53]. Furthermore, even if batteries are used according to the manufacturer's instructions, they lose capacity over time due to aging and repeated charging cycles. The development of improved battery technologies is a top priority for further research and development.

Most BEVs use Li-Ion batteries. Li-Ion batteries are the most common type of battery in BEVs today. Compared to other battery technologies, Li-Ion batteries have a high energy density, although they only provide about one-tenth the energy density of fuels used for CVs [45]. This characteristic also allows them to be lighter and smaller than other rechargeable batteries.

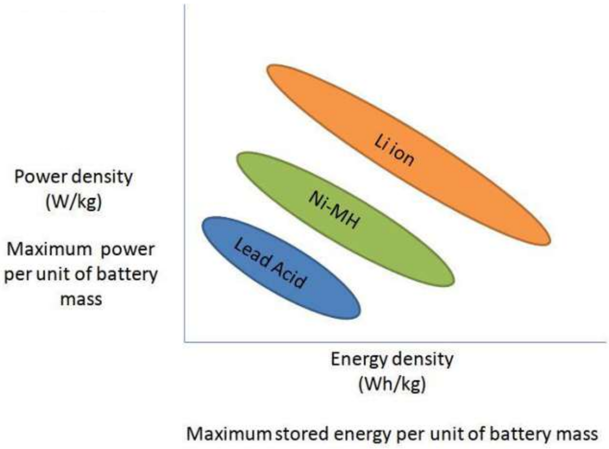


Fig. 6.5 - Power and energy by battery type [53]

They also have a low self-discharge rate, i.e., how much energy is lost over time that it cannot be used for driving. Such batteries can usually last about 10 years and can be charged up to 3,500 times [53]. Li-Ion batteries can also operate over a wide range of temperatures, although they are less efficient in extreme heat and cold. Most Li-Ion batteries can only be charged between 0 °C and 45 °C [45]. To protect the batteries, some vehicles include a heating and cooling system to ensure that the charging and operation of the battery takes place within the optimal temperature range [45]. Other advantages of Li-Ion batteries compared to lead-acid and nickel-metal hydride batteries include high energy efficiency, no memory effects, and a long lifetime. However, the cost of manufacturing Li-Ion batteries is high, and the cost of the battery can be a significant part of the total cost of a BEV.

The main drawbacks of currently available Li-Ion battery technologies are their still limited energy density and high production costs. Cost reduction can be achieved by developing the so-called the second generation of Li-Ion batteries, as well as the optimization of production processes with economies of scale, innovative production, waste reduction and the potential use of alternative, cheaper materials [45]. To significantly improve the range of electric driving, various battery technologies such as lithium-sulfur or solid-state batteries are also being investigated. Such technologies could potentially significantly increase battery capacities compared to current Li-Ion battery technologies. However, these modern technologies are still in their initial stages and do not yet meet current battery life and security requirements. Their durability is expected to improve in the future, but their performance at different temperatures is currently very uncertain.

6.2.1 How Does a Lithium-Ion Battery Work?

A Li-Ion battery is a rechargeable battery in which lithium ions move between the anode and cathode, creating a flow of electricity useful for electronic applications. In the discharge cycle, the lithium in the anode (carbon material) is ionized and emitted into the electrolyte. Lithium ions pass through a porous plastic separator and are inserted into atomic-sized holes in the cathode (lithium metal oxide) [53]. At the same time, electrons are released from the anode. This becomes an electric current that travels in an external electric circuit. During charging, lithium ions go from the cathode to the anode through a separator, see Figure 5.6. Since this is a reversible chemical reaction, the battery can be recharged.

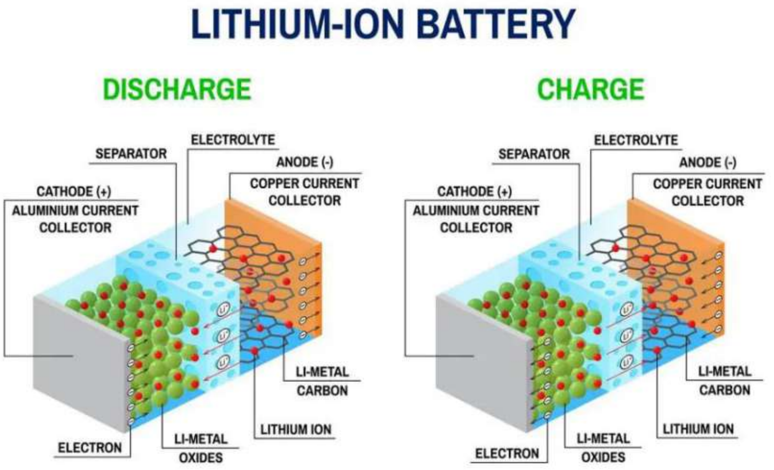


Fig. 6.6 - Charging/discharging mechanism of Li-Ion Battery [54]

6.2.2. Technological and Cost Challenges

The current performance of lithium-ion batteries is not sufficient for widespread use in BEVs. Along with the necessary increases in energy density and power (performance), other improvements in durability, safety, and cost are needed.

Durability: Batteries in BEVs must have reliable endurance for deep cycles to maintain a longer life. Vehicle manufacturers aim to develop Li-Ion batteries with a guaranteed five-year or 100,000 kilometers of driving. Deep cycles of a Li-Ion battery quickly reduce battery capacity, but BEVs will charge after the energy stored in the battery is depleted [53].

Safety: Li-Ion batteries are sensitive to short-circuiting and overcharging. Lead-acid batteries, Ni-Cd and Ni-MH batteries work safely even after short-circuiting and overcharging because they have a low energy capacity and use a flammable electrolyte. However, when a lithium-ion battery is short-circuited, large currents of electricity are generated and the temperature of the battery rises to several hundreds of degrees within seconds, heating the adjacent cells and resulting in the entire battery burning reaction. When Li-Ion batteries are inadvertently overcharged, the chemical structure of the anode and cathode is destroyed, and some of the lithium ions form snowflake-shaped lithium metal deposits called "dendrites," which can cause the battery to short circuit or, worse, explode and catch fire [53]. Impurities in lithium metal can also contaminate batteries and cause dendrites to form, potentially causing short circuits and explosions. To prevent overcharging, Li-Ion batteries must be sold as battery packs with very precise voltage control systems. In other words, cells cannot simply be installed into a specific electronic application. Although Li-Ion batteries have several safety measures, further safety measures need to be developed for vehicle use.

Cost: The cost of Li-Ion batteries for use in vehicles is a critical concern. According to the latest available estimates for vehicle batteries, the cost of Li-Ion is four to eight times higher than the cost of lead acid battery and one to four times higher than Ni-MH battery. However, the price of Li-Ion batteries is expected to decrease significantly. As the market grows and production increases, manufacturers can enjoy economies of scale. The price of Li-Ion batteries decreases every year, for comparison, in 2013 the price was 700 €/kWh, while in 2023 it was 143 €/kWh [53].

6.2.3. Charging

As already emphasized in the Chapter 6.1, BEVs are powered by EMs, which are powered by a battery. The battery must be charged for the vehicle to be in driving condition. There are three basic ways to charge a BEV.

- wireless charging
- battery replacement
- plug-in charging.

All these three types of charging are explained in following Chapter 6.2.3.1.

6.2.3.1 Wireless Charging

Wireless charging, also known as induction charging, as the name suggests, does not require a physical connection between the charger and the BEV. The principle of electromagnetic induction is used, so electricity can be transmitted through the air as a magnetic field. This means power can be sent from one device to another without physical contact but provided charger and the vehicle needs to be in proximity. In this case, a localized electromagnetic field is created in the pad of the charging station, which is activated only when the vehicle is placed above it. To charge the BEV, it is necessary that it also has a suitable pad, to activate the electromagnetic field.

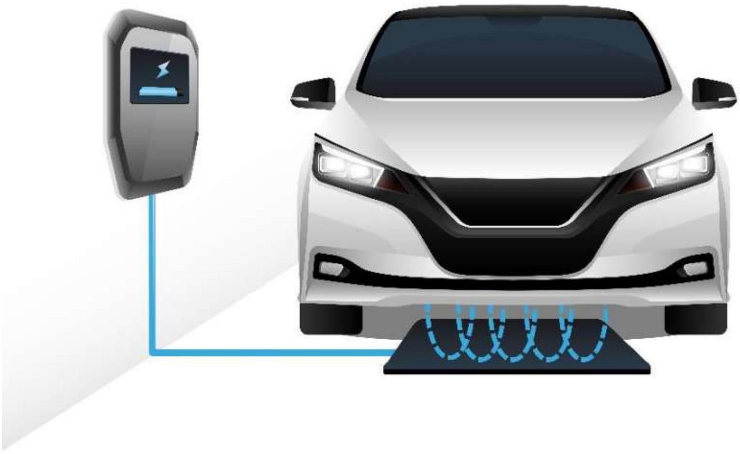


Fig. 6.7 - Wireless charging of BEV [45]

This type of charging could change the hole game for the automotive industry. The technology itself is very promising, and it could make charging of BEVs more convenient for consumers. Consumer would not be needed to step out of the vehicle, which could get more consumers interested in switching to electromobility.

Contactless charging promise to increase reliability, safety, and availability while at the same time making the experience more comfortable for BEV drivers.

This method of charging is still in the test phase. Siemens has been active in wireless-charging research for a decade, working on a prototype and advancing the technology in the past few years.

Volvo is testing wireless charging technology in Gothenburg in a live city environment as well. They use a 360-degree camera system to align the car with the charging pad. The producer pitched the service as quick and convenient, saying that the charging speeds are four times faster than a wired 11kW AC charger and as fast as a wired 50kW DC fast charger.

The technology is safe and effective. Optimized power electronics and coil designs keep energy loss to a minimum, meaning that wireless-charging systems are 90-93% efficient. As these systems keep evolving, this figure could rise to be on par with conductive charging, which has an efficiency rate of around 94-96% [55].

Another advantage is vehicle-to-grid (V2G) connectivity. BEV sales have seen increases around the globe and protecting energy infrastructure is key to supporting power systems. Wireless charging can play its part in relieving the grid by distributing the demand for energy throughout the day. But right now, it can only be used for charging electric buses at bus stations in Belgium, Germany, and the Netherlands.

How the block diagram of a BEV wireless charging system look like is shown in Figure 6.8. This block diagram consists of several blocks. Starting from the primary side, electrical power from the mains supply is first rectified into a DC voltage to maximize its real power using an AC/DC rectifier and a power factor correction circuit (PFC) [55]. This DC signal is then input into a high-frequency inverter to be up-converted to the operating frequency of interest. Compensation networks are then required to help operate the inductive link in resonance conditions [55]. On the secondary side, an AC–DC rectifier is utilized after the LCC compensation, to convert the coupled AC power to DC power that can charge the BEV battery. Between the rectifier and the battery, a DC/DC converter may be used to aid in the output power control process [55].

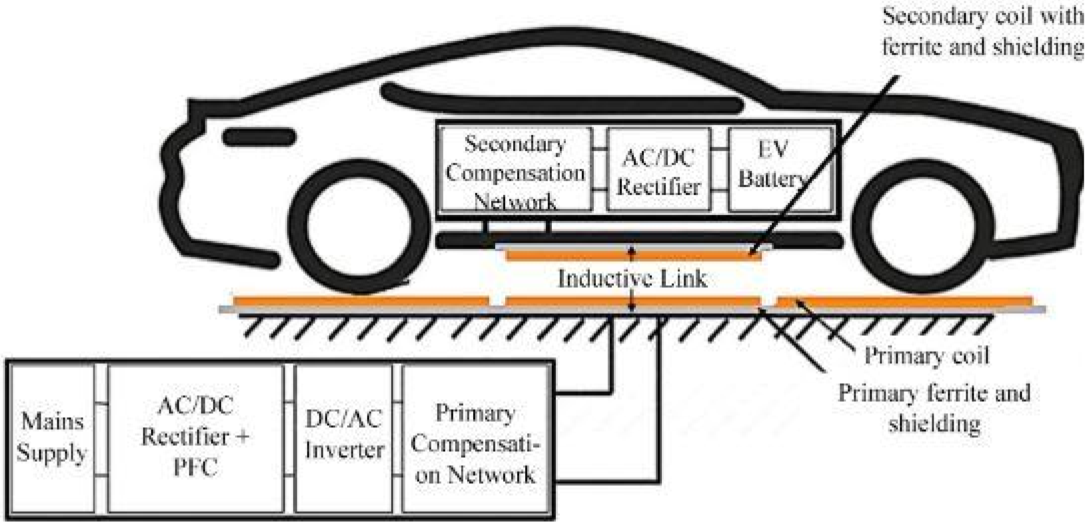


Fig. 6.8 – Block diagram of a BEV wireless charging system [55]

6.2.3.2. Battery Swapping

Another way of "charging" would be by completely replacing the battery. This would theoretically be the fastest way to "charge" the vehicle. This means a station where BEVs would be allowed to replace a discharged battery with a charged one. This would represent an alternative for vehicles with plug-in charging.

Currently, no major supplier in Europe offers battery replacement. However, China has made a big step towards the development of battery replacement. Why is battery swapping so successful in China? Well, mostly because of the strong government support. The exchange stations also benefit from the strict, state-controlled battery standards.

In May 2020, China included the development of battery swapping stations in its "New Infrastructure" campaign, a national project to offset the economic impact of the pandemic and promote sustainable growth [56].

Although China is very developed when it comes battery swapping, a few barriers have prevented the widespread adoption of battery swapping technology, including the lack of BEV models that support battery swapping, the lack of a standard battery type or size, and the high cost of developing the associated charging and swapping infrastructure [45].

6.2.3.3. Plug- In Charging

The third and at the same time the most widespread method of BEV charging is Plug-In charging. Unlike wireless charging, where no physical connection is required between the charging station and the BEV, in this case the vehicles are physically connected to the charging station using a cable and socket. The advantage of this charging method is that it can be charged wherever there are charging stations: in homes, on public streets, in business or private spaces. While the current shortcoming is the insufficiently developed infrastructure of the charging stations themselves. The Netherlands, as a leading country in the number of charging stations, has just over 80,000 stations [30]. In comparison with the number of BEVs, which in 2020 in the Netherlands was approx. 273,000 [3]. It can be concluded that even this probable number of charging stations is insufficient to charge all BEVs at the same time. BEVs can also be connected to the most common household sockets, but this method of charging is slow and can last over 8 hours, depending on the capacity of the battery itself.

Faster plug-in charging requires specialized infrastructure. To date, most public charging stations established at city, regional or national level only offer normal fast charging. At a charging speed of 10kV, charging for an average BEV would take an average of 2-3 hours.

As is already known, electrical networks provide AC current, while batteries only store DC current, this would mean that the electricity coming from the network must first be converted to charge the battery. This is achieved by installing an AC/DC converter inside the BEV itself or in the charging station itself. Chargers that have integrated converters are called DC fast chargers [45].

There are four ways of plug-in charging technology. Each of the methods can have different combinations of the power level delivered by the charging station, the type of electricity used and the type of plug. The power level depends on the voltage and the maximum current of the supply, and this depend on how quickly the battery is charged. Currently, there are charging stations in the range from 3.3 kW to 120 kW. In some Scandinavian countries the charging stations above 120 kW are being installed.

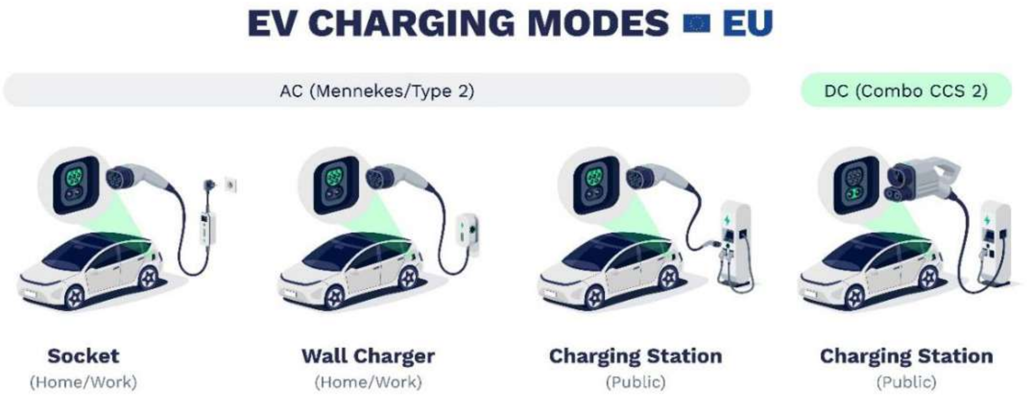


Fig. 6.9 - EV charging modes in EU [45]

Mode 1 - slow charging: allows the vehicle to be charged using common household sockets and cables. It is usually found in residential or commercial buildings. A typical charging power level is 2.3 kW. As household sockets have AC, it is therefore necessary for the BEV to have a built-in AC/DC converter.

Mode 2 - slow or semi-fast charging: also uses a non-dedicated socket, but with a special charging cable supplied by the car manufacturer. A protective device built into the cable ensures the protection of electrical installations. It enables AC, so even in this way of charging, an AC/DC converter is necessary.

Mode 3 - slow, semi-fast or fast charging: uses a special socket and a dedicated circuit that allows charging at higher power levels. Charging can be done through a box mounted on the wall (wall box) which is usually used in residential areas or on a free-standing pole which can often be seen in public places. It uses dedicated charging equipment to ensure safe operation and provides AC.

Mode 4 - fast charging: also, sometimes called 'off-board charging', delivers DC to the vehicle. As previously emphasized, in this method of charging, the AC/DC converter is integrated into the charger, instead of inside the vehicle as with other methods. One disadvantage of high-power fast charging is that higher currents mean more electrical energy is lost during transmission, i.e., the efficiency is lower. Also, fast charging can lead to a shortening of the life of the battery itself, thus reducing the number of total charging cycles. DC fast charging points are also about three times more expensive to install than a simple AC charger, so many users are reluctant to invest in the extra expense. While some new BEV models can be charged with DC, others require the purchase of an additional charging device. In Figure 6.10 are shown different powers of charger and their charging time, as well as their location.

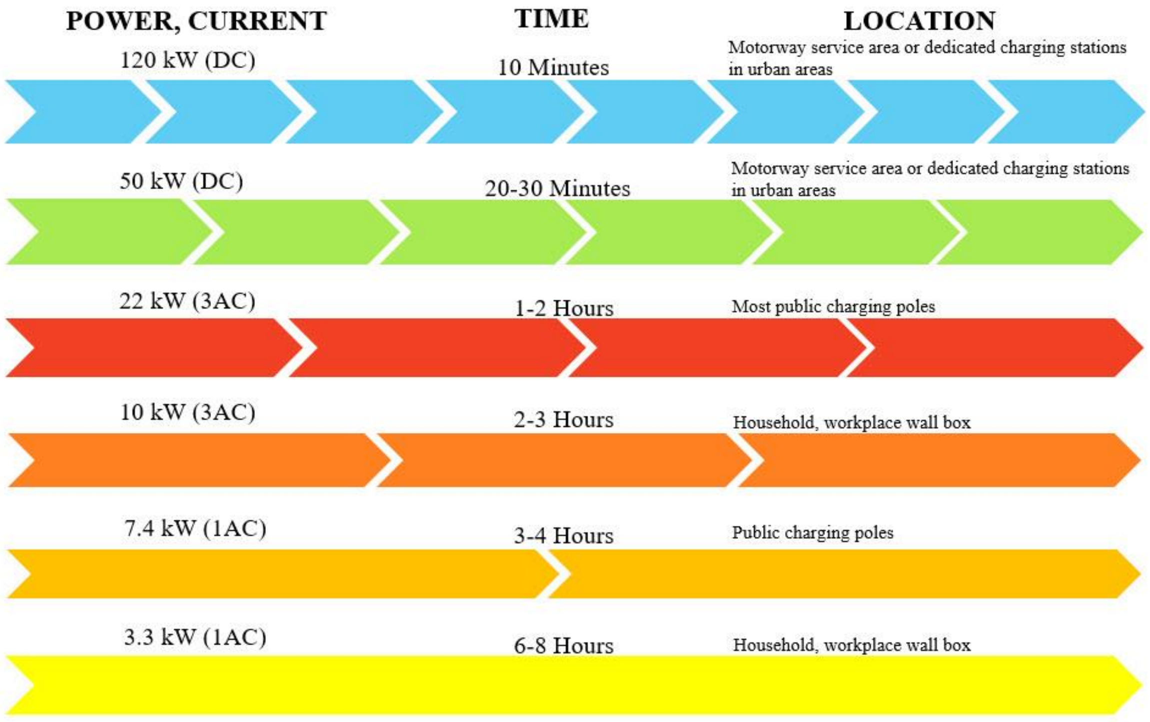


Fig. 6.10 - Charging time at different charging power and type of current [45]

6.3 Charging Time

One of the most important parameters for the development of the BEV market is the battery charging speed. The time-consuming charging of the battery is a main argument against BEV. However, why is this so and is this argument justified?

As it was discussed in Chapter 6.2.3 about charging methods, plug-in charging is the most common charging method for BEVs, both in the EU and globally. As part of plug-in charging, there are different power levels of chargers, from 3.3kW up to 120kW, see Figure 6.10.

In this Chapter, is analyzed how much time is needed, for diverse types of charging, until the batteries are fully charged for each of the observed vehicles.

The period for which the battery is fully charged depends on several parameters:

- **Charging power** – measured in kW, determines the rate at which the BEV charger can deliver energy to the battery [57].
- **Battery capacity** – measured in kWh, the battery capacity determines the amount of energy the battery can store [57].
- **State of charge (SOC)** – denotes the capacity that is currently available as a function of the rated capacity [58].
- **Charging efficiency** – accounts for energy losses during the charging process, which typically range from 94 to 96% [53].
- **Battery age**
- **Functionality of charger and battery**

Given that the battery and charger are fully functional, the charging time is easy to calculate using the parameters already mentioned. First, the certain assumptions are made.

To determine the charging time, it is necessary to know the current battery charge percentage and the target percentage. These two data are important to be able to determine the required energy. Therefore, research has shown that it is often recommended that a BEV's battery should be charged between 30% and 80% to maintain its state of health (SOH) [59]. So, for our calculation, exactly these values are chosen as SOC. The desired SOC is calculated by subtracting the current energy level from the target energy level, using the following formula (6.1) [57]:

$$E_{required} = C_{Bat} \frac{SOC_{Target}(\%) - SOC_{Current}(\%)}{100} \tag{6.1}$$

where:

- $E_{required}$ – required energy or energy needed to reach the targeted SOC [kWh]
- C_{Bat} – battery capacity [kWh]
- SOC_{Target} – targeted SOC [%]
- $SOC_{Current}$ – current SOC [%]

After that, it is necessary to determine the charging efficiency, which is obtained by simply dividing the required energy by the charging efficiency to determine the actual required energy. The efficiency of modern chargers is between 94 and 96% [53]. For this calculation, the value of 95% is used. The following formula was used during the calculation (6.2) [57]:

$$E_{Actual} = \frac{E_{required}}{\eta_{Ch}} \cdot 100 \tag{6.2}$$

where:

- $E_{required}$ – required energy or energy needed to reach the targeted SOC [kWh]
- E_{Actual} – actual energy needed to reach the targeted SOC [kWh]
- η_{Ch} – charging efficiency [%]

Finally, to calculate the charging time the formula (6.3) [57].

$$t_{Ch} = \frac{E_{Actual}}{P_{Ch}} \tag{6.3}$$

where:

- E_{Actual} – actual energy needed to reach the targeted SOC [kWh]
- t_{Ch} – charging time [h]
- P_{Ch} – charging power [kW]

For a better understanding, the charging time is calculated on the example of the Peugeot e-2008. Peugeot e-2008 has battery capacity of 54kWh. If it is assumed that the current SOC is equal to 30%, the target SOC is equal to 80%, the charging efficiency is equal to 95%, and the charging power is equal to 3.3kW, i.e., it is AC slow charging, then the charging time is equal to:

$$E_{required} = C_{Bat} \cdot \frac{SOC_{Target}(\%) - SOC_{Current}(\%)}{100} = 54kWh\frac{80-30}{100} = 27kWh$$

$$E_{Actual} = \frac{E_{required}}{\eta_{Ch}} \cdot 100 = \frac{27kWh}{95} \cdot 100 = 28.42kWh$$

$$t_{Ch-AC} = \frac{E_{Actual}}{P_{Ch-AC}} = \frac{28.42kWh}{3.3kW} = 8.612\ h$$

where:

- $E_{required}$ – required energy or energy needed to reach the targeted SOC [kWh]
- E_{Actual} – actual energy needed to reach the targeted SOC [kWh]
- C_{Bat} – battery capacity [kWh]
- SOC_{Target} – targeted SOC [%]
- $SOC_{Current}$ – current SOC [%]

- η_{Ch} – charging efficiency [%]
- t_{Ch-AC} – charging time with AC-charger [h]
- P_{Ch-AC} – AC-charging power [kW]

So, it takes 8.612 hours to charge the Peugeot e-2008 up to 80% of the total battery capacity using a 3.3kW AC charger. For the sake of comparison, a calculation for a DC charger with a power of 120 kW has been made:

$$t_{Ch-DC} = \frac{E_{Actual}}{P_{Ch-DC}} = \frac{28.42kWh}{120kW} = 0.2368\,h\ \cdot 60 = 14.21\,Min$$

where:

- E_{Actual} – actual energy needed to reach the targeted SOC [kWh]
- t_{Ch-DC} – charging time with DC-charger [h]
- P_{Ch-DC} – DC-charging power [kW]

It can be seen; the power of the charger contributes to the charging speed. With a fast charger of 120 kW, it only takes almost 14 minutes. How the charging time on the Peugeot e-2008 example changes depending on the power of the charger is shown in Figure 6.11. It can be shown how the charging time of the Peugeot e-2008 decreases exponentially with the increase in the power of the charger. This trend is also visible in all other analyzed vehicles.

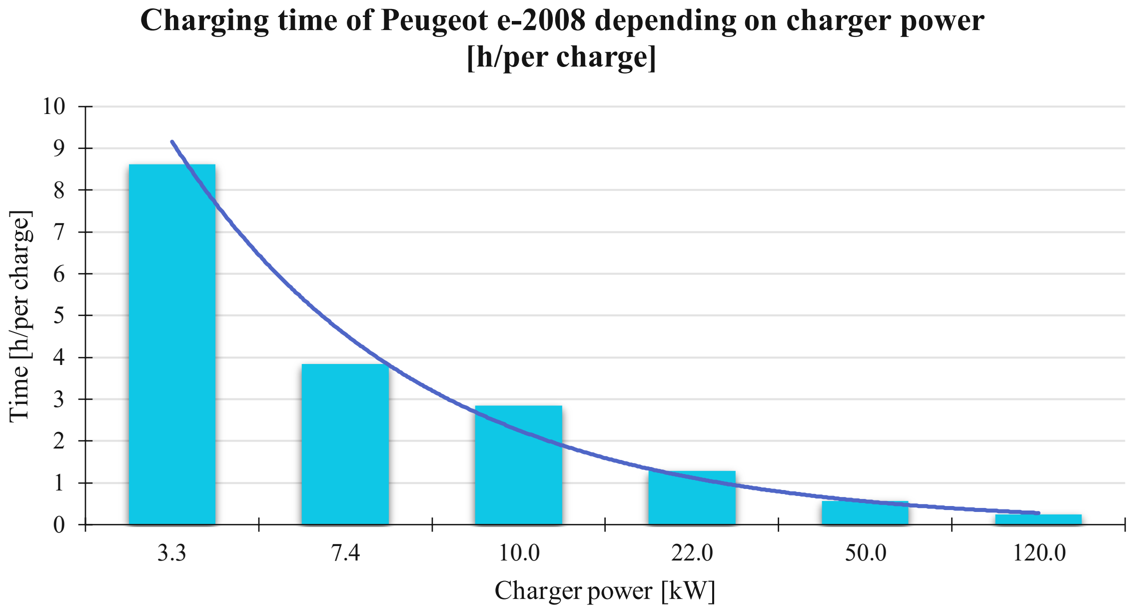


Fig. 6.11 - Charging time of Peugeot e-2008 depending on the charger power. [57]

It can be seen in Table 4 that the charging time using the 3.3 kW AC charger is the longest compared to other charger powers. For all vehicles, except for the Mazda MX-30, more than 6 hours are necessary, and for some, it can take up to 13 hours to charge the battery inside the BEV. The higher the capacity of the battery, the longer it takes to charge it.

It can be noticed that despite the fast charger with a power of 120 kW, most BEVs require a charging time longer than 10 minutes.

Some of the countries also introduced ultra-fast chargers with a charging power of 200 kW. However, fast charging reduces the life of the battery, which can lead to the premature need to replace the battery. Also, DC charging, or fast charging, is also more expensive compared to AC charging. Which is also another negative parameter. How BEV can oppose CV is discussed in more detail in Chapter 9.

Table 4 - Charging time of different BEVs [57]

		Battery Electric Vehicle					
		Small					
		Peugeot e-208		**Fiat 500e**		**Mini Cooper Electric**	
	Charger power [kW]	[h/per charge]	[Min/per charge]	[h/per charge]	[Min/per charge]	[h/per charge]	[Min/per charge]
AC	3.3	7.974	478.47	6.699	401.91	9.314	558.86
	7.4	3.556	213.37	2.987	179.23	4.154	249.22
	10	2.632	157.89	2.211	132.63	3.074	184.42
	22	1.196	71.77	1.005	60.29	1.397	83.83
DC	50	0.526	31.58	0.442	26.53	0.615	36.88
	120	0.219	13.16	0.184	11.05	0.256	15.37
		Sedan					
		BMW i5		**Citroen Ë C4**		**Hyundai Kona Elektro**	
	Charger power [kW]	[h/per charge]	[Min/per charge]	[h/per charge]	[Min/per charge]	[h/per charge]	[Min/per charge]
AC	3.3	12.951	777.03	8.612	516.75	10.431	625.84
	7.4	5.775	346.51	3.841	230.44	4.651	279.09
	10	4.274	256.42	2.842	170.53	3.442	206.53
	22	1.943	116.56	1.292	77.51	1.565	93.88
DC	50	0.855	51.28	0.568	34.11	0.688	41.31
	120	0.356	21.37	0.237	14.21	0.287	17.21
		SUV					
		Peugeot e-2008		**Mazda MX-30**		**BMW iX3**	
	Charger power [kW]	[h/per charge]	[Min/per charge]	[h/per charge]	[Min/per charge]	[h/per charge]	[Min/per charge]
AC	3.3	8.612	516.75	5.662	339.71	12.759	765.55
	7.4	3.841	230.44	2.525	151.49	5.690	341.39
	10	2.842	170.53	1.868	112.11	4.211	252.63
	22	1.292	77.51	0.849	50.96	1.914	114.83
DC	50	0.568	34.11	0.374	22.42	0.842	50.53
	120	0.237	14.21	0.156	9.34	0.351	21.05

6.4 Maximum Range

Another decisive factor when deciding to buy a new BEV is the maximum range of the vehicle. The vast majority of BEVs, even though they have high-capacity batteries and can travel long distances, cannot be compared to CVs. One fully charged battery can cover a shorter distance on average compared to a CV.

The maximum range depends on many parameters, driving style, electricity consumption, driving speed, etc. Considering the battery capacity and the average electricity consumption per 100 km, it is possible to calculate the maximum BEV range. It is talked about average values here. The maximum range of the analyzed vehicles was calculated as follows (equation (6.4)) [60]:

$$s_{Max.Range_{100\%}} = \frac{C_{Bat}}{AC} \tag{6.4}$$

where:

- C_{Bat} – battery capacity [kWh]
- $s_{Max.Range_{100\%}}$ – maximum range based on average electricity consumption in BEV

for 100% of targeted SOC [km]

- AC – average electricity consumption per 100km [kWh/100km]

This value refers to 100% battery charge. However, for the sake of the SOH of battery, it is recommended to charge the battery up to a maximum of 80%, then the maximum range is (equation (6.5)) [60]:

$$s_{Max.Range_{80\%}} = \frac{C_{Bat}}{AC} \cdot \frac{SOC_{Target}(\%) - SOC_{Current}(\%)}{100} \tag{6.5}$$

where:

- SOC_{Target} – targeted SOC [%]
- $SOC_{Current}$ – current SOC [%]
- C_{Bat} – battery capacity [kWh]
- $s_{Max.Range_{80\%}}$ – maximum range based on average electricity consumption in BEV

for 80% of targeted SOC [km]

- AC – average electricity consumption per 100km [kWh/100km]

For the sake of understanding, the maximum range of the Peugeot e-2008 has been calculated.

$$s_{Max.Range_{100\%}} = \frac{C_{Bat}}{AC} = \frac{54kWh}{\frac{15.13\ kWh}{100km}} = 356.91\ km$$

$$s_{Max.Range_{80\%}} = \frac{C_{Bat}}{AC} \cdot \frac{SOC_{Target}(\%) - SOC_{Current}(\%)}{100} = \frac{54kWh \cdot (0.80 - 0.30)}{\frac{15.13\ kWh}{100km}}$$

$$= 178.45\ km$$

Based on the calculations, it is evident that the maximum range of the BEV is lower compared to the average CV. The maximum range is further affected with an increase in the average speed of the BEV. With an increase in the average speed there is increase in consumption. Which further decrease the maximum range. The battery inside the BEV supplies the EM as well as all the electronic components inside the vehicle. This has impact on average electricity consumption per 100 km. With increase of average electricity consumption per 100km there is decrease of maximum range. It is to be expected that BEVs can cover a lower mileage compared to the calculation based on the average electricity consumption per 100 km.

In Figure 6.12, the maximum range of all observed vehicles does not exceed the value of 450km. This represents a major disadvantage of BEV compared to CV. However, with the development of Li-Ion battery technology, it is realistic to expect that the maximum BEV range could be increased significantly soon.

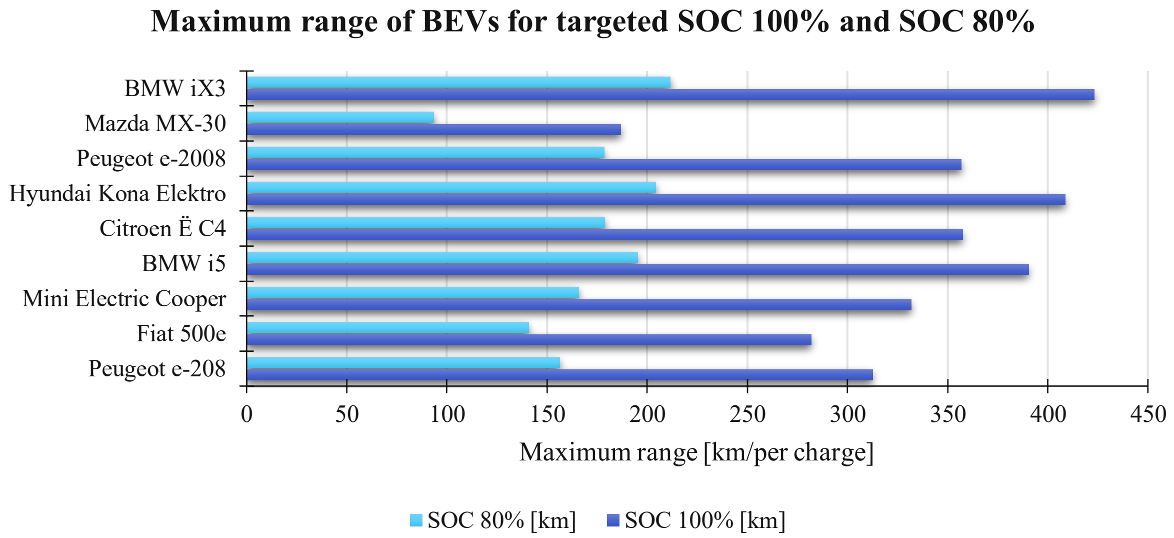


Fig. 6.12 - Maximum range of BEVs for targeted SOC 100% and SOC 80% [60]

Table 5 lists all the calculated values of the maximum range depending on the battery capacity, the average electricity consumption of the vehicle, as well as the maximum ranges of BEVs in the case when the value of SOC of 100% and 80% are taken. SOC of 80% is recommended for long battery life. This further reduces the maximum range of BEVs.

Table 5 - Maximum range of different BEVs with targeted SOC of 100% and 80% [60]

Battery Electric Vehicle			
	Small		
	Peugeot e-208	**Fiat 500e**	**Mini Cooper Electric**
Battery capacity [kWh]	50	42	58.40
Average electricity consumption [kWh/100km]	16	14.90	17.60
Maximum range for targeted SOC 100% [km/per charge]	312.50	281.88	331.82
Maximum range for targeted SOC 80% [km/per charge]	156.25	140.94	165.90
	Sedan		
	BMW i5	**Citroen Ë C4**	**Hyundai Kona Elektro**
Battery capacity [kWh]	81.2	54	65.4
Average electricity consumption [kWh/100km]	20.8	15.1	16
Maximum range for targeted SOC 100% [km/per charge]	390.38	357.62	408.75
Maximum range for targeted SOC 80% [km/per charge]	195.19	178.81	204.38
	SUV		
	Peugeot e-2008	**Mazda MX-30**	**BMW iX3**
Battery capacity [kWh]	54	35.5	80
Average electricity consumption [kWh/100km]	15.13	19	18.90
Maximum range for targeted SOC 100% [km/per charge]	356.91	186.84	423.28
Maximum range for targeted SOC 80% [km/per charge]	178.45	93.42	211.64

Figure 6.13 shows the relationship between BEVs battery capacity and their maximum range. The figure contains data points representing different BEV models, with each data point corresponding to a specific BEV model and its associated battery capacity and maximum range. It is evident that as battery capacity increases, so does the maximum range. Notably, the BMW iX3, with an 80kWh battery capacity, and the BMW i5, with an 81.2kWh capacity, have the largest ranges.

However, there is an interesting twist: if the battery is charged only to the target State of Charge (SOC) of 80%, the maximum ranges are halved. Even with an 80% SOC, the maximum range of the BMW i5 and BMW iX3 still surpasses the maximum range with a targeted SOC of 100% of the Mazda MX-30 due to the small battery capacity of only 35.5kWh.

The key takeaway from this figure is the influence of battery capacity on the BEV's driving range. It underscores the importance of considering battery size when evaluating the maximum range of BEVs.

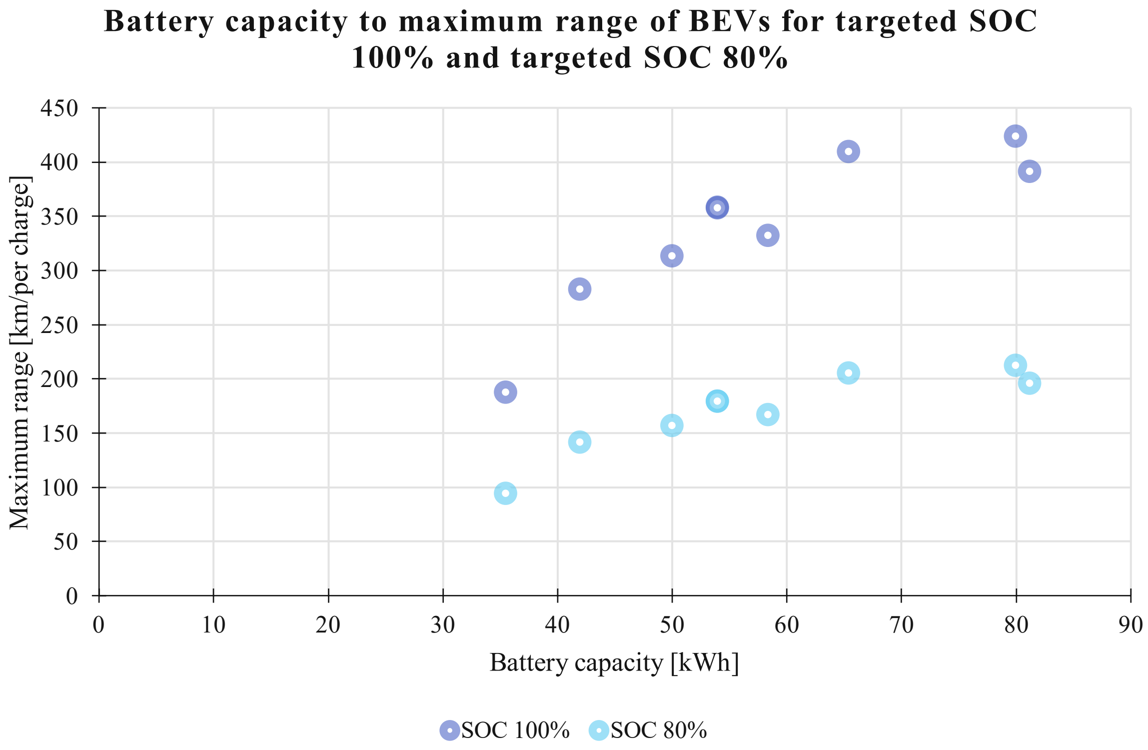


Fig. 6.13 - Battery capacity to maximum rage of BEVs for targeted SOC of 100% and targeted SOC of 80%

Another factor to consider is consumption. In Figure 6.14 shows the relationship between average electricity consumption measured in kWh per 100 kilometers and the maximum range in km per charge for two different batteries:

- battery with a capacity of 50 kWh and,
- battery with a capacity of 80 kWh.

Figure 6.14. shows on how average energy consumption directly impacts a BEV driving range.

For instance, a 50kWh battery, with a consumption rate of 15 kWh/100 km, results in a maximum range of approximately 330 km. However, if that same 50kWh battery has a higher consumption rate of 20 kWh/100 km, the maximum range decreases to 250 km.

In summary, understanding the interplay between battery capacity and consumption is essential for assessing a BEV’s maximum range.

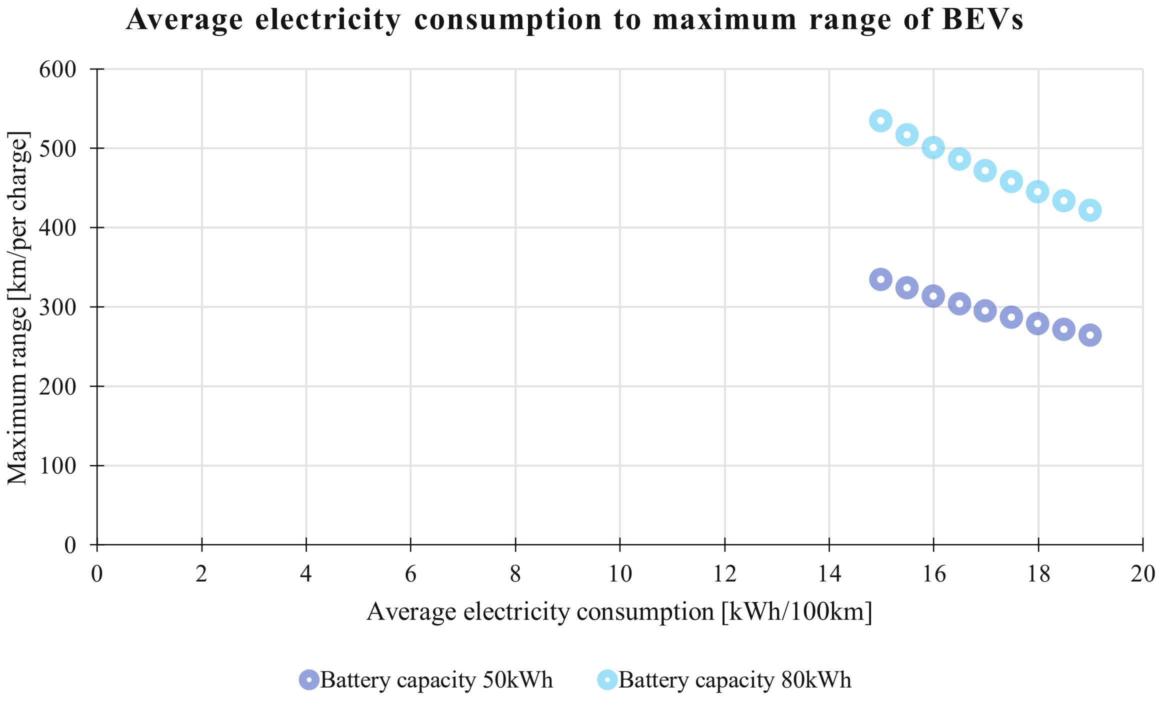


Fig. 6.14 - Average electricity consumption to maximum range of BEVs

In summary, the BEV’s maximum range depends on two key parameters: battery capacity and consumption. The BEV’s battery not only powers the EM but also all the electronics within the vehicle. As a result, average BEV consumption tends to be higher compared to CVs, which can impact overall charging costs. For more detailed information, see Chapter 8.2.

7. Conventional Vehicles

The term conventional vehicle (CV) refers to vehicles with an internal combustion engine (ICE). These are engines that use fuels such as diesel, gasoline, and LPG for their propulsion. Internal combustion engines provide outstanding driving characteristics and durability, and more than 270 million EU highway vehicles rely on them [3].

7.1. Internal Combustion Engine (ICE)

Inside CV there is ICE. Combustion, also known as burning, is the basic chemical process of releasing energy from a fuel and air mixture. In an ICE, the ignition and combustion of the fuel occur within the engine itself [61]. The engine then partially converts the energy from combustion into work. The engine consists of a stationary cylinder and a moving piston [61]. The expanding combustion gases push the piston.

Currently, two types of ICEs are produced:

- the spark-ignition gasoline engine and
- the compression-ignition diesel engine [61].

Today, most engines are four-stroke. The entire cycle takes place in four piston strokes, each of which corresponds to a different process: intake, compression, combustion and power stroke, and exhaust [61]. The four-stroke cycle of an ICE is shown in Figure 7.1.

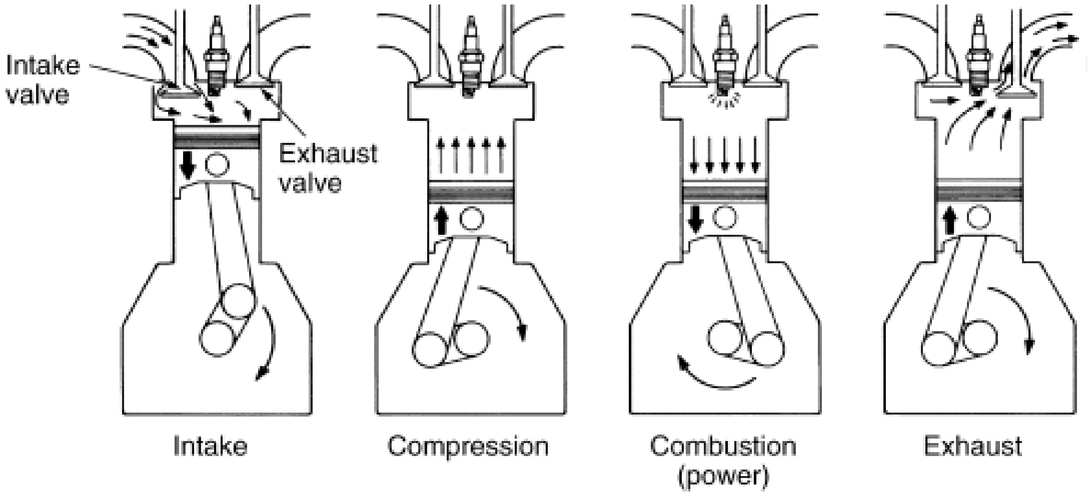


Fig. 7.1 – Four- Stroke Cycle of ICE [62]

Spark-ignition gasoline engines and compression-ignition diesel engines differ in how they supply and ignite fuel. In a spark-ignition engine, the fuel is mixed with air and then introduced into the cylinder during the intake process [61]. After the piston compresses the fuel-air mixture, the spark ignites it, causing combustion. The expansion of the combustion gases pushes the piston during the power stroke. In a diesel engine, only air is introduced into the engine and then compressed. Diesel engines then spray the fuel into the hot compressed air at a measured rate, causing it to ignite [61].

7.2. Refueling Time

When it comes to the refueling time of the fuel tank in the CV, it is one of the parameters that keeps the CVs competitive in the market with BEVs.

To calculate the average time of refueling a full tank with fuel, the following parameters are necessary:

- tank volume,
- the diameter of the pipe for pouring fuel
- the cross-sectional area of the hose for pouring fuel,
- flow rate,
- flow volume.

Assuming that it takes 3.5 minutes to fill a tank with a volume of 47 l [63], the flow volume can be calculated using the following formula (7.1) [64]:

$$Q = \frac{V_1}{t_1} \tag{7.1}$$

where is:

- Q – flow volume $[m^3/s]$
- V_1 – assumed tank volume $[m^3]$
- t_1 – assumed time required to fill the reservoir with volume V_1 $[s]$

It is known that the diameter of the fuel hose is 2.5 cm, therefore the cross-sectional area of the fuel hose can be calculated using the formula (7.2) [65]:

$$A = r^2\pi = \left(\frac{D}{2}\right)^2 \pi \tag{7.2}$$

where is:

- D – diameter of fuel hose $[m]$
- A – cross-sectional area of the refueling hose $[m^2]$
- r – radius of the refueling hose $[m]$

After calculating the flow volume and the cross-sectional area of the hose, the flow rate can be calculated using formula (7.3) [64]:

$$v = \frac{Q}{A} \tag{7.3}$$

where is:

- v – flow speed $[m/s]$
- A – cross-sectional area of the refueling hose $[m^2]$
- Q – flow volume $[m^3/s]$

Now that the flow rate is expressed for assumed values, the formula for the time required to fill a reservoir of volume V can be derived from the above formulas, and the formula (7.4) and (7.5) reads:

$$v = \frac{V_1}{t_1 \cdot A} \tag{7.4}$$

$$v = \frac{V}{t \cdot A} \tag{7.5}$$

where:

- v – flow speed $[m/s]$
- A – cross-sectional area of the refueling hose $[m^2]$
- t_1 – assumed time required to fill the reservoir with volume V_1 $[s]$
- t – time required to fill the reservoir with volume V $[s]$
- V_1 – assumed tank volume $[m^3]$
- V – tank volume $[m^3]$

Finally, the time required to fill a tank of volume V is calculated using formula (7.6):

$$t = \frac{V}{V_1} t_1 \tag{7.6}$$

By considering the tank volume for each observed vehicle and for each type of fuel, the refueling time is calculated.

For a clearer understanding, the refueling time for the Peugeot 2008 is calculated. A Peugeot 2008 with diesel fuel was used for this calculation. Given that the tank size is 44 liters, the following applies:

$$t = \frac{V}{V_1} t_1 = \frac{0.044m^3}{0.047m^3} \cdot 3.5Min = 3.28\ Min$$

This means it takes 3.28 minutes to completely refill the 44-liter tank of the Peugeot 2008. The times required to fill the tanks of all observed vehicles are calculated in the same way (see Table 6).

The refueling time in the CV ranges between 3-5 minutes. The time of refueling is directly proportional to the volume of the tank. The larger the tank, the longer it takes to refill it.

Table 6 - Refueling time of different CVs. [66] [64]

	Conventional Vehicle					
	Small					
	Peugeot 208		**Fiat 500**		**Mini Cooper**	
Maximum power output [kW]	56		63		100	
Fuel	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Tank size [l]	50	45	47	35	44	44
Time needed to refuel tank [Min/refuel]	3 Min 43 Sek	3 Min 21 Sek	3 Min 30 Sek	2 Min 36 Sek	3 Min 16 Sek	3 Min 16 Sek
	Sedan					
	BMW 5		**Citroen C4**		**Hyundai Kona**	
Maximum power output [kW]	135		82		152	
Fuel	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Tank size [l]	66	68	50	60	47	50
Time needed to refuel tank [Min/refuel]	4 Min 55 Sek	5 Min 4 Sek	3 Min 43 Sek	4 Min 28 Sek	3 Min 30 Sek	3 Min 43 Sek
	SUV					
	Peugeot 2008		**Mazda CX-30**		**BMW X3**	
Maximum power output [kW]	97		134		213	
Fuel	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Tank size [l]	44	44	51	51	60	68
Time needed to refuel tank [Min/refuel]	3 Min 17 Sek	3 Min 17 Sek	3 Min 48 Sek	3 Min 48 Sek	4 Min 28 Sek	5 Min 3 Sek

7.3. Maximum Range

The maximum range of CV vehicles is one of the most compelling arguments for CV. Modern IC engines have low average fuel consumption per 100 km, so their maximum range with a full tank is substantial. As already explained in Chapter 6.4, the maximum range depends on numerous parameters, primarily the driving style. Additionally, the vehicle's speed significantly affects the average fuel consumption, and thus indirectly influences the maximum range of the vehicle. An increase in speed leads to an increase in consumption and a reduction in the maximum range.

Both in this Chapter and in Chapter 6.4, the maximum range in relation to the average fuel consumption per 100 km is observed. Here, the engines are separated into two categories: those using diesel as fuel and those using petrol. Even though ICE technology has advanced significantly, the difference between the average fuel consumption of diesel and petrol engines is barely noticeable. However, on average, petrol engines still consume slightly more fuel for the same range compared to diesel engines.

The maximum range depends on many parameters, such as driving style, consumption, driving speed, etc. By considering the volume of the tank and the average fuel consumption per 100 km, it is possible to calculate the maximum range. The maximum range of the analyzed vehicles was calculated as follows:

$$s_{Max.Range} = \frac{V_T}{AC} \tag{7.7}$$

where:

- $s_{Max.Range}$ – maximum range based on average fuel consumption in CV [km/refill]
- AC – average fuel consumption per 100km [l/100km]
- V_T – tank volume $[m^3]$

For the sake of simplification, the maximum range of the Peugeot 2008 has been calculated.

$$s_{Max.Range} = \frac{V_T}{AC} = \frac{44l}{\frac{6.5l}{100km}} = 676.92\ km$$

Table 7 shows the maximum ranges of the analyzed vehicles, which depend on the average fuel consumption of the vehicle as well as the size of the tank.

In both Table 7 and Figure 7.2, SUV vehicles have, on average, the lowest maximum range. This is a consequence of the fact that SUV vehicles have a much bigger volume and weight than sedans and small cars. The average fuel consumption of SUVs is higher compared to other vehicles. Although their fuel tanks are bigger, their maximum range is shorter.

Table 7 - Maximum range of different CVs [37]

Conventional Vehicle						
	Small					
	Peugeot 208		**Fiat 500**		**Mini Cooper**	
Fuel	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Tank size [l]	50	45	47	35	44	44
Average fuel consumption [l/100km]	4.1		3.8		4.9	
Maximum range [km/refuel]	1,219.51	1,097.56	1,236.84	921.05	897.96	897.96
	Sedan					
	BMW 5		**Citroen C4**		**Hyundai Kona**	
Fuel	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Tank size [l]	66	68	50	60	47	50
Average fuel consumption [l/100km]	5.3		4.4		7.5	
Maximum range [km/refuel]	1,245.28	1,283.02	1,136.36	1,363.64	626.67	666.67
	SUV					
	Peugeot 2008		**Mazda CX-30**		**BMW X3**	
Fuel	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Tank size [l]	44	44	51	51	60	68
Average fuel consumption [l/100km]	6.5		5.6		7	
Maximum range [km/refuel]	676.92	676.92	910.71	910.71	857.14	971.43

Figure 7.2 shows clear deviations in the maximum range of the same vehicles with different fuels. This is precisely due to the previously mentioned fact that petrol engines, on average, consume more fuel per 100 km than diesel engines.

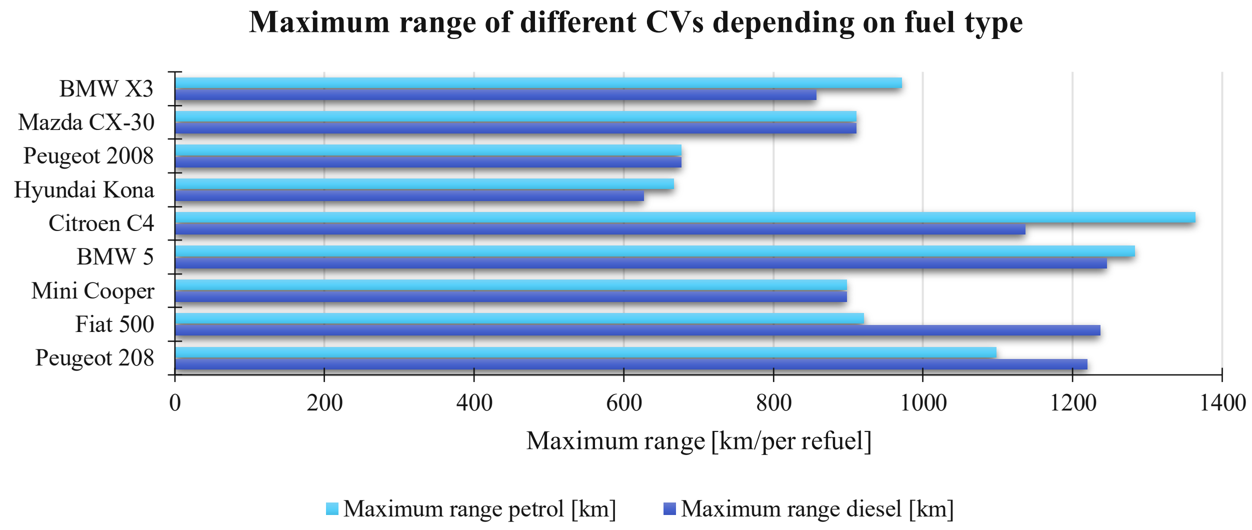


Fig. 7.2 - Maximum range of different CVs depending on fuel type. [60]

8. Costs of Battery Electric and Conventional Vehicles in Selected Countries

It is difficult to determine the average costs of a BEV and CV on the market because the costs depend on many parameters, such as the purchase cost, taxes, insurance, maintenance, etc.

To estimate the costs of BEVs and CVs. Vehicles are divided into three categories:

- small vehicles,
- sedans and
- An SUV.

This categorization of vehicles is based on the weight and volume of the vehicle.

For each of the categories, three previously selected vehicles are observed (see Table 1 and Table 2 in Chapter 3). Based on the costs for each individual vehicle, it becomes much easier to estimate the costs for a specific vehicle category.

The costs are divided into fix costs, and variable costs.

8.1. Fix Costs of Electrical Vehicles and Conventional Vehicles

In this chapter, fixed costs related to BEVs, and CVs are analyzed. These fixed costs include purchase costs and any existing subsidies. These costs are analyzed for each of the six selected countries and evaluated for each specific vehicle. Additionally, the fixed costs between BEVs and CVs are compered.

8.1.1. Purchase cost in Selected Countries

Purchase cost of Battery Electrical Vehicles

The purchase cost of a vehicle depends on its size. The purchase cost of BEVs varies depending on the battery in the vehicle. As the battery capacity increases, so does the cost of the BEV itself.

Within the category of small cars, the following three vehicles are analyzed:

- Peugeot e-208
- Fiat 500e
- Mini cooper electric

It can be inferred that the purchase cost of such BEVs falls within the range of 24,000€ to 37,000€ [37]. As per Table 8, the Fiat 500 is the least expensive vehicle in terms of purchase costs. However, it is important to note that it also has the smallest battery among the three vehicles compered. As for the remaining two vehicles, the difference in purchase cost is not as significant.

Table 8 - Purchase costs and battery size of different small BEVs in selected countries

Battery Electric Vehicle				
		Small		
		Peugeot e-208	**Fiat 500e**	**Mini Cooper electric**
Battery capacity [kWh]		50	42	58.4
Maximum power output [kW]		50	42	32.6
Purchase Costs [€]	Sweden [67] [68] [69]	34,127	36,460	34,250
	Germany [70] [71] [67]	35,975	29,490	32,900
	Netherlands [72] [73] [74]	35,870	28,990	36,990
	Cyprus [75] [76] [77]	36,200	29,900	33,450
	Croatia [78] [79] [80]	34,690	31,044	35,400
	Lithuania [81] [82] [83]	33,700	23,900	34,790

The next category of vehicles under consideration is sedans. Sedans are larger than compact cars in terms of volume, yet smaller than SUVs. Within the category of sedans, the following three vehicles are analyzed:

- BMW i5
- Citroen Ë C4
- Hyundai Kona Elektro

The purchase costs range for this category is quite broad, with BMW model priced at over than 70,000€ and Citroen Ë C4 lower than 40,000€ [37]. The average purchase cost within this category is around 55,000€ [37]. However, it is also quite plausible to find numerous vehicles from other manufacturers where the purchase cost falls below this average.

Table 9 - Purchase costs and battery size of different sedan BEVs in selected countries

Battery Electric Vehicle				
		Sedan		
		BMW i5	**Citroen Ë C4**	**Hyundai Kona Elektro**
Battery capacity [kWh]		81.20	54.00	65.40
Maximum power output [kW]		195	54	163
Purchase Costs [€]	Sweden [84] [85] [86]	73,754	40,949	36,987
	Germany [87] [88] [89]	72,200	39,265	41,990
	Netherlands [90] [91] [92]	77,942	37,665	36,995
	Cyprus [93] [94] [95]	73,000	40,700	42,500
	Croatia [96] [97] [98]	73,750	39,760	39,990
	Lithuania [99] [100] [101]	79,550	35,990	43,900

The last category that was analyzed within the overall purchase cost of EV are SUVs. Within this category, the following three vehicles are analyzed:

- Peugeot e-2008
- Mazda MX-30
- BMW iX3

The average purchase cost of such BEVs varies from 39,000€ to 75,000€ [37], depending on the manufacturer and the specific features of the vehicle. The BMW iX3 is priced significantly higher than the Mazda MX-30. However, one of the reasons for this large purchase cost difference is that the battery capacity of the BMW iX3 exceeds that of the Mazda MX-30 by more than 44.5kWh.

Table 10 - Purchase costs and battery size of different SUV BEVs in selected countries

		Battery Electric Vehicles		
		SUV		
		Peugeot e-2008	**Mazda MX-30**	**BMW iX3**
Battery capacity [kWh]		54	35.5	80
Maximum power output [kW]		115	50	80
Purchase Costs [€]	Sweden [102] [84] [103]	42,262	36,626	60,931
	Germany [70] [87] [104]	44,000	35,990	67,300
	Netherlands [72] [90] [105]	39,270	36,490	71,465
	Cyprus [75] [93] [106]	42,000	38,700	65,000
	Croatia [78] [96] [96]	39,790	37,370	72,063
	Lithuania [81] [99] [107]	39,300	37,380	75,360

Purchase cost of Conventional Vehicles

Three groups of vehicles are analyzed, small cars, sedans, and SUVs. Three previously selected vehicles are compared within each group, i.e., the vehicles listed in Table 2.

When talking about small vehicles, the following three vehicles are selected:

- Peugeot 208
- Fiat 500
- Mini cooper

These three vehicles are from different manufacturers but have similar dimensions.

The volume of all three vehicles is in the range of $8 - 10\ \mathrm{m}^3$, and their weight ranges from 950 to 1,150 kg [37].

The following characteristics that are important for the customer when purchasing a vehicle are:

- maximum torque,
- acceleration to 100 km/h and
- average fuel consumption per 100 km.

When comparing these three vehicles, the Mini Cooper stands out with the highest torque and acceleration among them. However, this leads to it also having the highest average fuel consumption per 100 km. In contrast, the Peugeot 208 has lower torque and acceleration, but its average fuel consumption is correspondingly low. The Fiat 500 presents a balanced profile in terms of these characteristics, as it has average values for both torque and acceleration, and its average fuel consumption is the lowest.

Based on the characteristics of these three vehicles, it would be reasonable to expect that their purchase costs are approximately the same. Indeed, this is the case. The purchase cost for any of these three vehicles would fall within the range of 19,000€ to 36,000€.

Table 11 - Purchase costs and maximum power output of different small CVs in selected countries

		Conventional Vehicle		
		Small		
		Peugeot 208	**Fiat 500**	**Mini Cooper**
Maximum power output [kW]		56	63	100
Purchase Costs [€]	Sweden [67] [68] [69]	20,513	15,526	24,895
	Germany [70] [71] [67]	19,990	21,990	28,682
	Netherlands [72] [73] [74]	19,695	22,700	31,950
	Cyprus [75] [76] [77]	21,500	25,000	26,616
	Croatia [78] [79] [80]	18,400	15,912	35,415
	Lithuania [81] [82] [83]	17,200	16,900	25,400

The next group of vehicles that are observed are sedans. The following three vehicles are selected for analysis:

- BMW 5
- Citroen C4
- Hyundai Kona

Similar to the case with small vehicles, these three vehicles have been purposefully selected due to their similar dimensions. The volume of all three vehicles falls within the range of 12-13 m^3, while their weight varies between 1,650 to 1,900 kg [37].

In this group of vehicles, its maximum torque acceleration up to 100 km/h and average fuel consumption per 100 km is compered. All three vehicles share similar characteristics. Their torque ranges from 250-290 Nm, and all three vehicles can reach a speed of 100 km/h in less than 5 seconds. However, due to their powerful engines, their average fuel consumption is remarkably high, ranging from over 4.4 l/100km up to over 7.5 l/100km.

The BMW 5, with a purchase costs of more than 60,000€, is particularly notable in terms of cost. However, its high cost is not a consequence of the engine characteristics or dimensions, but rather the numerous additional features that this car includes. The costs of the remaining two vehicles are quoted without additional equipment.

Table 12 - Purchase costs and maximum power output of different sedan CVs in selected countries

		Conventional Vehicle		
		Sedan		
		BMW 5	**Citroen C4**	**Hyundai Kona**
Maximum power output [kW]		135	82	152
Purchase Costs [€]	Sweden [84] [85] [86]	69,571	24,217	27,555
	Germany [87] [88] [89]	61,750	29,065	39,350
	Netherlands [90] [91] [92]	66,096	31,275	30,995
	Cyprus [93] [94] [95]	62,289	23,900	24,400
	Croatia [96] [97] [98]	64,039	20,670	23,990
	Lithuania [99] [100] [101]	69,316	21,490	38,840

And the last group are SUVs. The following three vehicles are observed here:

- Peugeot 2008
- Mazda CX-30
- BMW X3

The volume of these three vehicles exceeds 14 m³, which classifies them as large vehicles. They are popular today due to their exceptional comfort. Their weight, which ranges between 1,750 and 2,000 kg [37], is slightly higher compared to that of sedans. As the largest vehicles among all three groups, SUVs require high torque for operation. As a result, all three vehicles listed above have a maximum torque between 220 and 650 Nm. However, since their torque is not significantly higher compared to that of sedans, and their weight is on average about 100 kg more, this results in a slower acceleration up to 100 km/h. All three vehicles take more than 5 seconds to reach this speed. Similar to sedans, their average fuel consumption per 100 km is also high due to the high torque and heavy weight of the vehicle.

Based on all the characteristics, their purchase costs ranges between 20,000€-68,000€.

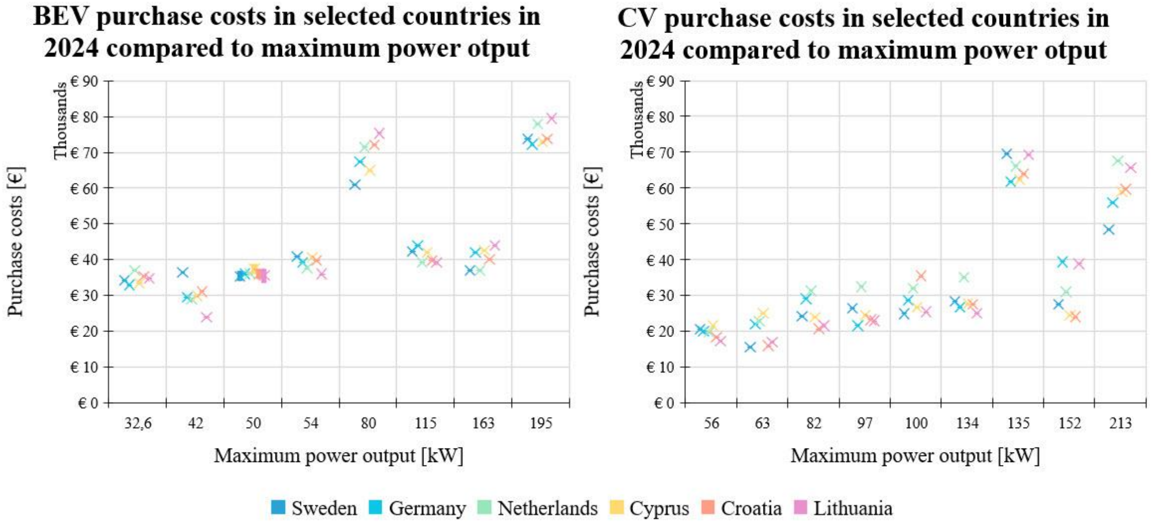
The purchase costs of these vehicles listed in Table 13 are important to be able to conduct the economic assessment of the purchase in the Chapter 9.

Table 13 - Purchase costs and maximum power output of different SUV CVs in selected countries

		Conventional Vehicle		
		SUV		
		Peugeot 2008	**Mazda CX-30**	**BMW X3**
Maximum power output [kW]		97	134	213
Purchase Costs [€]	Sweden [102] [84] [103]	26,410	28,304	48,335
	Germany [70] [87] [104]	21,549	26,690	55,900
	Netherlands [72] [90] [105]	32,420	34,990	67,576
	Cyprus [75] [93] [106]	24,500	27,600	59,000
	Croatia [78] [96] [108]	23,200	27,574	59,679
	Lithuania [81] [99] [107]	22,900	24,990	65,650

Figure 8.1 shows the purchase cost of a BEV in relation to its maximum output power. Purchase cost typically falls within the range of 30,000€ to 50,000€. In contrast, CVs have a purchase cost ranging from 20,000€ to 40,000€. Notably, there are exceptions such as the BMW i5/BMW 5 and BMW iX3/BMW X3.

This highlights how BEVs tend to be approximately 10,000€ more expensive on average compared to CVs. Considering this significant cost difference can impact the overall economic assessment of BEVs, as discussed in Chapter 9."



a) b)

Fig. 8.1 - Purchase costs of a) BEVs and b) CVs in selected countries in 2024 compared to maximum power output of different vehicles

8.1.2. Subsidies in Selected Countries

State subsidies are designed to assist consumers in purchasing a BEV. Each EU country offers different subsidies. Some countries, such as Germany, have introduced regulations where the amount of the subsidy is directly proportional to the purchase cost of the vehicle. In Germany, for instance, if a consumer purchases a BEV priced up to 40,000€, the state provides a subsidy of 6,750€ [109]. Vehicles priced between 40,000€ and 65,000€, the subsidy is 4,500€ [109]. However, there are no subsidies from the German government for vehicles priced above 65,000€.

In Sweden, the situation is different. Sweden has discontinued subsidies for the purchase of BEVs, redirecting the budget towards infrastructure improvements [28].

Among the selected countries, Cyprus provides the most substantial subsidies for BEVs. For all citizens who choose to buy a new BEV, Cyprus offers a subsidy of 19,000€ for vehicles with a purchase price of up to 80,000€ [109].

In 2024, the Netherlands abolished numerous subsidies. These subsidies had previously contributed to the Netherlands leading the EU in terms of both the number of registered BEVs and the number of charging stations. Currently, the Dutch government offers a subsidy of 2,950€ for the purchase of BEVs priced up to 45,000€ [109].

Some countries, such as Croatia and Lithuania, offer fixed subsidies regardless of the purchase cost of the BEV. The Croatian government provides a subsidy of 9,291€. However, the vehicle owner is required to retain ownership of the vehicle for a minimum of 2 years [109].

Lithuania provides consumers with a subsidy of 5,000€ per vehicle, regardless of the vehicle's size and purchase cost [109].

Regardless of the methods individual EU countries use to subsidize consumers for BEV purchases, all these measures have a positive impact on the BEV market. The introduction of various subsidies has also increased the demand for BEVs, which is a primary goal at the EU level.

Subsidies for BEVs are factored into the NPV calculations in Chapter 9. When these subsidies are considered, the purchase cost of the vehicle is reduced by the amount of the subsidy available in the respective country.

Table 14 presents the subsidy amounts for each of the selected countries and for each of the vehicles under consideration.

Table 14 - Subsidies in selected countries in €/per vehicle [109]

	Battery Electric Vehicles		
	Small		
	Peugeot e-208	**Fiat 500e**	**Mini Electric Cooper**
Sweden	-	-	-
Netherland	6,750	6,750	6,750
Germany	2,950	2,950	2,950
Cyprus	19,000	19,000	19,000
Croatia	9,291	9,291	9,291
Lithuania	5,000	5,000	5,000
	Sedan		
	BMW i5	**Citroen Ë C4**	**Hyundai Kona Elektro**
Sweden	-	-	-
Netherland	-	-	4,500
Germany	-	2,950	2,950
Cyprus	19,000	19,000	19,000
Croatia	9,291	9,291	9,291
Lithuania	5,000	5,000	5,000
	SUV		
	Peugeot e-2008	**Mazda MX-30**	**BMW iX3**
Sweden	-	-	-
Netherland	4,500	-	-
Germany	2,950	2,950	-
Cyprus	19,000	19,000	19,000
Croatia	9,291	9,291	9,291
Lithuania	5,000	5,000	5,000

There are no subsidies at the EU level to assist with the purchase of a CV. Any individual who decides to buy a new vehicle with ICE must pay the full price set by the seller. The EU aims to encourage the population to purchase vehicles with low or zero CO_2 emissions. However, CVs do not fall into this category, so there are no subsidies for these vehicles.

8.2. Variable Costs of Battery Electric Vehicles and Conventional Vehicles

In this chapter, variable costs related to BEVs, and CVS are analyzed. These variable costs include insurance, vehicle registration, maintenance, taxes, and refueling/recharging costs. These costs are analyzed for each of the six selected countries and evaluated for each specific vehicle. Additionally, the variable costs between BEVs and CVs are compered.

8.2.1. Cost of Charging in Selected Countries

In Chapter 6.2.3, the methods of charging BEVs were discussed in detail. At the EU level, plug-in charging is the most common method. This method encompasses a range of charging speeds, from 3.3kW to 120kW. Some EU countries have even introduced faster chargers. The three options analyzed are:

- AC charging
- DC charging
- Private charging

AC charging, also known as slow charging, involves charging at a rate from 3.3kW up to 22kW. DC charging, or fast charging, refers to charging at a speed of 50kW or faster. Private charging refers to charging conducted within a private home.

Each type of charger has a different price per kWh, and the prices per kWh also vary among the observed countries. Table 15 provides a list of charging prices for each type of charger and for each country under observation.

Table 15 - Charging prices form different chargers in selected countries in 2024. [110]

	Charging price [€/kWh]		
	AC	DC	Private
Sweden	0.426	0.533	0.267
Netherland	0.510	0.610	0.320
Germany	0.530	0.630	0.320
Cyprus	0.430	0.520	0.260
Croatia	0.550	0.720	0.130
Lithuania	0.420	0.610	0.140

How much it costs to fully charge the battery depends on parameters, such as:

- charging price per kWh,
- battery size

The monthly costs of battery charging for each vehicle are analyzed under the following conditions:

- charging exclusively from alternating current (AC) chargers,
- charging exclusively from direct current (DC) chargers,
- charging exclusively from private home charging,

To gain insight into the monthly costs of BEV charging, it is necessary to determine the distance that the vehicle will travel in a month. For this analysis, that distance is assumed to be 1,000 km.

The total monthly charging costs can be calculated using the following formula (8.1) [111]:

$$TC_{Ch} = P_{Ch} \cdot C_{Bat} \cdot \frac{R_{mth}}{\frac{C_{Bat}}{AC} \cdot 100km} \tag{8.1}$$

where:

- TC_{Ch} – the total monthly costs of charging the battery in [€]
- P_{Ch} – price of battery charging in selected country in [€/kWh]
- C_{Bat} – capacity of the battery in [kWh]
- R_{mth} – monthly range of BEV [km]
- AC – average electricity consumption per 100km in [kWh/100km]

For simplicity, the total monthly costs of charging the Peugeot e-2008 using a 3.3kW AC charger in Sweden have been calculated using formula (8.1):

$$TC_{Ch-AC} = P_{AC-Ch} \cdot C_{Bat} \cdot \frac{R_{mth}}{\frac{C_{Bat}}{AC} \cdot 100km} = 0.426 \frac{€}{kWh} \cdot 54kWh \cdot \frac{1000km}{\frac{54kWh}{15.13kWh} \cdot 100km}$$
$$= 64.50€$$

where:

- TC_{AC-Ch} – the total monthly costs of AC-charging the battery in [€]
- P_{AC-Ch} –price of battery AC-charging in selected country in [€/kWh]
- C_{Bat} – capacity of the battery in [kWh]
- R_{mth} – monthly range of BEV [km]
- AC – average electricity consumption per 100km in [kWh/100km]

The total monthly costs of charging the Peugeot e-2008 using 120kW DC charger in Sweden have been also calculated.

$$TC_{DC-Ch} = P_{DC-Ch} \cdot C_{Bat} \cdot \frac{R_{mth}}{\frac{C_{Bat}}{AC} \cdot 100km} = 0.533\frac{€}{kWh} \cdot 54kWh \cdot \frac{1000km}{\frac{54kWh}{15.13kWh} \cdot 100km}$$
$$= 80.66€$$

where:

- TC_{DC-Ch} – the total monthly costs of DC-charging the battery in [€]
- P_{DC-Ch} – price of battery DC-charging in selected country in [€/kWh]
- C_{Bat} – capacity of the battery in [kWh]
- R_{mth} – monthly range of BEV [km]
- AC – average electricity consumption per 100km in [kWh/100km]

The total monthly costs of charging the Peugeot e-2008 using private charger in Sweden have been calculated:

$$TC_{private-Ch} = P_{private-Ch} \cdot C_{Bat} \cdot \frac{R_{mth}}{\frac{C_{Bat}}{AC} \cdot 100km}$$
$$= 0.267\frac{€}{kWh} \cdot 54kWh \cdot \frac{1000km}{\frac{54kWh}{15.13kWh} \cdot 100km} = 40.40€$$

where:

- $TC_{private-Ch}$ – the total monthly costs of private-charging the battery in [€]
- $P_{private-Ch}$ – price of battery private-charging in selected country in [€/kWh]
- C_{Bat} – capacity of the battery in [kWh]
- R_{mth} – monthly range of BEV [km]
- AC – average electricity consumption per 100km in [kWh/100km]

The total monthly costs of charging the Peugeot e-2008 in Sweden, considering exclusive use of AC chargers, DC chargers and private chargers have been calculated. However, it is realistic to predict that monthly charging could involve a combination of these three methods. Therefore, two additional scenarios are considered:

- charging with a ratio of 60% private charging, 40% public charging, of which 24% is from AC chargers and 16% from DC chargers,

- charging with a ratio of 50% private charging and 50% public charging, of which 25% is from AC chargers and 25% from DC chargers.

These scenarios can be calculated using equation (8.2):

$$TC_{Ch} = C_{Bat} \cdot \frac{R_{mth}}{\frac{C_{Bat}}{AC} \cdot 100km} \cdot \left(p(\%)_{AC} \cdot P_{AC-Ch} + p(\%)_{DC} \cdot P_{DC-Ch} + p(\%)_{private} \cdot P_{private-Ch}\right) \tag{8.2}$$

where:

- TC_{Ch} – the total monthly costs of charging the battery in [€]
- C_{Bat} – capacity of the battery in [kWh]
- R_{mth} – monthly range of BEV [km]
- AC – average electricity consumption per 100km in [kWh/100km]
- P_{AC-Ch} – price of battery charging with an AC charger in selected country in [€/kWh]
- P_{DC-Ch} – price of battery charging with an DC charger in selected country in [€/kWh]
- $P_{Private-Ch}$ – price of battery charging with a private charger in selected country in [€/kWh]
- $p(\%)_{AC}$ – percentage of monthly charge from AC charger [%]
- $p(\%)_{DC}$ – percentage of monthly charge from DC charger [%]
- $p(\%)_{Private}$ – percentage of monthly charge from private charger [%]

For clarity, the calculation of the total monthly costs of charging the Peugeot e-2008 in Sweden is presented. In this scenario, 60% of the charging is done using private chargers, 24% from AC chargers, and 16% from DC chargers. The charging prices used for the calculation are taken from Table 15.

$$\begin{aligned} TC_{Ch} &= C_{Bat} \cdot \frac{R_{mth}}{\frac{C_{Bat}}{AC} \cdot 100km} \cdot \left(p(\%)_{AC} \cdot P_{AC-Ch} + p(\%)_{DC} \cdot P_{DC-Ch} + p(\%)_{private} \cdot P_{private-Ch}\right) \\ &= 54kWh \cdot \frac{1000km}{\frac{54kWh}{15.13kWh} \cdot 100km} \cdot \left(0.24 \cdot 0.426 \frac{€}{kWh} + 0.16 \cdot 0.533 \frac{€}{kWh} + 0.6 \cdot 0.267 \frac{€}{kWh}\right) = 52.62€ \end{aligned}$$

Based on the calculations, the total monthly costs depend on several parameters. The primary factor is the capacity of the batteries - as the battery capacity increases, so do the costs. The secondary factor is the range driven by the BEV. The tertiary factor is the ratio of chargers used.

The calculations for the Peugeot e-2008 clearly show that the lowest charging costs come from exclusive use of private charging stations, while the highest charging costs result from exclusive use of DC chargers.

For all other values, please see Tables 22 and 23 in the Appendix.

8.2.1.1. Charging prices in the next 10 years

As previously discussed in Chapter 5.2, electricity costs fluctuate over time, which in turn affects the charging costs of BEVs. To estimate the charging costs of BEVs as accurately as possible, it is necessary to calculate the charging prices for the projected period from 2024 to 2034.

The price of charging a BEV is composed of the baseload price and additional costs [112]. These additional costs can vary based on location, region, and charging speed. The cost of charging can be significantly influenced by whether it is done in an urban or rural area [112]. Urban charging stations may have higher rates due to increased operating costs, while rural stations might offer more competitive rates [112]. Charging stations in densely populated urban areas may impose substantial parking fees. The cost of charging can also differ from one region to another, influenced by factors such as electricity prices and local regulations. The speed of charging can also impact costs, with faster options like DC charging potentially having higher rates compared to slower alternatives [112].

Additional costs can be calculated by finding the difference between the charging price and the baseload price. The charging prices were derived from the values in Table 15. The baseload prices correspond to the prices shown in Figure 5.2.

To project the charging price in the upcoming years, the additional costs for each type of charger for the year 2024 are computed. The calculated values of these additional costs, when combined with the baseload price from Figure 5.2 for the subsequent years, give the charging price for the year under consideration. The formula used to calculate these additional costs is as follows [113]:

$$AC_{Ch} = P_{Ch} - P_{BL} \tag{8.3}$$

where:

- AC_{Ch} – additional costs of charging [€/kWh]
- P_{Ch} – price of charging [€/kWh]
- P_{BL} – baseload-price of electricity [€/kWh]

For a clearer understanding, the example of Sweden is considered. The additional costs in Sweden for AC charging are calculated based on the AC charging price of 0.426€/kWh and baseload electricity price of 0.079€/kWh in 2024 [110]. The additional costs amount to:

$$AC_{AC-Ch} = P_{AC-Ch} - P_{BL} = 0.426\frac{€}{kWh} - 0.079\frac{€}{kWh} = 0.347\frac{€}{kWh}$$

where:

- AC_{AC-Ch} – additional costs of AC-charging [€/kWh]
- P_{AC-Ch} – price of AC-charging [€/kWh]
- P_{BL} – baseload-price of electricity [€/kWh]

The additional costs in Sweden for DC-charging and private charging are computed in the same manner. The DC-charging price of 0.533€/kWh and the private charging price is 0.267€/kWh in 2024 [110]. The calculations are as follows:

$$AC_{DC-Ch} = P_{DC-Ch} - P_{BL} = 0.533\frac{€}{kWh} - 0.079\frac{€}{kWh} = 0.454\frac{€}{kWh}$$

where:

- AC_{DC-Ch} – additional costs of DC-charging [€/kWh]
- P_{DC-Ch} – price of DC-charging [€/kWh]
- P_{BL} – baseload-price of electricity [€/kWh]

$$AC_{private-Ch} = P_{private-Ch} - P_{BL} = 0.267\frac{€}{kWh} - 0.079\frac{€}{kWh} = 0.347\frac{€}{kWh}$$

where:

- $AC_{private-Ch}$ – additional costs of private-charging [€/kWh]
- $P_{private-Ch}$ – price of private-charging [€/kWh]
- P_{BL} – baseload-price of electricity [€/kWh]

The charging price is calculated by adding the additional costs obtained to the estimated baseload price of electricity for 2025. The formula used for this calculation is as follows [113]:

$$P_{AC-\,Ch_{2025}} = AC_{AC-Ch} + P_{BL_{2025}} \tag{8.4}$$

where:

- $P_{AC-\,Ch_{2025}}$ – price of AC-charging in 2025 [€/kWh]
- AC_{AC-Ch} – additional costs of AC-charging [€/kWh]
- $P_{BL_{2025}}$ – baseload-price of electricity in 2025 [€/kWh]

For a clearer understanding, the charging price for all three types of charging using Sweden as an example are calculated. The prices for AC, DC, and private charging in the year 2025 are as follows:

$$P_{AC-\,Ch_{2025}} = AC_{AC-Ch} + P_{BL_{2025}} = 0.347\frac{€}{kWh} + 0.073\frac{€}{kWh} = 0.420\frac{€}{kWh}$$

$$P_{DC-\,Ch_{2025}} = AC_{DC-Ch} + P_{Bl_{2025}} = 0.454\frac{€}{kWh} + 0.073\frac{€}{kWh} = 0.527\frac{€}{kWh}$$

$$P_{private-\,Ch_{2025}} = AC_{private-Ch} + P_{BL_{2025}} = 0.188\frac{€}{kWh} + 0.073\frac{€}{kWh} = 0.261\frac{€}{kWh}$$

where:

- $P_{AC-\,Ch_{2025}}$ – price of AC-charging in 2025 [€/kWh]
- AC_{AC-Ch} – additional costs of AC-charging [€/kWh]
- $P_{DC-\,Ch_{2025}}$ – price of DC-charging in 2025 [€/kWh]
- AC_{DC-Ch} – additional costs of DC-charging [€/kWh]
- $P_{private-Ch_{2025}}$ – price of private-charging in 2025 [€/kWh]
- $AC_{private-Ch}$ – additional costs of private-charging [€/kWh]
- $P_{BL_{2025}}$ – baseload-price of electricity in 2025 [€/kWh]

For additional values, please see Table 21 in the Appendix.

8.2.2. Cost of refueling in Selected Countries

ICE are engines that utilize fuels such as diesel and petrol for propulsion. The price of these types of fuels has experienced significant fluctuations in recent years. Particularly in 2023, a sudden surge in fuel prices was observed. This increase has had a substantial impact on the cost of refueling CVs.

When analyzing the charging price for CVs, the following parameters must be considered:

- type of fuel,
- tank size and,
- fuel price.

On average, diesel engines are slightly larger than gasoline engines. However, the price of diesel fuel is typically lower compared to petrol. Smaller vehicles tend to have smaller tanks, so the cost of a full tank, regardless of the fuel type, is lower compared to that of sedans and SUVs.

When considering the cost of refueling a CV, the prices of fuel in selected countries for the year 2024 are listed in Table 16

Table 16 - Prices of diesel and petrol in selected countries in 2024 [66]

Conventional Vehicle		
	Diesel [€/l]	Petrol [€/l]
Sweden	1.576	1.607
Netherland	1.693	1.990
Germany	1.620	1.751
Cyprus	1.532	1.506
Croatia	1.530	1.546
Lithuania	1.414	1.503

The GDP per capita and the development of individual EU member countries has an impact on the price of fuel. Therefore, the price of fuel in some countries is above the average, while in others it is below the average. For example, in Lithuania, is the price of diesel 1.414 €/l [66].

To gain insight into the monthly costs of refueling CV, it is necessary to determine the distance that the vehicle will cover in a period of one month. This value is assumed to be 1,000 km.

The total monthly costs of refueling can be calculated using the following formula (8.5) [114]:

$$TC_{Re} = P_{Re} \cdot V_T \cdot \frac{R_{mth}}{\frac{V_T}{AC} \cdot 100km} \tag{8.5}$$

where:

- TC_{Re} – the total costs of refueling the tank in [€]
- P_{Re} – price of fuel for refueling in selected country in [€/l]
- V_T – volume of the tank in [l]
- R_{mth} – monthly range of CV[km]
- AC – average fuel consumption per 100 km in [l/100km]

For clarity, the total cost of refueling the Peugeot 2008, which uses diesel as fuel at a price of 1.576 €/l in Sweden, has been calculated using formula (8.5):

$$TC_{Re} = P_{Re} \cdot V_T \cdot \frac{R_{mth}}{\frac{V_T}{AC} \cdot 100km} = 1.576\frac{€}{l} \cdot 44l \cdot \frac{1000km}{\frac{44l}{6.5l} \cdot 100km} = 102.44€$$

For additional values, please see Table 24 in the Appendix.

When examining formulas (8.1) and (8.5), by simplifying both the denominator and numerator, the total costs of refueling do not have a direct dependence on battery capacity or fuel tank volume. Instead, the total costs of recharging/refueling are directly proportional to the price of charging/refueling and the monthly range.

In other words, the cost of charging is influenced primarily by the cost per kWh (or per liter of fuel for CVs) and the range the vehicle can cover in a month. The specific battery capacity or fuel tank size does not play a significant role in determining these costs.

As in the case of maximum range, the total costs of charging the battery or refueling tank depend on average fuel/electricity consumption. Figure 8.2 shows the relationship between maximum output power and average fuel/electricity consumption. BEVs typically exhibit an average electricity consumption in the range of 15 kWh/100 km to 20 kWh/100 km. For BEVs, the average electricity consumption does not significantly depend on the maximum output power. However, with CVs, average fuel consumption does correlate with maximum output power. As the maximum output power increases in CVs, so does the average fuel consumption. Consequently, CVs with higher maximum output power tend to have slightly higher average fuel consumption.

It can be concluded that the average electricity consumption of BEVs is higher compared to average fuel consumption of CVs. This has a direct impact on the overall cost of charging the battery. As average electricity consumption increases, the maximum range of the BEV decreases, which results in more frequent battery charging. To cover the same range as a CV, BEVs require more frequent recharging. The total annual costs of refueling are discussed in detail in Chapter 9.1.

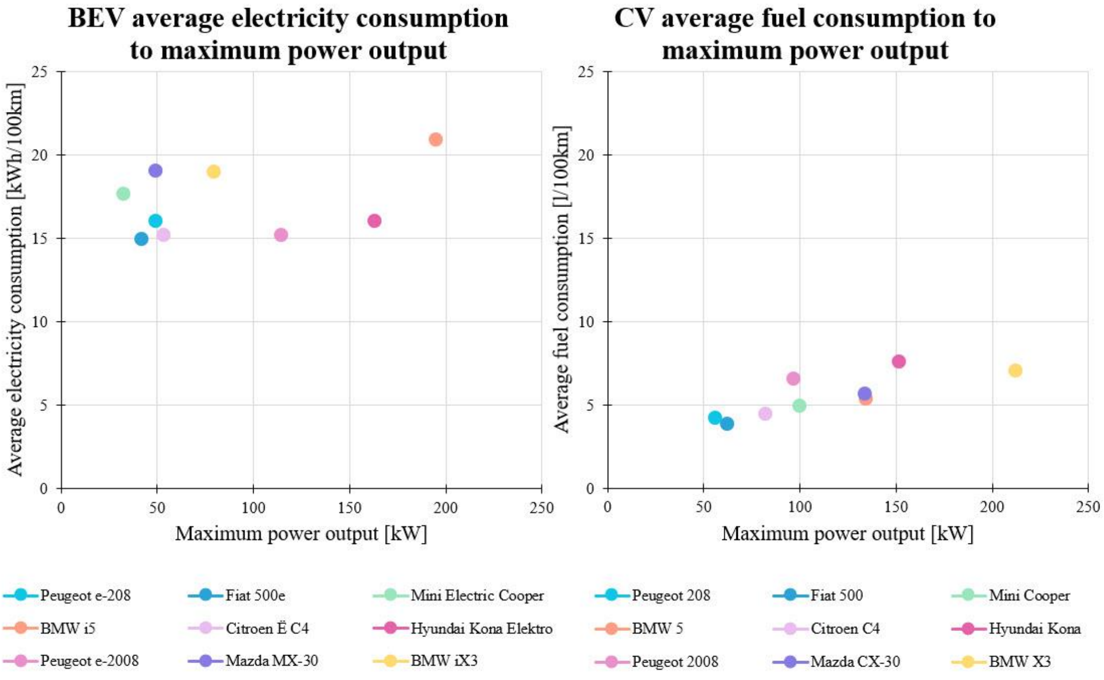


Fig. 8.2 – Average electricity/fuel consumption of a) BEVs and b) CVs compared to maximum power output of different vehicles

Figure 8.3 shows the relationship between BEV battery capacity and fuel tank volume for CVs with maximum output power. The battery capacity of BEVs and the size of CVs fuel tanks do not depend on the maximum output power. Figure 8.3 a) shows that batteries of varying capacities can be used for a maximum output power of 50 kW, ranging from 35 kWh to 54 kWh. In contrast, CVs typically have an average tank volume of approximately 50 liters. Exceptions such as the BMW X3 and BMW 5 have larger tank volumes of 60 liters and 66 liters, respectively.

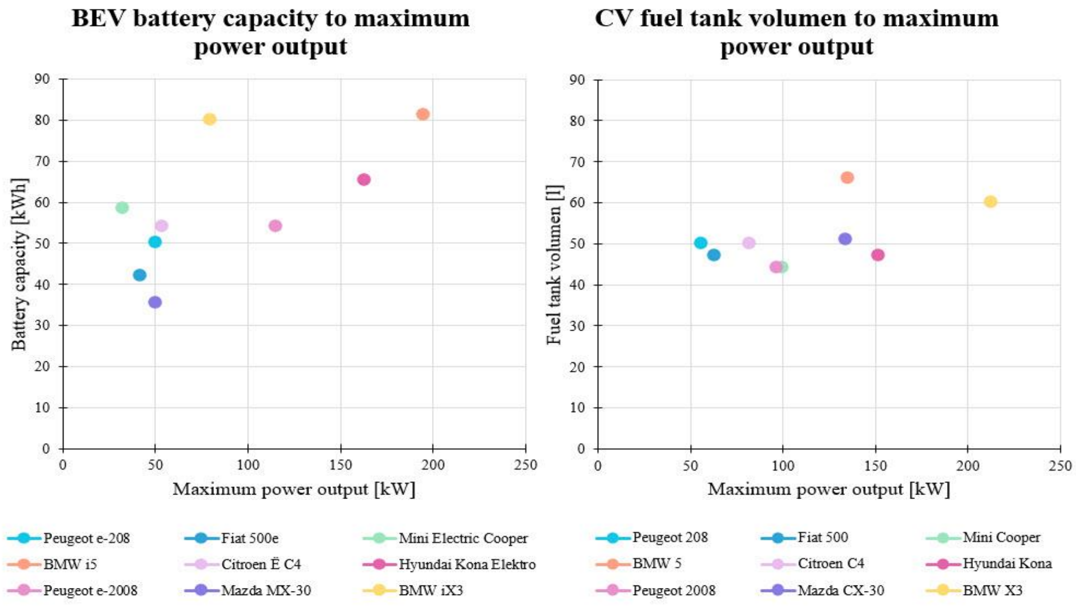


Fig. 8.3 - Battery capacity / fuel tank volume of a) BEVs and b) CVs compared to maximum power output of different vehicles

8.2.3. Maintenance costs

When it comes to maintenance costs on a BEV, they are lower compared to CVs. This is partly because BEVs have fewer moving parts.

Some maintenance costs are the same for both BEVs and CVs. Costs such as purchasing tires, maintaining suspension systems, including shock absorbers and struts are, identical for both types of vehicles. Although the brake pads on a BEV may eventually need to be replaced, the regenerative braking systems on BEVs use the resistance of the EMs to slow the vehicle down. For this reason, brake pads are not used as extensively as in CVs, resulting in less frequent brake wear on BEVs.

If maintained according to the manufacturer's recommendations, BEVs are on average 30% less expensive to maintain per year [115]. Consumers who own a BEV can expect to save on repair and maintenance costs over the lifetime of the vehicle compared to a CV.

The average annual maintenance costs of the vehicles observed in selected countries are listed in Table 17.

Table 17 - The average annual maintenance costs of the observed vehicles in selected countries [116]

Maintenance costs [€/year]		
	BEV	CV
Sweden	448.00	640.00
Germany	553.70	791.00
Netherland	511.70	731.00
Cyprus	383.60	548.00
Croatia	343.00	490.00
Lithuania	324.42	463.45

One significant factor that affects the cost of vehicle maintenance is the battery. The battery within a BEV is a crucial component for its operation. In the event of a battery failure, the cost of a new battery can amount to up to 30% of the total purchase price of the vehicle.

The cost of replacing the battery is dependent on the type of battery used and its capacity. A significant number of batteries used in BEVs are Li-Ion batteries. The price of Li-Ion batteries was 128.57 €/kWh in 2023 [117].

The cost of battery replacement can be calculated using formula (8.6) [118]:

$$BATC_{Bat} = CPE_{Bat} \cdot C_{Bat} \tag{8.6}$$

where:

- $BATC_{Bat}$ – the total costs of new the battery in [€]
- CPE_{Bat} – average costs of Lithium-Ion battery per unit of power in EU in [€/kWh]
- C_{Bat} – battery capacity in [kWh]

Table 18 lists the battery capacities for all the vehicles analyzed and the calculated cost of a new battery.

Table 18 – Average costs for new battery in BEVs [37]

	Battery Electric Vehicle								
	Small			Sedan			SUV		
	Peugeot e-208	**Fiat 500e**	**Mini Cooper electric**	**BMW i5**	**Citroen Ë C4**	**Hyundai Kona Elektro**	**Peugeot e-2008**	**Mazda MX-30**	**BMW iX3**
Battery capacity [kWh]	50	42	58.4	81.2	54	65.4	54	35.5	80
New battery price [€]	6,429	5,400	7,509	10,440	6,943	8,409	6,943	4,564	10,286

Battery manufacturers typically offer warranties on batteries for a duration of 8 years or 100,000 km [118]. This could mean that battery replacement might be completely free within this period.

In general, the batteries in BEVs last from 10 to 20 years [119]. Certain factors such as heat, cold, or fast charging can negatively impact this and reduce performance. Manufacturers have already implemented protective measures such as thermal management systems and charge limits to extend battery life.

Figure 8.4 shows the relationship between the total cost of battery replacement in 2024 and the battery capacity of different BEVs. It is clear from the figure that the cost of a new battery increases linearly with the increase in battery capacity.

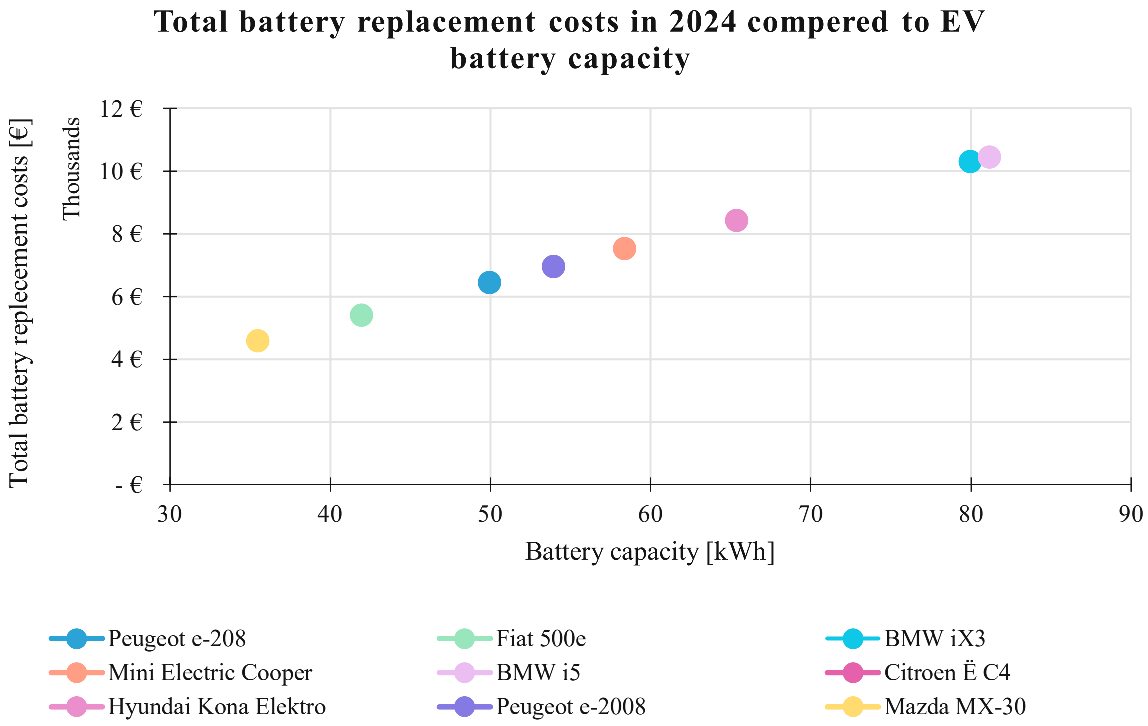


Fig. 8.4 - Total battery replacement costs in 2024 compared to BEV battery capacity [118]

8.2.4. Taxes

At the EU level, taxes on zero-emission vehicles have been abolished in many member countries. Since BEVs do not emit CO_2 during operation, this implies that BEV owners are exempt from paying certain taxes.

In some countries, such as the Netherlands, Cyprus, and Lithuania, consumers are exempt from paying tax at the time of purchase. However, taxes are still applicable in other countries, including Sweden, Germany, and Croatia. Nevertheless, the taxes on BEVs in many countries are significantly lower compared to those on CVs.

The tax exemption is not dependent on the purchase cost or the size of the vehicle. If a member state has adopted a provision for tax exemption, it applies to all vehicles with zero emissions. This is unlike subsidies, where the amount of subsidy often depends on the purchase cost of the vehicle.

For additional values, please see Tables 25 and 26 in the Appendix.

8.2.5. Insurance and Vehicle Registration Costs

Vehicle insurance is mandatory in all EU countries. The annual cost of vehicle insurance depends on numerous factors, such as:

- **Driving record** - this includes the history of traffic violations and accidents with fault. This is one of the principal factors that determines the vehicle insurance rate. Insurance companies check the driving history of the past 3 to 5 years, depending on the country. If there was a traffic accident, the rate increases, that is, if there were no traffic accidents in the observed period, the insurance rate decreases.
- **Age and driving experience** - a particularly important rating factor, especially for young drivers,
- **Coverage selections** - the amount of vehicle insurance is depended on the type of insurance. The most common types of vehicle insurance are liability insurance and comprehensive insurance. The vehicle liability insurance is mandatory in all EU countries.
- **Vehicle insurance history** - if the owner of the vehicle is a new driver or this is the consumer's first insurance policy, then the rate is higher in relation to other drivers.
- **Vehicle model** - the type of vehicle plays a significant role in the insurance rate. Thus, larger vehicles with stronger engines have a higher rate than smaller vehicles with lower engine power.

The amount of annual insurance at the EU level is on average 600€, or 50€ per month [120]. However, it is challenging to discuss the average cost of vehicle insurance at the EU level due to significant variations among member countries. For instance, in Croatia, the average annual vehicle insurance cost is 187.94€ [121], while in the Netherlands, it’s approximately 900€ [122].

Table 19 - Insurance and registration costs of BEV and CV in selected countries [122]

	Insurance costs [€/year]	**Registration costs [€/year]**
Sweden	640.80	45.00
Germany	468.00	90.00
Netherlands	900.00	235.65
Cyprus	1,998.00	205.00
Croatia	187.94	54.30
Lithuania	720.00	40.98

9 Economic Comparison of Battery Electric and Conventional Vehicles

For each of the six observed countries, the costs of BEVs and CVs are analyzed in detail. Based on the total costs calculated at the annual level, the NPV of the investment for the purchase of BEVs and CVs is determined. The NPV of the investment for the purchase of BEVs and CVs is calculated for each of the observed vehicles across the six analyzed countries. This calculation is performed to determine in which of the observed countries it is most profitable to own a BEV or a CV. Before delving into the economic assessment analysis in more detail, it is necessary to define the NPV.

"Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project." [40]

NPV is the result of calculations that find the present value of a future stream of payments using an appropriate discount rate. In general, projects with a positive NPV are worth undertaking, while those with a negative NPV are not.

NPV is calculated using the following formula (9.1) [40]:

$$NPV = -I_o + \sum_{i=1}^{n} \frac{R_t}{(1+r)^i} \tag{9.1}$$

where is:

- I_o – initial investment [€]
- r – required return or discount rate (5%) [%] [123]
- n – number of time periods (in this specific case is equal 10 years, which represents average lifetime of BEV-battery). [year]
- R_t – net cash inflows/outflows during one period i [€/year]

where R_t is calculated according to the formula [40]:

$$R_t = E_i - A_i \tag{9.2}$$

where is:

- E_i – net cash inflow during a single period [€/year]
- A_i – net cash outflow during a single period [€/year]

To calculate the NPV, it is necessary to define the corresponding parameters beforehand. The required return or discount rate r is equal to 5% for our calculations [123].

The following are understood as initial investments [40]:

- purchase price (reduced by the value of subsidies if they exist)
- vehicle registration

$$I_o = PC + VR - SUB \tag{9.3}$$

where is:

- PC – Purchase costs [€]
- VR – Vehicle registration costs [€]
- SUB – Subsidies [€]

In the case of investments for the purchase of cars, cash inflows are non-existent, which means that for all six countries, for all 18 vehicles, both BEV and CV, E_i is equal to zero.

Cash outflows include the sum of the following costs [40]:

- Charging / Refueling
- Maintenance
- Insurance
- Taxes

$$A_i = CC + MC + IN + T \tag{9.4}$$

where is:

- CC – charging/refueling costs [€/year]
- MC – Maintenance costs [€/year]
- IN – Insurance costs [€/year]
- T – Taxes [€/year]

It is particularly important to emphasize that when considering CVs, a distinction is made between the NPV of CVs with a diesel engine and the NPV of CVs with a gasoline engine. For BEVs, the NPV is distinguished based on the type of chargers used, which are as follows:

- exclusively from alternating current (AC) chargers,
- exclusively from direct current (DC) chargers,

- exclusively from private home charging,
- charging with a ratio of 60% private charging, 40% public charging, of which 24% is from AC chargers and 16% from DC chargers,
- charging with a ratio of 50% private charging and 50% public charging, of which 25% is from AC chargers and 25% from DC chargers.

After all the important parameters for the economic assessment of both BEVs and CVs have been processed, this Chapter makes a comparison between these two types of vehicles. The aim is to determine whether BEVs represent a worthwhile investment and whether they have a future in the European vehicle market.

9.1. Total Costs of Charging and Refueling

In Chapter 8, the calculation of the charging/refueling price for BEVs/CVs is explained in detail. This Chapter also includes a comparison of these values, allowing for an assessment of whether BEVs consistently present a more cost-effective option when it comes to charging/refueling.

Small Cars

Figure 9.1 shows the total annual charging costs of small BEVs in selected countries, depicted as a box plot. It shows the total annual charging cost, in € for diverse types of small BEVs across selected countries. The vehicles included are Peugeot e-208, Fiat 500e, and Mini Electric Cooper.

The graph uses box-and-whisker plots to represent the distribution of charging costs for each vehicle type within each country. Here is what each part of the box-and-whisker plot represents:

- The central line in the box indicates the median cost, which is the middle value of the data set.
- The top and bottom edges of the box show the interquartile range, which is the range between the first quartile (25th percentile) and the third quartile (75th percentile).
- The whiskers extend from each box to indicate variability outside the upper and lower quartiles.
- Outliers are represented as individual ‘x’ marks. These are values that fall outside the normal range of the data set.

In this case, the minimum represents the total charging costs from exclusively private chargers, while the maximum represents the total charging costs from exclusively DC chargers. The upper quartile, lower quartile, and median represent the total costs of charging from AC chargers and a combination of all three types of chargers. The mean value of these five calculations is marked with an “x”, indicating the average total annual BEV charging costs.

Figure 9.1 shows total annual charging costs of small BEVs in selected countries in 2024. The highest total annual charging costs are in the Netherlands. This could be due to the higher charging price from different chargers compared to the other observed countries. The graph also suggests that in countries with a higher GDP per capita, the total annual charging costs of BEVs are significantly higher. The average total costs of BEV charging, regardless of the observed country, are around 800€.

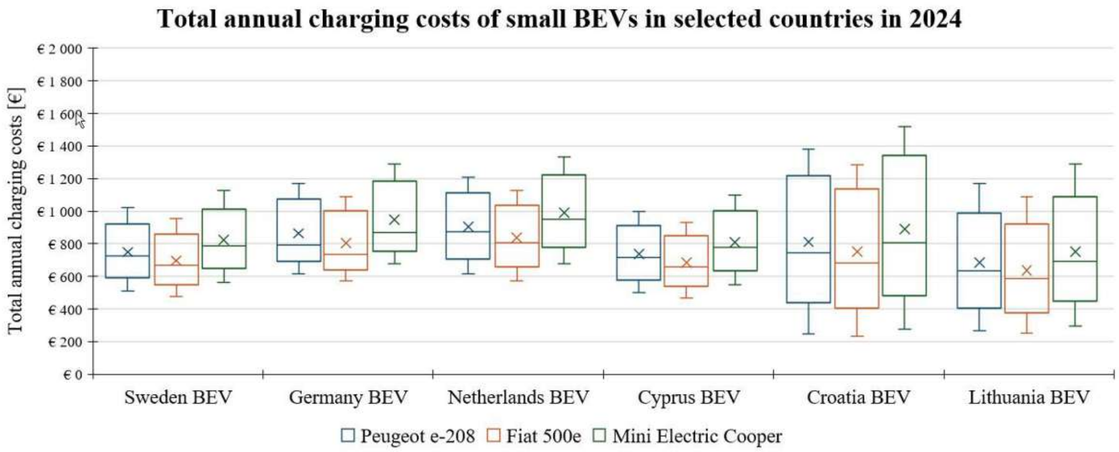


Fig. 9.1 - Total annual charging costs of small BEVs in selected countries in 2024

However, when it comes to CV, then the deviation is greater.

Figure 9.1 shows total annual refueling costs of small CVs across six selected countries: Sweden, Germany, Netherlands, Cyprus, Croatia, and Lithuania in 2024. The vehicles compared are the Peugeot 208, Fiat 500, and Mini Cooper. The total annual refueling costs are the highest in the Netherlands, while they are the lowest in Croatia, Cyprus, and Lithuania.

This could be due to the higher fuel prices in the Netherlands compared to the other observed countries. The Figure 9.2 also suggests that in countries with a higher GDP per capita, the total annual refueling costs of CVs are higher, particularly in Germany and Netherlands.

The average total cost of refueling a CV, regardless of the country observed, is around 850€. The total annual refueling costs of CVs are slightly higher than those of BEVs. This observation leads to the conclusion that the GDP per capita, as well as fuel costs of an observed country influences the total refueling costs of CVs.

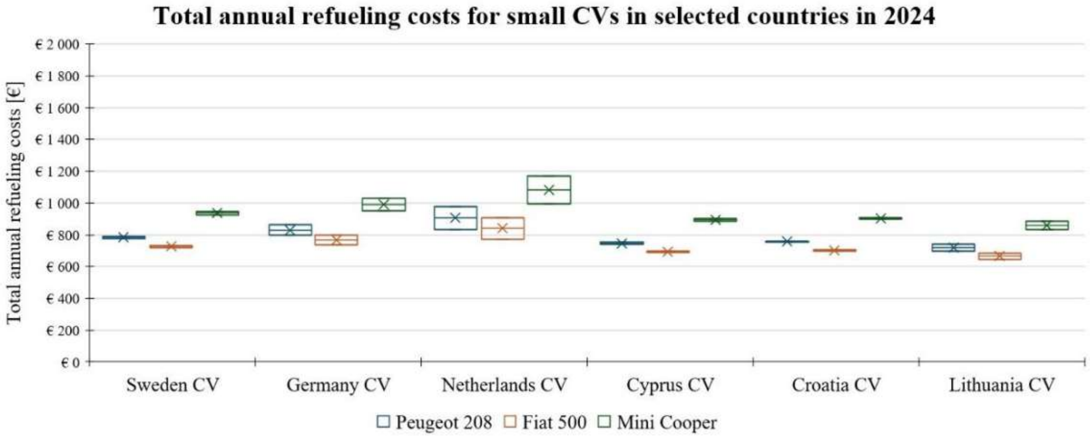


Fig. 9.2 - Total annual refueling costs for small CVs in selected countries in 2024.

Sedans

Figure 9.3 shows the total annual charging costs of sedan BEVs in selected countries, depicted as a box plot. It shows the total annual charging cost, in € for diverse types of sedan BEVs across selected countries. The vehicles included are BMW i5, Citroen Ë C4, and Hyundai Kona Elektro.

When it comes to sedan vehicles, the situation is like that of small vehicles. The total annual charging costs for BEVs are highest in the Netherlands, followed by Germany. The lowest costs are observed in Cyprus and Lithuania, see Figure 9.3.

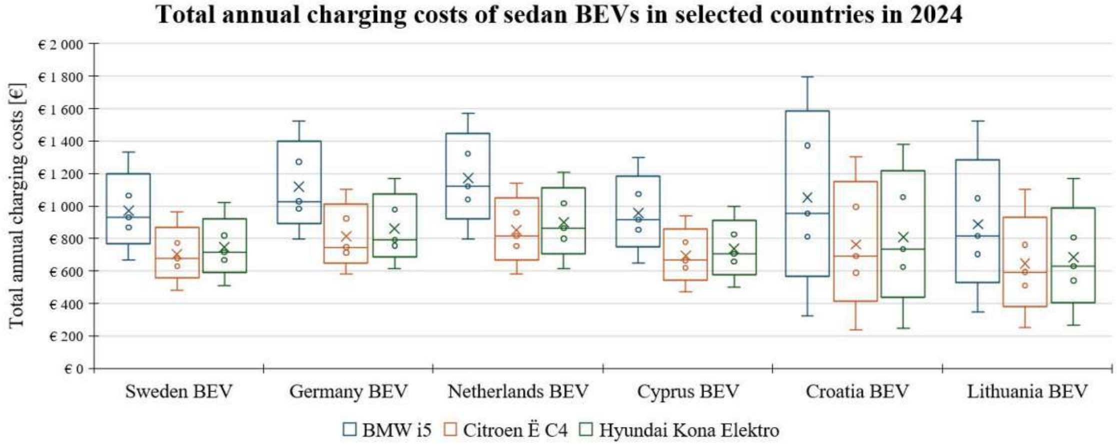


Fig. 9.3 - Total annual charging costs of sedan BEVs in selected countries in 2024

Figure 9.4 shows the total annual refueling costs of sedan CVs in selected countries, depicted as a box plot. It shows the total annual refueling cost, in € for diverse types of sedan CVs across selected countries. The vehicles included are BMW 5, Citroen C4 and Hyundai Kona.

It can be concluded that the total annual costs of charging/refueling BEVs/CVs are highest in countries with a higher GDP per capita compared to countries with a lower GDP per capita. The average total annual costs of charging sedan vehicles, regardless of the country observed, are around 1,000€, while for CVs they are around 1,200€. This is a significant difference compared to BEVs. This difference can impact the overall NPV of CVs in relation to BEVs. More details can be found in Chapter 9.4.

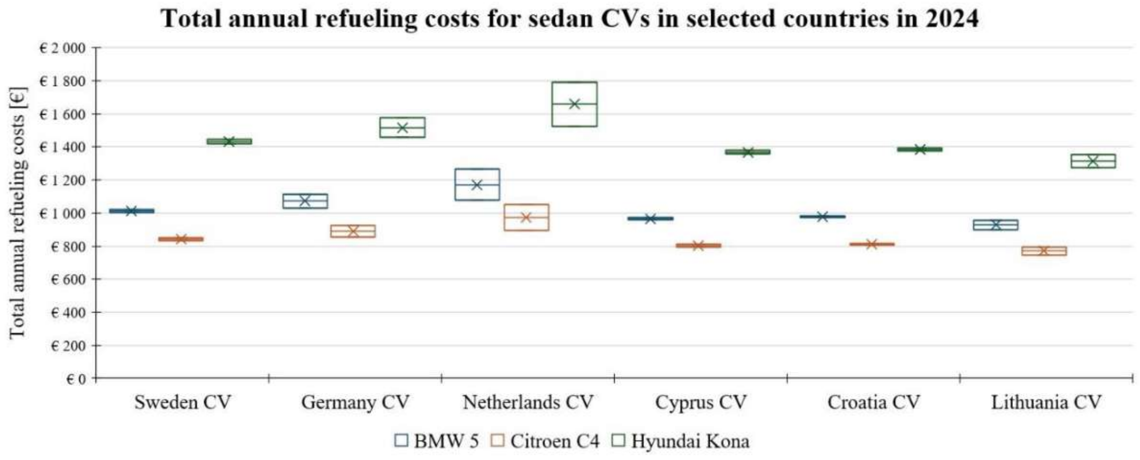


Fig. 9.4 - Total annual costs for sedan CVs in selected countries in 2024

SUV

Figure 9.5 shows the total annual charging costs. in € for diverse types of SUV BEVs across selected countries. The vehicles included are Peugeot e-2008, Mazda MX-30, and BMW iX3.

SUV BEV also have similar total annual charging costs. Countries with a higher GDP per capita have higher total annual costs of charging BEVs, with the Netherlands standing out as having the highest costs, see Figure 9.5.

However, there is a significant difference between the total annual costs of charging SUV BEVs exclusively from private chargers and DC chargers in Croatia and Lithuania. This is attributed to the substantial difference in the charging costs associated with these types of chargers.

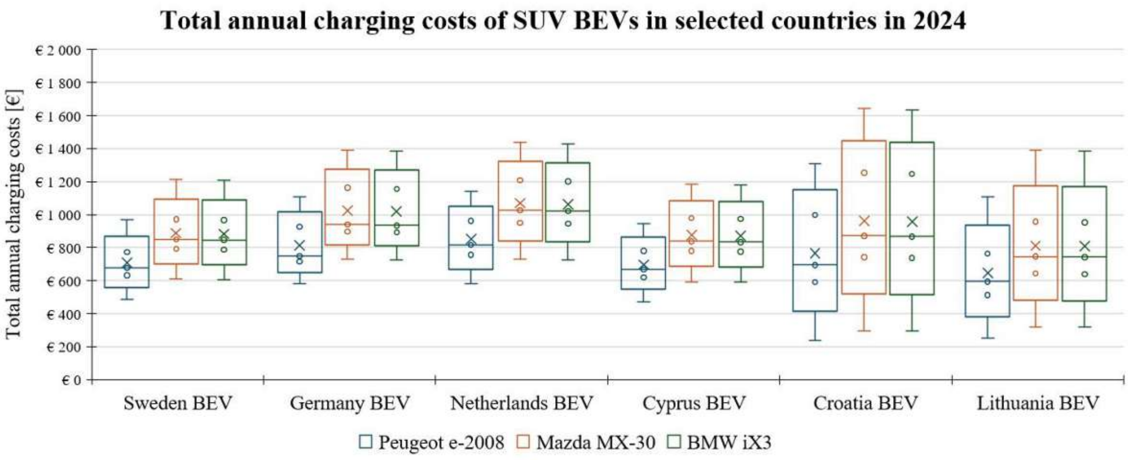


Fig. 9.5 - Total annual charging costs of SUV BEVs in selected countries in 2024

Figure 9.6 shows the total annual refueling costs, in € for diverse types of SUV CVs across selected countries. The vehicles included are Peugeot 2008, Mazda CX-30, and BMW X3.

In the case of CVs, the situation differs. The total annual costs of refueling are higher compared to BEVs. The Netherlands stands out due to its high fuel prices, which results in higher total refueling costs compared to other considered countries. This can be used as an indicator that the fuel/electricity price is an important parameter when calculating the total costs of charging/refueling. Due to the high fuel price in Netherlands, the total annual refueling costs for SUV CVs are higher, see Figure 9.6.

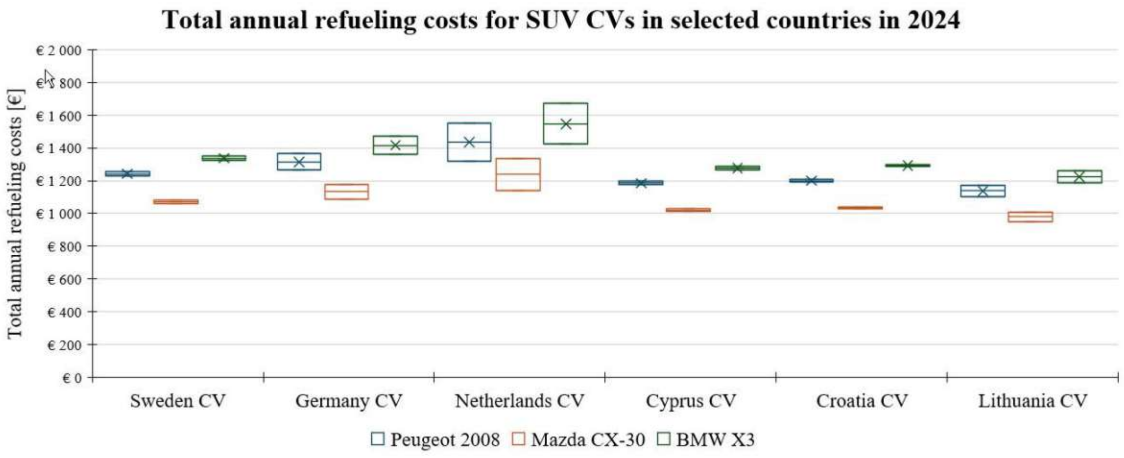


Fig. 9.6 - Total annual refueling costs for SUV CVs in selected countries in 2024.

9.2. Charging and Refueling Time

With the advancement of BEVs, the development of fast chargers has become essential. The average charging time of 8 or more hours with a 3.3kW AC charger poses a significant obstacle to the obstacle of BEVs. This is precisely why fast chargers are being developed daily. However, even with a fast 120kW charger, the average BEV still requires slightly less than an hour to charge.

The evolution of transport infrastructure and the increase in the number of road vehicles have made travel easier, simpler, and faster than ever before. In today's fast-paced world, more people are striving to complete tasks as quickly as possible. Consequently, the necessity to charge a BEV for several hours is a factor that deters many people from purchasing a BEV.

Considering that the average refueling time for a CV tank is only 4 to 5 minutes, it is clear why fast charging is not yet the most ideal solution. Although developed EU countries are installing ultra-fast 200kW chargers, even this type of charger takes up to 20 minutes to fully charge the battery.

However, the lengthy charging time is not the only drawback when it comes to fast charging. There are additional disadvantages to consider.

- **Higher cost** - Fast chargers are more expensive to install. This means that it is necessary to pay more for the convenience of fast charging.
- **Shorter lifetime of battery** - Rapid charging can cause the battery to shorten its lifetime more quickly over time, resulting in the need to replace the battery more often. Which, in addition to their high price, is inadequate.
- **Heat** - Rapid charging can cause the battery to heat up quickly. This can be a problem if the car is not equipped for this.
- **Less efficient** - Fast charging is not as efficient as standard charging. This means that overall, the more electricity is used and is paid more.

It can be concluded that BEVs require careful planning to avoid situations where it is impossible to find a free charging station, or any charging station within a radius of several kilometers. This is a significant problem in less developed countries. With adequate planning and efficient use of time, despite the lengthy charging duration, BEVs can increasingly compete with CVs due to the development of faster chargers.

In Table 20, the relationship between the time required to charge the observed vehicles with a 120kW fast charger and the time required to refuel the CV tank can be seen. On average, the maximum range of BEVs is shorter than that of CVs.

Table 20 - Charging/refueling time of BEVs and CVs [57] [64]

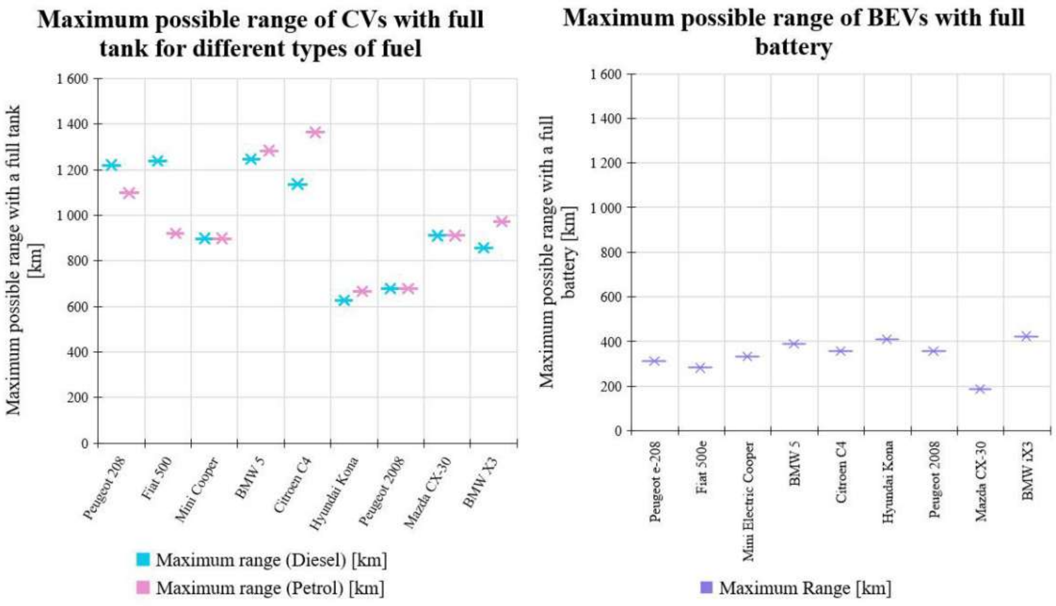
Refueling (diesel) [Min/refuel]		**Charging DC-120kW [Min/charge]**	
Small cars			
Peugeot 208	3.72	Peugeot e-208	26.32
Fiat 500	3.50	Fiat 500e	22.10
Mini Cooper	3.28	Mini Electric Cooper	30.73
Sedans			
BMW 5	4.91	BMW i5	42.73
Citroen C4	3.72	Citroen Ë C4	28.42
Hyundai Kona	3.50	Hyundai Kona Elektro	34.42
SUVs			
Peugeot 2008	3.28	Peugeot e-2008	28.42
Mazda CX-30	3.80	Mazda MX-30	18.68
BMW X3	4.47	BMW iX3	40.02

9.3. Maximum Range

When comparing BEVs and CVs as shown in Figure 9.7, it is evident that the maximum range of a BEV is less than that of a CV. In the case of small vehicles, the BEV battery is smaller, which justifies the shorter ranges. For instance, with the CV Peugeot 208, the maximum range of the engine with diesel as fuel exceeds 1,200 km. This figure depends on the average fuel consumption of the vehicle, but despite this, the range is greater compared to the less than 400 km maximum range of the electric Peugeot e-208. For the electric Peugeot e-208 to travel the same distance as a conventional Peugeot 208, the BEV battery needs to be charged at least four times. A slightly smaller difference between the maximum ranges is visible in the Fiat 500 and its electric variant, the Fiat 500e, but even in this case, the battery needs to be charged at least three times.

If a consumer has their own private charger at home, which they would use to regularly charge the battery, this will not pose a problem. However, this can be a significant issue if there is not a sufficiently developed charging station infrastructure.

Figure 9.7 shows maximum range of CVs with full tank for diverse types of fuel and BEVs with full battery. The maximum ranges of BEVs are significantly lower compared to CVs. This means that for a BEV to cover the same range as a CV, it is necessary to charge the battery multiple times.


Maximum possible range of CVs with full tank for different types of fuel

Maximum possible range of BEVs with full battery

a) b)

Fig. 9.7 - Maximum range of a) CVs with full tank for diverse types of fuel and b) BEVs with full battery

9.4. Economic Assessment of Battery Electrical Vehicles

To assess the economic relationship between CVs and BEVs, NPV is used. By calculating the NPV of a CV and its electric variant, taking all costs into consideration, it can be determined which vehicle is more cost-effective. For all vehicles, the NPV was calculated based on the type of fuel or charger, as already explained in Chapter 8. Since purchasing a vehicle is not a profitable investment (as there is no inflow of money during the observed period, only costs), the NPV of all vehicles has a negative value. However, the vehicle that is considered "more profitable" is the one with the higher value.

Small Cars

Figure 9.8 shows the NPV of small BEVs and CVs in selected countries as a box graph. In the box plot, a box is drawn between the lower and upper quartiles. The mean value of calculations is marked with an "x", representing the average NPV of BEVs and CVs. NPVs are shown for all six observed countries.

Figure 9.8 a) shows the NPV of small BEVs and CVs in Sweden. By observing the average NPV values of BEVs and CVs, it can be immediately noticed that the NPV values of BEVs are lower compared to CVs. This indicates that in the observed period of 10 years, BEVs are a less cost-effective investment. A consumer in Sweden would incur higher costs with a small BEV compared to a small CV. The NPV of the small Peugeot e-208 in Sweden after 10 years is around -60,000€, while its conventional version, the Peugeot 208, has an NPV value of around -50,000€. Over a period of 10 years, a consumer in Sweden would spend an average of 10,000€ more. A smaller difference between the NPV of BEVs and CVs is seen in the example of the Mini Cooper. However, even here, the higher costs of owning a BEV compared to a CV are noticeable. In Figure 9.8 a), it is evident that the situation in Sweden is like the other observed countries except for Cyprus. In Cyprus, when it comes to small BEVs, the NPV is lower compared to the NPV of CVs. If a consumer decides to buy a BEV in Cyprus, after 10 years they could have lower costs compared to a CV. However, it should not be forgotten that Cyprus has the highest BEV subsidies of all the observed countries. The difference between the average NPV values of small BEVs and the average NPV values of small CVs is the largest in the case of the Mini Cooper. This difference is around 8,000€. If the Cyprus government decides to abolish BEV subsidies, it would lead to a decrease in the NPV of small BEVs. This is also an especially important indicator that government subsidies can significantly impact the economic assessment of BEVs.

When analyzing Figures 9.1 and 9.2 from Chapter 9.1, the total annual costs associated with charging or refueling BEVs, and CVs are remarkably similar. This arises due to several factors.

BEVs exhibit high average energy consumption, which require frequent battery charging. Their limited maximum range contributes to this requirement. Consequently, refueling costs do not significantly impact the overall cost-effectiveness of BEVs.

The lower cost-effectiveness of small BEV arises due to several factors. Firstly, the primary difference lies in the initial purchase price. Small BEVs typically command a higher price compared to CVs. Additionally, the absence of substantial subsidies for BEVs worsens this cost difference. Even when subsidies are available, they often fail to sufficiently narrow the gap in purchasing costs between BEVs and CVs. Secondly, BEV maintenance costs play a crucial role. Although annual maintenance expenses for BEVs average 30% lower than those for CVs, the total costs over a 10-year period tend to be higher. The key factor here is battery replacement. As emphasized in Chapter 6, the typical lifespan of a BEV battery is around 10 years. Beyond this period, battery replacement becomes necessary. In 2024, the cost of replacing a BEV battery amounts to 125€/kWh. This replacement constitutes approximately 30% of the BEV’s total purchase price, impacting overall maintenance costs significantly.

All these factors collectively contribute to the negative impact on the cost-effectiveness of BEVs, showing them as unprofitable.

Additionally, the purchasing power of consumers must be considered. Figure 9.8 shows the NPV of small BEVs, falling within the range of 60,000€ to 65,000€. Although this may not seem like a significant difference, it gains significance when considering the substantial difference in GDP per capita across countries. For example, Sweden boasts a GDP per capita 30,000€ higher than that of Croatia. Surprisingly, despite this considerable GDP gap, the costs associated with owning a small BEV in Croatia are, on average, only 8,000€ lower than in Sweden. When consumers’ purchasing power is low, it directly affects the development of the BEV market. This phenomenon contributes to the slower growth of the BEV market in countries with a lower GDP per capita, in contrast to countries where GDP per capita is higher.

In summary, addressing the cost disparities, improving subsidies, and extending battery longevity are crucial steps toward enhancing the cost-effectiveness and widespread adoption of small BEVs. Additionally, policymakers should consider the economic context of each country to promote sustainable electric mobility.

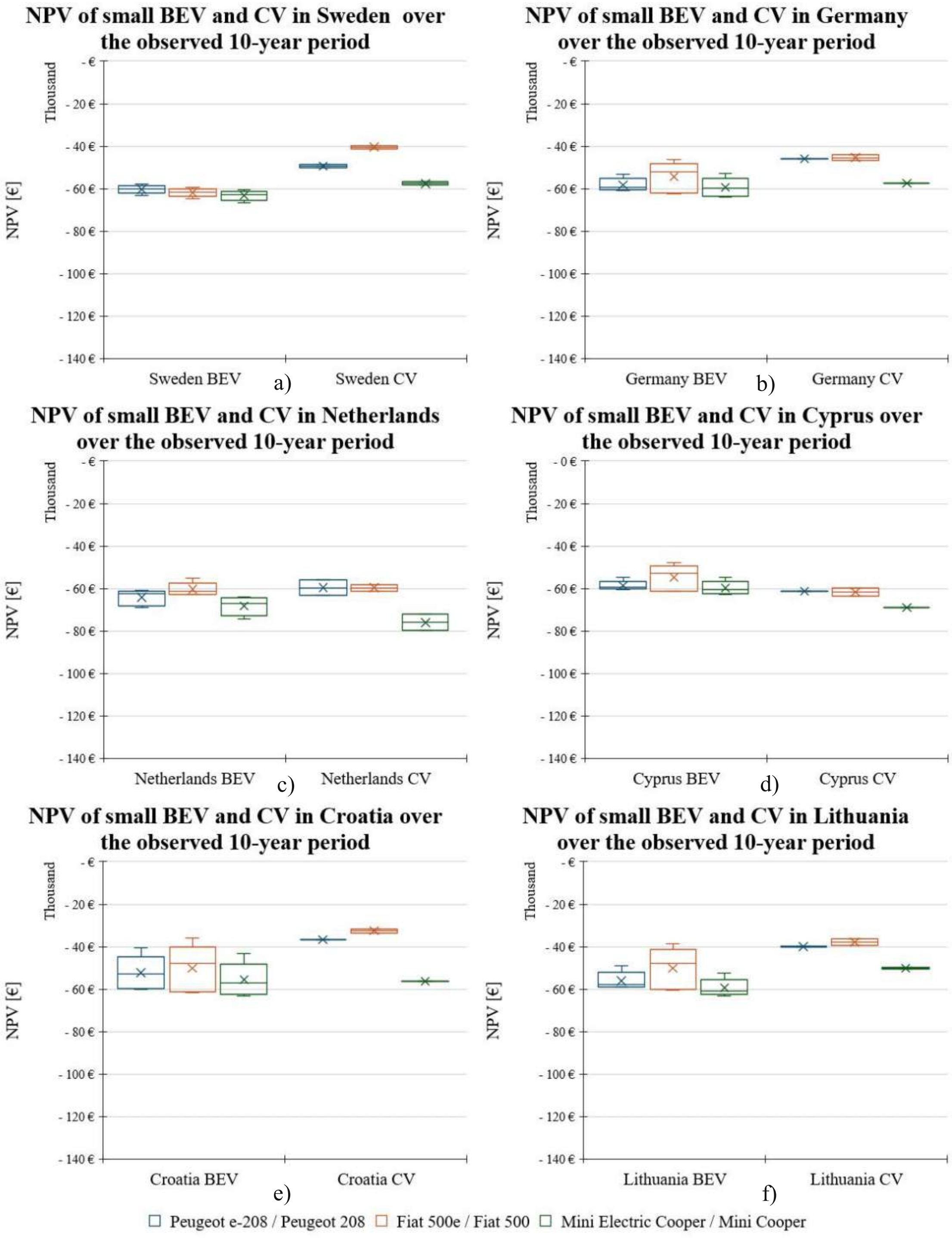


Fig. 9.8 - NPV of small BEV and CV in a) Sweden, b) Germany, c) Netherland, d) Cyprus, e) Croatia and f) over observed 10-year period

Sedans

Figure 9.9 a) shows NPV of sedan BEVs and CVs in Sweden. Upon examining the average NPV values for both vehicle types, it becomes evident that BEVs have lower NPV compared to CVs. This indicates that over the observed period of 10 years, BEVs are a less profitable investment. Consumers in most of the observed countries would incur higher costs with a sedan BEV compared to a sedan CV.

For instance, consider the BMW i5 sedan in Germany: its NPV after 10 years is approximately -110,000€, while the conventional version, the BMW 5, has an NPV of around -90,000€. Over a decade, a German consumer would spend an average of 20,000€ more on the BEV. The situation in Sweden closely mirrors that of other observed countries, except for Cyprus and the Netherlands.

In Cyprus, NPV for sedan BEVs is lower than that for CVs, similar to the case with small BEVs. This discrepancy arises due to Cyprus offering the most substantial BEV subsidies among all observed countries. Interestingly, the Netherlands demonstrates high cost-effectiveness for sedan BEVs compared to sedan CVs, driven not primarily by subsidies but by exceptionally high taxes on CVs.

When analyzing Figures 9.3 and 9.4 from Chapter 9.1, the total annual costs associated with charging BEVs and CVs are, on average, approximately 200€ higher for CVs. Several factors contribute to this difference:

- Battery Capacity and Range: BEVs, despite their higher average energy consumption, benefit from larger battery capacities, resulting in increased maximum range. Consequently, small BEVs require less frequent battery charging than their larger counterparts.
- Price Trends: Depending on calculation considerations, future trends may see a decrease in the cost of charging (for BEVs) and an increase in fuel prices (for CVs).

Additionally, the primary difference lies in the initial purchase price. While this difference is smaller for small vehicles, sedan vehicles globally have a higher purchase price compared to small vehicles. As a result, subsidies for sedans are often smaller or even non-existent, depending on the purchase price.

BEV maintenance costs also play a crucial role for sedans. Replacing the battery inside a sedan BEV accounts for approximately 20% of the total purchase price of the vehicle, significantly affecting overall maintenance costs.

All these factors together contribute to a negative impact on the profitability of BEVs, showing them less attractive for consumers. Figure 9.8 shows the NPV of sedan BEVs, which falls in the range of 70,000€ to 110,000€. This represents a significant obstacle for consumers in countries with low GDP per capita, contributing to the slower growth of the sedan BEV market in such nations compared to those with higher GDP per capita.

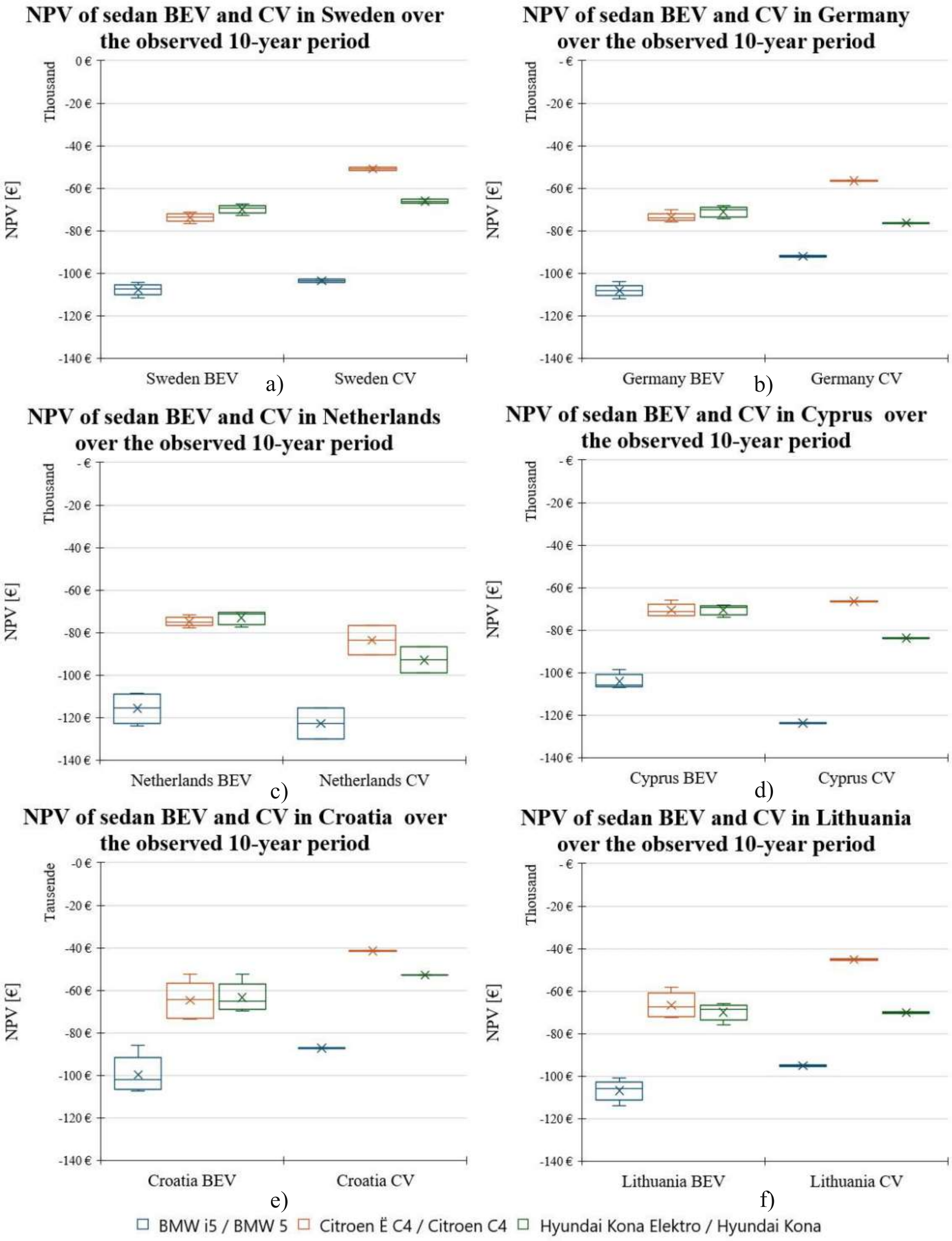


Fig. 9.9 - NPV of sedan BEV and CV in a) Sweden, b) Germany, c) Netherland, d) Cyprus, e) Croatia and f) Lithuania over observed 10-year period

SUVs

Figure 9.10 a) shows the NPV of SUV BEVs, and CVs in Sweden. After analyzing the average NPV values for both vehicle types, it becomes evident that BEVs have a lower NPV compared to CVs. This suggests that over the observed 10-year period, BEVs are a less profitable investment. Consumers in most of the observed countries would incur higher costs with an SUV BEV compared to an SUV CV.

For instance, consider the Peugeot e-2008 in Sweden. After 10 years, its NPV is approximately -75,000€, whereas the conventional version, the Peugeot 2008, has an NPV of around -60,000€. Over a decade, a Swedish consumer would spend an average of 15,000€ more on an SUV BEV. The situation in Sweden aligns closely with that in other observed countries, except for Cyprus and the Netherlands.

In Cyprus, the NPV of SUV BEVs is lower than that of CVs due to high subsidies. Interestingly, the Netherlands demonstrates high profitability for SUV BEVs compared to SUV CVs, driven not primarily by subsidies but by extremely high taxes on CVs.

When examining Figures 9.5 and 9.6 from Chapter 9.1, we find that the total annual costs associated with charging BEVs and CVs are, on average, approximately 400€ higher for BEVs. This cost difference is influenced by factors such as battery capacity, range, and price trends.

Similar to other vehicle categories, the primary difference lies in the initial purchase price. SUVs have the highest purchase price, resulting in limited subsidies for this vehicle type, except in Cyprus and Croatia. Additionally, replacing the battery in an SUV BEV constitutes approximately 20% of the total vehicle purchase price, significantly impacting maintenance costs.

Collectively, these factors contribute to a negative impact on the profitability of SUV BEVs, making them less appealing to consumers. Figure 9.8 shows the NPV of BEV sedans, falling within the range of 100,000€ to 60,000€. This financial challenge is particularly pronounced for consumers in countries with low GDP per capita.

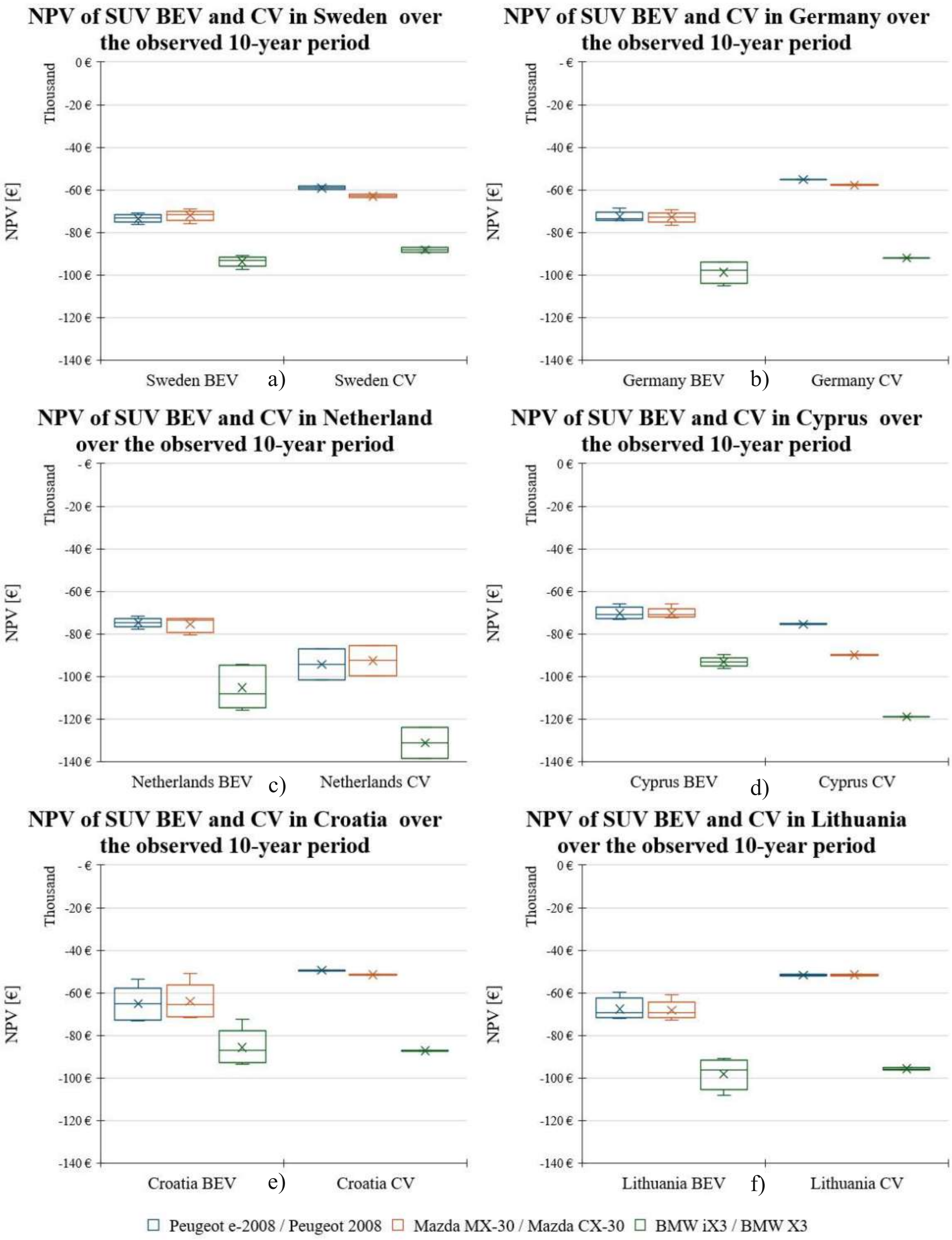


Fig. 9.10 - NPV of SUV BEV and CV in a) Sweden, b) Germany, c) Netherland, d) Cyprus, e) Croatia and f) Lithuania over the observed 10-year period

10 Conclusion

An analysis of the economic assessment of BEVs at the EU level, considering several parameters, finds that currently BEVs are not yet economically competitive with conventional vehicles. Factors such as higher purchase prices, shorter driving ranges, more frequent battery charging, and expensive batteries are major barriers for the broader acceptance of electric vehicles. However, the ongoing development of BEV technology could in the future make electric vehicles more competitive on the market. Based on calculations conducted in this work for six different EU countries, with different GDP per capita, it can be noticed that the economic assessment of BEVs depends on multiple factors.

After examining small BEVs, it becomes apparent that they may not be a cost-effective investment compared to CVs. Small BEVs come with small battery capacity, resulting in a relatively short driving range. Consequently, this leads to higher charging frequency. However, their unprofitability can be attributed to the relatively high purchase costs in comparison to the purchase price of conventional small vehicles.

Sedans, often categorized as luxury vehicles, typically come with a higher purchase price. The significant difference in purchase prices between BEV sedans and CV sedans leads to an unfavorable NPV. Therefore, a BEV sedan might be considered as an unprofitable investment. However, in the future with the reduction of the battery prices and increasing taxes on fossil fuels situation can be changed.

Analyzed SUV BEVs prove to be a profitable investment when compared to conventional SUV in the Netherlands and Cyprus. However, in other countries, SUV BEVs are less cost-effective. In the Netherlands, the profitability of SUV BEVs derives primarily from the significant tax burden imposed by the Dutch government on conventional SUV. Meanwhile, in Cyprus, the economic profitability of SUV BEVs is a direct result of high subsidies. These two countries serve as compelling examples of how BEV profitability can be enhanced through well-designed subsidy programs and strategic taxation policies.

Furthermore, a country's GDP per capita directly influences the development of the BEV market. While the NPV values of all BEVs compared to CVs approximate each other in countries with higher GDP per capita, consumer purchasing power remains a critical factor in driving further BEV market growth.

Regarding the economic comparison of BEVs and CVs it has to be considered that some parameters such as fuel consumption, ranges, charging fees, fuel and registration taxes vary considerably between countries and car models.

The varying development rates of individual EU countries also play a role. EU countries with lower GDP per capita experience a slower increase in the number of BEVs due to inadequate infrastructure development. As demonstrated by examples from Cyprus and Croatia, BEVs do not yet pose a competitive threat to CVs in these less developed markets. Due to the numerous obstacles that many countries are currently facing, the negative economic assessment of BEVs slows down the further development of the BEV market.

Policymakers should consider targeted incentives to promote BEV adoption. While subsidies play a role, high taxes on CVs (as seen in the Netherlands) can also drive BEV profitability. Crafting a balanced approach that encourages BEV purchases without compromising revenue is crucial. The investment in charging infrastructure is important. The higher annual costs associated with BEV charging highlight the need for accessible and efficient charging stations. Public-private partnerships can facilitate this infrastructure expansion.

Moreover, research and development in battery technology, as well as development of the appropriate battery recycling can reduce overall costs and, make BEVs more environmentally friendly and more appealing to consumers.

BEV adoption should be viewed as part of a broader strategy for sustainable economic growth. Aligning policies with GDP per capita can ensure equitable access to cleaner transportation options.

In conclusion, with the current state of technology, purchase prices, taxes, subsidies, and other costs considered in this thesis, BEVs are not a profitable investment compared to CVs. Purchase prices, subsidies, taxes, vehicle size, battery size and charging type have a significant impact on the development of the BEV market. While the low GDP per capita slows down the development of the BEV market, the economic profitability of investing in BEVs is questionable. Solutions must be found for BEVs to increase their economic competitiveness with CVs. Policymakers should combine different incentives, development of infrastructure, and rise of consumer awareness to drive BEV adoption while considering each country’s unique circumstances.

Appendix

Table 21 - Charging prices in selected countries from 2025 until 2034

	Sweden			Germany		
Year	**AC-Charging price [€/kWh]**	**DC-Charging price [€/kWh]**	**Private-Charging price [€/kWh]**	**AC-Charging price [€/kWh]**	**DC-Charging price [€/kWh]**	**Private-Charging price [€/kWh]**
2025	0.420	0.527	0.261	0.504	0.604	0.314
2026	0.419	0.526	0.260	0.503	0.603	0.313
2027	0.417	0.524	0.258	0.501	0.601	0.311
2028	0.413	0.520	0.254	0.497	0.597	0.307
2029	0.411	0.518	0.252	0.495	0.595	0.305
2030	0.409	0.516	0.250	0.493	0.593	0.303
2031	0.408	0.515	0.249	0.492	0.592	0.302
2032	0.408	0.515	0.249	0.492	0.592	0.302
2033	0.409	0.516	0.250	0.493	0.593	0.303
2034	0.410	0.517	0.251	0.494	0.594	0.304
	Netherland			Cyprus		
Year	**AC-Charging price [€/kWh]**	**DC-Charging price [€/kWh]**	**Private-Charging price [€/kWh]**	**AC-Charging price [€/kWh]**	**DC-Charging price [€/kWh]**	**Private-Charging price [€/kWh]**
2025	0.524	0.624	0.314	0.424	0.514	0.254
2026	0.523	0.623	0.313	0.423	0.513	0.253
2027	0.521	0.621	0.311	0.421	0.511	0.251
2028	0.517	0.617	0.307	0.417	0.507	0.247
2029	0.515	0.615	0.305	0.415	0.505	0.245
2030	0.513	0.613	0.303	0.413	0.503	0.243
2031	0.512	0.612	0.302	0.412	0.502	0.242
2032	0.512	0.612	0.302	0.412	0.502	0.242
2033	0.513	0.613	0.303	0.413	0.503	0.243
2034	0.514	0.614	0.304	0.414	0.504	0.244
	Croatia			Lithuania		
Year	**AC-Charging price [€/kWh]**	**DC-Charging price [€/kWh]**	**Private-Charging price [€/kWh]**	**AC-Charging price [€/kWh]**	**DC-Charging price [€/kWh]**	**Private-Charging price [€/kWh]**
2025	0.544	0.714	0.124	0.414	0.604	0.134
2026	0.543	0.713	0.123	0.413	0.603	0.133
2027	0.541	0.711	0.121	0.411	0.601	0.131
2028	0.537	0.707	0.117	0.407	0.597	0.127
2029	0.535	0.705	0.115	0.405	0.595	0.125
2030	0.533	0.703	0.113	0.403	0.593	0.123
2031	0.532	0.702	0.112	0.402	0.592	0.122
2032	0.532	0.702	0.112	0.402	0.592	0.122
2033	0.533	0.703	0.113	0.403	0.593	0.123
2034	0.534	0.704	0.114	0.404	0.594	0.124

Table 22 - Total monthly charging costs in Sweden, Germany, and Netherland in 2024

Total monthly charging costs in selected countries [€]					
	Sweden				
	100% AC	100% DC	100% Private	24% AC, 16% DC, 60% Private	25% AC, 25% DC, 50% Private
Small					
Peugeot e-208	68.21	85.30	42.72	55.65	60.42
Fiat 500e	63.52	79.43	39.78	51.82	55.63
Mini Electric Cooper	75.03	93.83	46.99	61.21	65.71
Sedan					
BMW i5	88.67	110.88	55.54	72.34	77.66
Citroen Ë C4	64.37	80.50	40.32	52.52	56.38
Hyundai Kona Elektro	68.21	85.30	42.72	55.65	59.74
SUV					
Peugeot e-2008	64.50	80.66	40.40	52.62	56.49
Mazda MX-30	81.00	101.29	50.73	66.08	70.94
BMW iX3	80.57	100.76	50.46	65.74	70.56
	Germany				
	100% AC	100% DC	100% Private	24% AC, 16% DC, 60% Private	25% AC, 25% DC, 50% Private
Small					
Peugeot e-208	81.60	97.60	51.20	65.92	63.90
Fiat 500e	75.99	90.89	47.68	61.39	58.75
Mini Electric Cooper	89.76	107.36	56.32	72.51	69.39
Sedan					
BMW i5	106.08	126.88	66.56	85.70	82.01
Citroen Ë C4	77.01	92.11	48.32	62.21	59.54
Hyundai Kona Elektro	81.60	97.60	51.20	65.92	63.08
SUV					
Peugeot e-2008	77.16	92.29	48.42	62.34	59.65
Mazda MX-30	96.90	115.90	60.80	78.28	74.91
BMW iX3	96.39	115.29	60.48	77.87	74.52
	Netherlands				
	100% AC	100% DC	100% Private	24% AC, 16% DC, 60% Private	25% AC, 25% DC, 50% Private
Small					
Peugeot e-208	84.80	100.80	51.20	66.69	72.85
Fiat 500e	78.97	93.87	47.68	62.10	67.05
Mini Electric Cooper	93.28	110.88	56.32	73.36	79.20
Sedan					
BMW i5	110.24	131.04	66.56	86.69	93.60
Citroen Ë C4	80.03	95.13	48.32	62.94	67.95
Hyundai Kona Elektro	84.80	100.80	51.20	66.69	72.00
SUV					
Peugeot e-2008	80.19	95.32	48.42	63.06	68.09
Mazda MX-30	100.70	119.70	60.80	79.19	85.50
BMW iX3	100.17	119.07	60.48	78.78	85.05

Table 23 - Total monthly charging costs in Cyprus, Croatia, and Lithuania in 2024

Total monthly charging costs in selected countries [€]					
	Cyprus				
	100% AC	100% DC	100% Private	24% AC, 16% DC, 60% Private	25% AC, 25% DC, 50% Private
Small					
Peugeot e-208	68.80	83.20	41.60	54.78	59.49
Fiat 500e	64.07	77.48	38.74	51.02	54.76
Mini Electric Cooper	75.68	91.52	45.76	60.26	64.68
Sedan					
BMW i5	89.44	108.16	54.08	71.22	76.44
Citroen Ë C4	64.93	78.52	39.26	51.70	55.49
Hyundai Kona Elektro	68.80	83.20	41.60	54.78	58.80
SUV					
Peugeot e-2008	65.06	78.68	39.34	51.81	55.60
Mazda MX-30	81.70	98.80	49.40	65.06	69.83
BMW iX3	81.27	98.28	49.14	64.71	69.46
	Croatia				
	100% AC	100% DC	100% Private	24% AC, 16% DC, 60% Private	25% AC, 25% DC, 50% Private
Small					
Peugeot e-208	88.00	115.20	20.80	52.03	62.08
Fiat 500e	81.95	107.28	19.37	48.45	56.99
Mini Electric Cooper	96.80	126.72	22.88	57.24	67.32
Sedan					
BMW i5	114.40	149.76	27.04	67.64	79.56
Citroen Ë C4	83.05	108.72	19.63	49.11	57.76
Hyundai Kona Elektro	88.00	115.20	20.80	52.03	61.20
SUV					
Peugeot e-2008	83.22	108.94	19.67	49.20	57.87
Mazda MX-30	104.50	136.80	24.70	61.79	72.68
BMW iX3	103.95	136.08	24.57	61.46	72.29
	Lithuania				
	100% AC	100% DC	100% Private	24% AC, 16% DC, 60% Private	25% AC, 25% DC, 50% Private
Small					
Peugeot e-208	67.20	97.60	22.40	45.18	53.07
Fiat 500e	62.58	90.89	20.86	42.08	48.80
Mini Electric Cooper	73.92	107.36	24.64	49.70	57.64
Sedan					
BMW i5	87.36	126.88	29.12	58.74	68.12
Citroen Ë C4	63.42	92.11	21.14	42.64	49.45
Hyundai Kona Elektro	67.20	97.60	22.40	45.18	52.40
SUV					
Peugeot e-2008	63.55	92.29	21.18	42.73	49.55
Mazda MX-30	79.80	115.90	26.60	53.66	62.23
BMW iX3	79.38	115.29	26.46	53.37	61.90

Table 24 - Total monthly refueling costs in selected countries.

Total monthly refueling costs in selected countries [€]				
	Sweden		Germany	
	Diesel	Petrol	Diesel	Petrol
	Small			
Peugeot 208	64.62	65.89	66.42	71.79
Fiat 500	59.89	61.07	61.56	66.54
Mini Cooper	77.22	78.74	79.38	85.80
	Sedan			
BMW 5	83.53	85.17	85.86	92.80
Citroen C4	69.34	70.71	71.28	77.04
Hyundai Kona	118.20	120.53	121.50	131.33
	SUV			
Peugeot 2008	102.44	104.46	105.30	113.82
Mazda CX-30	88.26	89.99	90.72	98.06
BMW X3	110.32	112.49	113.40	122.57
	Netherland		Cyprus	
	Diesel	Petrol	Diesel	Petrol
	Small			
Peugeot 208	69.41	81.59	62.81	61.75
Fiat 500	64.33	75.62	58.22	57.23
Mini Cooper	82.96	97.51	75.07	73.79
	Sedan			
BMW 5	89.73	105.47	81.20	79.82
Citroen C4	74.49	87.56	67.41	66.26
Hyundai Kona	126.98	149.25	114.90	112.95
	SUV			
Peugeot 2008	110.05	129.35	99.58	97.89
Mazda CX-30	94.81	111.44	85.79	84.34
BMW X3	118.51	139.30	107.24	105.42
	Croatia		Lithuania	
	Diesel	Petrol	Diesel	Petrol
	Small			
Peugeot 208	62.73	63.39	57.97	61.62
Fiat 500	58.14	58.75	53.73	57.11
Mini Cooper	74.97	75.75	69.29	73.65
	Sedan			
BMW 5	81.09	81.94	74.94	79.66
Citroen C4	67.32	68.02	62.22	66.13
Hyundai Kona	114.75	115.95	106.05	112.73
	SUV			
Peugeot 2008	99.45	100.49	91.91	97.70
Mazda CX-30	85.68	86.58	79.18	84.17
BMW X3	107.10	108.22	98.98	105.21

Table 25 - Car taxes of BEVs in selected countries

Car Taxes [€]						
Battery Electric Vehicle						
Small						
	Sweden	Germany	Netherlands	Cyprus	Croatia	Lithuania
Peugeot e-208	32.04	45.00	-	-	39.82	-
Fiat 500e	32.04	45.00	-	-	39.82	-
Mini Electric	32.04	33.75	-	-	39.82	-
Sedan						
BMW i5	32.04	72.12	-	-	79.63	-
Citroen Ë C4	32.04	45.00	-	-	79.63	-
Hyundai Kona Elektro	32.04	56.25	-	-	79.63	-
SUV						
Peugeot e-2008	32.04	45.00	-	-	79.63	-
Mazda MX-30	32.04	50.63	-	-	79.63	-
BMW iX3	32.04	66.11	-	-	79.63	-

Table 26 - Car taxes of CVs in selected countries

		Car Taxes [€]					
		Conventional Vehicle					
		Small					
		Sweden	Germany	Netherlands	Cyprus	Croatia	Lithuania
Peugeot 208							
	Diesel	466.32	134.00	1288.00	125.72	53.09	-
	Petrol	317.73	44.00	452.00			
Fiat 500							
	Diesel	283.98	85.50	1288.00	93.38	53.09	-
	Petrol	155.84	18.00	452.00			
Mini Cooper							
	Diesel	616.49	190.50	1480.00	171.14	79.63	-
	Petrol	451.05	78.00	556.00			
		Sedan					
BMW 5							
	Diesel	627.22	240.00	2816.00	1821.00	199.08	-
	Petrol	460.58	90.00	1272.00			
Citroen C4							
	Diesel	204.70	202.50	2624.00	316.74	199.08	-
	Petrol	32.04	90.00	1172.00			
Hyundai Kona							
	Diesel	528.48	262.00	2624.00	1113.12	199.08	-
	Petrol	325.74	142.00	1172.00			
		SUV					
Peugeot 2008							
	Diesel	230.60	206.50	3004.00	582.28	199.08	-
	Petrol	55.54	94.00	1376.00			
Mazda CX-30							
	Diesel	627.22	240.00	2816.00	1821.00	199.08	-
	Petrol	460.58	90.00	1272.00			
BMW X3							
	Diesel	774.56	338.00	3004.00	1274.96	199.08	-
	Petrol	548.95	188.00	1376.00			

Table 27 - NPV in selected countries for CVs.

Conventional Vehicle				
NPV [€]				
	Germany		Sweden	
	Diesel	Petrol	Diesel	Petrol
Peugeot 208	-45,935.38	-45,861.03	-50,153.16	-48,735.30
Fiat 500	-44,025.54	-46,679.49	-39,617.95	-41,144.65
Mini Cooper	-57,458.32	-57,315.14	-58,335.61	-56,774.73
BMW 5	-92,175.54	-91,709.19	-104,203.69	-102,650.71
Citroen C4	-56,592.42	-56,337.57	-51,784.07	-50,117.34
Hyundai Kona	-76,093.50	-76,448.48	-67,013.21	-65,179.42
Peugeot 2008	-54,920.20	-55,134.35	-59,904.92	-58,322.71
Mazda CX-30	-57,944.08	-57,544.73	-63,742.97	-62,205.84
BMW X3	-92,098.60	-92,011.91	-89,156.24	-87,044.54
	Netherlands		Cyprus	
	Diesel	Petrol	Diesel	Petrol
Peugeot 208	-63,142.28	-56,022.23	-61,254.21	-61,072.48
Fiat 500	-61,104.88	-58,009.46	-59,837.62	-63,446.49
Mini Cooper	-79,818.28	-72,135.30	-68,959.24	-68,742.05
BMW 5	-129,814.78	-115,514.33	-123,825.41	-123,590.49
Citroen C4	-90,284.15	-76,540.01	-66,538.90	-66,343.87
Hyundai Kona	-98,951.53	-86,777.01	-83,895.65	-83,563.21
Peugeot 2008	-101,670.28	-87,053.43	-75,544.63	-75,256.51
Mazda CX-30	-99,574.65	-85,426.10	-89,919.94	-89,671.72
BMW X3	-138,269.11	-123,905.42	-118,970.00	-118,659.72
	Croatia		Lithuania	
	Diesel	Petrol	Diesel	Petrol
Peugeot 208	-36,699.93	-36,811.77	-39,678.97	-40,301.06
Fiat 500	-31,561.94	-33,533.07	-36,422.05	-39,232.36
Mini Cooper	-56,093.56	-56,227.22	-49,807.46	-50,550.93
BMW 5	-87,075.04	-87,219.61	-94,687.70	-95,491.86
Citroen C4	-41,358.33	-41,478.35	-44,692.15	-45,359.76
Hyundai Kona	-52,764.27	-52,968.84	-69,515.04	-70,653.00
Peugeot 2008	-49,365.90	-49,543.20	-51,164.43	-52,150.66
Mazda CX-30	-51,392.42	-51,545.17	-51,084.88	-51,934.56
BMW X3	-87,148.78	-87,339.72	-95,119.73	-96,181.83

Table 28 - NPV in Germany, Sweden, and Netherlands for BEVs

Battery Electric Vehicles					
NPV [€]					
Germany					
	100% AC	100% DC	100% Private	60% Private, 24% AC, 16% DC	50% Private, 25% AC, 25% DC
Peugeot e-208	-61,045.74	-63,301.35	-57,681.32	-59,355.94	-59,982.78
Fiat 500e	-62,529.96	-64,630.51	-59,396.85	-60,954.14	-61,456.50
Mini Cooper electric	-64,139.79	-66,620.96	-60,438.93	-62,284.22	-62,877.61
BMW i5	-108,694.32	-111,626.63	-104,320.58	-106,507.21	-107,208.49
Citroen Ë C4	-74,478.25	-76,606.98	-71,303.08	-72,881.70	-73,390.81
Hyundai Kona Elektro	-70,607.39	-72,863.00	-67,242.97	-68,917.59	-69,457.04
Peugeot e-2008	-74,177.46	-76,310.43	-70,995.98	-72,577.81	-73,087.92
Mazda MX-30	-73,043.09	-75,721.64	-69,047.85	-71,042.47	-71,624.83
BMW iX3	-94,619.31	-97,283.75	-90,645.09	-92,629.05	-93,208.34
Sweden					
	100% AC	100% DC	100% Private	60% Private, 24% AC, 16% DC	50% Private, 25% AC, 25% DC
Peugeot e-208	-57,043.84	-59,155.84	-53,031.04	-60,711.68	-60,442.39
Fiat 500e	-49,972.74	-51,939.54	-46,235.82	-62,216.67	-61,868.06
Mini Cooper electric	-57,204.31	-59,527.51	-52,790.23	-63,775.53	-63,363.74
BMW i5	-109,080.93	-111,826.53	-103,864.29	-108,269.66	-107,783.01
Citroen Ë C4	-73,806.46	-75,799.66	-70,019.38	-74,161.18	-73,807.88
Hyundai Kona Elektro	-72,345.79	-74,457.79	-68,332.99	-70,273.33	-69,898.98
Peugeot e-2008	-72,430.96	-74,428.12	-68,636.36	-73,859.83	-73,505.83
Mazda MX-30	-73,912.14	-76,420.14	-69,146.94	-72,652.41	-72,248.28
BMW iX3	-102,652.71	-105,147.51	-97,912.59	-94,230.51	-93,828.51
Netherlands					
	100% AC	100% DC	100% Private	60% Private, 24% AC, 16% DC	50% Private, 25% AC, 25% DC
Peugeot e-208	-66,930.29	-69,042.29	-62,495.09	-60,813.06	-61,623.53
Fiat 500e	-59,344.75	-61,311.55	-55,214.47	-62,311.08	-62,964.06
Mini Cooper electric	-71,793.35	-74,116.55	-66,914.63	-63,887.04	-64,658.34
BMW i5	-121,184.38	-123,929.98	-115,418.62	-108,401.45	-109,312.99
Citroen Ë C4	-75,765.75	-77,758.95	-71,580.03	-74,256.85	-74,918.59
Hyundai Kona Elektro	-75,310.09	-77,422.09	-70,874.89	-70,374.71	-71,075.89
Peugeot e-2008	-75,761.05	-77,758.21	-71,567.01	-73,955.69	-74,618.75
Mazda MX-30	-78,012.51	-80,520.51	-72,745.71	-72,772.79	-73,529.75
BMW iX3	-113,195.31	-115,690.11	-107,956.23	-94,350.26	-95,103.24

Table 29 - NPV in Cyprus, Croatia, and Lithuania for BEVs

Battery Electric Vehicles					
NPV [€]					
Cyprus					
	100% AC	100% DC	100% Private	60% Private, 24% AC, 16% DC	50% Private, 25% AC, 25% DC
Peugeot e-208	-58,418.44	-60,319.24	-54,828.04	-59,241.73	-59,860.01
Fiat 500e	-51,135.50	-52,905.62	-47,791.94	-60,847.78	-61,341.45
Mini Cooper electric	-58,518.50	-60,609.38	-54,569.06	-62,158.58	-62,741.70
BMW i5	-103,135.13	-105,606.17	-98,467.61	-106,358.73	-107,047.87
Citroen Ë C4	-69,395.90	-71,189.78	-66,007.46	-72,773.91	-73,274.20
Hyundai Kona Elektro	-71,898.60	-73,799.40	-68,308.20	-68,803.38	-69,333.49
Peugeot e-2008	-69,082.24	-70,879.68	-65,687.06	-72,469.80	-72,971.09
Mazda MX-30	-70,302.86	-72,560.06	-66,039.26	-70,906.84	-71,479.12
BMW iX3	-93,873.66	-96,118.98	-89,632.50	-92,494.13	-93,063.40
Croatia					
	100% AC	100% DC	100% Private	60% Private, 24% AC, 16% DC	50% Private, 25% AC, 25% DC
Peugeot e-208	-49,203.70	-52,794.10	-40,333.30	-58,878.46	-60,202.15
Fiat 500e	-44,319.32	-47,662.88	-36,058.76	-60,509.49	-61,636.47
Mini Cooper electric	-52,936.00	-56,885.44	-43,178.56	-61,758.99	-63,090.18
BMW i5	-97,297.42	-101,964.94	-85,765.90	-105,886.48	-107,459.71
Citroen Ë C4	-60,965.31	-64,353.75	-52,593.87	-72,431.08	-73,573.18
Hyundai Kona Elektro	-61,433.41	-65,023.81	-52,563.01	-68,440.11	-69,650.29
Peugeot e-2008	-61,858.28	-65,253.45	-53,470.21	-72,126.29	-73,270.66
Mazda MX-30	-61,355.82	-65,619.42	-50,822.22	-70,475.47	-71,781.91
BMW iX3	-82,915.71	-87,156.87	-72,437.55	-92,065.03	-93,364.59
Lithuania					
	100% AC	100% DC	100% Private	60% Private, 24% AC, 16% DC	50% Private, 25% AC, 25% DC
Peugeot e-208	-55,011.74	-59,024.54	-49,098.14	-57,974.53	-59,013.09
Fiat 500e	-44,124.95	-47,861.87	-38,617.91	-59,667.70	-60,554.73
Mini Cooper electric	-58,812.31	-63,226.39	-52,307.35	-60,764.66	-61,812.42
BMW i5	-108,596.70	-113,813.34	-100,909.02	-104,711.37	-105,949.63
Citroen Ë C4	-63,672.71	-67,459.79	-58,091.75	-71,577.99	-72,476.92
Hyundai Kona Elektro	-71,666.37	-75,679.17	-65,752.77	-67,536.18	-68,488.69
Peugeot e-2008	-65,368.65	-69,163.25	-59,776.60	-71,271.51	-72,172.23
Mazda MX-30	-67,918.19	-72,683.39	-60,895.79	-69,402.04	-70,430.32
BMW iX3	-103,170.31	-107,910.43	-96,184.87	-90,997.25	-92,020.12

Abbreviation

Abbreviation	Meaning
A	
AC	Alternating Current
AFIR	Alternative Fuel Infrastructure Regulation
B	
BEV	Battery Electric Vehicle
BLDC	Brushless Direct Current Motor
BMS	Battery Management System
C	
C	Consumption
CC	Charging Costs
CCS	Combined Charging System
CNG	Compressed Natural Gas
CO2	Carbon Dioxide
CPMS	Charge Point Management System
CV	Conventional Vehicle
D	
DC	Direct Current
E	
EED	Energy Efficiency Directive
EM	Electric Motor
EU	European Union
EUR	Euro
EV	Electric Vehicle
F	
FC	Fuel Cells
G	
G	Government Spending
GDP	Gross Domestic Product
GHG	Greenhouse Gas
H	
HEV	Hybrid Electric Vehicle
I	
I	Investment
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IN	Insurance Costs
K	
kg	Kilogram
kWh	Kilowatt-hour
L	
LCC	Inductor-Capacitor-Capacitor Compensation
Li-Ion	Lithium-Ion
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
M	
MC	Maintenance Costs
N	
Ni-Cd	Nickel-Cadmium Battery
Ni-MH	Nicke-Metal-Hydride Battery
NO2	Nitrogen Dioxide
NPV	Net Present Value
NX	Net Exports
P	
P/E	Power-to-Energy Ratio
PC	Purchase Costs
PFC	Power Factor Correction Current
PMSM	Permanent-Magnet-Synchronous Motor
R	
RED	Renewable Energy Directive
S	
SOC	State of Charge
SOH	State of Health
SRM	Switched Reluctance Motor
SUB	Subsidies
SUV	Sport Utility Vehicle
T	
T	Taxes
TCO	Total Costs of Ownership
TEN-T	Trans-European Transport System
TWh	Terawatt-hour
U	
USD	United States Dollar
V	
V2G	Vehicle-to-Grid
VR	Vehicle Registration Costs
W	
W	Watt

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