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An analysis of the economic performance of electric vehicles in selected EU countries for different types of charging

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Abstract

The transport sector contributes around 24% of global greenhouse gas emissions, primarily due to conventional gasoline and diesel vehicles. Battery electric vehicles (BEVs) offer an alternative that can help improve air quality and reduce CO_2 emissions. However, these electric vehicles face challenges such as higher purchase prices, limited range, and longer charging times.

The main objective of this study is to provide an overview of the current state of the economic viability of battery electric vehicles. Factors such as charging types, charging prices, and different climate conditions are taken into account. To evaluate the impact of various cost factors for BEVs in the European Union, the Total Cost of Ownership (TCO) method is applied.

The study analyzes both battery electric and conventional vehicles in three vehicle categories—small, medium, and large cars—across six EU countries with differing climatic conditions. Charging costs are calculated for various scenarios, considering different charging prices at public AC or DC charging stations (low, average, and high prices).

The results show that small battery electric vehicles have lower operating costs compared to conventional vehicles when direct subsidies from selected EU countries are taken into account. However, for medium and large battery electric vehicles, the situation is different. In countries without direct subsidies, higher purchase prices and other costs make medium and large BEVs more expensive than their conventional counterparts.

Key words: Battery electric vehicles, low temperature performance of Li-ion batteries, charging price, total cost of ownership (TCO)

Kurzfassung

Der Verkehrssektor trägt ca. 24 % zu den globalen Treibhausgasemissionen bei, vor allem durch konventionelle Benzin- und Dieselfahrzeuge t. Eine Alternative dazu sind batteriebetriebene Elektrofahrzeuge, die zur Verbesserung der Luftqualität und zur Verringerung der CO2-Emissionen beitragen können. Diese Elektroautos stehen jedoch vor Herausforderungen wie höheren Anschaffungspreisen, begrenzter Reichweite und längeren Ladezeiten.

Das zentrale Ziel dieser Arbeit ist es, einen Überblick zum aktuellen Stand der Wirtschaftlichkeit batteriebetriebener Elektrofahrzeuge zu geben. Dabei werden Faktoren wie Ladetypen, Ladepreise und verschiedene Klimabedingungen berücksichtigt. Um die Auswirkungen der verschiedenen Kostenfaktoren batteriebetriebener Elektrofahrzeuge in der Europäischen Union zu bewerten, wird die Methode der Berechnung der Gesamtbetriebskosten angewandt.

Die Studie untersucht sowohl batterieelektrische Fahrzeuge als auch konventionelle Fahrzeuge in drei Fahrzeugkategorien: kleine, mittlere und große Autos in sechs EU-Ländern mit unterschiedlichen klimatischen Bedingungen. Die Ladekosten werden für verschiedene Szenarien berechnet, wobei unterschiedliche Ladepreise an öffentlichen AC- oder DC-Ladegeräten (niedrige, durchschnittliche und hohe Preise) berücksichtigt werden.

Die Ergebnisse zeigen, dass kleine batteriebetriebene Elektrofahrzeuge im Vergleich zu konventionellen Fahrzeugen niedrigere Betriebskosten haben, wenn direkte Subventionen von ausgewählten EU-Ländern berücksichtigt werden. Bei mittleren und großen batteriebetriebenen Elektrofahrzeugen ist die Situation jedoch anders. In Ländern ohne direkte Subventionen machen höhere Anschaffungspreise und andere Kosten mittlere und große batteriebetriebene Elektrofahrzeuge teurer als konventionelle Fahrzeuge.

Schlüsselwörter: Batterieelektrische Fahrzeuge, Leistung von Li-Ionen-Batterien bei niedrigen Temperaturen, Ladepreis, Gesamtkosten des Besitzes (TCO)

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1. Introduction

One of the major risks of the 21st century is global warming, primarily caused by greenhouse gas (GHG) emissions. These gases affect the temperature of Earth's atmosphere. The main greenhouse gas is carbon dioxide (CO_2). Additionally, the other greenhouse gases are water vapor, methane (CH_4), nitrous oxide (N_2O), and ozone [1]. Since the Industrial Revolution, human activities have increased CO_2 levels by over 50% [2] and CH_4 levels by about 150% [3].

As shown in Fig. 1.1, the main contributors to CO_2 emissions are energy use, electricity and heat generation, buildings, transport, and industry. The largest source of carbon dioxide emissions is electricity and heat generation, accounting for 38%, followed by buildings at 26% and transport at 24%. It is evident that transport is a significant contributor to CO_2 emissions [4].

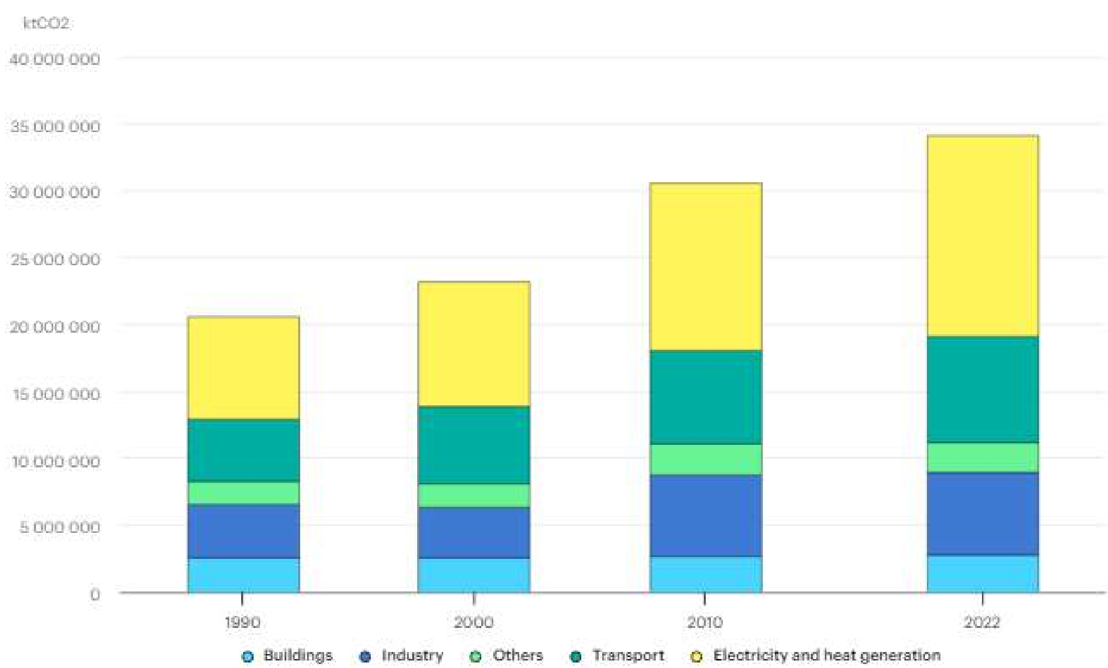

Fig. 1.1– Global CO_2 emissions from fuel combustion by sector with electricity and heat reallocated [4]

Of the total emissions from the transport sector, more than 70% come from road transport, while the remaining comes from aviation, shipping, and rail [5]. In the European Union (EU), in 2022, approximately 760 million tons of carbon dioxide were released from road transport, and the majority of these emissions coming from cars and motorcycles [6].

Around 60% of the total emissions were attributed to cars and motorcycles, making them the largest contributors to road transport emissions. The remaining emissions from road transport came from heavy-duty trucks and buses, which accounted for 27%, and light-duty trucks, contributing 12%. As mentioned earlier, the level of carbon dioxide has increased due to human activities, and carbon dioxide emissions from road transport have increased by 24% since 1990 [6].

As shown in Fig. 1.2, the number of passenger vehicles is increasing every year. Despite the development of urban transportation, trains, and aviation, the number of passenger cars continues to rise. Compared to previous years, the current number of passenger cars alone exceeds the total number of vehicles including passenger cars, buses, and trucks in 2010. In 2010, the total number of vehicles was approximately 240 million, whereas in 2023, there are around 256 million passenger cars alone [7].

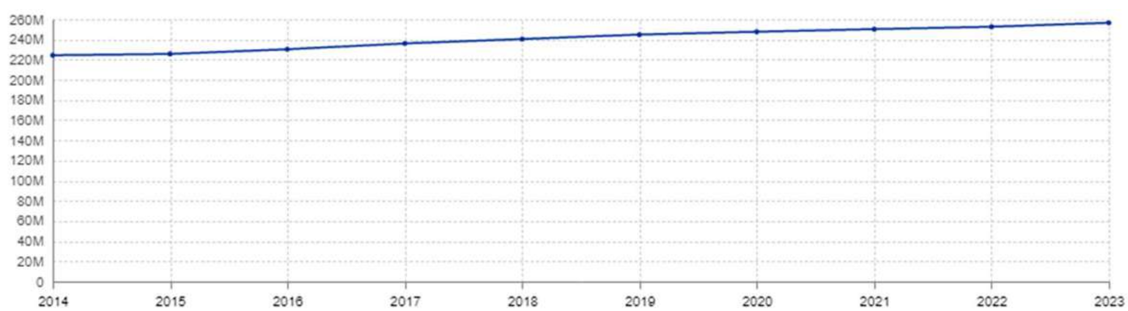

Fig. 1.2– Number of all types of passenger cars in the EU from 2014 to 2023 [7]

Over the past decade, the number of Battery Electric Vehicles (BEVs) has steadily increased. Replacing conventional vehicles (CVs) with BEVs has a direct impact on reducing GHG emissions and is widely regarded as a key solution. Governments across the EU are actively promoting BEV adoption through various policies and incentives to boost the number of zero-emission vehicles. These incentives include, for example, tax reductions, subsidies, and free parking [8].

A positive trend is the steady year-over-year increase in the number of BEVs. As shown in Fig. 1.3, the growth in BEV numbers was relatively modest until 2018. However, after 2018, the adoption of BEVs in the EU accelerated significantly. In 2018, the EU had approximately half a million BEVs, while by 2023, this number had surged to around 4.5 million [8].

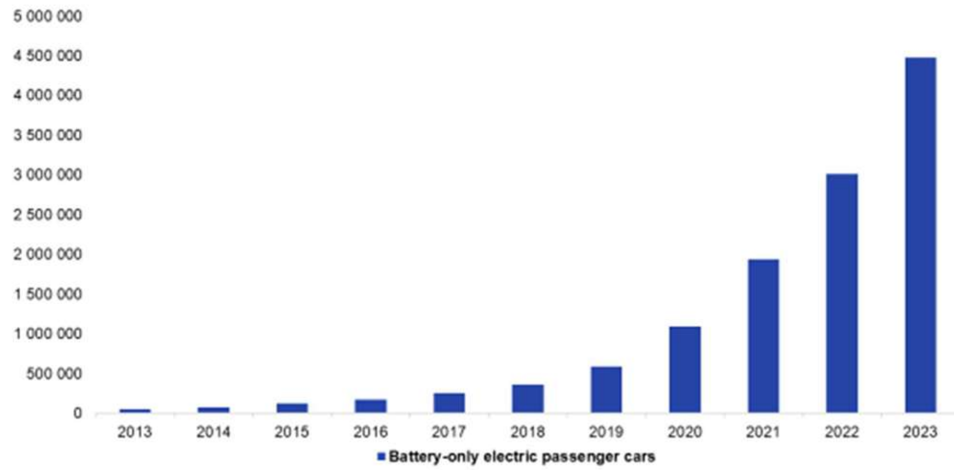

Fig. 1.3– Number of BEVs in the EU from 2013 to 2023 [8]

This rapid increase in the number of BEVs can be attributed to several factors. Over the past five years, the performance of BEVs has steadily improved. Key drivers of this growth include increased driving range, higher efficiency, and advancements in charging technology and infrastructure.

The development of lithium-ion (Li-ion) batteries has been a game-changer in recent years. Improvements in energy density and efficiency have directly contributed to the extended range of BEVs [11]. Additionally, charging infrastructure has significantly advanced in many countries. One of the targets set by EU member states is the "60 km rule," which mandates the installation of fast-charging stations with a capacity of at least 150 kW every 60 km along the trans-European transport network [23].

In this study, six different EU countries are chosen:

- Germany,
- Austria,
- Spain,
- Sweden,
- Norway and
- Slovenia.

As shown in Fig. 1.4, Germany has the highest number of BEVs, while Slovenia has the lowest. However, when comparing the proportion of BEVs to the total number of vehicles in 2023, Norway leads with 23.9% of its total vehicle fleet consisting of BEVs, followed by Sweden with 5.8%. Spain has the lowest share, with only 0.6% [7].

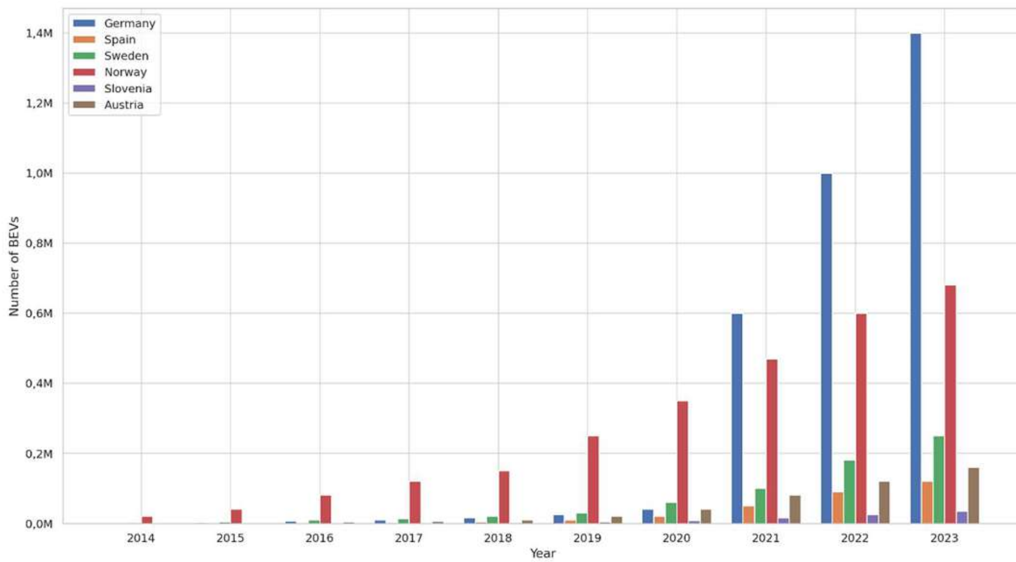

Fig. 1.4– Number of EVs in selected countries from 2014 to 2023 [7]

The selected countries were chosen for various reasons. Germany, Spain, Austria, Norway, and Sweden, for example, have a higher GDP per capita [9], a larger number of BEVs, and more developed charging infrastructure. In contrast, Slovenia, has a lower GDP per capita [9], which means that consumers tend to purchase more affordable cars. As a result, the number of electric vehicles is lower, and the charging infrastructure is less developed compared to the other selected countries.

The efficiency of BEVs changes over time and varies depending on environmental temperature and the number of charge-discharge cycles [10]. These efficiency factors are considered in this study. To examine the impact of low temperatures on BEV performance, two Nordic countries, Norway and Sweden, were included in the analysis, as they experience longer winters and lower average temperatures. Ambient temperature has a particularly significant impact on battery performance. The impact of low temperatures leads to decreased battery efficiency [13]. This directly reduces the vehicle's range and increases the number of required recharges, which in turn raises costs for consumers [12]. To analyze the economic performance of BEVs in these countries, three different car categories were considered.

The Total Cost of Ownership (TCO) is calculated for each vehicle. The TCO calculation includes:

- Fixed costs: Purchase price and government subsidies,
- Variable costs: Fuel/recharging costs, maintenance costs, taxes and insurance costs [14].

The analysis considered several scenarios. For instance, in cases where a car is used for short trips and the daily driving range is below the vehicle's maximum range, it is possible to rely entirely on home charging (100% home charging). However, for individuals living in apartments without access to a garage, public charging becomes necessary, either through 100% public AC charging or 100% public DC charging.

Another scenario involves long daily trips, where 50% of the charging takes place at home and the remaining 50% via public AC and DC charging, considering three electricity price levels (minimum, average, maximum). Additionally, a typical charging pattern identified in a European Union study was considered, in which 70% of charging is done at home and 30% at public charging stations (AC or DC), also evaluated for the three pricing levels (min, avg., max) [17].

For BEVs, charging prices vary depending on the charging mode, operator, local electricity costs, and time of charging [16]. With the support of a Mobility Service Provider (MSP), real-time charging price data was made available.

Calculations have been made for:

- Min: The cost of public recharging using the lowest electricity price in the country
- Avg.: The average cost of public recharging using the average electricity price in the country
- Max: The cost of public recharging using the highest electricity price in the country
- Home Charging: The cost of recharging at home [4].

For CVs the calculation have been made for:

- diesel
- petrol.

There are many scientific papers dealing with the advantages and disadvantages of BEVs. The main papers that were chosen are:

Kumar and Chakrabarty (2020) [14] conducted a Total Cost of Ownership (TCO) analysis comparing electric vehicles (EVs) and internal combustion engine (ICE) vehicles in India across various segments: 2-wheelers, 3-wheelers, 4-wheelers (hatchbacks and sedans), and buses. Their findings show that electric 2-wheelers and 3-wheelers are more cost-effective than their ICE counterparts under typical Indian usage conditions. Obrador Rey et al. (2024) [10] reviews the sustainability of electric vehicles (EVs) across their life cycle. They highlight benefits like lower emissions during use, but also point to challenges in battery production, raw material sources, and recycling. The study emphasizes the need for supportive policies and circular economic approaches to enhance long-term EV sustainability. Wang et al. (2021) [12] discuss the main challenges and recent developments in lithium-ion batteries (LIBs) used in low-temperature environments. The study focuses on the performance degradation of LIBs in cold climates and reviews improvements in electrolytes, electrode materials, and battery design. Taborda-Ospina et al. (2024) [18] conduct a techno-economic comparison of the total cost of ownership (TCO) of a light electric commercial vehicle and its combustion counterpart. Sensitivity analyses also show that rising fuel prices or reduced EV costs make electric options financially attractive for both private and commercial users. Campanari et al. (2009) [11] compare battery and fuel cell electric vehicles using a well-to-wheel analysis. The study compares different energy pathways (renewables, coal, natural gas) and finds that BEVs offer the highest efficiency and lowest emissions when charged with renewable electricity, but their efficiency drops with increasing driving range. Adhikari et al. (2020) [20] identify and rank 17 key barriers to electric vehicle (EV). The study categorizes these into technical, economic, infrastructure, policy, and social barriers. The most critical challenges include a lack of charging stations, high purchase prices, and insufficient long-term government planning. Falvo et al. (2014) [19] compare European and American standards for EV charging stations and modes. The study outlines key international standards (like IEC 61851 and SAE J1772), charger types (Modes 1–4), and charging levels. It also examines how energy storage systems (ESS) like batteries, flywheels, and supercapacitors can support fast EV charging and smart grid integration.

Compared to the studies mentioned above, this thesis analyzes the economic performance of electric vehicles (EVs) in selected EU countries for different types of charging. In addition, it considers the efficiency of lithium-ion (Li-ion) batteries and how this affects the overall cost of ownership for consumers. The study compares countries with different climates and electricity prices to see how these factors change battery performance and overall costs.

This thesis considers battery efficiency in low temperatures and how cold conditions affect the performance of lithium-ion batteries, leading to reduced BEV range and an increased number of charging cycles. The impact of charging prices on the total cost of ownership is also analyzed. Several charging scenarios are examined, including charging only at home, only at public stations (AC or DC), or a combination of both.

The main goal of this work is to analyze the economic performance of electric vehicles in selected EU countries for different types of charging.

This thesis is divided into 7 chapters. Chapter 2 explains the methodological approach. Chapter 3 discusses the main components of BEVs, including the functioning of lithium-ion batteries and how their performance is influenced by low temperatures. Additionally, it describes the charging methods and types utilized in BEVs. Chapter 4 describes in detail how variable costs are calculated for the selected countries. It also examines the purchase costs of new CVs and BEVs and whether any subsidies are available in those countries. In Chapter 5, a detailed economic comparison between BEVs and CVs is presented, highlighting which type of vehicle has a lower TCO, while Chapter 6 presents the thesis conclusion.

2. Method of approach

In this master's thesis, the TCO is used to provide a clear comparison between CVs and BEVs for different charging prices. Parameters such as purchase costs, subsidies, recharging/refueling prices, Li-ion battery efficiency, depreciation, maintenance costs, insurance, and taxes have been taken into consideration. Six EU member states have been chosen for analysis:

- Germany,
- Austria,
- Spain,
- Sweden,
- Norway and
- Slovenia.

The TCO of BEVs and CVs in these countries provides a financial metric to assess the overall cost of owning and operating a vehicle over its lifespan. In this analysis, the TCO is calculated for a one-year period, helping to determine which vehicle is more economical for the consumer. Moreover, the study analyzes how temperature affects the performance and charging costs of BEVs.

Fig. 2.1 shows the parameters we have considered for two types of cars: EV and CV. For each type of car, we have selected three different vehicle categories:

- small cars (Mini cooper, e-Mini cooper)
- medium cars and (BMW 5, BMWi5)
- and large cars (SUV) (BMW X3, BMW iX3)

All the factors mentioned earlier, as well as those that could affect the results, have been taken into consideration. Additionally, the cost of installing a home charging station has been included for home charging scenarios, see Fig. 2.1.

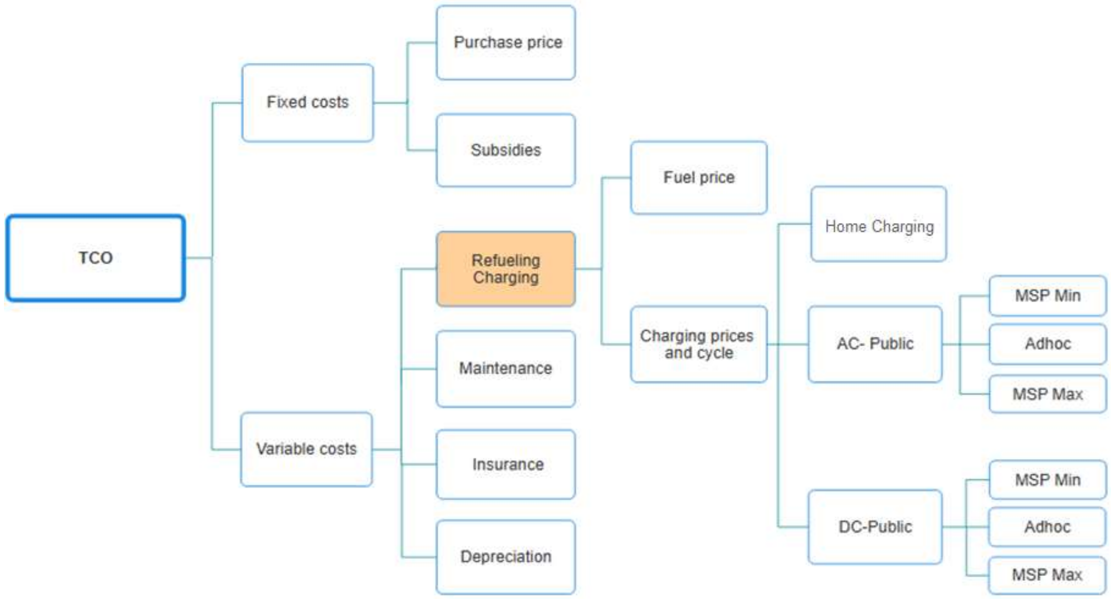

Fig. 2.1– Flowchart diagram-parameters that we have taken into consideration

In Table 2.1, all the main technical parameters required for the calculations of the selected vehicles are provided.

Table 2.1– Technical parameter of BEV and CV [25] [26]

	Average fuel consumption [l/100km]	Average electricity consumption [kWh/100km]	Total range [km]	CO2-Emissionen [g/km]
MINI Cooper C	6	/	733	134
MINI Cooper E	/	14,2	295	/
BMW 520d	5,3	/	1283	140
BMW 520i	6,1	/	1115	136
BMW i5 eDrive	/	16,9	558	/
BMW X3 20d	5,9	/	1135	158
BMW X3 20i	7	/	971	156
BMW iX3	/	17,6	464	/

3. Battery electric vehicles

The BEVs play an important role in reducing emissions from the transport sector. As mentioned earlier, 24% of emissions come from transport, and more than half of those are from cars [4]. Replacing CVs with BEVs can directly reduce emissions and improve local air quality. The environmental benefits are even greater when BEVs are powered by electricity from renewable sources. Over the past decade, there has been strong progress in the development of BEVs. Many countries now offer direct subsidies, tax reductions, and free parking to encourage people to buy electric cars [27]. BEVs are also more efficient than other types of vehicles. For example, the "well-to-wheel" efficiency of BEVs is around 81%, while for CVs it is about 30% [28].

As shown in Fig. 3.1, the main parts of a BEV are the battery, electric motor, converter, transmission, onboard charger, and charging point. The most important parts are the electric motor and the battery, as they determine how the BEV performs. The electrical energy stored in the battery pack is converted into mechanical energy [27].

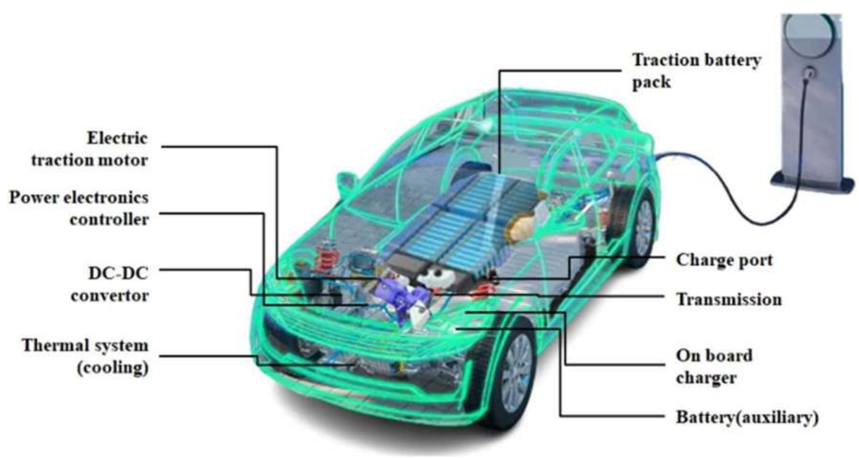

Fig. 3.1– Important Components of BEVs

Different BEVs, depending on the manufacturer, can use various types of electric motors. The types of motors commonly used in BEVs include:

- Permanent Magnet Synchronous Motor (PMSM)
- Induction Motor (IM)
- Brushless DC Motor (BLDC)
- Reluctance Motor (RM)

3.1 Lithium-ion battery

Batteries are one of the key components of BEVs, as they determine the vehicle's range. In recent years, battery capacity has increased, which has helped BEVs increase their range. There are different types of batteries, but the most common one used in BEVs is the lithium-ion (Li-ion) battery [27].

One of the biggest advantages is energy density. This means they can store more energy for each kilogram of weight compared to other battery types. Because of this, BEVs can drive longer distances, which used to be a big problem in the past [29]. Today, their energy density can reach up to 250 Wh/kg [12], see Fig. 3.2.

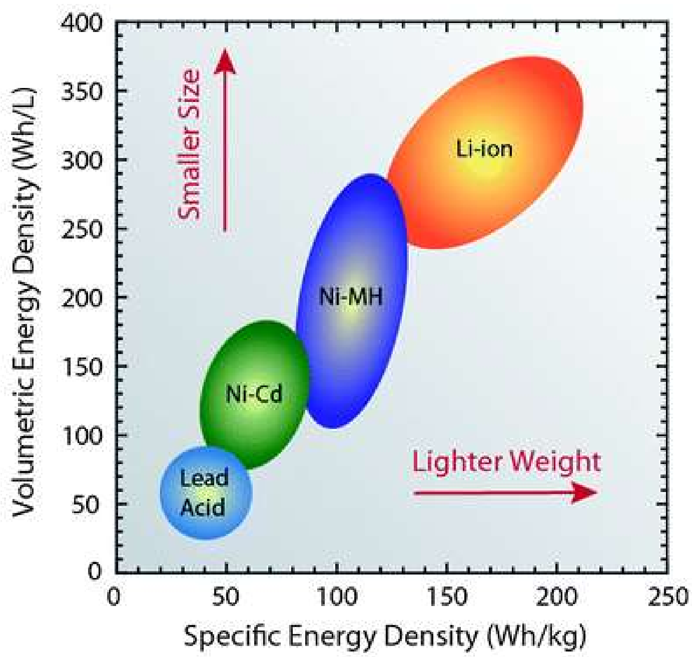

Fig. 3.2– Energy density by battery type [30]

Besides having high energy density, Li-ion batteries are also characterized by high cycle durability, which significantly extends their lifespan. Li-ion batteries have a lifetime of about 10 years and a number of cycles over 3500 times [31]. So, Li-ion batteries don't need to be replaced for 10 years; if this is converted to km, then the batteries will last more than 100000 km [31]. Li-ion batteries have a low self-discharge rate of just 1–2% per month, making them highly efficient when not in use. Lithium-ion batteries are not affected by the memory effect, meaning they can be charged at any time without reducing capacity [29].

In addition to the advantages of Li-ion batteries, they also have their disadvantages. Compared with other types of batteries, Li-ion batteries are the most expensive, but their price has decreased in the last decade. If you compare the price in 2013 to 2024, there is a very large decrease around 84%. In recent years, the price of Li-ion batteries has decreased. Compared to 2019, the price in 2024 is about 40% lower. Although the price drop has been smaller in the last few years, making them much more affordable [32]. The lower price of Li-ion batteries will help make BEVs more competitive in the market. Fig. 3.3 shows the price of Li-ion batteries (€/km) over the last 10 years.

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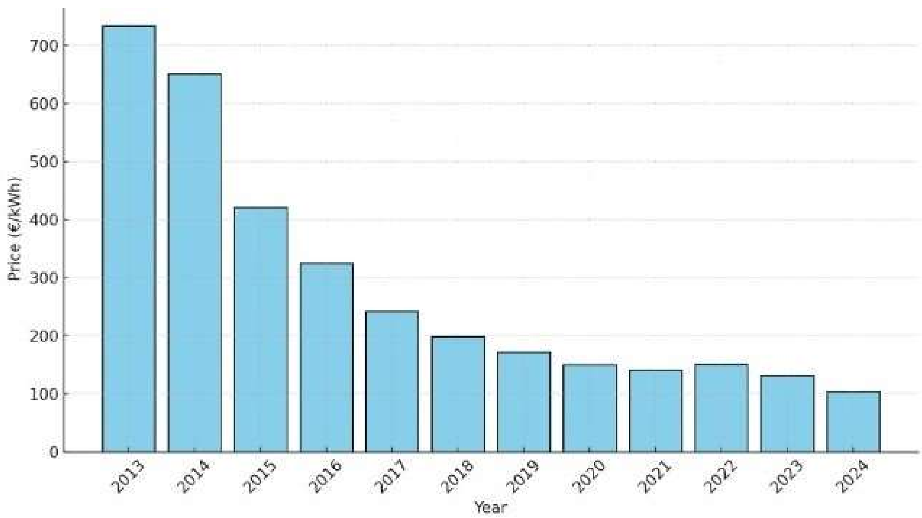

Fig. 3.3– Li-ion batteries price worldwide (2013-2024) [32]

Other disadvantages are overcharging and the risk of overheating. Li-ion batteries are sensitive to high temperatures and can overheat, which may lead to fire or explosion. Their liquid parts are flammable, and they become less safe as they get older. Damage or short circuits also increase the risk. To make them safer, better materials, designs, and monitoring systems are needed [33].

Another disadvantage, which is also a main point in this master's thesis, is the sensitivity of Li-ion batteries to low temperatures. This directly affects the efficiency of Li-ion batteries.

3.1.1 How does a lithium-ion battery work?

The main parts of the Li-ion battery are:

- anode – made from lithium metal oxides
- cathode – typically made of graphite (carbon material)
- and electrolyte- a liquid organic solution, which enables the flow of lithium ions from the anode to the cathode and back again.

A Li-ion battery is a type of rechargeable battery that works by moving lithium ions (Li^+) through the electrolyte inside the battery, while electrons flow through an external circuit to power devices. When the battery is in charging or recharging mode, it is connected to a power source. This power source provides electricity, which forces the electrons to flow in the opposite direction compared to when the battery is being discharged. In this case, the electrons move through the external circuit from the cathode (positive side) to the anode (negative side). At the same time, Li^+ move through the electrolyte inside the battery from the cathode to the anode, see Fig. 3.4. The battery stores this energy in the anode, where lithium ions are inserted into the graphite layers. This stored energy can then be used later when the battery is discharged, for example, when we are driving our vehicles [31].

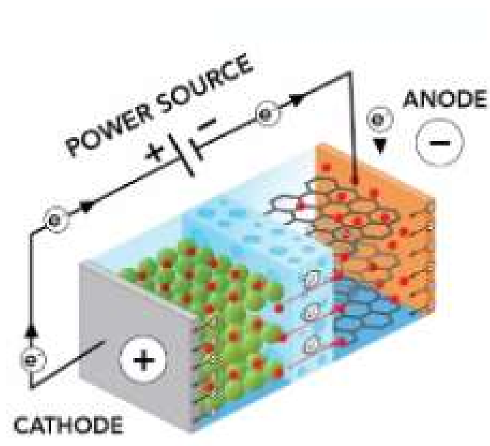

Fig. 3.4– Li-ion battery charging mode [34]

When the battery is in discharge mode, it is connected to a device. For example, in a BEVs, the battery connects to the electric motor to provide power. This connection closes the circuit, allowing electricity to flow. At the anode (negative side), lithium atoms lose electrons and turn into Li^+ [31].

The electrons travel through the external circuit from the anode to the cathode (positive side), powering the device. At the same time, Li^+ move through the electrolyte inside the battery, from the anode to the cathode, to keep the battery balanced see Fig. 3.5 [31].

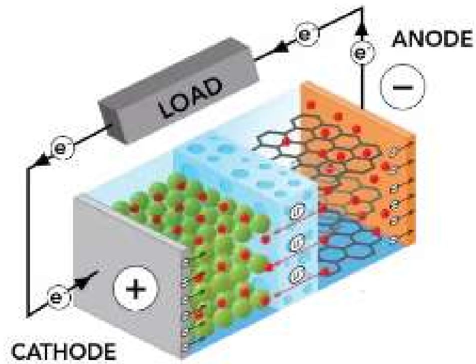

Fig. 3.5– Li-ion battery discharging mode [34]

3.1.2 Lithium-ion battery at low temperature

The movement of Li^+ during the charge and discharge involves four steps: transfer in the liquid phase, solvation/ desolvation, migration at the interphase, and diffusion in the solid phase. At lower temperatures, the most significant problem is the slow movement of Li^+. This can cause the battery to charge and discharge more slowly, reduce its capacity, and affect its overall performance. For electric vehicles, this results in shorter driving ranges in low temperatures [12].

Battery performance at low temperature is mainly limited by the Li^+ movement during discharge and charge through four processes: liquid-phase transfer, binding and unbinding with molecules, interphase migration, and solid-phase diffusion. At low temperatures, the slow movement of lithium ions is a significant issue. This can cause the battery to charge and discharge more slowly, reduce its capacity, and affect its overall performance. For BEVs, this results in shorter driving ranges in low temperatures [12].

As the temperature drops, the viscosity of the electrolyte increases. This higher viscosity slows down the movement of ions within the electrolyte, reducing the battery's efficiency. The higher viscosity also affects the wettability of the electrodes and separators. Wettability is important because it ensures good contact between the electrolyte and the battery's internal components, allowing for efficient ion transfer.

When the temperature drops below a certain point, the electrolyte can solidify, making it difficult for the battery to function properly. This solidification slows down the movement of Li^+ ions, which are essential for the battery's operation [12].

This difficult movement of the Li^+ affects directly the efficiency of the Li-ion battery. So, by discharging the Li-ion battery the output power of the Li-ion battery is lower. The lower output power of the Li-ion battery at BEVs directly means shorter range and the shorter range means more recharging cycle and higher recharging cost.

As seen in Fig. 3.6, the efficiency of Li-ion batteries decreases significantly with lower temperatures. For each selected country, we considered the temperatures throughout the year for each month [13].

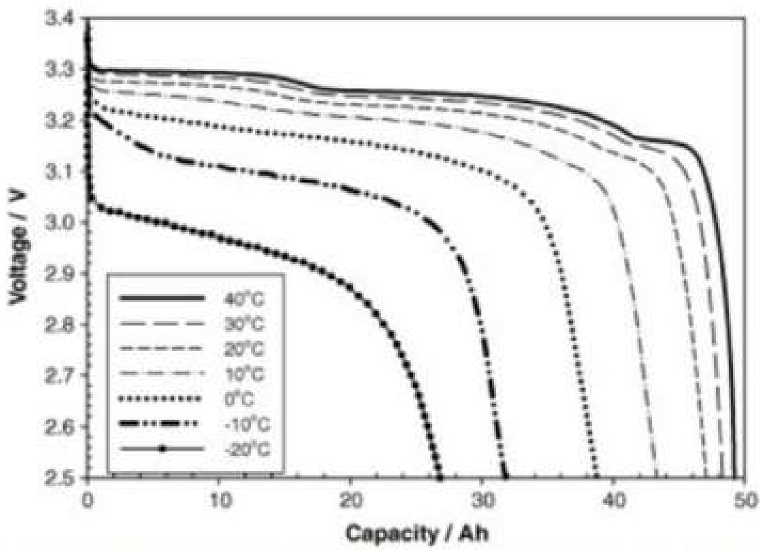

Fig. 3.6– The efficiency of Li-ion batteries depends on temperatures [12]

The efficiency of Li-ion batteries depends on temperature and is calculated using formula (4.1) [63] [12]:

$$\eta = \frac{Q_{temp.}}{Q} \tag{3.1}$$

Where:

- $Q_{temp.}$– capacity of the Li-ion battery depending on temperature [Wh]
- Q – capacity of the Li-Ion battery [Wh]
- η – efficiency

For each month and each selected country, the efficiency of Li-ion batteries was calculated, and the efficiency values for each country can be seen in Figure 3.7. The input data are in the Appendix.

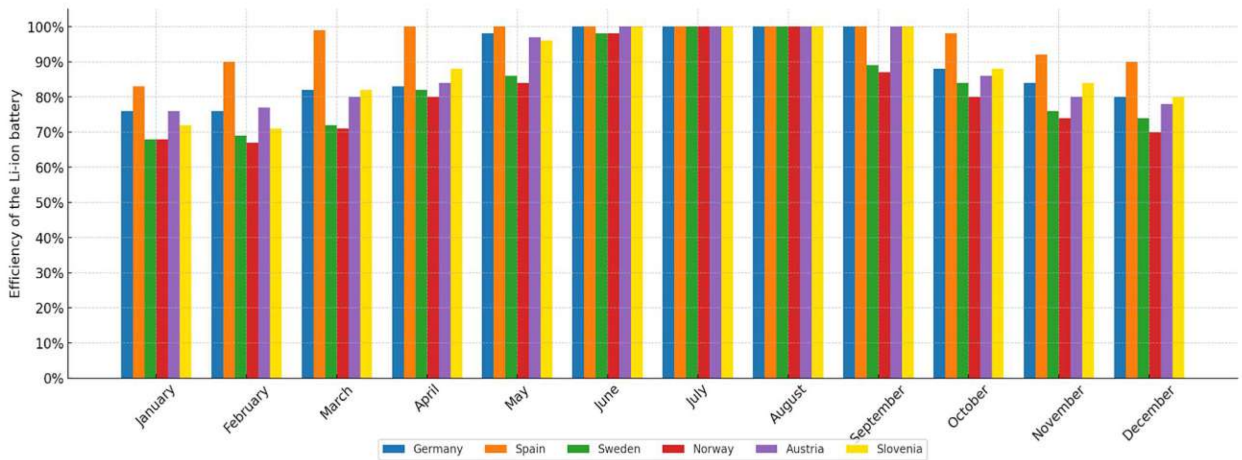

Fig. 3.7– Efficiency of Li-ion batteries depending on temperature

3.2 Charging options

Charging infrastructure plays a crucial function in the development of BEVs. The main goal in developing an extensive and reliable network of charging stations is to ensure that BEV owners have easy and convenient access to charge their vehicles. This not only addresses the issue of range anxiety but also promotes the transition to electric mobility by providing the necessary support for daily commutes and long-distance travel [24].

Moreover, the integration of fast-changing technologies and the expansion of charging stations in urban and rural areas are crucial steps in accelerating the adoption of BEVs [24].

There are three basic ways to recharge the BEVs:

- wireless charging
- battery swapping
- plug-in charging

Charging time and battery life depend on charger characteristics, with efficient chargers being high in power density, low in cost, volume, and weight. Charger power level significantly impacts charging time, cost, and grid effects [19].

3.2.1 Wireless charging

Wireless charging, or induction charging, allows electric vehicles to charge without needing a physical connection. Wireless power transmission works occurs through electromagnetic induction. This involves generating an electric current in a conductor by exposing it to a changing magnetic field. The primary coil is supplied by an AC power source, which creates a changing electric current. The current generates a magnetic field around the primary coil. The magnetic field produced by the primary coil extends to the nearby area. There is a secondary coil placed close to the primary coil, see Fig. 3.8 [37].

As the magnetic field from the primary coil changes, it induces an electric current in the secondary coil. The amount of current generated in the secondary coil depends on two things: the number of turns (loops) in the secondary coil and how strong the magnetic field is [36].

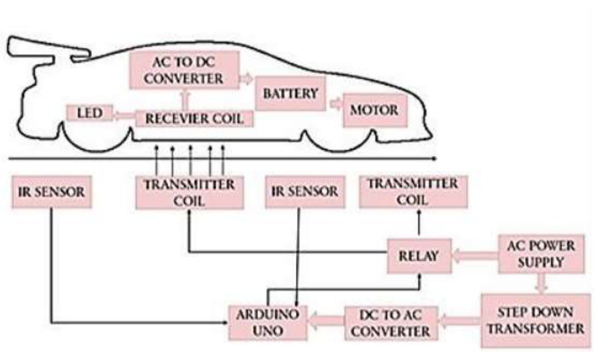

Fig. 3.8– Wireless Electric Vehicle Charging System [37]

Wireless charging is very convenient because you don't need to plug in cables-just place your device on a pad to charge. It reduces wear and tear on your device and cables, creating a cleaner, more organized space. It's also safer, with no exposed wires, and easier for people with mobility issues [36].

3.2.2 Battery swapping

Battery Swapping Stations (BSS) help keep BEV running by replacing low-charge batteries with fully charged ones. Implementing battery swapping for vehicles requires detailed planning.

This includes ensuring the availability of batteries and chargers, managing data in the cloud, and enabling communication between all components for smooth operation. The BSS relies on continuous communication between the smart vehicle, the exchange station, and the information system.

Vehicles use wave communication to request battery swaps, and the station prepares the battery in advance. When the vehicle arrives, the driver swipes a registration card for verification. All data, including battery and swap information, is stored in the cloud for transparency. After swapping, the old battery is inspected for signs of charge, degradation, age, and total number of charge/discharge cycles [38].

Battery swapping for BEVs has the advantage of avoiding charging time. On the other side BSS faces several challenges. One of the major challenges is that needed a standardization of battery and BEVs for different manufacturers. Other challenges are higher cost and limited charging stations [38].

An example of a BSS company named NIO Inc. NIO has 30 Power Swap Stations in Europe, in countries like Sweden, Germany, Netherlands, Denmark, and Norway. These stations can swap batteries in three minutes and store up to 21 batteries [39].

This technology makes charging easy and helps stabilize the power grid by storing energy. Another advantage of NIO's battery swapping technology not only offers a convenient charging solution but also supports grid stability by acting as decentralized energy storage units [39].

3.2.3 Plug-in charging

This method is dominant in charging infrastructure used to charge the BEVs in Europe, involving a physical connection between the vehicle and a charging point using a cable and plug. This type of charging can be done in many places, such as at home, on public streets, or at commercial and private properties. Those chargers are categorized in different types depending on power level (kW), the type of current (AC or DC). As electrical grids deliver AC electricity while batteries require DC electricity for storage, a converter between the two is necessary. Depending on power level and current there are 4 modes of charging types:

Mode 1 is the simplest charging mode of BEVs, utilizing standard household sockets and unmodified cables. This mode of charging operates at a power level of 3 kW $\leq$ P $\leq$ 7,4 kW using alternative current (1-phase or 3-phase AC) [40]. It is particularly suitable for residential use, especially for overnight charging when vehicles remain stationary for extended periods.

As a result of the low power of charger and this mode of charger is the slowest one. To charge full BEV is needed a long time depending on the battery size it needed about 12-24 hours [27].

Mode 2 again is a simple charging mode of BEV but with a specialized charging cable equipped with a protection device. This cable, typically provided by the car manufacturer, safeguards the electrical system from overcurrent or overheating and it allows slightly higher power levels [27]. This mode of charging operates at a power level of 7,4 kW $\leq$ P $\leq$ 22 kW using alternative current (1-or 3- phase AC) [40]. Mode 2 is known as semi-fast AC charging.

Mode 3 charging introduces dedicated equipment specifically designed for EVs. Charging in Mode 3 can be done via wall-mounted boxes in homes or stand-alone poles in public spaces and workplaces. It requires a specialized plug socket and a dedicated circuit, allowing higher power levels P > 22 kW (3- phase AC) [40]. Mode 3 is particularly popular among EV owners who require faster charging but can still leave their vehicles plugged in for several hours and is known as fast AC charging [27].

Mode 4 represents the most advanced and powerful form of charging. This mode uses DC electricity, which bypasses the vehicle's on-board AC/DC converter. The fast-charging station itself performs the AC-to-DC conversion and delivers power directly to the battery. This mode is especially beneficial for high-demand scenarios, such as long-distance travel or commercial fleet operations. However, Mode 4 has several drawbacks, including higher energy losses during electricity transfer, which reduces overall efficiency. Another disadvantage of this mode of recharging is that it can also degrade battery health over time, shortening the battery's lifespan and reducing the number of charge cycles [27]. Mode 4 operates at power levels ranging from 50 kW $\leq$ P < 150 kW, known as fast DC charging. Another category operates at power levels ranging from 150 kW $\leq$ P < 350 kW, referred to as Level 1 ultra-fast DC charging, while the final category operates at power levels of P $\geq$ 350 kW, referred to as Level 2 ultra-fast DC charging [40].

In Fig. 3.9, we can see the difference in charging time for different modes of charging for a battery with a capacity of 40 kWh.

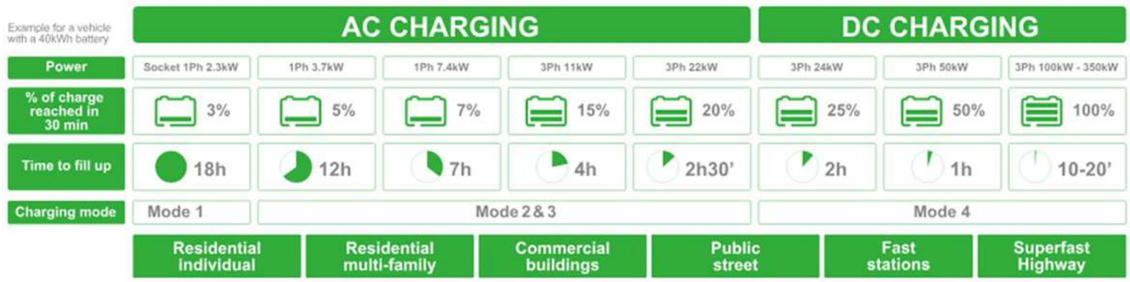

Fig. 3.9– Charging time depending on Mode of charger [41]

As shown in Fig. 3.10, for different charging modes we use different connectors (plugs). For the EU, electric vehicles must be equipped with at least Type 2 socket outlets or vehicle connectors, such as Mennekes (for AC normal and high-power recharging points), and connectors of the combined charging system, CCS/Combo 2 (for DC high power recharging points).

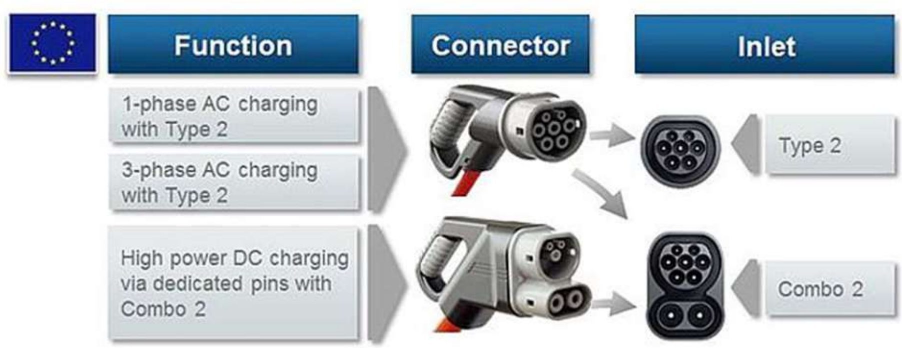

Fig. 3.10– Connector Types [40]

As mentioned before, the number of BEVs has rapidly increased in recent years [8]. This increasing number of BEV has the state of EU to increase the number of the public charging points for BEVs. As shown in Fig. 3.11, by the end of 2023, there were about 632 thousand public charging points in the EU. Of the total number of public charging points, about 87%, or 550 thousand, are AC public charging points, and 13%, or 81 thousand, are DC charging points [35].

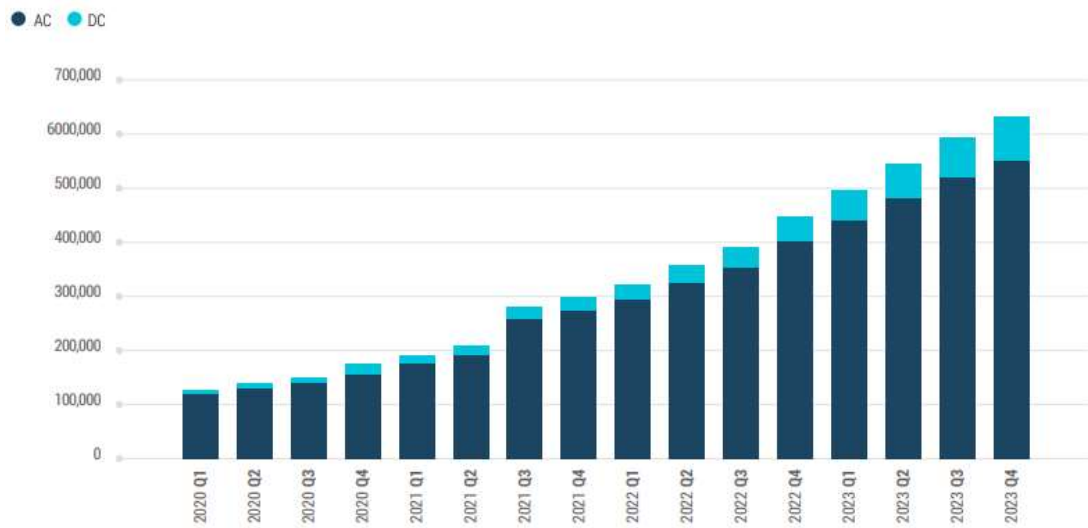

Fig. 3.11– Number of the charging points AC/DC in EU [35]

The European Commission target is 3,5 million charging points in 2030 and that means needs to install about 410 thousand per year. The are approximately 4,5 million BEVs on the road of EU and that means about 7 cars per charging points [35].

3.3 Charging time

One of the disadvantages of BEVs is the long charging time. As mentioned before, the charging time depends on the battery size and charger mode. As seen in the technical data of BEVs, the capacity of the study cases differs. The charging time calculations were done for selected BEVs with different charger power levels and were calculated using the formulas provided below [42]:

$$t_{ch} = \frac{E}{P_{ch}} \tag{3.2}$$

Where:

- t_{ch} - charging time [h]
- P_{ch} -charging power [kW]
- E – amount of energy required to fully charge the battery [kWh]

To calculate the amount of energy needed to charge the battery to 100%, we need to know the state of charge (SOC) and take into consideration the efficiency of the charger. The efficiency of modern chargers is higher and varies from 90–96%. In our calculations, we will use a value of 93%. Using the formula below, we calculate the amount of energy required to fully charge the battery [42]:

$$E = \frac{1}{\eta_{\text{ch}}} C_b \frac{SOC - SOC_c}{100} \tag{3.3}$$

Where:

- C_b – battery capacity [kWh]
- SOC – targeted SOC [%]
- SOC_c – current SOC [%]
- η_{ch} - charging efficiency
- E – amount of energy required to fully charge the battery [kWh]

Table 3.1 shows the calculated time required to charge the selected BEVs from 5% to 100%.

Table 3.1– Charging time for selected BEVs at different charger power levels

	Charger power [kW]	Mini e Charging time [h]	BMW i5 Charging time [h]	BMW ix3 Charging time [h]
1-phase AC	2,2	19,1	42,3	37,3
	3,7	11,4	25,1	22,2
3-phase AC	7,4	5,7	12,6	11,1
	11	3,8	8,5	7,5
	22	1,9	4,2	3,7
DC	50	0,8	1,9	1,6
	150	0,3	0,6	0,5
	250	0,2	0,4	0,3
	350	0,1	0,3	0,2

4. Cost of battery electric vehicles and conventional vehicles

This chapter examines all the costs associated with CVs and BEVs. It explores the initial purchase prices, comparing the upfront costs of both types of vehicles. Additionally, it analyzes the variable costs, including fuel or energy costs, maintenance, and taxes.

4.1 Fixed costs

Fixed costs include the purchasing cost of BEVs and CVs. For BEVs, the cost of a charging box at home must also be included. Another significant fixed cost is the subsidies given by governments in different countries to promote the usage of BEVs. These subsidies make BEVs more competitive compared to CVs.

4.1.2 Purchasing costs of battery electric vehicles and conventional vehicles

The purchase price of a CV depends on various factors such as the brand and model of the car, vehicle type, fuel consumption per kilometer, engine power, and CO_2 emissions.

In this thesis, three categories of cars have been considered:

- small cars (Mini cooper, e-Mini cooper)
- medium cars and (BMW 5, BMWi5)
- and large cars (SUV) (BMW X3, BMW iX3).

The Table 4.1 shows the CV prices for all vehicles analyzed in this thesis. For Norway, there is no data available for the price of CVs:

Table 4.1– Price of CV in selected countries

	MINI Cooper C	BMW 520d	BMW 520i	BMW X3 20d	BMW X3 20i
Germany [43] [44]	29 100 €	65 990 €	61 980 €	60 499 €	55 179 €
Austria [45] [46]	31 408 €	68 950 €	-	64 175 €	-
Spain [47] [48]	33 900 €	70 893 €	-	67 948 €	60 252 €
Sweden [49] [50]	30 586 €	64 961 €	-	58 623 €	-
Norway	-	-	-	-	-
Slovenia [51] [52]	31 090 €	59 650 €	-	59 800 €	-

The price of BEVs depends on various factors such as the brand and model of the car, vehicle type, electricity consumption per kilometer, and engine power. Another key element that determines the price of a BEV significantly is the battery size. As mentioned before, Li-ion batteries are expensive. To achieve a good range, a larger battery is required, and that means higher costs.

The Table 4.2 shows the BEV prices for all vehicles analyzed in this thesis:

Table 4.2– Price of BEV in selected countries

	MINI Cooper e	BMW i5	BMW iX3
Germany [43] [44]	36 260 €	75 140 €	70 480 €
Austria [45] [46]	38 114 €	76 920 €	73 950 €
Spain [47] [48]	39 600 €	78 520 €	73 900 €
Sweden [49] [50]	40 414 €	72 563 €	68 554 €
Norway [53] [54]	32 752 €	69 900 €	62 508 €
Slovenia [51] [52]	40 189 €	71 850 €	73 950 €

4.1.2 Subsidies in selected countries

There is no financial support available for CVs. Additionally, CVs are subject to CO_2 taxes, which are based on engine size and emission levels (in grams per km). These taxes can add a significant cost to owning and operating a CV, making them less economically attractive compared to more environmentally friendly alternatives.

As already mentioned, many governments support BEVs both directly and indirectly. Indirect support plays a significant role in promoting BEV adoption. It generally includes benefits such as free or priority parking, access to exclusive charging stations, exemptions or reductions in toll fees, and exemptions from congestion charges. Additionally, tax incentives and lower registration fees further enhance the affordability of BEVs. Alongside these indirect measures, direct subsidies are also provided, such as purchase grants and financial incentives, which lower the upfront cost of electric vehicles and make them more accessible to buyers.

In Germany, the subsidy for purchasing BEVs directly is up to 4500 €. The government supports buyers with a subsidy of 3000 € in cooperation with the seller, who contributes an additional 1500 €. However, this subsidy applies only to vehicles with a maximum net price of 45000 €. In comparison to 2023, from January 1, 2024, the German government subsidies are lower, for example, in 2023, these subsidies were 6000 € [55].

The Spanish government also provides significant support for the purchase of BEVs. These subsidies can reach up to 5500 €, depending on the specific vehicle and the circumstances of the buyer. A BEV must have a minimum range of 90 km and. The subsidy is available for vehicles with a maximum price limit of 45000 € for standard models. For larger vehicles, such as those with 7-8 seats, the maximum price limit is extended to 55000 € [56].

In Sweden, the situation is different. The Swedish government has discontinued subsidies for the purchase of BEVs, redirecting the budget towards infrastructure improvements. It is a tactical decision that will enhance the charging network and other essential infrastructure for electric cars such that there will be sustainable and long-term support for the adoption of BEV [57].

Norway does not give direct purchase subsidies for buying BEVs. However, its tax incentives effectively make BEVs cheaper than fossil-fuel cars, making direct subsidies unnecessary. Norway's indirect supports for BEVs, such as toll exemptions, free parking, reduced ferry fees, and access to bus lanes, help lower operational costs and increase convenience for BEV owners. These incentives are part of a broader strategy to make BEVs more attractive and easier to adopt [58].

In Slovenia, the government offers substantial incentives for the purchase of electric vehicles. These incentives are designed to promote the adoption of environmentally friendly vehicles by making them more affordable for consumers. Up to 7200 € for new BEVs priced up to 35000 €, up to 6500 € for BEVs priced between 35000 € and 45000 €, and up to 4500 € for BEVs priced between 45000 € and 65000 €. These financial incentives are part of Slovenia's broader strategy to reduce carbon emissions and promote sustainable transportation. By providing significant subsidies, the government aims to make electric vehicles more accessible to the public and encourage a shift away from fossil fuel-powered cars [59].

In Austria, the government provides purchase subsidies. The funding rates for BEVs include a subsidy amount of 5000 € for private purchasers. There are additional conditions that apply to these subsidies. The list price cap for BEVs is 60000 € for companies and 50000 € for private purchasers [60]. In addition to direct purchase subsidies, Austria offers several indirect incentives to encourage the adoption of electric vehicles. These include exemptions from registration, pollution, and motor insurance taxes, as well as ownership tax benefits where BEVs are 100% tax-exempt from all relevant federal taxes [60].

Table 4.3 shows the subsidies provided by selected countries for the vehicles analyzed in this study.

Table 4.3- Direct Subsidies for BEVs in Selected Countries in year 2024

	MINI Cooper e	BMW i5	BMW iX3
Germany [55]	4 500 €	-	-
Austria [60]	5 000 €	-	-
Spain [56]	5 500 €	-	-
Sweden [57]	-	-	-
Norway [58]	-	-	-
Slovenia [59]	4 500 €	-	-

4.1.3 Cost of home charging station

To calculate the TCO of a BEV, it is essential to consider the purchase price of installing a home charging station. This expense can vary significantly depending on factors such as the country, local labor costs, electricity infrastructure, and government incentives or subsidies.

Table 4.4 provides an overview of the average installation costs for home charging stations across different countries.

Table 4.4– Price of Installing a Home Charging Station in year 2024 [71] [72]

	Charging Station
Germany	2 500 €
Austria	2 500 €
Spain	2 300 €
Sweden	2 430 €
Norway	1 850 €
Slovenia	2 150 €

4.2 Variable costs

TCO for CVs and BEVs includes variable costs like maintenance and insurance. BEVs also have charging costs, which depend on electricity tariffs and charging methods. CV refueling costs are affected by fuel prices, and CO_2 taxes.

4.2.1 Charging costs

Charging is often the highest variable cost associated with electric vehicles, and it can vary significantly depending on where the vehicle is charged and the prevailing electricity prices. Different charging locations, such as public charging stations and home charging setups, have distinct cost structures.

Additionally, electricity prices fluctuate based on factors such as the time of day, region, and energy provider. The cost can also vary depending on the charger mode (AC or DC) and the power of the charger.

In this thesis, three charging options are considered:

- Charging at home
- Public charging AC
- Public charging DC

Each charging station has a different charging price (€/kWh). In this thesis, three types of prices for public AC/DC charging are considered [4]:

- maximal price
- average price
- and minimal price

For private charging or charging at home, there is only one electricity price (€/kWh) that doesn't change, unlike at public charging stations, where the charging price (€/kWh) varies depending on the charging type, location, and time.

In Table 4.5, the prices for public and private chargers in selected countries are provided.

Table 4.5– Charging prices on selected countries in 2024 (€/kWh) [17]

		AC-Public			DC-Public		
	Home ch.	Min	Avg.	Max	Min	Avg.	Max
Germany	0,41	0,01	0,87	4	0,01	0,81	2,79
Austria	0,27	0,09	1,37	1,83	0,22	0,94	1,87
Spain	0,18	0,05	0,37	1,65	0,05	0,49	0,97
Sweden	0,27	0,02	0,37	0,7	0,03	0,48	0,85
Norway	0,19	0,01	0,3	1,37	0,05	0,4	1,02
Slovenia	0,19	0,1	0,47	0,89	0,16	0,56	1,12

Calculating the price of a charging cycle involves several factors, primarily the battery size and the charging price. To illustrate this, let's consider a scenario where one car travels 1250 km per month, that means 15000 km per year [61]. In this calculation, it is essential to also account for the efficiency of the Li-ion battery, which can vary depending on temperature.

Taking all these factors into consideration, we calculated the number of recharging cycles required for each car in the selected country. Additionally, we determined the monthly recharging cost for each car in the selected country, considering the specific conditions and variables present in that region.

The recharging cost is calculated with the formula below [62]:

$$Cost_{ch} = P_{ch} \cdot C_{bat} \cdot n_c \tag{4.1}$$

where:

- $Cost_{ch}$ – the total cost of charging per month in [€]
- P_{ch} – the charging price [€/kWh]
- C_{bat} – capacity of the car's battery [kWh]
- n_c – number of recharging cycles per month

The number of recharging cycles is calculated with the formula below [62]:

$$n_C = \frac{D_m}{C_{bat-out} \cdot \frac{1}{AC_e}} \tag{4.2}$$

where:

- n_C – number of recharging cycles per month
- $C_{bat-out}$ – discharging capacity of the car's battery [kWh]
- D_m– travel distance of the car for one month
- AC_e – average electricity consumption per 100km [kWh/100km]

The discharging capacity of Li-ion battery is calculated with the formula below [63]:

$$C_{bat-out} = \eta \cdot C_{bat} \tag{4.3}$$

where:

- $C_{bat-out}$ – discharging capacity of the car's battery [kWh]
- C_{bat} – capacity of the car's battery [kWh]
- η – efficiency of Li-ion battery depending on the temperature.

As an example, the monthly recharging cost of a Mini Cooper-E (BEV) in Norway is calculated by taking into account the efficiency of the Li-ion battery. It is assumed that the vehicle travels 1250 km per month. The technical data used for the calculation, such as energy consumption (kWh/100 km) and battery capacity (kWh), are shown in Table 2.1. Based on the data provided in Fig. 3.7, the battery efficiency in January is observed to be 68% (η = 0.68). It is assumed that the customer charge vehicle exclusively at home using AC charging (Home charging AC):

$$C_{bat-out} = \eta \cdot C_{bat} = 0{,}68 \cdot 41{,}9 \text{ kWh} = 28{,}492 \text{ kWh}$$

The number of recharged cycles per month:

$$n_C = \frac{D_m}{C_{bat-o} \cdot \frac{1}{AC_e}} = \frac{1250\ km}{28{,}492\ kWh \cdot \frac{100\ km}{14{,}2\ kWh}} = 6{,}23$$

The total cost of charging a Mini Cooper at home in January in Norway is:

$$Cost_{ch} = P_{ch-home} \cdot C_{bat} \cdot n_c = 0{,}19 \frac{€}{kWh} \cdot 41{,}9 \text{ kWh} \cdot 6{,}23 = 49{,}597\ €$$

When customers can't charge the BEV at home because they don't have a garage, they use public chargers instead. This is common for people living in flats. If we calculate the total cost of recharging at a public charger (AC or DC), the number of cycles in January is the same, but the charging prices are different.

This thesis also examines the scenarios mentioned in Chapter 1, where customers travel longer distances and charge both at home and in public. These scenarios, in addition to charging 100% at home, are also:

- 50% of the charging is done at home, and the other 50% at public AC and DC chargers for three types of prices (min, average, max)
- 70% of the charging is done at home, and 30% at public AC and DC chargers for three types of prices (min, average, max)

The total charging cost of the Mini Cooper-E in Norway, based on the amount β charged at home and at public AC and DC chargers with average prices for AC and DC, was calculated using formula below:

$$Cost_{ch-\beta\%} = (P_{ch-ho} \quad \cdot \beta_{\%.} \cdot \ C_{bat} + P_{ch-AC-ave.} \cdot (1 - \beta_{\%}) \ \cdot \ C_{bat}) \cdot n_c \qquad (4.4)$$

where:

- $Cost_{ch-\beta\%}$ – the total cost of charging, including the share of home charging (β) and the share of public AC charging [€]
- $P_{ch-AC.}$ – the charging price in public station AC/DC [€/kWh]
- $P_{ch-home}$ – the charging price at home [€/kWh]
- C_{bat} – capacity of the car's battery [kWh]
- n_c – number of recharging cycles per month
- $\beta_{\%.}$ – share of charging done at home.

As seen from the calculations, the total charging cost is determined by the charging price and the efficiency of the Li-ion battery at low temperatures. Since the calculations are made for January in Norway, when temperatures are low, the efficiency of the Li-ion battery decreases. As shown in Fig. 3.7, the efficiency is around 68% of the total power output from the battery, reducing the range from 295 km to 200 km. This means that for each recharging session in January, we lose 95 km of range.

Assuming the customer travels 1250 km per month, they would need approximately 6.23 recharging cycles per month. With 6.23 recharging cycles in January in Norway, we will make 592 km less than in normal conditions. If we translate this into recharging cycles, it means more than two additional recharging cycles in January compared to July or other months with higher temperatures.

Table 4.6 shows all calculations for Norway for the charging scenarios mentioned in Chapter 1: 100% home charging, 100% public AC/DC charging at three price levels (minimum, average, and maximum), 50% home and 50% public charging (AC or DC) at three price levels, and 70% home and 30% public charging (AC or DC).

Table 4.6– Cost of recharging in Norway per year

	Mini-E	BMW i5	BMW iX3
100% charging at home	505 €	601 €	626 €
100% charging in Public AC-min	27 €	32 €	33 €
100% charging in Public AC-ave.	798 €	949 €	989 €
100% charging in Public AC-max	3643 €	4336 €	4515 €
100% charging in Public DC-min	133 €	158 €	165 €
100% charging in Public DC-ave.	1064 €	1266 €	1318 €
100% charging in Public DC-max	2712 €	3228 €	3362 €
50% charging at home and 50% charging at public AC-min	266 €	316 €	330 €
50% charging at home and 50% charging at public AC-ave.	652 €	775 €	807 €
50% charging at home and 50% charging at public AC-max	2074 €	2469 €	2571 €
50% charging at home and 50% charging at public DC-min	319 €	380 €	396 €
50% charging at home and 50% charging at public DC-ave.	784 €	934 €	972 €
50% charging at home and 50% charging at public DC-max	1609 €	1915 €	1994 €
70% charging at home and 30% charging at public AC-min	362 €	430 €	448 €
70% charging at home and 30% charging at public AC-ave.	593 €	706 €	735 €
70% charging at home and 30% charging at public AC-max	1447 €	1722 €	1793 €
70% charging at home and 30% charging at public DC-min	394 €	1389 €	488 €
70% charging at home and 30% charging at public DC-ave.	673 €	801 €	834 €
70% charging at home and 30% charging at public DC-max	1167 €	468 €	1447 €

For a clear overview of the effect of low temperatures on Li-ion batteries, see Fig. 4.1. The figure shows the recharging cycles of BEVs with the same parameters per year for all selected countries. As can be seen, the lowest number of cycles is observed in Spain, as temperatures, even in winter, do not fall below 0°C, which positively affects the efficiency of the Li-ion battery. On the other hand, in Norway and Sweden, where winters are longer than in other countries (about 5 months), the number of recharging cycles is higher, resulting in increased recharging costs.

The number of recharging cycles of BEVs in Norway and Sweden is higher compared to Germany, Austria, Slovenia, and Spain.

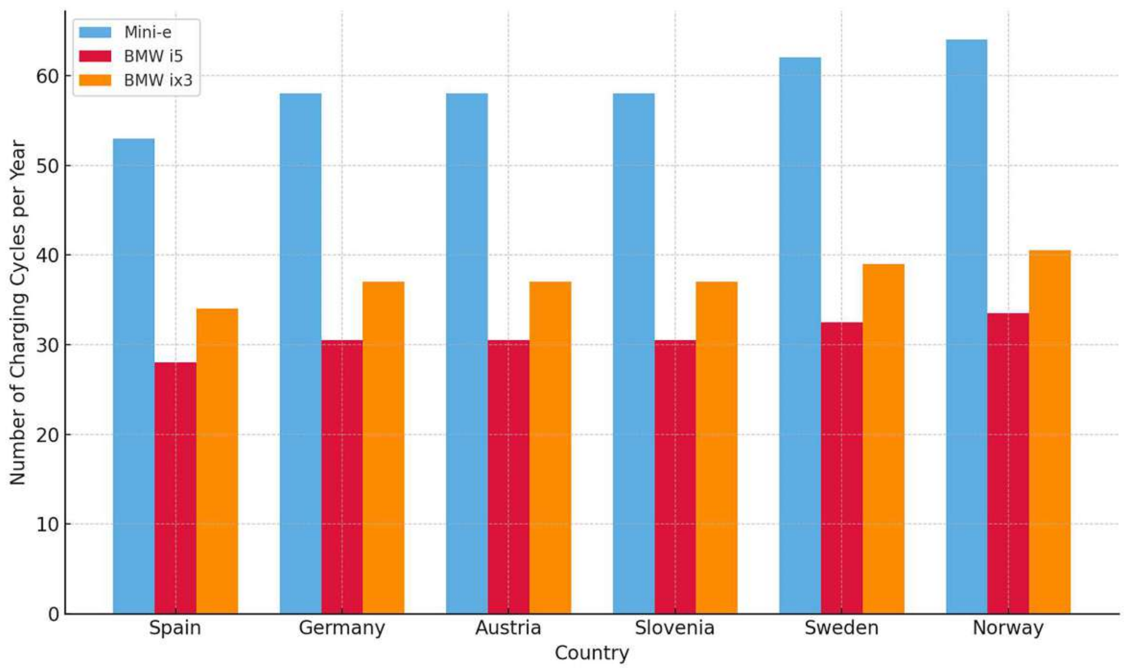

Fig. 4.1– Number of recharging cycles per year for selected BEVs

4.2.2 Future charging prices

Electricity prices are influenced by the cost of primary energy sources and the price of CO_2 emissions per ton. The cost of primary energy can fluctuate over time and is also affected by extraordinary events, such as the war in Ukraine two years ago.

Currently, prices of primary energy sources like gas, oil, and coal have stabilized. Given this, the price of CO_2 is expected to remain at 114 €/tCO_2 until 2030. After 2030, it is projected to rise to 140 €/tCO_2 [64].

According to Fig. 4.2, we observe a slight decrease in prices, which is expected to persist until 2030. After that, prices will start to rise.

As shown in Fig. 4.2, the baseload price in 2024 is approximately 78 €/MWh, while in 2030, it is around 65 €/MWh. Due to increasing CO_2 taxes, the baseload price is expected to rise to 85 €/MWh by 2050. The diagram also indicates a margin of possible variation in the baseload price, estimated at ±10% [64].

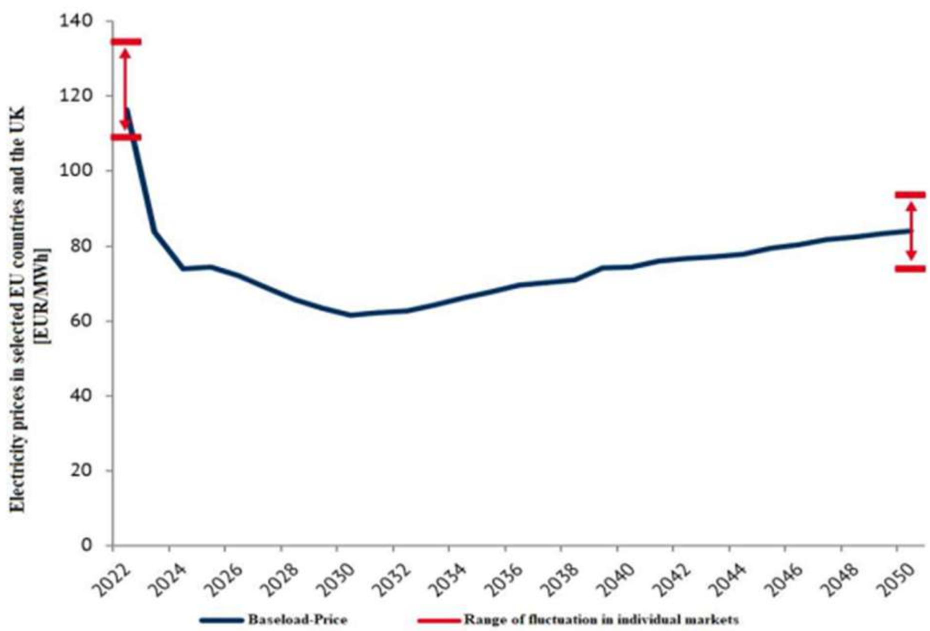

Fig. 4.2- Presents the average annual baseload electricity prices and their fluctuation ranges across various national markets in selected European countries [64]

To estimate BEV charging costs as accurately as possible, it's necessary to calculate charging prices for the projected period from 2024 to 2029. The total cost of charging a BEV consists of the baseload price and additional costs [65]. These additional costs can vary based on the country, location, local regulations, and charging power [65]. Urban charging stations often have higher rates due to increased operating costs, while rural stations may offer lower prices. In busy city areas, charging stations may also include higher parking fees [64]. However, in many countries, parking is free while charging, as part of policies aimed at encouraging BEV adoption.

Faster charging options, such as DC charging, tend to be more expensive than slower alternatives [64]. The factors mentioned earlier determine the additional costs, which are unlikely to change significantly in the coming years, as most countries are expected to maintain their BEV policies to achieve the targets of the Paris Agreement [22].

Based on this assumption, it is expected that additional costs will stay mostly the same over the next five years, and changes in charging prices will mainly come from changes in the baseload price.

To calculate the additional cost, we will compare the charging prices presented in Table 4.5 with the baseload prices extracted from Figure 4.2 [66]. These calculations are made for selected countries, for three different types of chargers and three different types of charging prices.

The additional cost are calculated with formula below [66]:

$$c_{additional} = c_{charging} - c_{baseload} \tag{4.5}$$

where:

- $c_{charging}$ – charging costs [€/kWh]
- $c_{baseload}$ – baseload-cost of electricity [€/kWh]
- $c_{additional}$ – additional costs of charging [€/kWh]

As an example for calculating the additional costs, Germany is chosen. Table 4.4 shows the charging price at home, and Fig. 4.2 presents the baseload price. The additional cost of home charging in Germany is calculated as follows:

$$c_{add.-home} = c_{charg.-home} - c_{baseload} = 0{,}41\,\frac{€}{kWh} - 0{,}078\,\frac{€}{kW} = 0{,}332\,\frac{€}{kW}$$

Table 4.7 shows the charging prices for the next five years in selected countries, for both private and public charging.

Table 4.7– Charging Prices in Selected Countries from 2024 to 2029 (€/kWh)

Year 2024							
		AC-Public			DC-Public		
	Home	Min	Avg.	Max	Min	Avg.	Max
Germany	0,41	0,01	0,87	4	0,01	0,81	2,79
Austria	0,27	0,09	1,37	1,83	0,22	0,94	1,87
Spain	0,18	0,05	0,37	1,65	0,05	0,49	0,97
Sweden	0,27	0,02	0,37	0,7	0,03	0,48	0,85
Norway	0,19	0,01	0,3	1,37	0,05	0,4	1,02
Slovenia	0,19	0,1	0,47	0,89	0,16	0,56	1,12
Year 2025							
		AC-Public			DC-Public		
	Home	Min	Avg.	Max	Min	Avg.	Max
Germany	0,404	0,01	0,864	3,994	0,01	0,804	2,784
Austria	0,264	0,09	1,364	1,824	0,22	0,934	1,864
Spain	0,174	0,05	0,364	1,644	0,05	0,484	0,964
Sweden	0,264	0,02	0,364	0,694	0,03	0,474	0,844
Norway	0,184	0,01	0,294	1,364	0,05	0,394	1,014
Slovenia	0,184	0,1	0,464	0,884	0,16	0,554	1,114
Year 2026							
		AC-Public			DC-Public		
	Home	Min	Avg.	Max	Min	Avg.	Max
Germany	0,402	0,01	0,862	3,992	0,01	0,802	2,782
Austria	0,262	0,09	1,362	1,822	0,22	0,932	1,862
Spain	0,172	0,05	0,362	1,642	0,05	0,482	0,962
Sweden	0,262	0,02	0,362	0,692	0,03	0,472	0,842
Norway	0,182	0,01	0,292	1,362	0,05	0,392	1,012
Slovenia	0,182	0,1	0,462	0,882	0,16	0,552	1,112
Year 2027							
		AC-Public			DC-Public		
	Home	Min	Avg.	Max	Min	Avg.	Max
Germany	0,4	0,01	0,86	3,99	0,01	0,8	2,78
Austria	0,26	0,09	1,36	1,82	0,22	0,93	1,86
Spain	0,17	0,05	0,36	1,64	0,05	0,48	0,96
Sweden	0,26	0,02	0,36	0,69	0,03	0,47	0,84
Norway	0,18	0,01	0,29	1,36	0,05	0,39	1,01
Slovenia	0,18	0,1	0,46	0,88	0,16	0,55	1,11

Year 2028							
		AC-Public			DC-Public		
	Home	Min	Avg.	Max	Min	Avg.	Max
Germany	0,397	0,01	0,857	3,987	0,01	0,797	2,777
Austria	0,257	0,09	1,357	1,817	0,22	0,927	1,857
Spain	0,167	0,05	0,357	1,637	0,05	0,477	0,957
Sweden	0,257	0,02	0,357	0,687	0,03	0,467	0,837
Norway	0,177	0,01	0,287	1,357	0,05	0,387	1,007
Slovenia	0,177	0,1	0,457	0,877	0,16	0,547	1,107
Year 2029							
		AC-Public			DC-Public		
	Home	Min	Avg.	Max	Min	Avg.	Max
Germany	0,396	0,01	0,856	3,986	0,01	0,796	2,776
Austria	0,256	0,09	1,356	1,816	0,22	0,94	1,856
Spain	0,166	0,05	0,356	1,636	0,05	0,49	0,956
Sweden	0,256	0,02	0,356	0,686	0,03	0,48	0,836
Norway	0,176	0,01	0,286	1,356	0,05	0,4	1,006
Slovenia	0,176	0,1	0,456	0,876	0,16	0,56	1,106

4.2.3 Refueling costs

The cost of refueling conventional vehicles, typically running on gasoline or diesel, can vary depending on several factors such as location, fuel prices, and the size of the vehicle's fuel tank. Another factor influencing refueling costs is the size of the vehicle's engine. Diesel engines are generally larger than petrol engines, and for achieving better range, diesel vehicles usually have larger fuel tanks compared to petrol vehicles.

The price of petrol and diesel also depends on additional costs, such as taxes on CO_2 emissions. In Table 4.8, the prices of diesel and petrol for selected countries were presented.

Table 4.8– Fuel prices in selected countries in year 2024 (€/*l*) [67]

	Diesel	Petrol
Germany	1,596	1,656
Austria	1,559	1,523
Spain	1,420	1,505
Sweden	1,547	1,488
Norway	1,750	1,815
Slovenia	1,538	1,478

Calculating the refueling costs involves several factors, primarily the tanks size, fuel consumption (*l*/100 km) and the fuel price. To illustrate this, let's consider a scenario where one car travels 1250 km per month, that means 15000 km per year.

The calculation of refueling costs for a month is done with the help of the formula below [68]:

$$Cost_{refuel} = P_{fuel} \cdot C_{tank} \cdot n_{refuel} \tag{4.6}$$

where:

- $Cost_{refuel}$ – the total cost of refueling per month in [€]
- P_{fuel} – the price fuel [€/*l*]
- C_{tank} – capacity of the car's tank [*l*]
- n_{refuel} – number of recharging cycles per month

The number of refueling cycles is calculated with the formula below [68]:

$$n_{refuel} = \frac{D_m}{C_{tank} \cdot \frac{1}{AC_{fuel}}} \tag{4.7}$$

where:

- n_{refuel} – number of recharging cycles per month
- C_{tank} – capacity of the car's tank [*l*]
- D_m – travel distance of the car for one month
- AC_{fuel} – average fuel consumption per 100km [*l*/100km]

To clearly illustrate monthly refueling costs, a Mini Cooper in Sweden is used as an example for the calculations. As previously assumed, the car travels 1250 km per month. Based on the technical data for the Mini Cooper C in Table 2.1 and the fuel price from Table 4.7, the number of refueling cycles per month can be calculated as follows:

$$n_{refuel} = \frac{D_m}{C_{tank} \cdot \frac{1}{AC_{fuel}}} = \frac{1250\ km}{44\ l \cdot \frac{100\ km}{6\ l}} = 1{,}705$$

The total cost of refueling per month:

$$Cost_{refuel} = P_{petrol} \cdot C_{tank} \cdot n_{refuel} = 1{,}488\ \frac{€}{l} \cdot 44\ l \cdot 1{,}705 = 111{,}6\ €$$

Figure 4.3 shows the monthly refueling costs for selected countries and vehicles

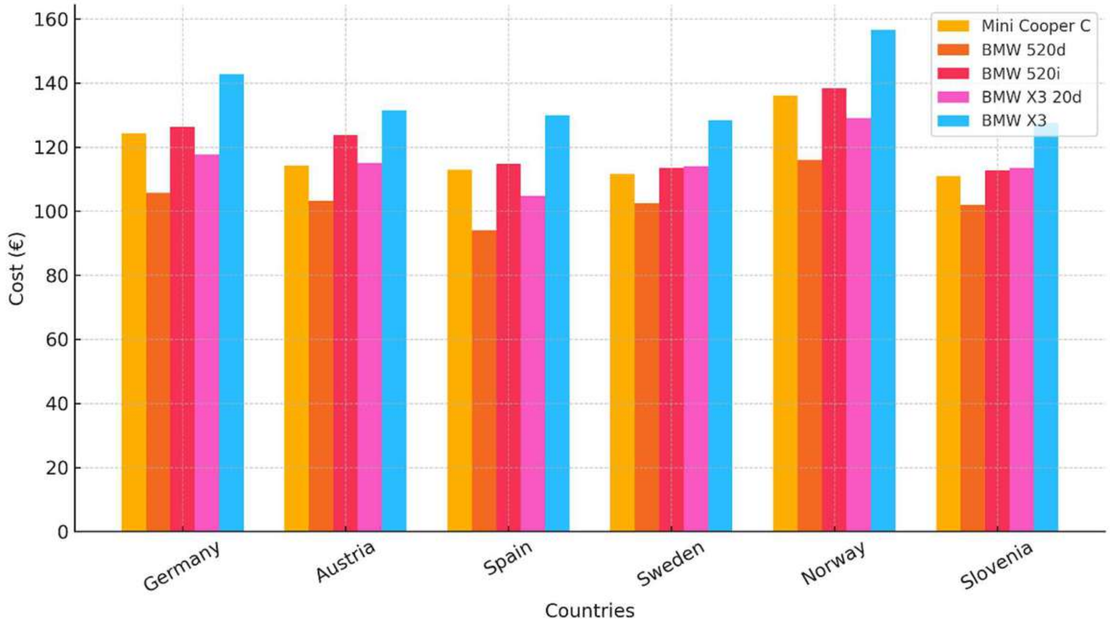

Fig. 4.3- Refueling cost for selected countries and vehicles per month

4.2.4 Future fuel price

Petrol and diesel prices are influenced by several factors. The most significant factor is the price of oil, which is determined by global supply and demand dynamics, production decisions, and geopolitical events that may disrupt supply. After the COVID-19 pandemic and the beginning of the Ukraine war, fuel prices increased rapidly due to fuel shortages and sanctions against Russia. Currently, fuel prices are stable, unless there are extraordinary developments like those mentioned above. The price is now also influenced by state policies, such as emission reduction policies and CO_2 emissions targets [69].

The European Union's carbon market (EU ETS) is a major regulatory tool. If CO_2 taxes rise significantly, this would increase the cost diesel and petrol [70]. The EU aims to decarbonize the transport sector by encouraging a shift to BEVs and cleaner alternatives [22]. A study by Cambridge Econometrics suggests that, under EU carbon policies, fuel prices could increase, with fuel expected to see a 0.50 €/liter rise by 2030. This projection is based on an estimated carbon price of €180 per ton by that year [70].

Based on the Cambridge study and assuming no extraordinary developments in the EU over the following five years, the projected diesel and petrol prices for that period are presented in Table 4.9.

Table 4.9– Fuel prices in the next five years in selected countries (€/*l*) [70]

		Germany	Austria	Spain	Sweden	Norway	Slovenia
2024	Diesel	1,60	1,56	1,42	1,55	1,75	1,54
	Petrol	1,66	1,52	1,51	1,49	1,82	1,48
2025	Diesel	1,70	1,66	1,52	1,65	1,85	1,64
	Petrol	1,76	1,62	1,61	1,59	1,92	1,58
2026	Diesel	1,80	1,76	1,62	1,75	1,95	1,74
	Petrol	1,86	1,72	1,71	1,69	2,02	1,68
2027	Diesel	1,90	1,86	1,72	1,85	2,05	1,84
	Petrol	1,96	1,82	1,81	1,79	2,12	1,78
2028	Diesel	2,00	1,96	1,82	1,95	2,15	1,94
	Petrol	2,06	1,92	1,91	1,89	2,22	1,88
2029	Diesel	2,10	2,06	1,92	2,05	2,25	2,04
	Petrol	2,16	2,02	2,01	1,99	2,32	1,98

4.2.5 Maintenance costs

Car maintenance costs are a part of the overall TCO. In the first year, these costs are usually low, as they mainly cover routine maintenance recommended by the manufacturer, such as oil changes or check-ups. However, in the following years, maintenance costs tend to rise. This is because, as the car gets older, there may be more issues that need fixing, and parts like tires may need to be replaced. The maintenance costs also vary depending on the country you live in, as well as how many kilometers the car is driven each year [74]. As the number of kilometers driven increases, maintenance costs also increase.

The brand and size of the car play a significant role in determining maintenance costs. Larger vehicles or those from certain manufacturers may have higher maintenance expenses due to more complex systems or the need for more expensive parts. Additionally, maintenance costs differ between CVs and BEVs. BEVs generally have lower maintenance costs, often about 30% lower than those of CVs. This is mainly because BEVs have fewer moving parts, no need for oil changes, and less frequent brake repairs due to regenerative braking systems, all of which contribute to lower overall maintenance costs [75].

Assuming that cars typically travel around 15000 km per year, maintenance costs can vary based on several factors, such as the type of vehicle, local labor rates, and the specific model. Table 4.10 shows the estimated yearly maintenance costs for the selected countries.

Table 4.10– Maintenance cost of CV and BEV for a year [73] [74]

		Germany	Austria	Spain	Sweden	Norway	Slovenia
MINI-C	CV	350 €	315 €	305 €	325 €	345 €	230 €
	BEV	270 €	221 €	214 €	228 €	242 €	161 €
BMW 5er	CV	580 €	510 €	490 €	517 €	535 €	355 €
	BEV	406 €	392 €	377 €	398 €	412 €	273 €
BMW X3	CV	535 €	487 €	470 €	485 €	505 €	307 €
	BEV	374 €	375 €	362 €	373 €	385 €	236 €

4.2.6 Depreciation rate

The depreciation of any vehicle whether a CV or a BEV depends on a mix of factors including usage, technological changes, market trends, and regulatory impacts. For potential buyers or sellers, understanding these dynamics can help in making informed decisions regarding purchase timing, maintenance, and resale strategies [76].

The depreciation rate is not the same for BEV and CV, it depends on several factors. In general, BEVs tend to depreciate faster than CVs in the first few years [77]. This is largely due to concerns over battery degradation and rapid technological advancements that make older models seem outdated [77]. In Table 4.11, the depreciation rates for BEVs and CVs are shown.

Table 4.11 – Depreciation of CV and BEV [78]

	Depreciation Rate (Per Year)	
Year	BEV	CV
1	25%	20%
2-5	18%	15%

After the first five years the depreciation rate will be between 5-7% per year [78].

Assuming that both BEVs and combustion vehicles CVs travel 15000 km per year, the depreciated value is calculated with formula (4.8) [15]:

$$DV = PC_{vehicle} \cdot (1 - DR)^n \tag{4.8}$$

where:

- DV – the estimated value of the vehicle after n years [€]
- $PC_{vehicle}$– purchase price of the vehicle [€]
- DR– annual depreciation rate
- n– number of years the vehicle has been in use

The Table 4.12 shows the estimated values of BEV and CV for selected countries after one year of use.

Table 4.12– Values of BEVs and CVs after one year

	Germany	Austria	Spain
MINI Cooper C	23 280 €	25 126 €	27 120 €
MINI Cooper E	27 195 €	28 586 €	29 700 €
BMW 520d	52 790 €	55 160 €	56 714 €
BMW 520i	49 584 €	-	-
BMW i5 eDrive	56 355 €	57 690 €	58 890 €
BMW X3 20d	48 399 €	51 340 €	54 358 €
BMW X3 20i	44 143 €	-	48 202 €
BMW iX3	52 860 €	55 463 €	55 425 €
	Sweden	**Norway**	**Slovenia**
MINI Cooper C	24 468 €	-	24 468 €
MINI Cooper E	30 311 €	24 564 €	30 142 €
BMW 520d	51 969 €	-	47 720 €
BMW 520i	-	-	-
BMW i5 eDrive	54 422 €	52 425 €	53 888 €
BMW X3 20d	46 898 €	-	47 840 €
BMW X3 20	-	-	-
BMW iX3	51 416 €	46 881 €	55 463 €

4.2.7 Insurance costs and taxes

Vehicle insurance and taxes are two essential aspects of vehicle ownership that serve distinct purposes while incurring ongoing costs. Insurance premiums are influenced by a range of factors, including the driver's age, driving record, and experience, as well as the vehicle's make, model, and age. A driver's insurance history also impacts rates, as first-time policyholders or new drivers generally pay more. Therefore, we have taken the average cost of insurance for selected countries and vehicles as shown in Table 4.13.

Table 4.13– Insurance costs per year for selected countries

	Mini Cooper	BMW 5er	BMW x3
Germany [80]	560 €	750 €	650 €
Austria [79]	690 €	830 €	720 €
Spain [81]	580 €	660 €	620 €
Sweden [82]	670 €	840 €	750 €
Norway [83]	820 €	1 050 €	950 €
Slovenia [84]	430 €	620 €	500 €

CO_2 taxes on vehicles are meant to reduce pollution and encourage people to use cleaner cars. These taxes are usually based on how much CO_2 a vehicle emits (g/km), with higher-emission cars paying more. Depending on the country, CO_2 taxes can be a one-time fee when registering a car, a yearly tax, or extra charges on fuel [89].

BEVs should not pay CO_2 taxes because they do not produce emissions while driving. Many governments exempt BEVs from these taxes or give incentives to make them more affordable. However, the environmental impact of BEVs still depends on how the electricity used for charging is produced [89]. When registering the vehicle, CVs must pay a tax based on CO_2 emissions. These taxes are shown in Table 4.14 for selected cars and countries.

Table 4.14– CO_2 taxes per year for CV in selected countries

	Mini C	BMW 520d	BMW 520i	BMW X3 20d	BMW X3i
Germany [85]	108 €	384 €	379 €	445 €	390 €
Austria [86]	170 €	209 €	-	244 €	-
Spain	N/A	N/A	N/A	N/A	N/A
Sweden [87]	402 €	457 €	-	628 €	-
Norway	-	-	-	-	-
Slovenia [88]	145 €	180 €	-	210 €	-

5. Total cost of ownership

Total cost of ownership (TCO) is a financial analysis metric that helps assess the overall cost of owning and operating an asset. It includes both direct and indirect costs, making it a comprehensive way to evaluate the true economic performance of an investment or asset. All costs that arise over the course of one year are included: purchase costs, maintenance costs, insurance costs, registration costs, and costs for refueling or recharging [90].

TCO is calculated for six selected countries with specific costs for each country. It also compares the TCO between CV and BEV, as well as the TCO for different charging prices of BEVs in different countries, taking into consideration the efficiency of the Li-ion battery in low temperatures.

In this study, the TCO is conducted with formula (6.1) [14]:

$$TCO = \frac{(PC_t - RV \times PVF) \times CRF \quad AOC}{AKT} \tag{5.1}$$

Where:

- TCO – is the Total Cost of Ownership (TCO) per km [€/km]
- PC_t – total purchase price [€]
- RV – resale value after a period of use [€]
- PVF – present value factor
- CRF – capital recovery factor
- AOC – annual operating cost of the vehicle [€/year]
- AKT – annual kilometers travelled per year [km/year]

The total purchase price of a BEV includes the vehicle's purchase cost and any subsidies provided by the state, if available. These subsidies can help reduce the overall cost of ownership, making BEVs more affordable. Additionally, the cost of a home charging station is factored into the purchase price if the owner plans to charge the vehicle at home. However, if the vehicle is charged exclusively at public charging stations, the cost of the home charger does not need to be included. It is important to account for these factors to get a clear picture of the overall expenses associated with purchasing and owning a BEV.

The total purchase price of a BEV is calculated with formula (6.2):

$$PC_t = PC_{vehicle} + PC_{charger} - SUB \tag{5.2}$$

Where:

- PC_t – total purchase price [€]
- PC_{vehic} – purchase price of vehicle [€]
- $PC_{charger}$ – purchase price of charger at home [€]
- SUB – subsidies from countries [€]

The annual cost of operating a vehicle includes expenses such as refueling or recharging, maintenance, and insurance. For CVs, additional costs like CO2 taxes are also included. All of these factors play a role in determining the overall TCO, as they impact how much is spent on the vehicle each year. Understanding these annual costs is essential for comparing the long-term financial impact of owning both BEVs and CVs.

The annual cost of operating a vehicle is calculated with formula (6.3):

$$AOC = C_m + C_i + C_{char/refuel} + C_{CO2} \tag{5.3}$$

Where:

- AOC – annual operating cost [€/year]
- C_m – maintenance cost of vehicles [€/year]
- C_i – insurance cost of vehicles [€/year]
- $C_{char/refuel}$ – recharging or refueling cost of vehicles [€/year]
- C_{CO2} – CO_2 costs [€/year]

When conducting a TCO analysis, it is essential to consider that different costs occur at different points in time, such as purchase costs, maintenance, and operational expenses. Since the value of money changes over time due to factors like inflation and opportunity cost, future expenses must be adjusted to reflect their present-day value. This adjustment is made using a discounted cash flow method, typically through the present value formula.

The following formula (6.4) is applied when accounting for future revenues [14]:

$$PVF = \frac{1}{(1+r)^T} \tag{5.4}$$

Where:

- PV – present value
- r – real discount rate
- T – time (expressed as number of years)

and in the case of recurring costs, the capital recovery factor (CRF) is calculated with following formula (6.5):

$$CRF = \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \tag{5.5}$$

where:

- CRF – the capital recovery factor
- r – is the discount rate
- T – time (expressed as number of years)

For our calculation, we have assumed a depreciation rate of 5% per year [91].

After processing all the key parameters for the economic assessment of both BEVs and CVs, we will have a clear overview of the TCO for both vehicle types over a five-year period. The analysis covers six countries and considers different types of chargers. For each year, it is assumed that the car will travel 15000 km, allowing for a comprehensive comparison of the total costs incurred during the ownership period, including factors such as fuel, maintenance, insurance, taxes, and charging infrastructure.

5.1 Total cost of ownership for battery electric vehicles and conventional vehicles in selected countries

5.1.1 Germany

The calculations are made for different scenarios, including charging at home and at public DC or AC stations. The charging scenarios described below consider three recharging price options: maximum, average, and minimum to reflect the variability in charging costs. Additionally, combinations of home charging and public DC or AC charging are analyzed using the same three price levels.

The price of recharging depends on both the time of charging and the power of the charger. The time of charging refers not only to the duration of the recharge but also to whether the charging occurs during peak or off-peak hours on the electricity grid. Charging during peak hours, when electricity demand is highest, can result in higher costs due to increased energy prices. On the other hand, charging during off-peak hours, when demand is lower, typically costs less. Additionally, the power of the charger influences the overall cost, as faster charging requires more energy and may be more expensive depending on the charging station's pricing structure.

This analysis compares both CVs and BEVs, including different fuel and charging methods, to provide a comprehensive comparison of TCO. This approach offers a detailed understanding of how charging and fuel costs affect the overall cost of ownership for both vehicle types in various situations.

As shown in Fig. 5.1, the analysis presents charging and refueling scenarios. The vertical axis (y-axis) represents the cost per kilometer, while the horizontal axis (x-axis) displays the following scenarios:

- **100% Home**: charging the BEV only at home
- **100% DC**: charging the BEV exclusively at public DC stations, using maximum, average, and minimum prices.
- **100% AC**: charging the BEV exclusively at public AC stations, using maximum, average, and minimum prices.
- **50% Home + 50% DC**: charging the BEV 50% at home and 50% at public DC stations using maximum, average, and minimum prices.
- **50% Home + 50% AC**: charging the BEV 50% at home and 50% at public AC stations using maximum, average, and minimum prices.

- **70% Home + 30% DC**: charging the BEV 70% at home and 30% at public DC stations using maximum, average, and minimum prices.
- **70% Home + 30% AC**: charging the BEV 70% at home and 30% at public AC stations using maximum, average, and minimum prices.
- **Petrol**: refueling the CV with petrol
- **Diesel**: refueling the CV with diesel

The diagram compares the cost per kilometer (€/km) for the Mini Cooper C (CV) and the Mini Cooper E (BEV) under various charging scenarios. Along the x-axis, different charging scenarios are listed.

An analysis of Fig. 5.1 for the Mini Cooper C and Mini Cooper E shows that a major part of the total cost comes from fixed costs. For home charging and refueling, variable costs are represented using a single color (light green), as both electricity and fuel prices are fixed and do not vary. In contrast, public charging stations involve three different pricing levels, minimum, average, and maximum, each shown in a separate color, as previously explained.

Comparing the TCO of the CV with that of the BEV, we see that the CV generally has a lower TCO, except in cases where the BEV is charged at public DC or AC stations using the minimum or average charging price. A key role was played by direct government subsidies, which helped make BEVs more competitive.

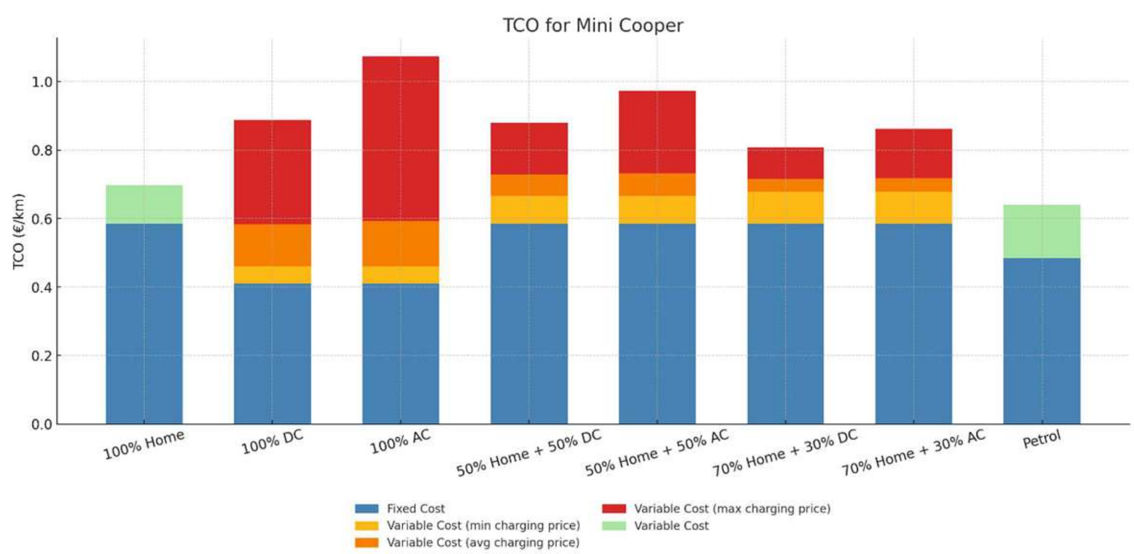

Fig. 5.1- TCO of the Mini Cooper C (CV) and Mini Cooper E (BEV)

Comparing the TCO of a BEV charged at home with that of a CV, we see that the CV is about 0.10 €/km cheaper. In all other scenarios except the two mentioned earlier BEVs have a higher TCO.

Assuming that the purchase price of vehicles remains unchanged, the development of variable costs over the next five years is examined. The variable costs have been calculated for each year, and in most charging scenarios, the variable costs of BEVs are lower compared to those of CVs. The figures present the variable costs per year, as the changes over time are minimal.

As shown in Fig. 5.2, in most charging scenarios, the variable costs of the Mini Cooper E (BEV) are lower compared to those of the Mini Cooper C (CV). The variable costs for BEVs remain lower in all scenarios, except when charging at maximum public prices, where the BEVs variable costs are slightly higher.

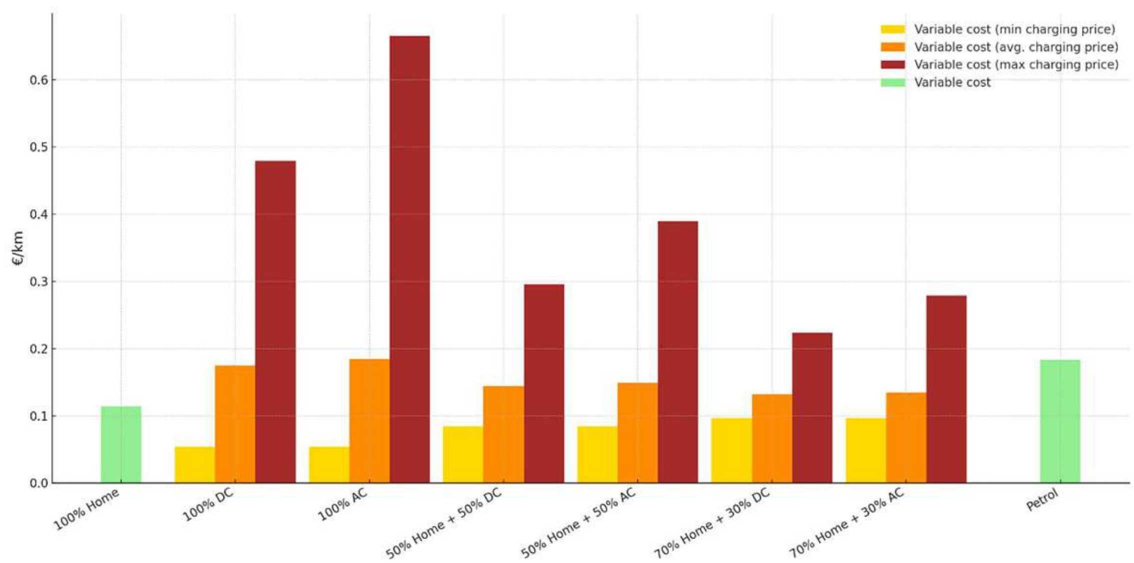

Fig. 5.2- Variable Costs for the Mini Cooper C (CV) and Mini Cooper E (BEV)

The same detailed analysis was conducted for the BMW 5 Series, considering three types of vehicles: CVs, which include both petrol (BMW 520i) and diesel (BMW 520d) models, and BEVs (BMW i5). All the factors that were considered in the previous analysis, such as purchase price, depreciation, recharging/fueling costs, and the overall TCO, are also taken into account for the BMW 5er.

Analyzing Fig. 5.3 reveals that both the BMW 520d (CV) and the BMW 520i (CV) are cheaper compared to the BMW i5 (BEV). A key factor contributing to this is the higher purchase price of BEVs and the lack of direct government subsidies, which makes them less competitive than CVs. Even when BEVs are charged at the minimum electricity price, CVs still tend to be more cost-effective.

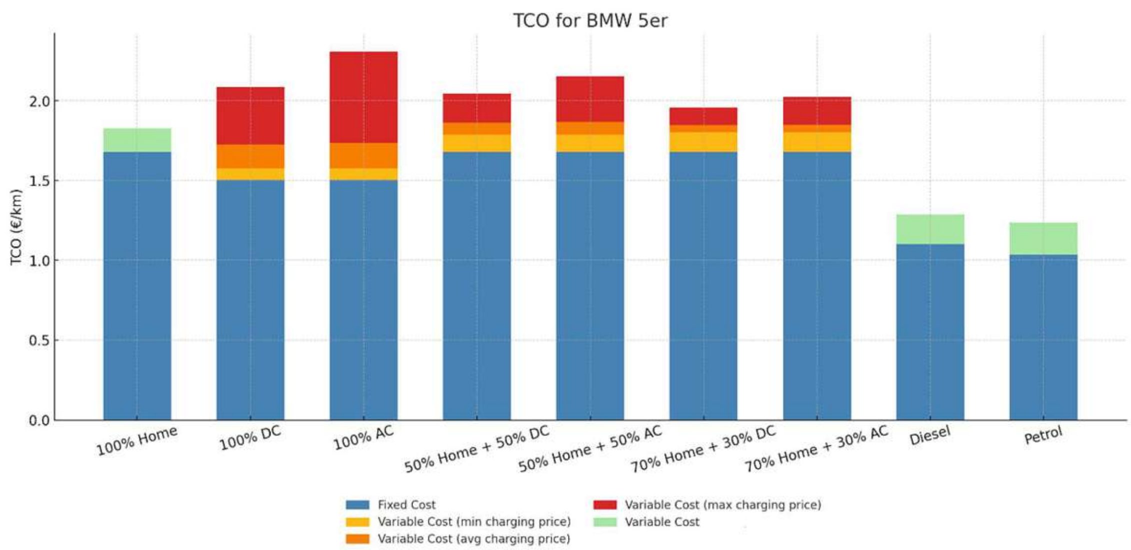

Fig. 5.3- TCO of the BMW 520d (CV), BMW 520i (CV) and BMW i5 (BEV)

Assuming that the purchase price of the vehicles remains unchanged and only variable costs are considered, the analysis shows that the variable costs of BEVs are, in most cases, lower than those of CVs, except when charging is done at the highest public charging prices, see Fig. 5.4.

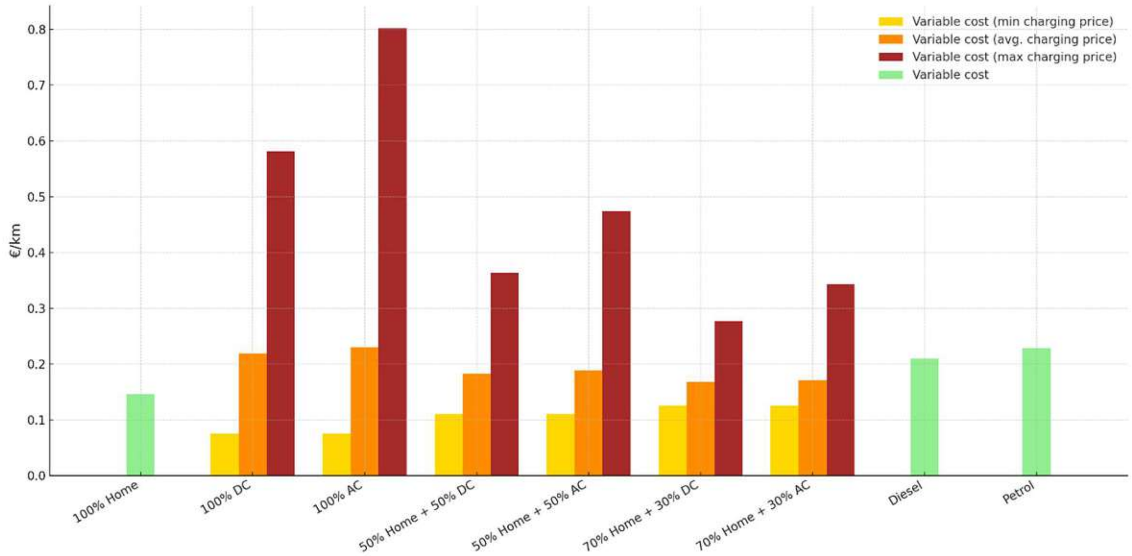

Fig. 5.4- Variable Costs of the BMW 520d (CV), BMW 520i (CV) and BMW i5 (BEV)

The same detailed analysis was done for BMW X3, considering three types of vehicles: the CVs, which include both petrol (BMW X3 20i) and diesel (BMW X3 20d) models, and the BEV (BMW iX3). All the factors considered in the previous analysis, such as purchase price, depreciation, recharging/fueling costs, and overall TCO are also taken into account for the BMW X3 Series.

As shown in Fig. 5.5, the difference in TCO between CVs and BEVs is clearly significant. Once again, the high purchase price of BEVs, and the lack of direct government subsidies, make them less competitive. Even when BEVs are charged at the lowest available recharging price, CVs still tend to be the more cost-effective option.

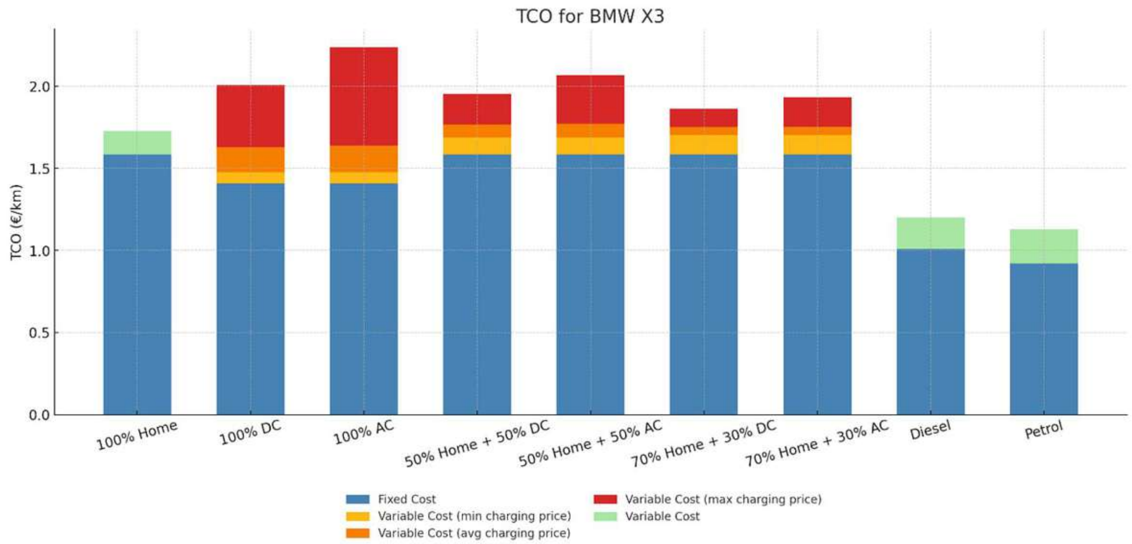

Fig. 5.5- TCO of the BMW X3 20d (CV), BMW X3 20i (CV) and BMW iX3 (BEV)

Assuming that the purchase price of the vehicles remains unchanged and only variable costs are considered, the analysis shows that the variable costs of BEVs are, in most cases, lower than those of CVs, except when charging is done at the highest price at public stations, see Fig. 5.6.

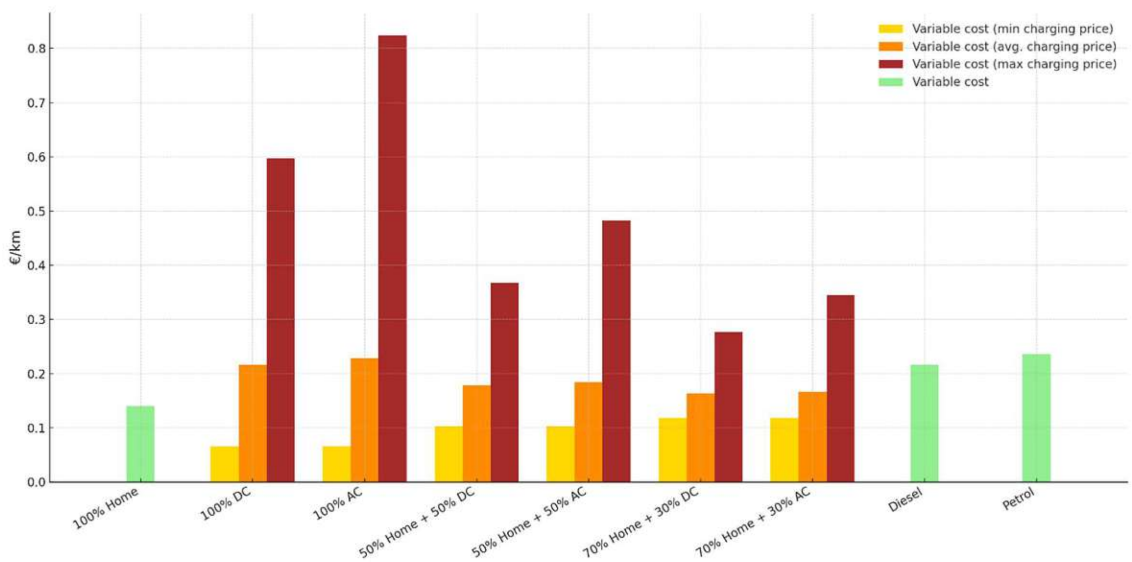

Fig. 5.6- of the BMW X3 20d (CV), BMW X3 20i (CV) and BMW iX3 (BEV)

In conclusion, the TCO analysis for the three vehicle types in Germany shows that conventional vehicles are usually still the more affordable option. Small cars are an exception, as BEVs are cheaper than CVs. For medium-sized cars and SUVs, however, BEVs remain less competitive due to their higher purchase prices and the absence of direct government subsidies. Nevertheless, BEVs generally have lower variable costs than CVs in most scenarios.

5.1.2 Spain

For Spain, the TCO for both CVs and BEVs was calculated. Unlike other countries, Spain has high temperatures throughout the year; even in winter, temperatures rarely drop below 0°C. These higher temperatures, even during winter, positively affect the efficiency of Li-ion batteries, resulting in better performance of electric vehicles and lower charging costs.

As shown in Fig. 5.7, BEVs were generally the more cost effective option. The only exception was a scenario in which 50% of the BEV charging was done at public DC stations with the highest charging price, and 50% was done at home. In all other scenarios, BEVs were more cost effective than CVs. A key role was played by direct government subsidies, which helped make BEVs more competitive. Additionally, the charging price is a key factor influencing the overall cost, as shown by the variations across different scenarios.

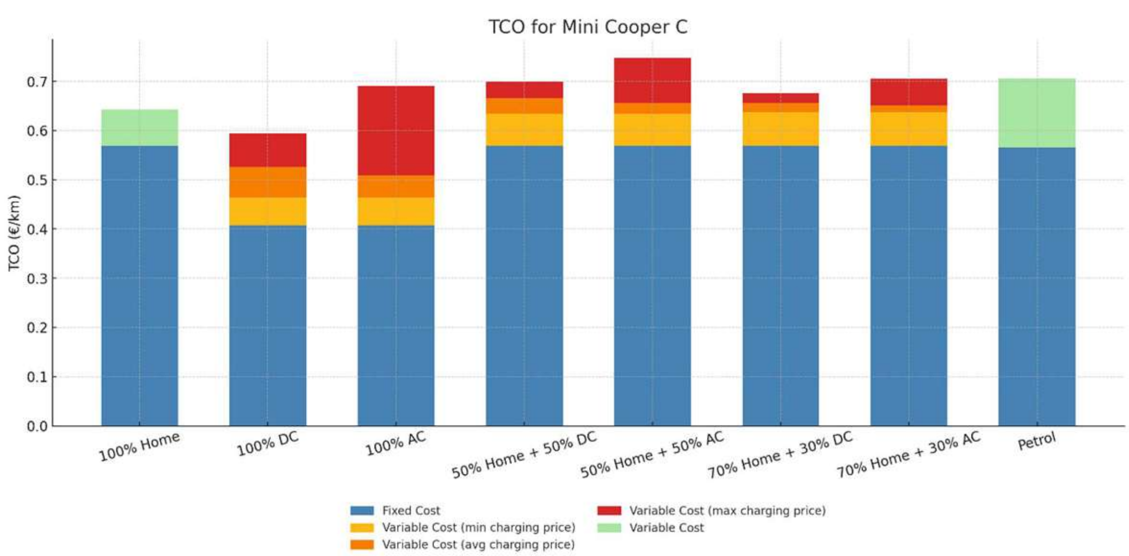

Fig. 5.7- TCO of the Mini Cooper C (CV) and Mini Cooper E (BEV)

Figure 5.8 presents the variable costs of CVs and BEVs. In all considered scenarios, the variable costs of BEVs were lower than those of CVs, except in three scenarios where charging occurred at DC public stations with the highest electricity prices.

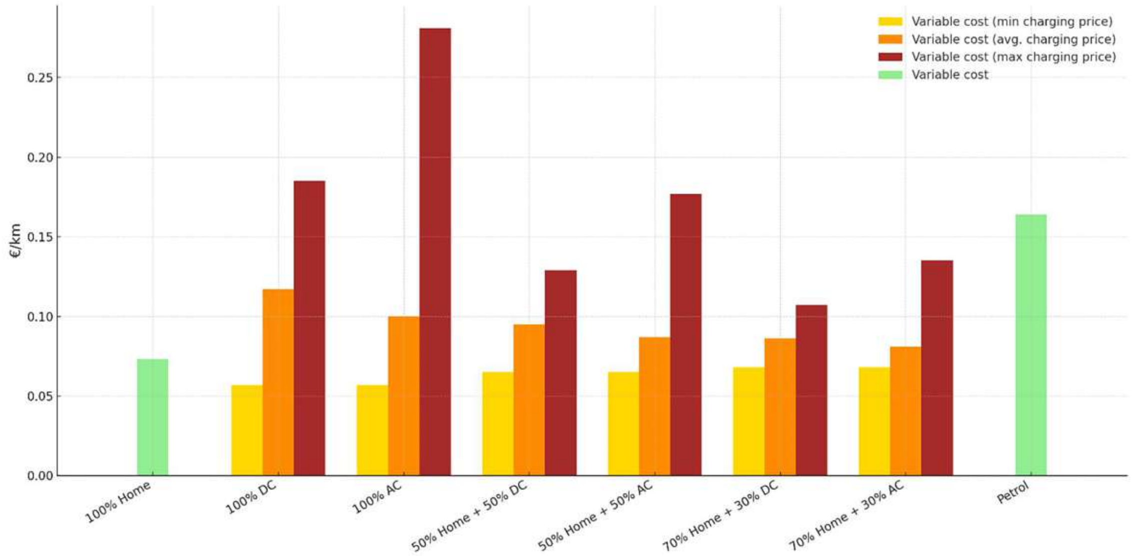

Fig. 5.8- Variable Costs of the Mini Cooper C (CV) and Mini Cooper E (BEV)

The same detailed analysis was done for the BMW 5 Series, considering two types of vehicles: CVs and BEVs. All the factors used in calculating the TCO for the BMW 520d (CV) and BMW i5 (BEV) were taken into account.

As shown in Fig 5.9, the situation changes significantly, the CV is consistently cheaper compared to the BEV across all charging scenarios. Even when the BEV is charged at the lowest possible price, it remains more expensive than the CV. It is important to note that high purchase prices and the lack of direct government subsidies play a critical role in making BEVs less competitive.

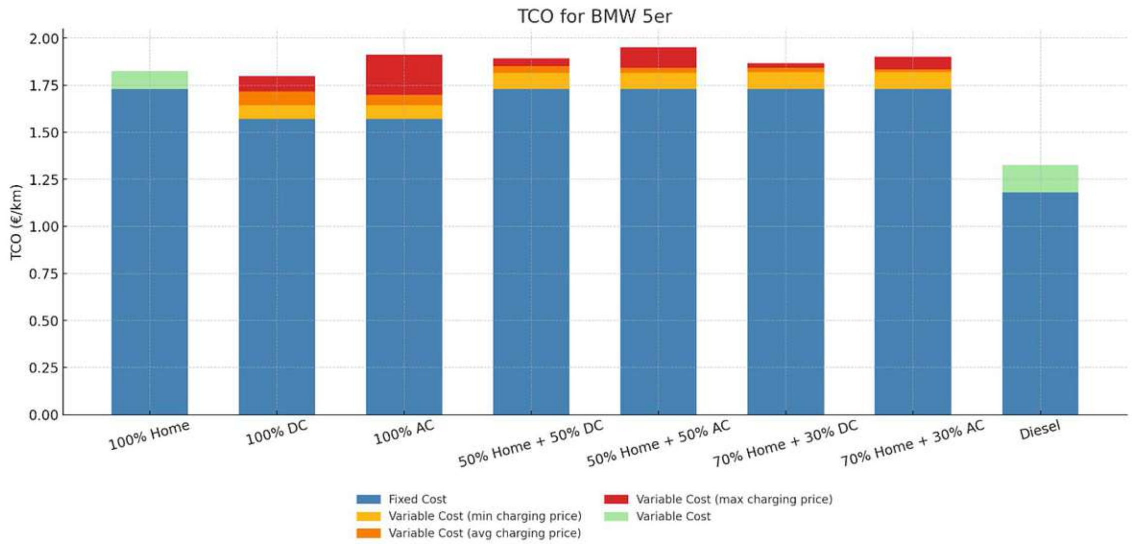

Fig. 5.9- TCO of the BMW 520d (CV) and BMW i5 (BEV)

For the BMW 5 Series, the BEV had lower variable costs than the CV in most scenarios, except for four scenarios where the BEVs variable costs were higher: charging 100% at public DC stations with higher charging prices, 100% at public AC stations with higher charging prices, a 50/50 mix of public AC (with higher charging prices) and home charging, and a 70/30 mix of public AC (with higher charging prices) and home charging. In all other scenarios, the BEV had lower variable costs than the CV, see Fig. 5.10.

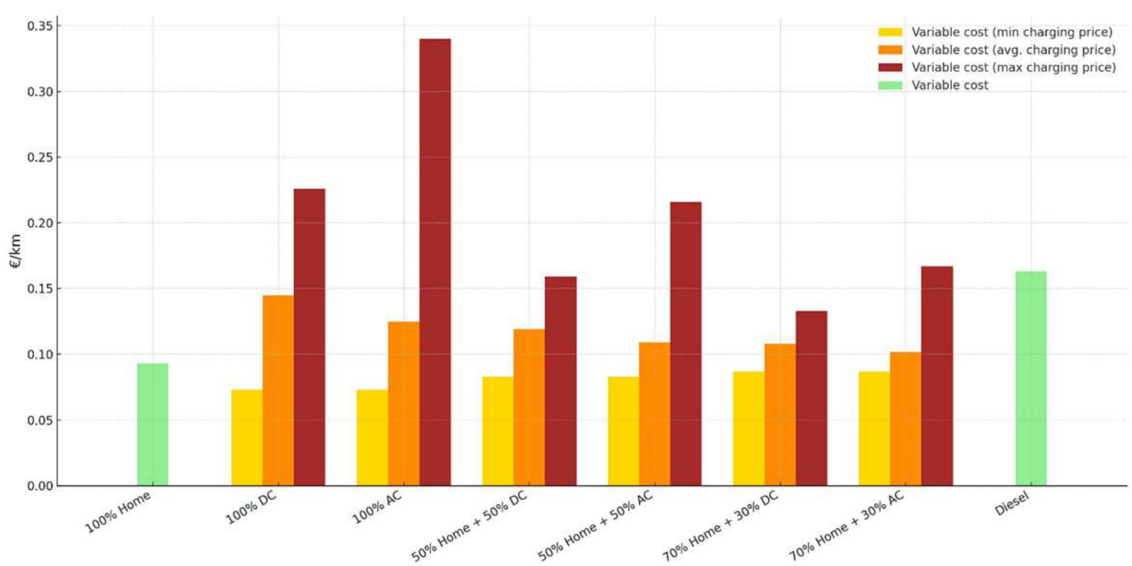

Fig. 5.10- Variable Costs of the BMW 520d (CV) and BMW i5 (BEV)

The same detailed analysis was done for the BMW X3 series, considering CVs with petrol (BMW X3 20i) and diesel (BMW X3 20d), as well as the BEV (BMW iX3).

As shown in Fig. 5.11, CVs are generally more cost-effective than BEVs. The high purchase price of BEVs and the lack of direct government subsidies, make them less competitive. Even when BEVs are charged at the lowest available recharging price, CVs still tend to be the more cost effective option.

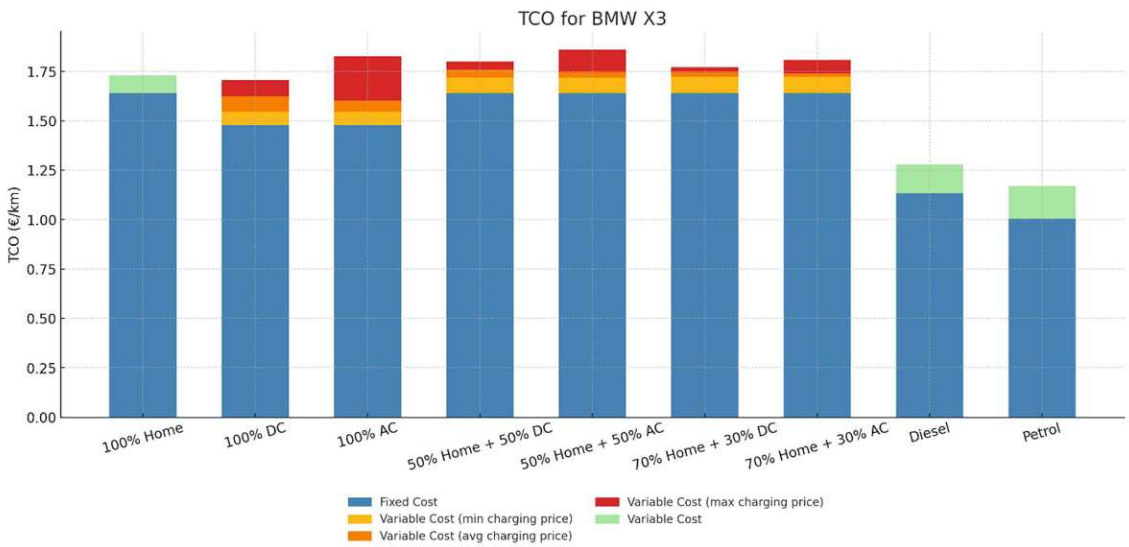

Fig. 5.11- TCO of the BMW X3 20d (CV), BMW X3 20i (CV) and BMW iX3 (BEV)

The situation changes when only the variable costs are analyzed. For the BMW X3 Series, the BEV had lower variable costs than the CV in most scenarios. As shown in Fig. 5.12, in most scenarios, the variable costs of the BEV are lower compared to those of the CV, except in scenarios where the BEV is charged with the highest charging price.

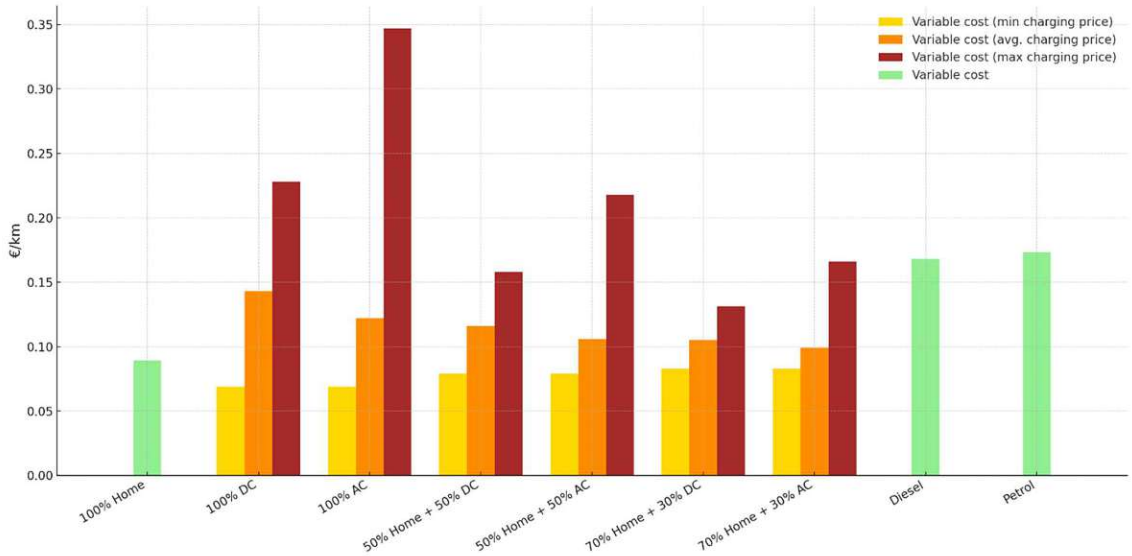

Fig. 5.12- Variable Costs of the BMW X3 20d (CV), BMW X3 20i (CV) and BMW iX3 (BEV)

5.1.3 Sweden

For Sweden, the TCO was also calculated for both CVs and BEVs. However, Sweden's long winter, lasting around five months, with temperatures often dropping below 0 °C has a significant impact on electric vehicles. In cold weather, the efficiency of Li-ion batteries decreases, leading to a reduced driving range and an increased number of charging cycles. This makes electric cars less efficient compared to other seasons.

As shown in Fig. 5.13, the CV (Mini Cooper C) is cheaper than the BEV (Mini Cooper E), even when the BEV is charged with the minimum public charging price. Compared to the two previously discussed countries, this highlights the impact that direct subsidies can have in making BEVs more competitive. Unlike the countries mentioned earlier, which provide direct subsidies for the BEV, Sweden does not offer such support. This absence of government incentives plays a key role in making the BEV less competitive compared to CVs. Compared to the two previously discussed countries, BEVs in Sweden are more expensive, even for small cars.

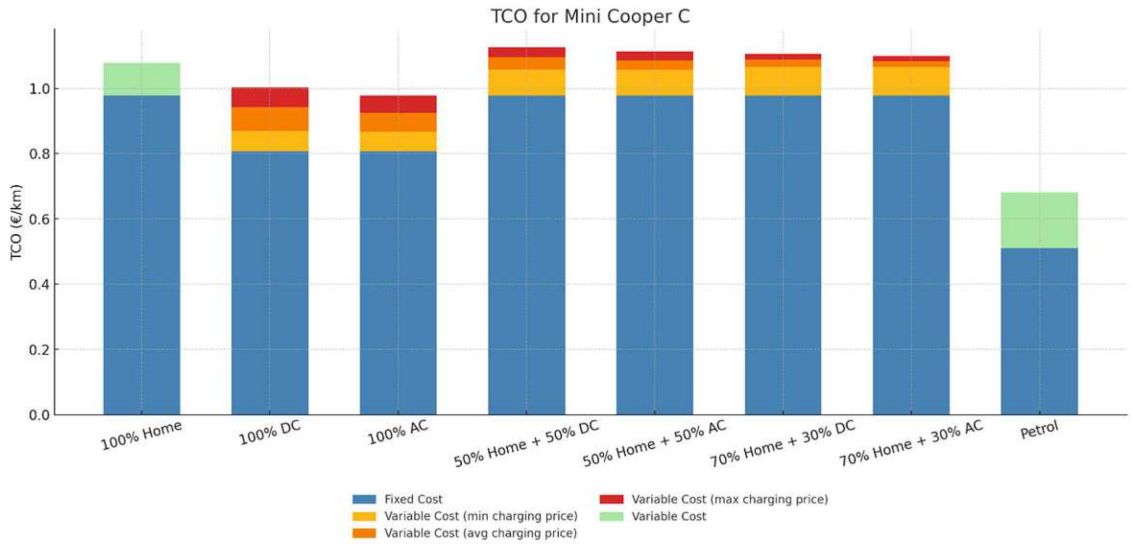

Fig. 5.13- TCO of the Mini Cooper C (CV) and Mini Cooper E (BEV)

As shown in Fig. 5.14, the BEV had lower variable costs than the CV in most scenarios, except when charged at the highest public DC price, here the BEV's variable costs were slightly higher.

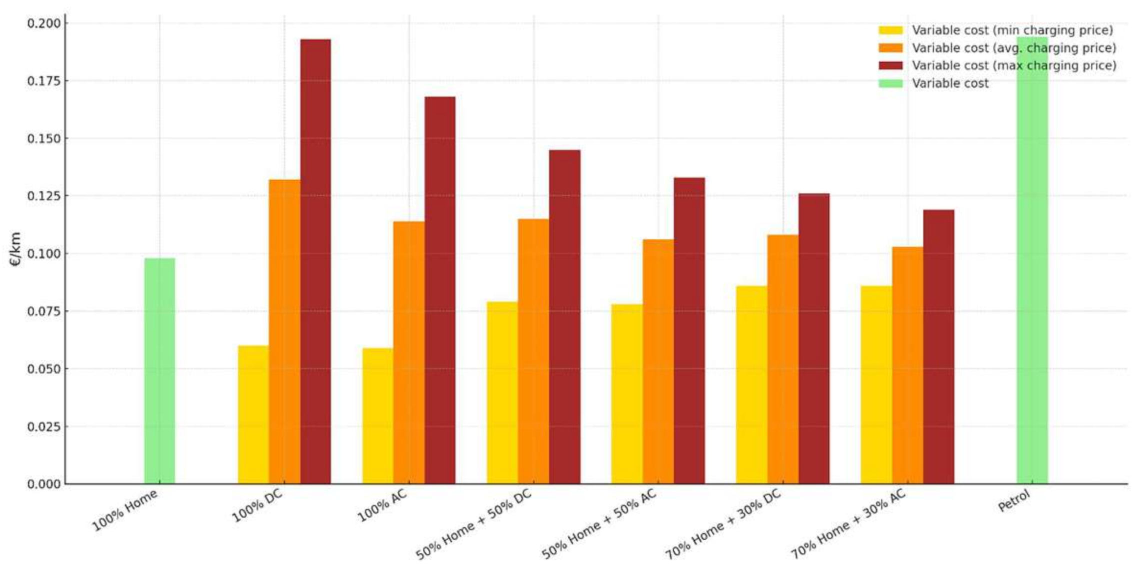

Fig. 5.14- Variable Costs of the Mini Cooper C (CV) and Mini Cooper E (BEV)

As with the previously discussed countries, the situation in Sweden for the BMW 5 Series is similar. As shown in Fig. 5.15, the CV (BMW 520d) remains consistently cheaper than the BEV (BMW i5) across all charging scenarios. Even when the BEV is charged with the lowest price, it remains more expensive than the CV. Furthermore, the lack of subsidies and the higher purchase price make BEVs less competitive.

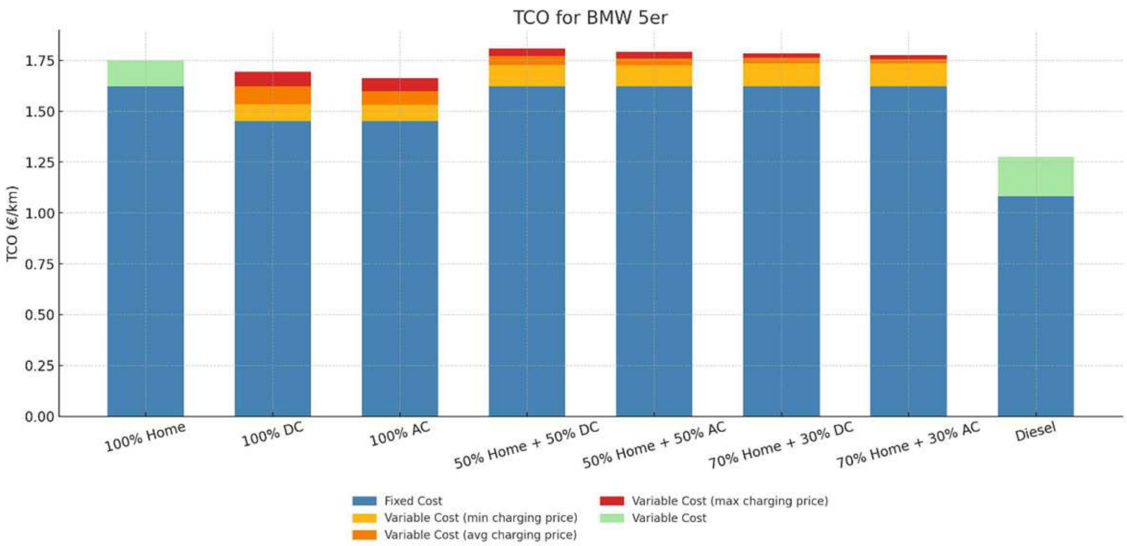

Fig. 5.15- TCO of the BMW 520d (CV) and BMW i5 (BEV)

In all scenarios, the variable costs of the BEV are lower than those of the CV, except in scenarios where the BEV is charged entirely at public AC and DC stations with the highest charging prices, see Fig. 5.16.

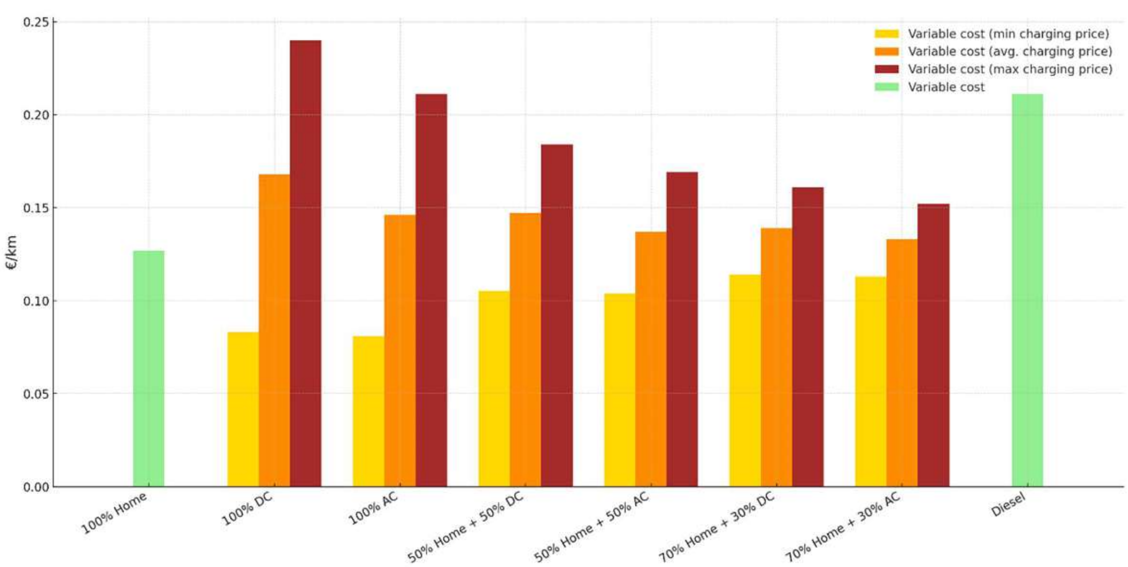

Fig. 5.16- Variable Costs of the BMW 520d (CV) and BMW i5 (BEV)

The same detailed analysis was conducted for the BMW X3 series, considering two types of vehicles: the CV and the BEV. Here too, the CV (BMW X3) was consistently cheaper than the BEV (BMW iX3) across all charging scenarios. Factors such as the higher purchase price of the BEV and the lack of government subsidies play a key role in driving up the TCO for the BEV. Additionally, the cost of recharging further impacts on the overall cost for BEVs.

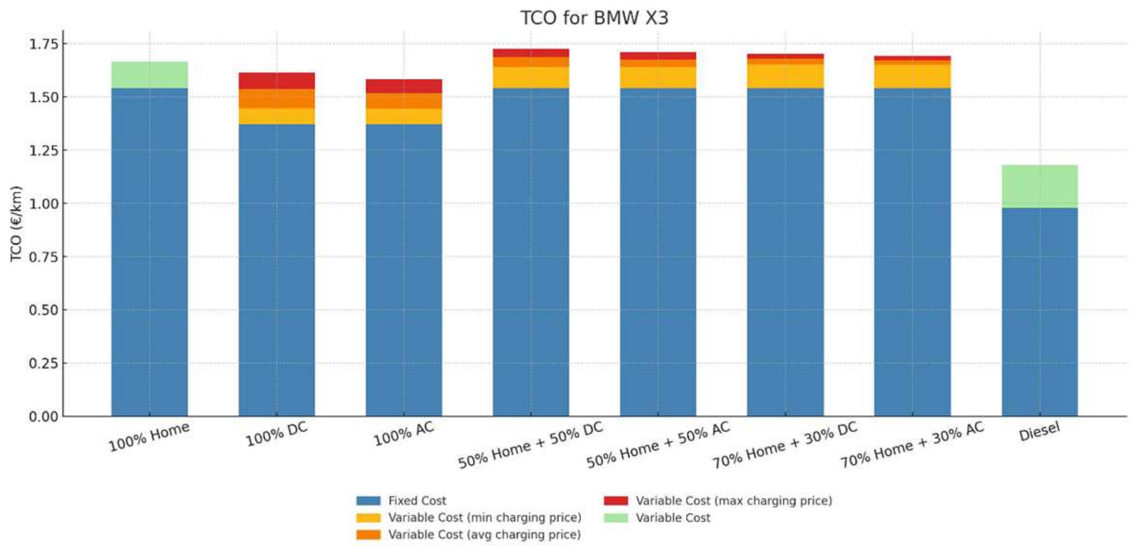

Fig. 5.17- TCO of the BMW X3 20d (CV) and BMW iX3 (BEV)

The situation changes completely when only the variable costs are analyzed. For the BMW X3 Series, the BEV had lower variable costs than the CV in most scenarios, except in the scenario where the BEV is charged at public stations with the highest charging price, see Fig. 5.18.

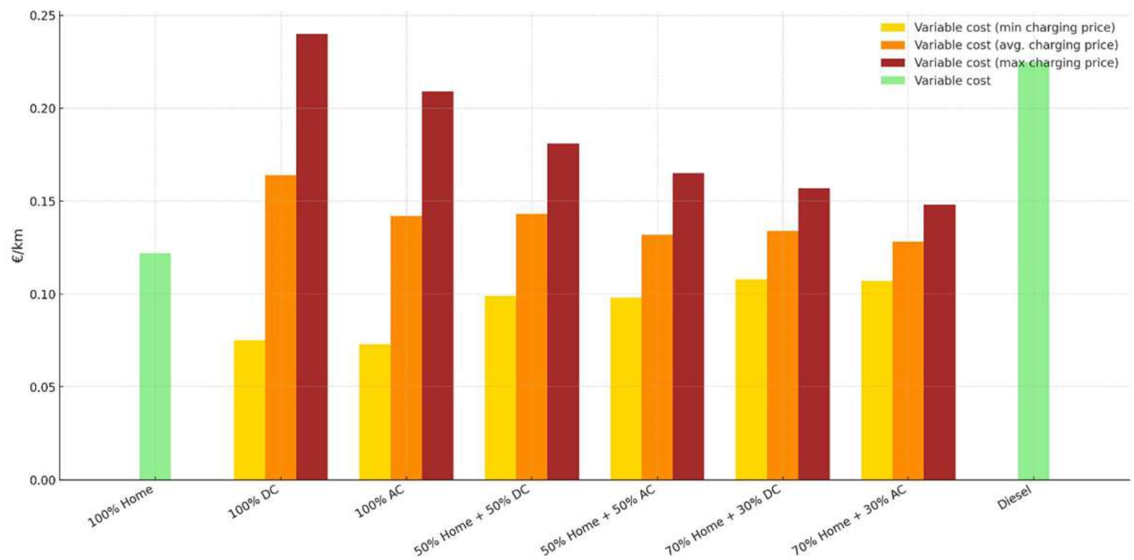

Fig. 5.18- Variable Costs of the BMW X3 20d (CV) and BMW iX3 (BEV)

5.1.4 Norway

The TCO calculation for Norway was done only for the BEV, as data for the CV with the same parameters as in the other five countries could not be found on the official page. Like Sweden, Norway has a cold climate, which significantly impacts the performance of electric vehicles.

Norway does not provide direct subsidies for customers purchasing new BEVs. As shown in Fig. 5.19, charging a BEV (Mini Cooper E) in public with the minimal price option proves to be the cheapest.

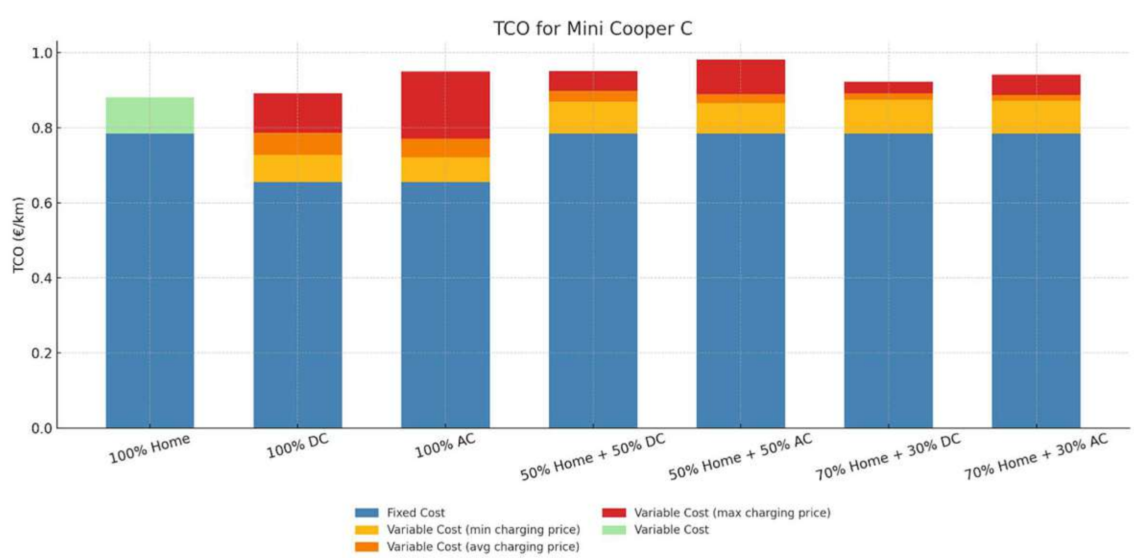

Fig. 5.19- TCO of the Mini Cooper E (BEV)

As shown in Fig. 5.20, the lowest variable costs are seen when the BEV is charged in public stations AC and DC using the minimum charging price.

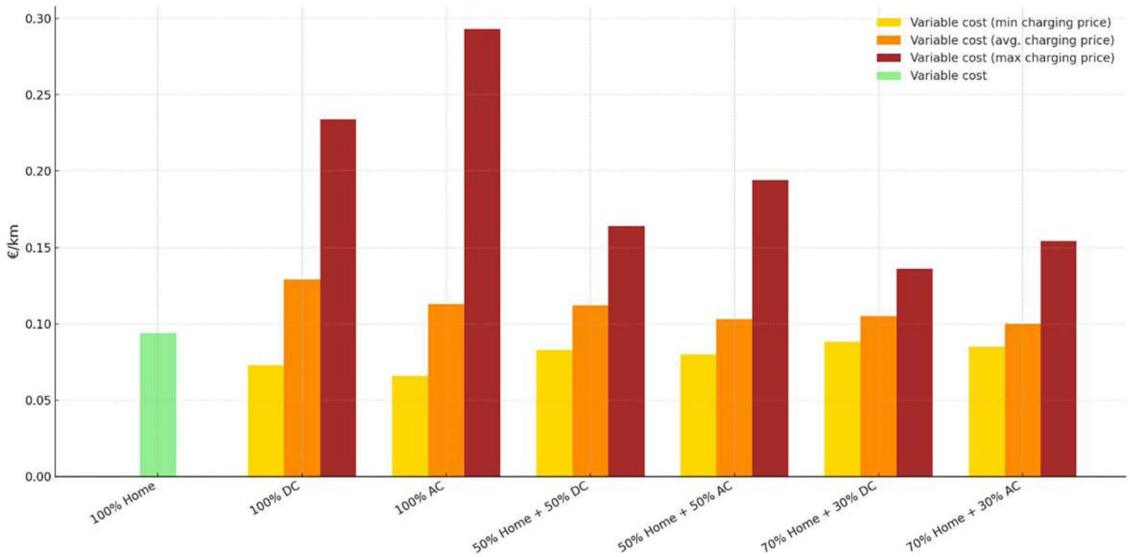

Fig. 5.20- Variable Costs of the Mini Cooper E (BEV)

The same detailed analysis was done for the BMW i5 (BEV) and BMW iX3 (BEV). Figure 5.21 shows all charging scenarios for the BMW i5, and Figure 5.22 shows the charging scenarios for the BMW iX3.

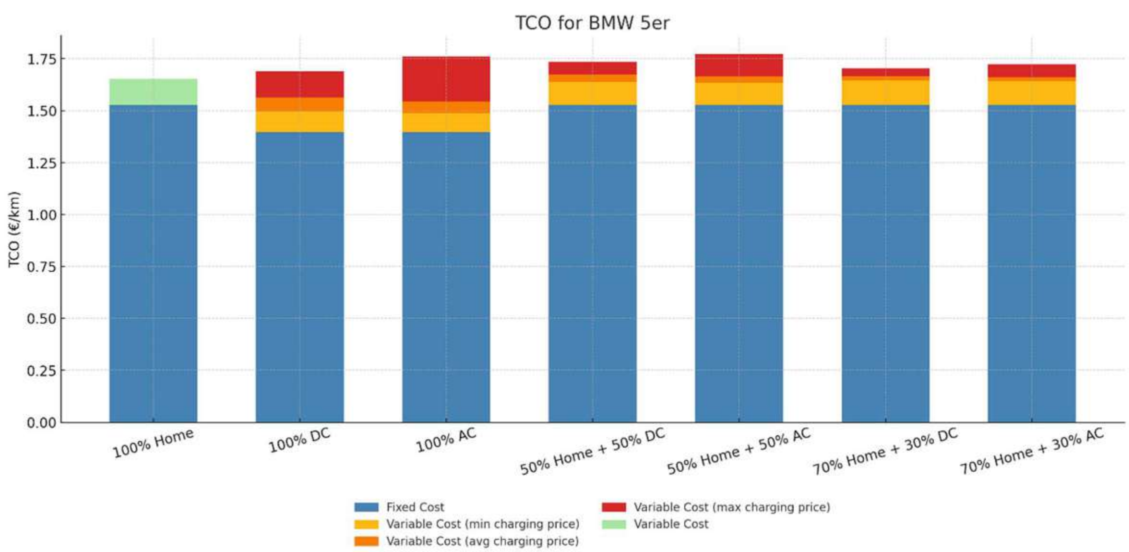

Fig. 5.21- TCO of the BMW i5 (BEV)

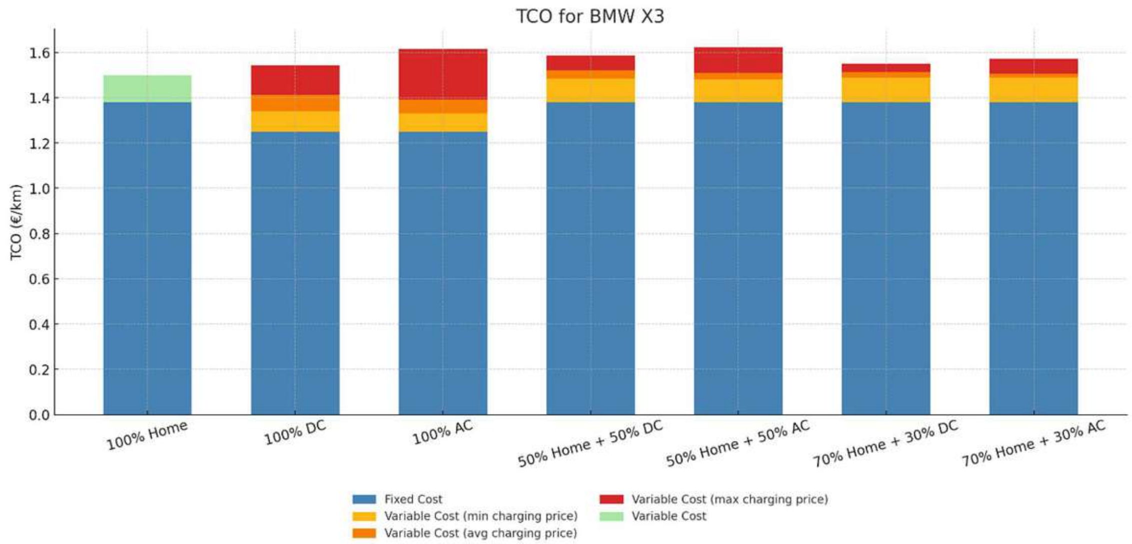

Fig. 5.22- TCO of the BMW iX3 (BEV)

Figure 5.23 shows the variable costs of the BMW i5 (BEV), and as seen, the variable costs are lowest when the BEV is charged at public AC or DC stations with the lowest charging prices.

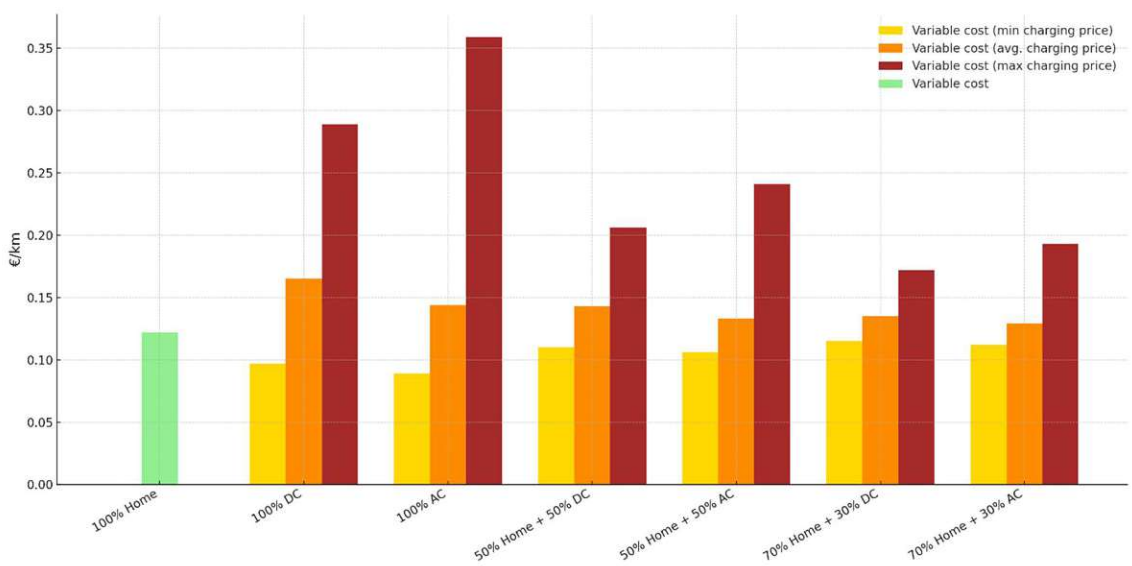

Fig. 5.23- Variable Costs of the BMW i5 (BEV)

Figure 5.24 shows the variable costs of the BMW iX3 (BEV). Again, the lowest variable costs occur when the BEV is charged at public AC and DC stations with the lowest electricity prices.

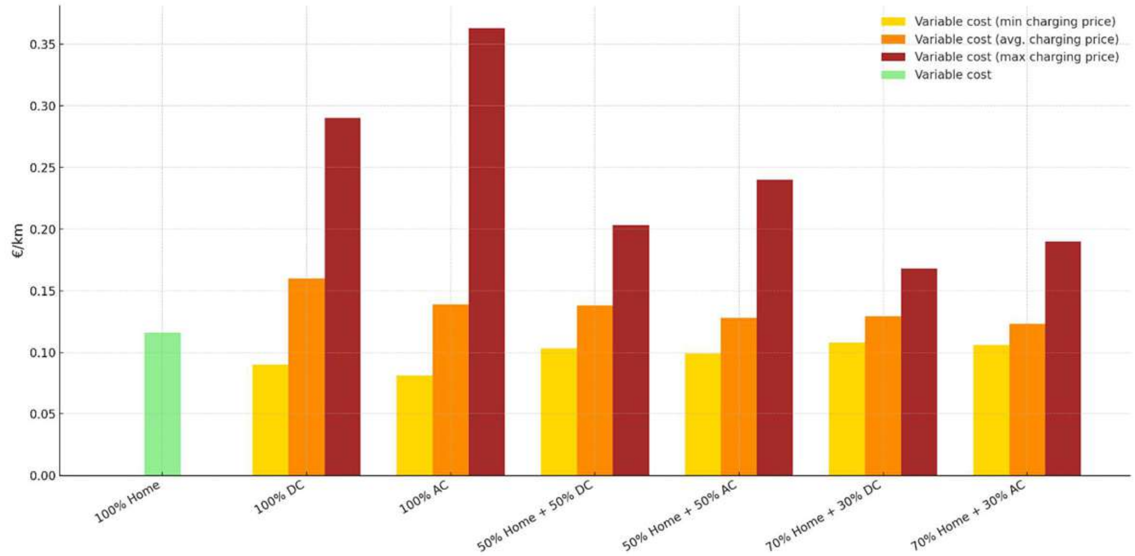

Fig. 5.24- Variable Costs of the BMW iX3 (BEV)

5.1.5 Slovenia

For Slovenia, the TCO was also calculated for both CVs and BEVs. Slovenia also provides direct subsidies for the BEV (Mini Cooper E). As shown in Fig. 5.25, in most charging scenarios, the CV (Mini Cooper C) is cheaper than the BEV, except in scenarios where the BEV is charged entirely in public AC or DC stations with minimum or average charging prices, in which case the BEV is more cost effective.

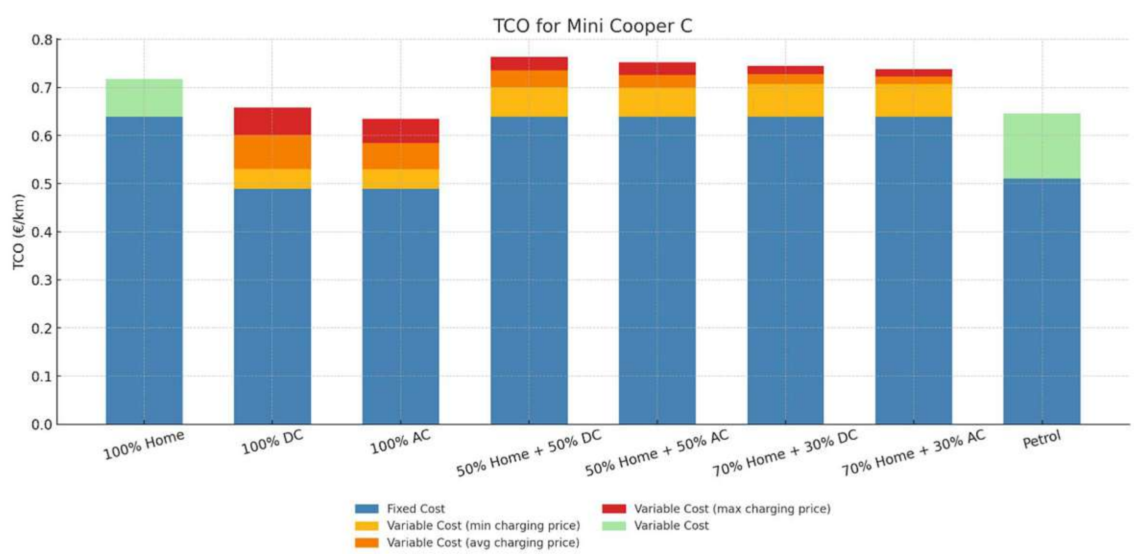

Fig. 5.25- TCO of the Mini Cooper C (CV) and Mini Cooper E (BEV)

Fig. 5.26 compares the variable costs of the Mini Cooper. The variable costs of BEV are lower in most scenarios, except when charged entirely at the highest public DC price.

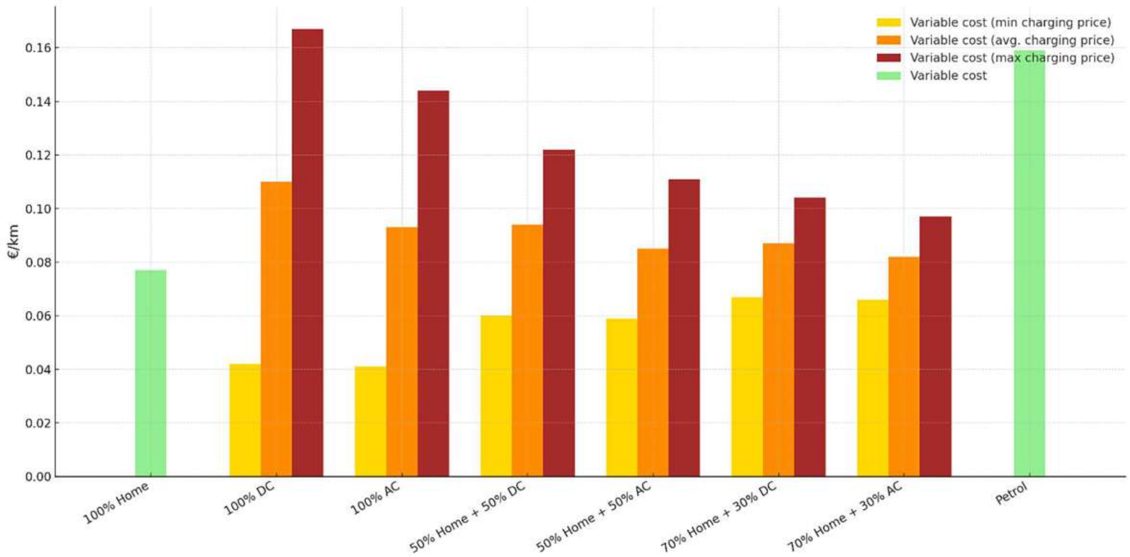

Fig. 5.26- Variable Costs of the Mini Cooper C (CV) and Mini Cooper E (BEV)

The same detailed analysis was done for the BMW 5 Series, comparing two types of vehicles: CVs (BMW 520d) and BEVs (BMW i5). The higher purchase price, and the lack of direct government subsidies for the BMW 5 Series contribute to the increased TCO of the BEV. As shown in Fig. 5.27, the CV consistently remains the cheaper option across all charging scenarios. Even when the BEV is charged at the lowest available price, it is still less cost effective compared to the CV.

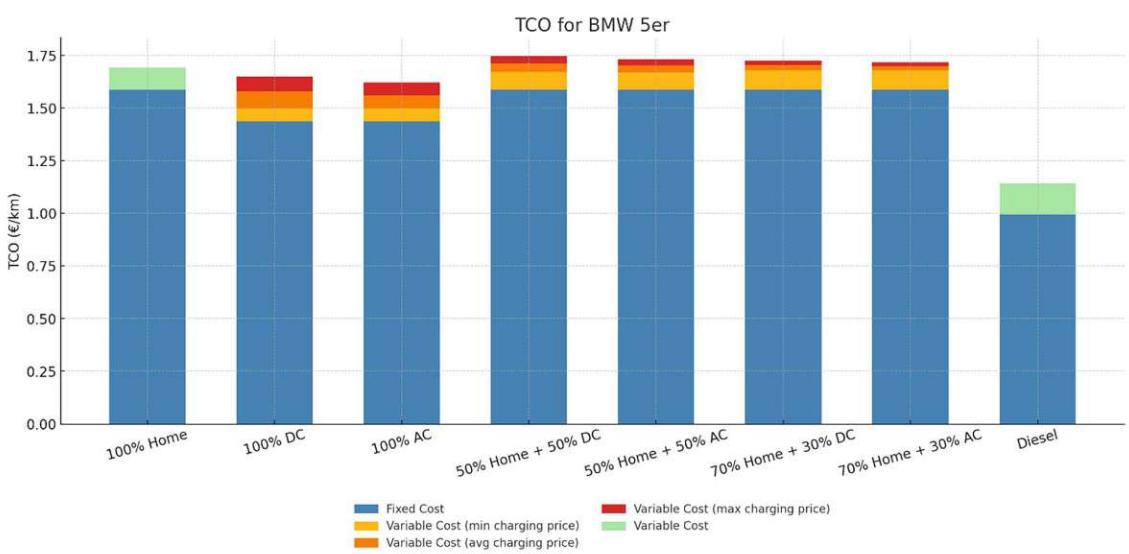

Fig. 5.27- TCO of the BMW 520d (CV) and BMW i5 (BEV)

Fig. 5.28 shows that the BEV generally has lower variable costs than the CV for the BMW 5 Series. The only exception is when the BEV is charged entirely at public DC or AC stations with the most expensive charging prices.

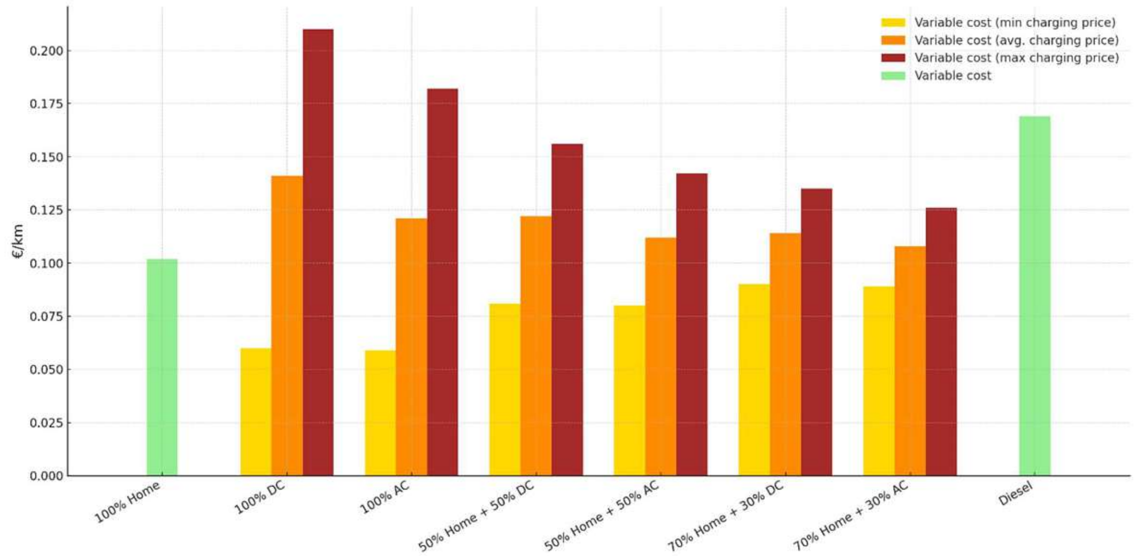

Fig. 5.28- Variable Costs of the BMW 520d (CV) and BMW i5 (BEV)

The same detailed analysis was done for the BMW X3 series, comparing two types of vehicles: CVs (BMW X3) and BEVs (BMW iX3). Fig. 5.29 shows that the CV is generally cheaper than the BEV, even in scenarios where the BEV is charged with the minimum price, the CV still remains more affordable.

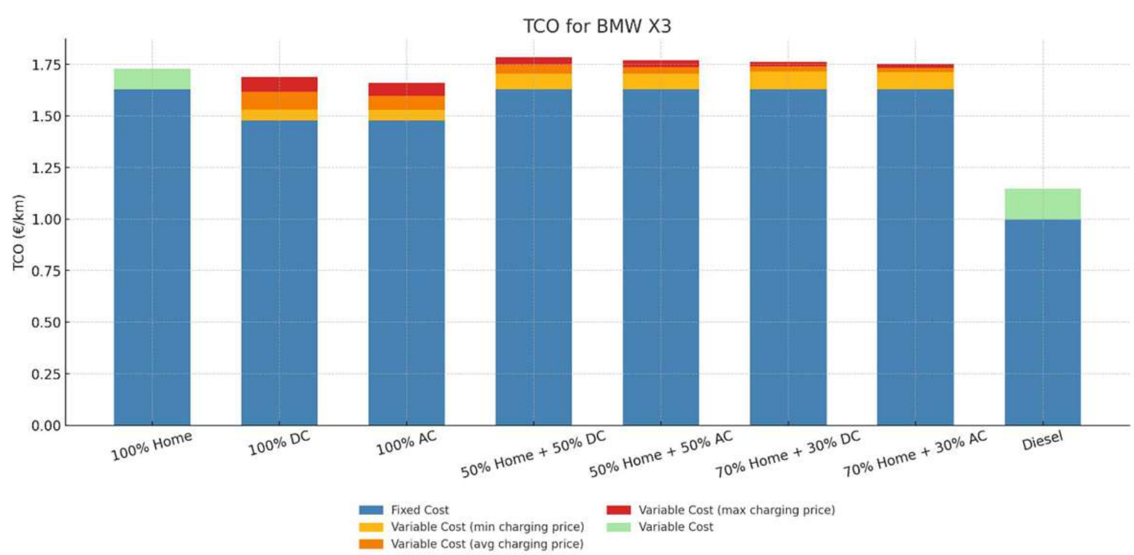

Fig. 5.29- TCO of the BMW X3 20d (CV) and BMW iX3 (BEV)

The BEV generally has lower variable costs than the CV for the BMW X3 Series, except when the BEV is charged entirely at public DC or AC stations with the most expensive charging prices, see Fig.5.30.

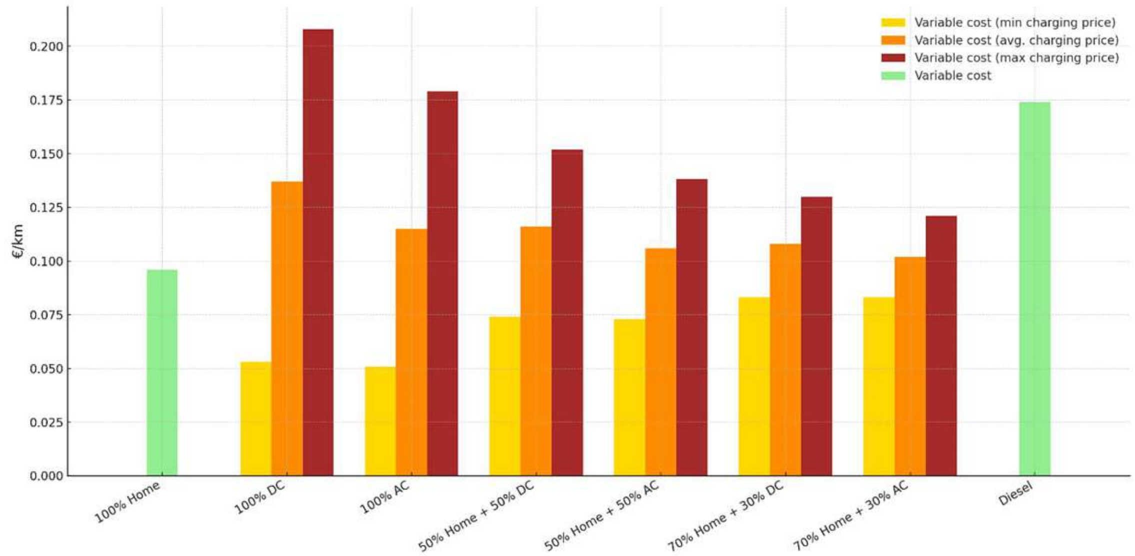

Fig. 5.30- Variable Costs of the BMW X3 20d (CV) and BMW iX3 (BEV)

5.1.6 Austria

For Austria, the TCO was calculated for both CVs and BEVs. The comparison began with the TCO of the CV (Mini Cooper C) and the BEV (Mini Cooper E). In Austria, where government subsidies play a significant role, the BEV generally has a lower TCO compared to the CV, see Fig. 5.31.

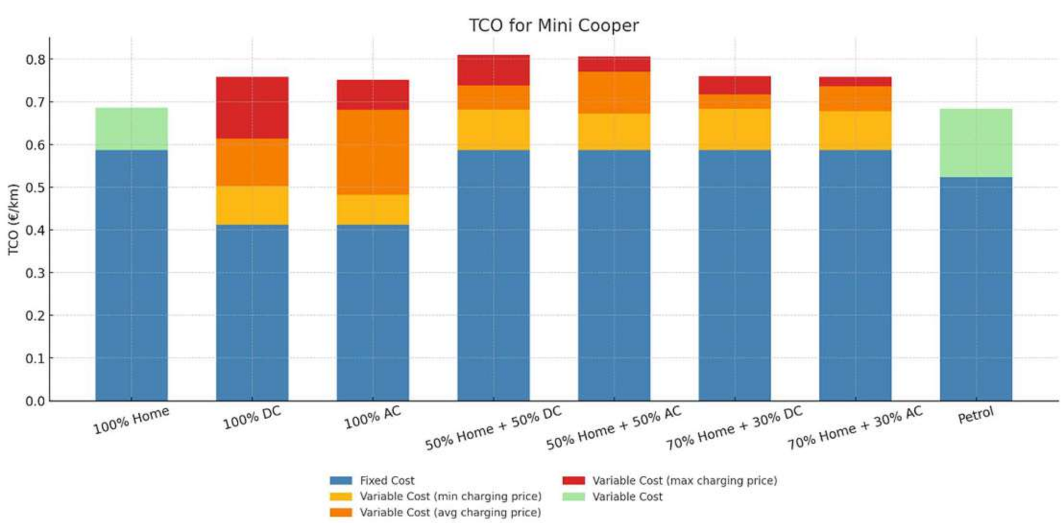

Fig. 5.31- TCO of the Mini Cooper C (CV) and Mini Cooper E (BEV)

As shown in Fig. 5.32, the variable costs for the BEV are lower than those of the CV in most scenarios, except in scenarios where the BEV is charged at public stations with the highest electricity prices.

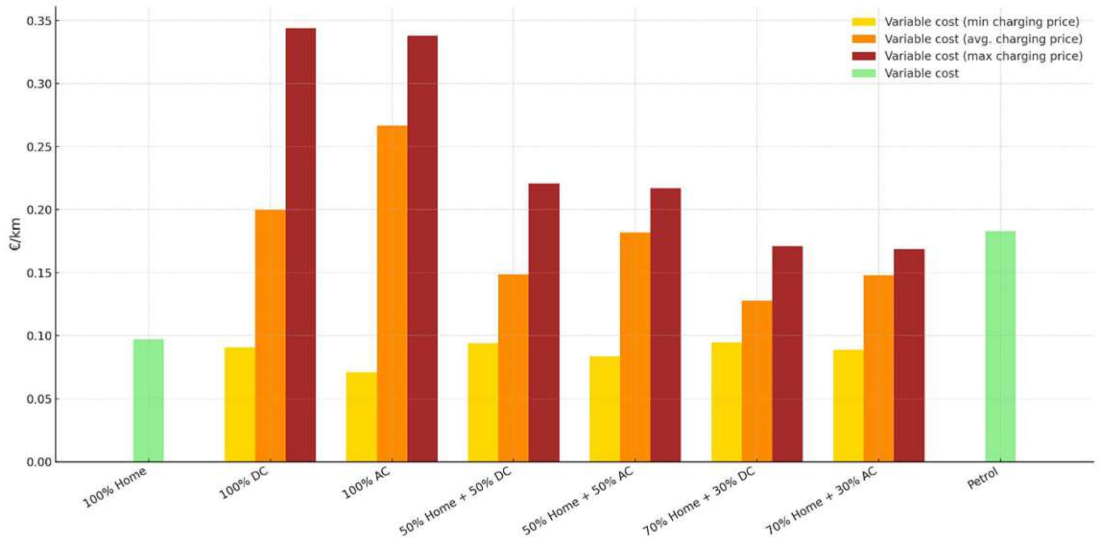

Fig. 5.32- Variable Costs of the Mini Cooper C (CV) and Mini Cooper E (BEV)

For the BMW 5 and BMW X3 series, the situation changes significantly, as the TCO of the CV is lower than that of the BEV in these cases. The higher purchase price and the lack of direct government subsidies for the BMW 5 and BMW X3 series all contribute to the higher TCO of the BEV.

As shown in Fig. 5.33, the CV (BMW 520d) consistently remains the more economical option across all charging scenarios compared to the BEV (BMW i5). Even when the BEV is charged at the lowest charging price, its TCO is still higher than that of the CV.

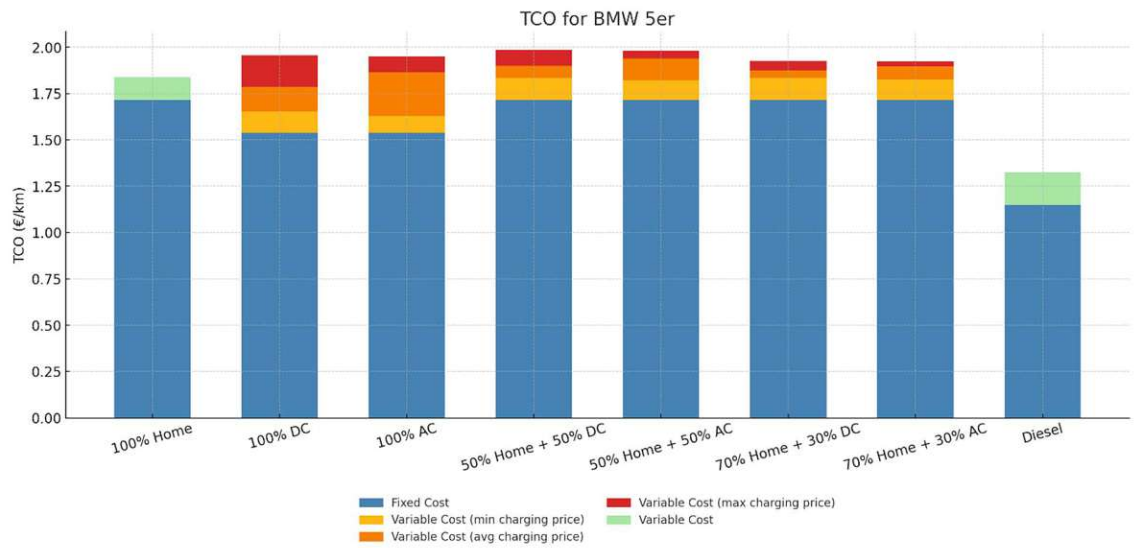

Fig. 5.33- TCO of the BMW 520d (CV) and BMW i5 (BEV)

On the other hand, as shown in Fig. 5.34 the BEV generally has lower variable costs than the CV. The only exception is when the BEV is charged entirely at public AC or DC stations using the most expensive charging prices.

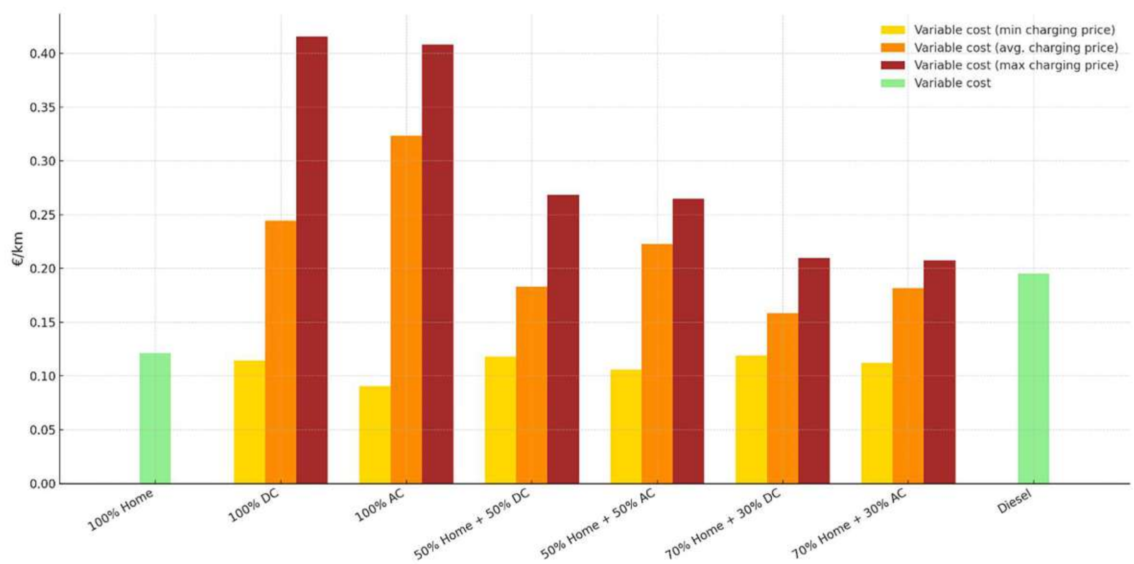

Fig. 5.34- Variable Costs of the BMW 520d (CV) and BMW i5 (BEV)

As shown in Fig. 5.35, the CV (BMW X3) also consistently remains the more economical option across all charging scenarios compared to the BEV (BMW iX3). Comparing the CV and BEV, charging at home, the difference will be 0.50 €/km.

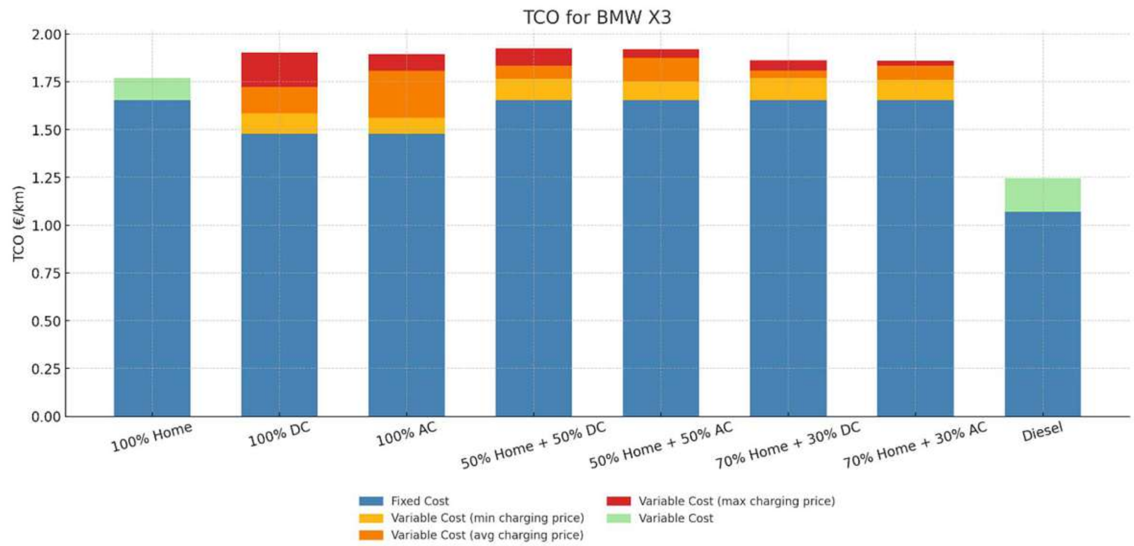

Fig. 5.35 TCO of the BMW X3 20d (CV) and BMW iX3 (BEV)

On the other hand, as shown in Fig. 5.36, the BEV generally has lower variable costs than the CV. The only exception is when the BEV is charged entirely at public AC or DC stations using the most expensive charging prices.

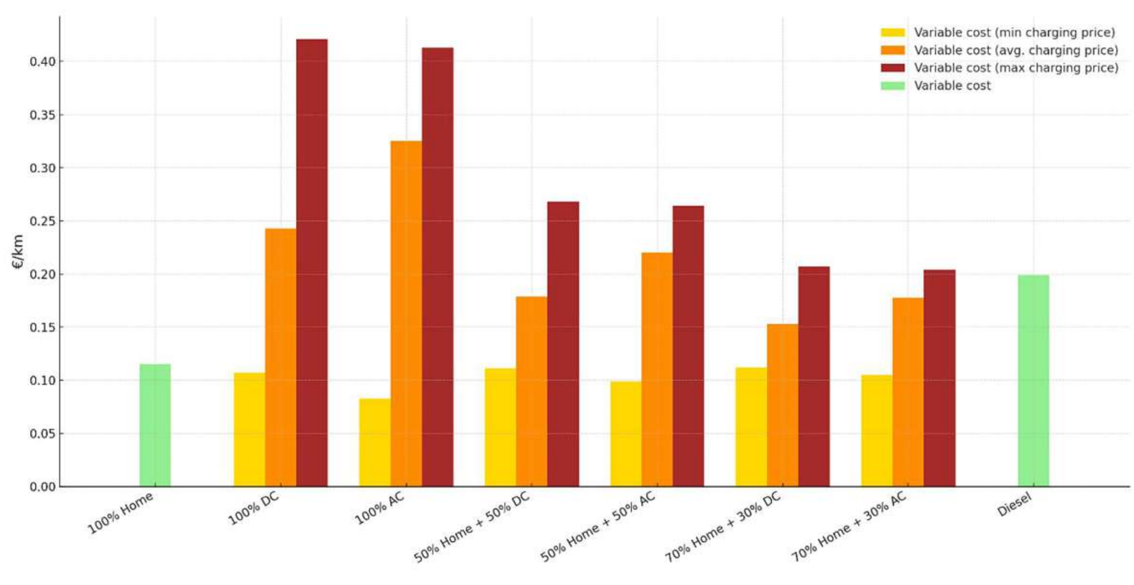

Fig. 5.36- Variable Costs of the BMW X3 20d (CV) and BMW iX3 (BEV)

6. Conclusion

This study analyzes the factors affecting the TCO for BEVs and CVs across various European countries. Key factors influencing TCO include charging costs (minimal, average, maximal), environmental conditions, subsidies, maintenance, insurance, and taxes.

In cold environments like Sweden and Norway, low temperatures negatively impact the performance of BEVs by decreasing battery efficiency, increasing energy consumption, and raising the number of charging cycles, which in turn increases charging costs. When comparing the number of recharging cycles across the selected countries, it becomes evident that the Nordic countries have a higher number of charging cycles. The increased frequency of charging accelerates the degradation of Li-ion batteries and reduces their capacity over time. These factors contribute to increasing the TCO of BEVs.

Direct government subsidies are critical in improving the economic viability of BEVs. The selected countries offer subsidies exclusively for small cars (e.g., the Mini Cooper E). In all countries that provide subsidies, BEVs are more cost-competitive than CVs across various charging scenarios. However, for medium and large vehicles, the absence of direct subsidies reduces the competitiveness of BEVs, leading to consumer hesitation in purchasing them. Reducing the financial burden could encourage more consumers to switch from CVs to BEVs, accelerating the broader adoption of electric vehicles.

To foster greater BEV adoption, governments should extend subsidies to all types of electric vehicles not just small cars. Expanding subsidies to cover small, medium, and large BEVs would help offset the higher purchase price and operational costs typically associated with these vehicles. This would reduce the overall TCO, making BEVs more competitive with CVs across different charging scenarios, including minimal, average, and maximal pricing tiers.

In addition to direct subsidies, complementary policies such as tax allowances, reduced registration fees, or toll road fees waived for BEVs need to be implemented. Investment in public charging infrastructure, particularly affordable high-speed AC and DC chargers, would further improve the convenience and cost-efficiency of BEV ownership.

In short, the selected small electric vehicles that receive government subsidies are currently more affordable to own in most charging scenarios across Europe. However, the selected medium and large BEVs remain less cost-effective due to the lack of funding support, resulting in a higher total cost of ownership compared to conventional vehicles.

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Appendix

Table 8.1- Average Monthly Temperatures in Selected Countries [13]

	Germany	Spain	Sweden	Norway	Austria	Slovenia
January	-1,6	8,5	-6,2	-6,3	-2	-3
February	-1,5	9,3	-6,5	-6,5	-0,8	-2
March	4,4	11,7	-3	-4,8	3,4	5,8
April	8,4	13,5	4,6	2	7,7	9,9
May	12,4	16,9	9,6	6,3	12,2	14,3
Juni	15,7	20,8	14	10,1	15,8	18,2
July	17,9	23,4	16,8	13,1	17,5	20,2
August	17,7	23,7	15,7	12,4	17,3	20
September	14	20,6	11,4	9	13	15,5
October	9,6	16,6	6	4	8,3	11
November	5	11,8	-1	-2	2,8	6,2
December	1,9	9,3	-3	-5	-1,7	1,4