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Electrifying the Road to Net-Zero: Implications of Electric Vehicles and Carbon Emission Coefficient Factors in European Power Systems

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Abstract: The global trend is shifting towards adopting low-carbon transportation solutions, with electrification emerging as a prominent approach. The effectiveness of this transition in mitigating climate change hinges significantly on the source of electricity used for charging electric vehicles. This study focuses on four European Union countries: Switzerland, Italy, Germany, and Poland, each characterized by varying levels of carbon emissions from their power systems. Assumptions are made for the short-term (10%), medium-term (30%), and long-term (60%) penetration of electric vehicles, aligning with the 2050 net zero emissions targets. The study investigates the impact of these penetration levels on energy demand, exploring scenarios ranging from 100% renewable source-generated electricity to 100% coal-generated electricity for EV charging. Finally, utilizing PSS®E 35.5 simulation software, the study assesses the implications of the electric vehicles' load on medium-voltage transmission lines. The findings highlight the substantial influence of electrifying the transport sector on both environmental sustainability and the power system infrastructure, underscoring the critical role of regional energy mixes and the power system carbon emissions coefficient factor. Regions with lower carbon emission coefficient factors witness significant benefits even with a modest transition to electric vehicles, whereas regions with high carbon emission coefficient factors experience minimal impact despite large-scale EV adoption. Additionally, densely populated urban areas may encounter challenges related to transmission line congestion to meet the growing demand for electric vehicle charging.

Keywords: electric vehicles; renewable energy sources; carbon emission coefficient factor; decarbonization; climate change; power transmission lines; PSS®E

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1. Introduction

The global climate is increasingly erratic and unpredictable, with a 1.1 °C rise in temperature already yielding widespread disasters. Events like the devastating flood in Pakistan affecting over 33 million people, unforeseen bushfires in Australia, and frequent wildfires in Italy and the United States underscore the significant impact of climate change. Moreover, occurrences like the Himalayan glacier burst in India and urban floods in Europe further highlight this trend. These events, along with extreme droughts and high temperatures, pose severe threats to the livelihoods and food security of millions globally [1–3]. The Intergovernmental Panel on Climate Change (IPCC) report shows that these extreme weather conditions will be more severe and more frequent, resulting in the sea level rising and forcing the mass migration of people [4]. The change will impact the ecosystem since crops will be likely to fail and human life will be at high risk. Climate change will soon have far-reaching effects on human life. To address global warming, many European Union (EU) countries have established both short-term and long-term goals for reducing greenhouse gas (GHG) emissions, in alignment with commitments made under the Paris Agreement. These goals include a Net-Zero Pledge, aiming to decrease Carbon Dioxide (CO_2) emissions to 21.1 Gt by 2030 from 33.9 Gt in 2022, with a further reduction target to 6.3 Gt by 2040, ultimately aiming for zero CO_2 emissions by 2050 (NZE2050) [5]. The Sustainable Development Scenario (SDS) shows different goals and projections for the reduction in GHG emissions in various sectors by 2030 [6]. A goal of 5.9, 1.2, 1.1, and 0.7 Gt reductions in emission from the power, industry, transport, and buildings sectors, respectively, has been set, shown in Figure 1. Compared to SDS goals, there will be an additional reduction in GHG emissions for each sector for the NZE2050 scenario by 2030.

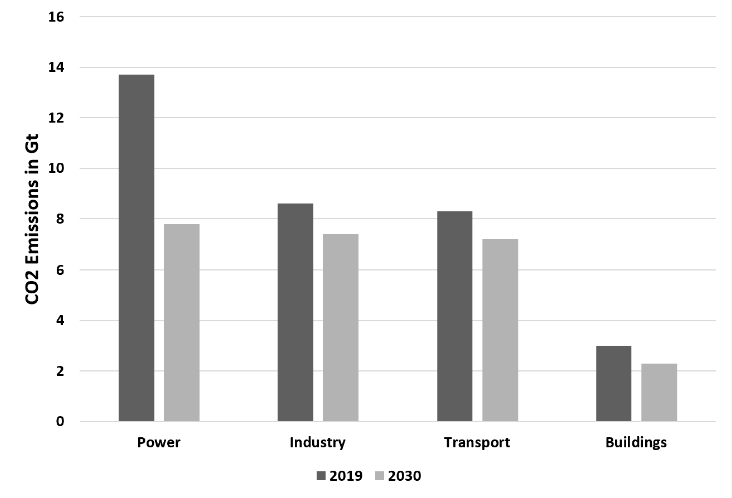


Figure 1. Share of each sector in GHG emissions from the energy sector [5].

The transport sector is one of the highest contributors to CO_2 emissions globally. The energy sector contributes approximately 73.2% of global emissions, of which 16.2% is from the transport sector [7]. Road transport, particularly passenger cars, stands as the largest contributor to greenhouse gas (GHG) emissions in the transport sector. In 2019, cars alone contributed approximately 500 thousand kt of CO_2 emissions in the EU, surpassing emissions from other vehicle types. This underscores the significant role of passenger cars in climate change and the pursuit of NZE2050 goals. Without appropriate measures, road transport is projected to contribute over 70% of GHG emissions from the entire transport sector by 2050 [7].

Also, the energy demand for the transport sector is growing much faster as compared to any other sector; thus, this sector needs to be cleaner and more environmentally friendly, as it accounts for 29% of the final energy consumption, and only 3.7% is from Renewable Energy Sources (RES) [8]. Many governments all over the world are working on the electrification of the transport sector and moving toward electric vehicles (EVs) [9]. Global EV market shares have increased exponentially, as both government and consumers spent double on EVs in 2021, which led to a significant increase in the EU and China [10]. The rising global EV sales and market shares are shown in Figure 2. In 2021, there were approximately 2.3 million EV registrations in the EU, and in China, 3.4 million EV registrations were recorded [11].

It has been estimated that there are approximately 16 million EVs on the roads to date, consuming around 30 TWh of electric energy annually. The market for EVs tends to increase more and more quickly. For example, the United States set a goal to achieve 50% electrification of new cars by 2050, and also to install 500,000 charging stations. EU countries and automakers have announced a target of 30% of EVs by 2035 [11]. The prediction shows that there will be around 70 million EVs by 2025 and nearly 230 million EVs by 2030, and the stock shares of EVs will rise to 12% [12].

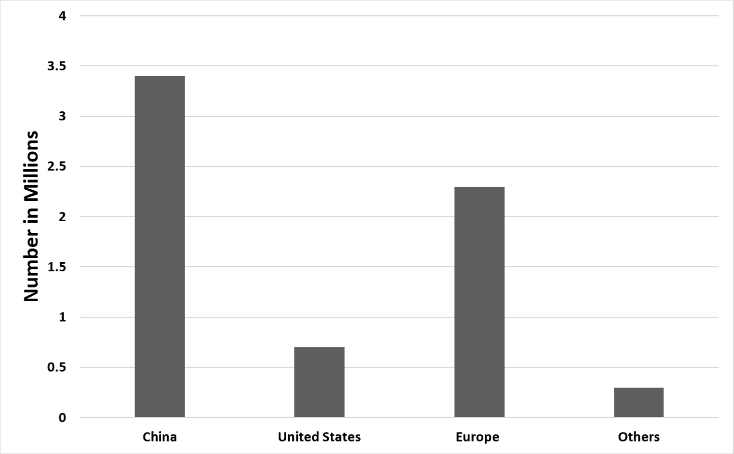


Figure 2. Electric cars global sales 2021 [11].

The shift from Traditional Passenger Vehicles (TPVs) to EVs is significant and could strain the power system without prompt implementation of proper strategies. EVs equipped with fast onboard charging of 350 kW per charge could increase building power demand by over 250%. By 2030, in China, the EU, and the United States alone, the energy needed to charge EVs will exceed 270 billion kilowatt hours [13]. The substantial energy demand for charging EVs presents a challenge for achieving clean and carbon-free transportation systems. Figure 3 illustrates the electric energy required by EVs in 2025 and 2030. By 2030, a total of 271 billion kWh of energy from RES will be needed to achieve a net-zero-emission transport sector [14]. RES play a crucial role in decarbonizing transportation and are closely linked [14]. Shifting the energy mix towards RES is essential to reduce indirect emissions from EVs and make them emission-free. Currently, coal constitutes about 38% of global electricity generation, exceeding 60% in some growing economies like India and China [15]. Timely solutions to these challenges are imperative to ensure a clean and environmentally friendly transport sector.

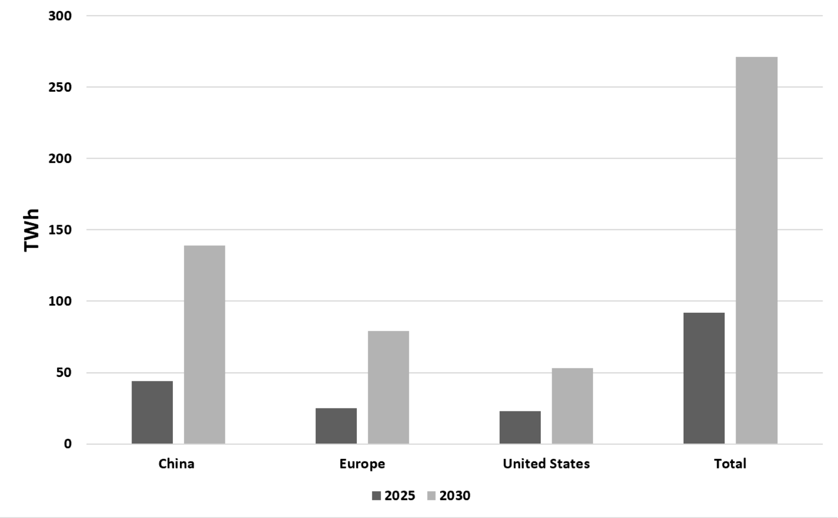


Figure 3. Energy demand to charge EVs [14].

Many studies have already been carried out to study the impact of EVs on power systems and climate change. One of the studies examined 30 provinces of China and focused on the role of electric vehicle (EV) charging infrastructure in mitigating climate change [16]. Similar studies on how EVs can contribute to reducing GHG emissions and improving air quality have been carried out [17–23]. Many researchers have examined the carbon footprint of the EV lifecycle, including the production, use, and recycling phases.

However, most of these studies are generic and do not consider different levels of EV market penetration [24–27]. Many of these analyses have concentrated on the emissions associated with EV battery production and have compared the entire lifecycle emissions of EVs to those of conventional internal combustion engine vehicles. Previous research has predominantly addressed indirect emissions from EVs across their entire lifecycle. This study focused on the use phase of EVs with three different penetration levels of 10%, 30%, and 60% of EVs with consideration of the short-term, medium-term, and long-term goals, respectively, and for Switzerland, Italy, Germany, and Poland with low, medium, medium–high, and high Carbon Emission Coefficient Factors (COECFs), respectively. These four countries were selected due to their varying COECF levels: Switzerland has the lowest COECF, Poland has the highest, and Italy and Germany fall in between. Therefore, this choice enables the results of the study to be extrapolated across the entire European region by incorporating data from other countries that exhibit similar energy profiles to the one analyzed in the study. In addition to this, the study also focuses on the impact of fast charging demand requirements on the power transmission lines. In concluding this study, the capital cities of the four examined countries are taken into account. The study investigates the power demand in each city as well as the projected requirements for the fast charging of electric vehicles, employing the IEEE-14 bus system with modifications made using PSS$^{®}$E software. The key contributions of this study are given in Section 1.

Novelty and Key Contribution of the Study

This research brings several novel contributions to the field:

- Use Phase of EVs: Unlike previous studies that look at the entire lifecycle, this work specifically examines the use phase of EVs at different market penetration levels.
- Comparative Analysis: The study compares the environmental impact of EVs in Switzerland, Italy, Germany, and Poland, chosen for their varying COECFs.
- Impact of Fast Charging on Power Grids: This research explores the effects of fast charging requirements on power distribution lines, a less studied area.
- Scenario Analysis with Extreme Energy Mixes: It examines two extreme scenarios—100% renewable energy and 100% coal-powered plants for charging EVs to understand the range of impacts on greenhouse gas emissions.
- Use of Simulation Software: The study uses the IEEE-14 bus system with modifications in PSS$^{®}$E software to simulate and evaluate the EVs' impact on power system.
- Derivation of Maximum COECF Limit: Additionally, the paper derives the maximum COECF limit for EU countries for which an EV can reduce CO_2 emissions compared to an internal combustion engine passenger car (ICEPC).

This study is aimed at engineers, scholars, policymakers, and industry experts in the fields of energy, transportation, and environmental sustainability. It conducts a thorough examination of the ramifications of EV adoption on energy consumption, focusing on four EU nations. By analyzing scenarios aligned with net-zero emissions goals and exploring various energy mix configurations for EV charging, this study underscores the significance of regional energy compositions. Leveraging simulation software, this study assesses the impact of EV load on transmission infrastructure, highlighting the imperative of infrastructure upgrades. Moreover, this study offers actionable insights for policymakers, emphasizing the urgency of renewable energy objectives and integrated strategies to alleviate grid pressure. Overall, this research contributes valuable insights to the discourse surrounding the shift toward sustainable transportation and energy systems, outlining challenges and suggesting solutions for a resilient and environmentally conscious future.

2. Methodology

Four EU countries were selected for this study, Switzerland with low COEF, Italy with medium COEF, Germany with medium–high COECF, and Poland with high COECF of the power grid. The flow chart in Figure 4 shows the step-by-step methodology of this research. This research focused on two areas:

(i) The Environmental Impact of EVs, which is an analytical study aimed at analyzing the impact on greenhouse gas emissions if traditional vehicles are replaced by a certain percentage of electric vehicles, taking into account the share of RES in electricity production.

(ii) The impact of EVs on the grid infrastructure, which is a simulation-based study, performed in the PSS®E environment and aimed at assessing whether the replacement of conventional vehicles with EVs, even if it has a potentially positive environmental impact, may lead to the establishment of excessive power flows in electricity distribution networks.

For the simulation study, the capital cities of the four selected countries were considered. After the selection of the regions for both the studies, the data were collected to carry out both the analytical study and the simulations. For the analytical study, necessary data for the energy mix, COECF, population, Number of Internal Combustion Engine Passenger Cars (ICEPCs) per person, number of EVs, EVs' efficiencies, and average traveling distances for all the regions were gathered. After the data collection, the study was extended to the NZE2050 scenario for all four countries with different penetration levels of EVs. Two scenarios, the ideal scenario of 100% of wind energy available for charging the EVs and the extreme scenario of 100% power available from coal power plants to charge the EVs were also discussed to study the role of RES in the electrification of the transport sector in more detail. After collecting the data, they were transformed into useful charts and graphs for better understanding. The data then were analyzed, and results were obtained. For the simulation study, the necessary data of the capital city of each country were collected as shown in Figure 6, and then the IEEE-14 bus system was used as a test case power system using PSS®E simulation software. The details of this study are given in the following sections in depth.

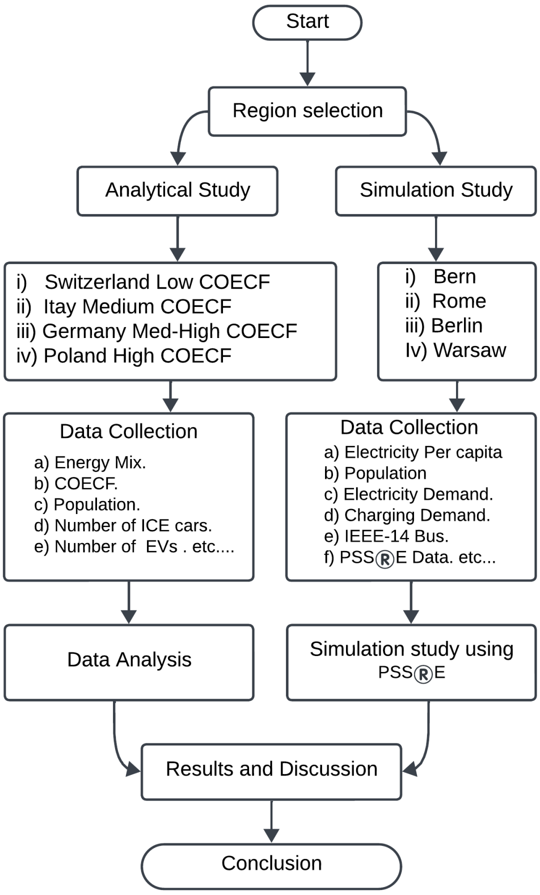


Figure 4. Flow chart of the methodology.

2.1. Sources Used for Data Collection

In this research, data were collected from various sources, including online websites, reports from reputable organizations, journal papers, and books. Notably, about 70% of the data came from online sources and reports from international organizations, such as the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), the International Automobile Federation Foundation (FIA), the World Food Program (WFP), the International Renewable Energy Agency (IRENA), and European Commission energy reports. Specifically, for 57% of data from online websites, 37% of the online data was sourced from prestigious European industry websites, 18% from reputable international organizations, 18% from government agency websites, 12% from EU project websites, and the remaining 18% from small company websites, blogs, and researcher websites as shown in Figure 5.

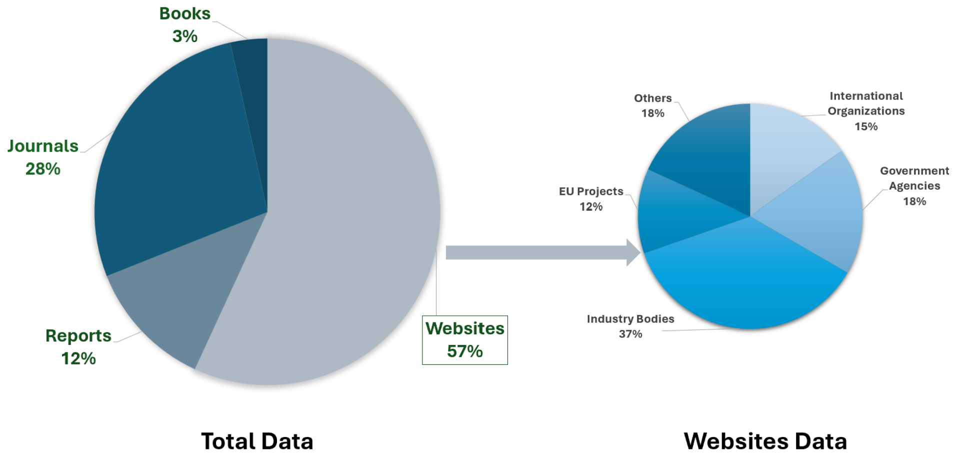


Figure 5. Sources used for data collection.

To ensure robustness, the data were cross-checked from multiple sources. The collected data were then analyzed and are discussed in detail in the following sections.

2.2. Data for the Four European (EU) Countries

In this section, the data which were used for the four countries are discussed briefly. For the EU, a CO_2 emission goal of 110 g CO_2/km for new ICEPCs has been set [28,29], and we used this value for our study. The average distances covered by each car per year are 13,602 km, 13,505 km, 7700 km, and 8607 km for Germany, Switzerland, Italy, and Poland, respectively [30,31]. To make the calculation and comparison simple and easy to understand, a traveled distance value of 11,300 km/year by each car was used for the study, which is an average value for the EU [30,31].

2.3. Carbon Emission Coefficient Factor of Selected Regions

The four countries selected for this study have different COECFs, which are shown in Figure 6 for each month of 2022. For this study, the average COECF of the year 2022 was used for the selected regions. Switzerland has the lowest COECF with 152 g CO_2/kWh, Italy with 452 CO_2/kWh, followed by Germany with an average COECF of 507.5 g CO_2/kWh, and Poland has the highest COECF of 823 g CO_2/kWh [32].

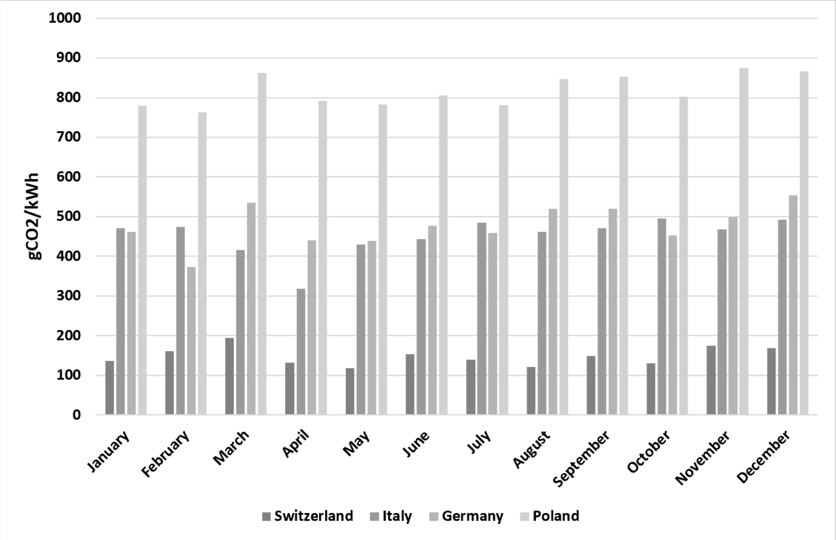


Figure 6. COECF for Switzerland, Italy, Germany, and Poland for the year 2022 [32].

2.4. Internal Combustion Engine Passenger Cars (ICEPCs) Data

The number of passenger cars per 1000 inhabitants is highest in Poland, which is 664, followed by Italy and Germany with 663 and 580 cars per 1000 inhabitants, respectively, and for Switzerland, it is 550 cars per 1000 persons [33–36]. The total number of passenger cars for each country was calculated using Equation (1):

$$T_{ICE} = N_p * A_{vc} \tag{1}$$

where T_{ICE} is the total number of ICEPCs, N_p is the population of each country, and A_{vc} is the average number of cars per person. The average number of cars per person is 0.58, 0.55, 0.663, and 0.664 for Germany, Switzerland, Italy, and Poland, respectively [33–36]. Thus, the total number of ICEPCs can be calculated for each country and also their emissions using Equation (2):

$$CE_{ICE} = D_t * E_m * T_{ICE} \tag{2}$$

where D_t is the average distance traveled by car per year in kilometers, E_m is the emissions from each car in g CO_2/km, and T_{ICE} is the total number of ICEPCs.

2.5. Electric Vehicles Data

There are many EVs available in the market with different efficiencies, ranges, and battery capacities from different companies. For this study, the most recent data on EVs were analyzed and used. Based on the data of the most recent 10 models of EVs [37] shown in Figure 7, the average efficiency was calculated and used for the study, which is 0.164 kWh/km. The study was performed for 10, 30, and 60% penetration levels of EVs for the four countries, and the total number of EVs for each penetration level was calculated using Equation (3):

$$N_{EV} = N_p * A_{vc} * P_{ev} \tag{3}$$

where N_{EV} is the total number of EVs for each penetration level, N_p is the total population for each country, A_{vc} is the average number of cars per person, and P_{ev} is the penetration level of EVs. The CO_2 emissions related to EVs were calculated using Equation (4):

$$CE_{EVs} = E_c * N_{EV} * COECF \tag{4}$$

where CE_{EVs} are the total annual emissions of EVs, E_c is the electricity consumed by each EV annually for charging, N_{EV} is the total number of EVs for each penetration level, and

COECF is the carbon emission coefficient factor of each region. The total number of ICEPCs and EVs for each penetration level is shown in Table 1.

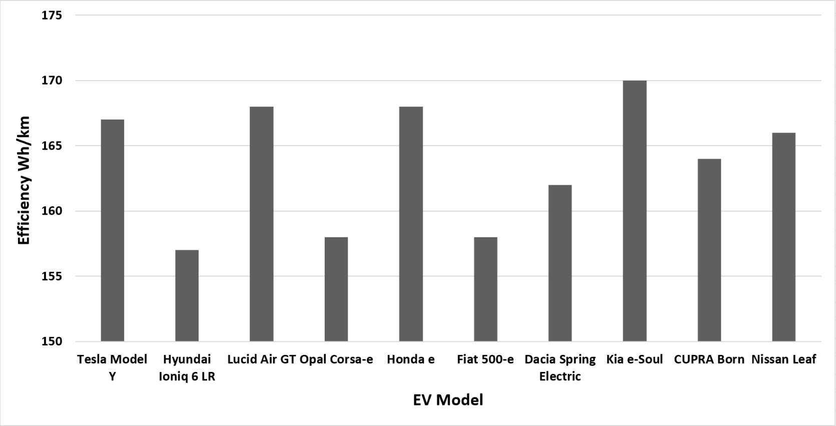


Figure 7. Different EV models and their efficiencies.

Table 1. Total number of ICEPCs and EVs of each country.

Country	Total ICEPCs	10% of EVs	30% of EVs	60% of EVs
Switzerland	4,841,650	484,165	1,452,495	2,904,990
Italy	39,918,272	3,991,827	11,975,481	23,950,963
Germany	48,955,300	4,895,530	14,686,590	29,373,180
Poland	25,066,937	2,506,694	7,520,081	15,040,162

2.6. Net Zero Emission 2050 (NZE2050) Goals

The electricity generated in Germany, Switzerland, Italy, and Poland in the year 2021 was 552, 64.2, 278, and 176.52 TWh, respectively [38–43]. According to NZE2050 goals, the demand will increase by 2% each year for the EU [44,45]. To meet the demand, each country has to increase its electricity generation by 2% each year. It has been estimated that the electricity generation will be approximately 980, 114, 493, and 317 TWh for Germany, Switzerland, Italy, and Poland, respectively, by 2050 as shown in Figure 8.

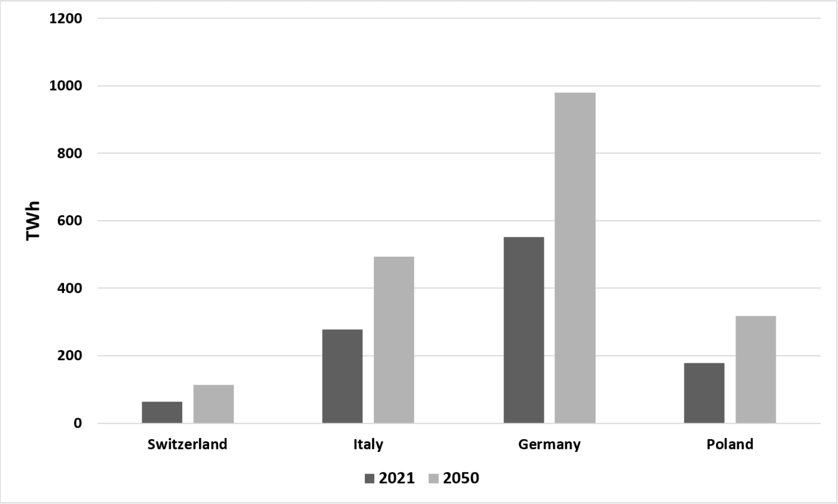


Figure 8. Estimated generation of NZE2050 scenario by 2050.

Different goals have been set to achieve a 33% electricity share from solar generation, 35% electricity share from wind, 12% share from hydro, 5% share from biomass, 8% share from nuclear energy, 3% from geothermal, and only 4% electricity production from fossil fuels by NZE2050 scenario for EU by 2050 [44,45]. In this study, the goals of NZE2050 were assumed for the selected countries, and the new COECF for each country was calculated using Equation (5):

$$COECF_n = \frac{\sum E_{gi} * COECF_{ei}}{T_g} \tag{5}$$

where E_g is the share of electricity generated from each source, $COECF_e$ is the carbon emission coefficient factor for each source of generation, and T_g is the total generation of each country. From Figure 9, it can be seen that if the NZE2050 goals are achieved by the four countries, the new COECF will be reduced to 57.55 gCO_2/kWh for all four countries because high shares of electricity generation will be from solar and wind.

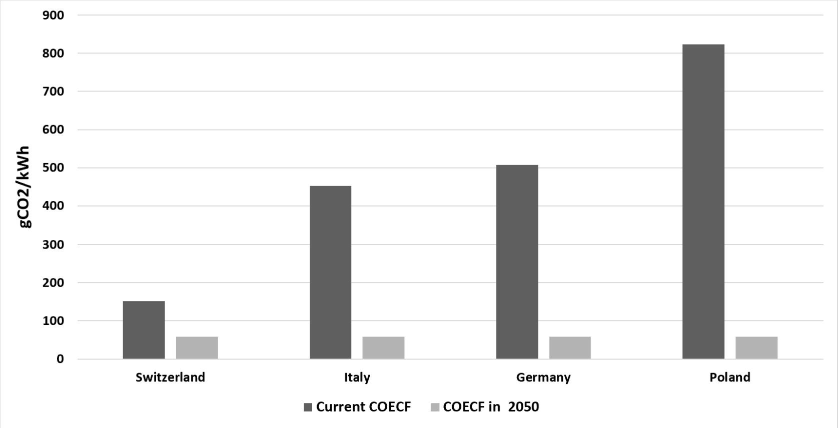


Figure 9. COECF for the four countries for the years 2022 and 2050.

2.7. Maximum COECF Limits

In this section, the maximum limit of COECF for which an EV will have a positive impact in terms of CO_2 emissions reduction in comparison to ICEPCs is derived by comparing Equations (2) and (4). Hence, the comparison is performed for a single EV and a single ICEPC. Hence, we will obtain Equation (6) to calculate the maximum required value of COECF:

$$COECF_m = \frac{D_t * E_m}{E_c} \tag{6}$$

As previously outlined in this study, D_t is the distance traveled by car annually, and the average distance traveled by each car for the EU is 11,300 km/year. E_m is the new CO_2 emissions standard set by the EU for ICEPCs, which is 110 gCO_2/km, and E_c is the energy consumed by each EV annually, which is 1853.2 kWh, and thus the value for the maximum COECF limit estimated is 670 gCO_2/kWh. This means that the power generation system with COECF less than 670 gCO_2/kWh will experience a reduction in CO_2 emissions for each EV added to the transport system.

2.8. Simulation Data

For the simulation, the data of the capital cities of the four countries were gathered. The electricity consumption per capita in the year 2022 was 6.395, 5.270, 4.435, and 7.302 MWh for Berlin, Rome, Warsaw, and Bern, respectively [46]. The total consumption of the city was calculated by multiplying the electricity consumption per capita of the city by the population of the city, which is 3.677 million for Berlin, 4.332 million for Rome, 1.799 million for Warsaw, and 0.445 million for Bern [47–50]. The Tesla Model Y electric vehicle has emerged as the best-selling car in Europe in recent years. For this study, the standard fast-charging rate of 100 kW was taken into account [51,52].

Simulation studies have focused solely on the long-term objective of achieving 60% electric vehicle (EV) adoption. Globally, there is around 1 public charger for every 10 EVs [53], and only 1 out of 9 chargers in Europe is a fast charging station [54], so approximately only

1% of EVs will have fast charging station availability according to the current fact and figures. Hence, a case study was formulated under the assumption that only 1% of the total 60% of EVs in each city are simultaneously connected to the power network for fast charging. The outcome was generated utilizing PSS®E software, with the power network modeled using the IEEE-14 bus test system for this study. Figure 10 illustrates the modified single-line diagram of the IEEE-14 bus system [55]. The power network comprises a Slack bus designated as Bus 1, housing generator Gen1, and four generator buses identified as Gen2, Gen3, Gen4, and Gen5. Also, loads are labeled as L1, L2, L3, etc. In Figure 10, the green side indicates the 33 kV system and the red lines indicate a low-voltage system of 11 kV. The results and the impact of this section are discussed in depth in the Results and Discussion of Simulation Study section, and the Impact Assessment section below.

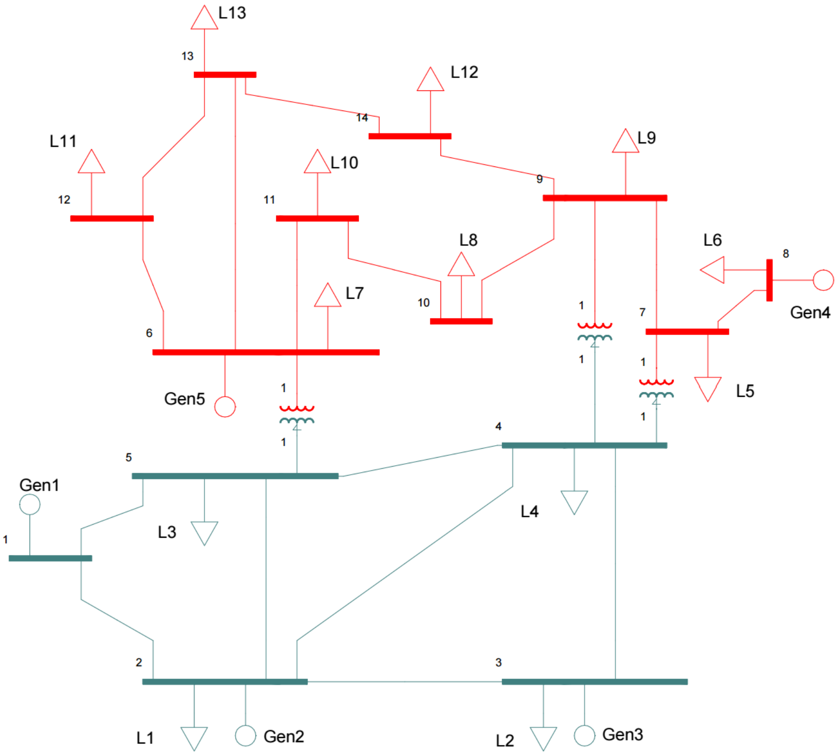


Figure 10. Single line diagram of IEEE-14 bus system.

3. Results and Discussion

Three scenarios, with 10% EVs considered as a short-term goal, 30% EVs considered as a medium-term goal, and 60% EVs considered as a long-term goal, were studied for each of the four countries. Similarly, these scenarios were also studied for NZE2050 goals, and lastly, ideal and extreme scenarios were also discussed. The data for each scenario were studied and analyzed, the calculation was performed, and the results were obtained and briefly discussed in the following subsections.

3.1. Short-Term Goal, 10% EVs

In the first scenario, only 10% of ICEPCs are replaced by EVs for each region and the results are obtained as shown in Table 2. When there are no ICEPCs replaced by EVs, the CO_2 emissions are 6.018 Mt for Switzerland, 49.62 Mt for Italy, 60.85 Mt for Germany, and 31.16 Mt for Poland. When 10% of the ICEPCs are replaced by EVs and the combined CO_2 emissions of remaining ICEPCs and 10% EVs are calculated, it is observed that the only significant emissions reduction occurs for Switzerland because of the low COECF. The total CO_2 emissions are reduced by almost 8% for Switzerland. For Italy, 1.62 Mt CO_2 is reduced with 10% EVs. The CO_2 emissions for Germany with 10% EVs is reduced by 1.479 Mt, from

60.85 Mt to 59.37 Mt, which shows only a 2.3% reduction. This is due to the relatively high COECF of the power generation system. However, the impact of EVs is negative for Poland; instead of reducing the CO_2 emissions, it adds up emissions as shown by the negative sign in the table. With very high COECF, CO_2 emissions for Poland will increase by 0.705 Mt per year from 31.16 Mt to 31.865 Mt.

If all four countries achieve NZE2050 goals, there will be a significant reduction in CO_2 emissions as can be seen in the table. The CO_2 emissions are reduced by 0.55 Mt, 4.54 Mt, 5.56 Mt, and 2.85 Mt per year for Switzerland, Italy, Germany, and Poland, respectively, with 10% EVs. In an ideal scenario, if all these 10% EVs are charged from wind energy which has the lowest COECF, then there will be approximately a 9.9% reduction in CO_2 emissions for all four countries as compared to the emissions from ICEPCs. For an extreme scenario, if all the EVs are charged from electricity generated from coal power plants which have the highest COECF of 980 gCO_2/kWh [56], then there will be 4.77% higher CO_2 emissions than the emissions of ICEPCs without EVs.

Table 2. CO_2 emissions with 10% EVs.

Country	CO_2 Emissions from ICE Cars in Mt/Year	CO_2 Emissions with 10% EVs in Mt/Year	The Difference in Mt/Year	CO_2 Emissions in NZE2050 Scenario in Mt/Year	The Difference in Mt/Year
Switzerland	6.018	5.552	0.46	5.468	0.55
Italy	49.62	48	1.62	45.1	4.54
Germany	60.85	59.75	1.478	55.29	5.562
Poland	31.16	31.865	−0.705	28.31	2.85

3.2. Medium-Term Goal, 30% EVs

In this scenario, 30% of the ICEPCs are replaced by EVs, and the results obtained are shown in Table 3. With 30% EVs, the CO_2 emissions are reduced by 1.406 Mt, from 6.018 Mt to 4.612 Mt, for Switzerland; for Italy, the CO_2 emissions are reduced by 4.856 Mt; for Germany, the decrease in CO_2 emissions is low in percentage as compared to the total emissions, being reduced by only 4.44 Mt per year. The negative impact of EVs is increased due to an increase in indirect emissions from charging EVs for Poland due to there being fewer renewable energy sources and high CO_2 emission resources being used to produce the electricity. The CO_2 emissions are increased by 2.121 Mt, from 31.16 Mt to 33.281 Mt per year, with a 30% penetration of EVs. By achieving the goals of NZE2050, all four countries will reduce the CO_2 emissions to a high extent as can be seen from Table 3; there are reductions of 1.65 Mt, 13.61 Mt, 16.69 Mt, and 8.547 Mt for Switzerland, Italy, Germany, and Poland, respectively. The impact of EVs will be much higher if the ideal scenario is used for charging the EVs; there will be a 29.5% reduction in CO_2 emissions for all four countries, and for the extreme scenario, the CO_2 emissions will be increased by approximately 14.5% per year for each country.

Table 3. CO_2 emissions with 30% EVs.

Country	CO_2 Emissions from ICE Cars in Mt/Year	CO_2 Emissions with 30% EVs in Mt/Year	The Difference in Mt/Year	CO_2 Emissions in NZE2050 Scenario in Mt/Year	The Difference in Mt/Year
Switzerland	6.018	4.612	1.406	4.367	1.65
Italy	49.62	44.764	4.856	36.01	13.61
Germany	60.85	56.408	4.441	44.162	16.69
Poland	31.16	33.281	−2.212	22.613	8.547

3.3. Long-Term Goal, 60% EVs

In the last scenario, 60% of ICEPCs are replaced by EVs, and the results are obtained as given in Table 4. The CO_2 emissions for Switzerland are reduced significantly, as for the first two scenarios, with no EVs, the emissions are 6.018 Mt, and are reduced by 2.792 Mt per year with 60% EVs in the system. For Italy, the reduction in CO_2 emissions is higher than for Poland and Germany because of medium COECF, and the CO_2 emissions are reduced by 9.71 Mt/year for 60% EVs. For Germany, the CO_2 emissions are declined by a small percentage even with such a high penetration level of EVs, with only 8.88 Mt per year. As Poland's electricity generation system is highly dependent on coal generation, the impact of EVs is increased negatively with the increase in the EV penetration level. With 60% EVs, the CO_2 emissions are increased by 4.243 Mt per year. The NZE2050 goals show a promising reduction in CO_2 emissions of 3.301 Mt, 27.22 Mt, 33.377 Mt, and 17.09 Mt per year for Switzerland, Italy, Germany, and Poland, respectively, with 60% EVs. In the ideal scenario charging, if all the EVs get charged with electricity generated from wind turbines, there will be almost a 59% reduction in CO_2 emissions for all four countries, and for the extreme scenario, the emissions will increase by 28.2%.

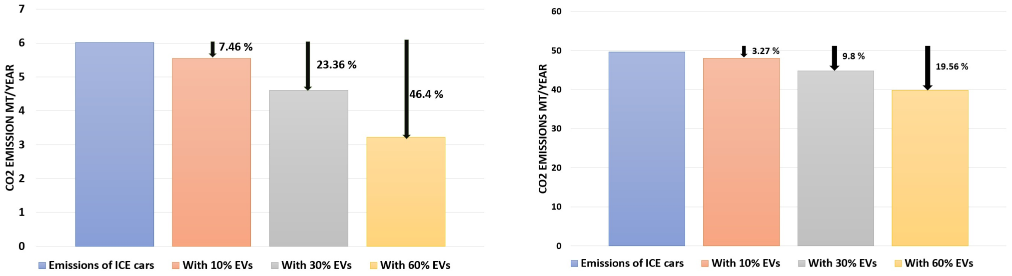
Table 4. CO_2 emissions with 60% EVs.

Country	CO_2 Emissions from ICE Cars in Mt/Year	CO_2 Emissions with 60% EVs in Mt/Year	The Difference in Mt/Year	CO_2 Emissions in NZE2050 Scenario in Mt/Year	The Difference in Mt/Year
Switzerland	6.018	3.225	2.792	2.717	3.301
Italy	49.62	39.91	9.71	22.402	27.22
Germany	60.85	51.965	8.884	27.473	33.377
Poland	31.16	35.403	−4.243	14.07	17.09

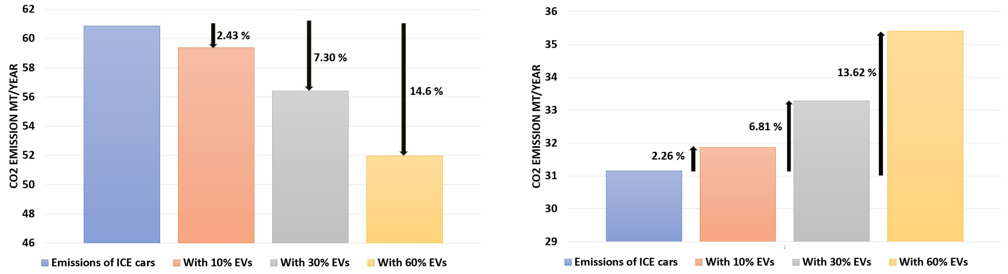
4. Impact Assessment of Current COECF on Each Country

To evaluate the impact of COECF of current power generation on CO_2 emissions of the transport sector for 10, 30, and 60% EVs, the results are graphically represented in Figures 11 and 12 for better understanding and assessment. The result shows that the only significant reduction in CO_2 emissions for a 10% penetration level of EVs is for Switzerland, which is almost 7.46% per year, this is due to very low COECF and high dependency on RES for electricity generation. For Italy, the reduction is noticeable, and the CO_2 emissions are reduced by 3.25% shown in Figure 11b. The 10% penetration of EVs has not much impact on the CO_2 emissions reduction for Germany due to the relatively high COECF with a considerable share of electricity generation from coal, and the emissions are reduced by only 2.4% per year. On the other hand, due to the high dependency on coal power plants for electricity generation and with COECF higher than 670 gCO_2/kWh, Poland will experience a negative impact with each replacement of ICEPC with EV, and with 10% EVs, the CO_2 emissions are increased by 2.26% shown in Figure 11d.

When the ICEPCs are replaced with 30, and 60% EVs, a noticeable decline of 23.36% and 46.40% per year, respectively, in the CO_2 emissions is seen for Switzerland, shown in Figure 11a. For Italy, the CO_2 emissions are reduced by 9.8% for 30% EVs and 19.56% for 60% EVs, respectively, shown in Figure 11b. The impact with 30% and 60% EVs is positive but not very promising for Germany; with 30% EVs, the CO_2 emissions are only reduced by 7.3%, and even with a 60% penetration level of EVs, only a 14.6% reduction per year is noticed, shown in Figure 11c. However, as mentioned before, because of the high COECF of the electricity generation sources, the negative impact is increased with an increase in the EV penetration level, and it is noticed that for a 30% penetration level, the CO_2 emissions are increased by 6.81% per year, and for 60% EVs, the rise in CO_2 emissions is 13.6% per year shown in Figure 11d.

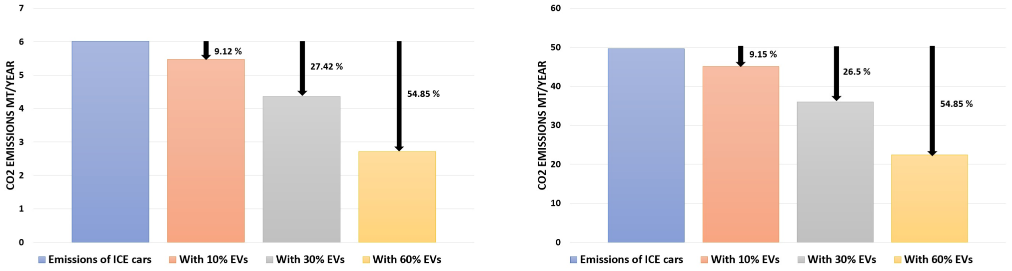


(**a**) Switzerland (**b**) Italy

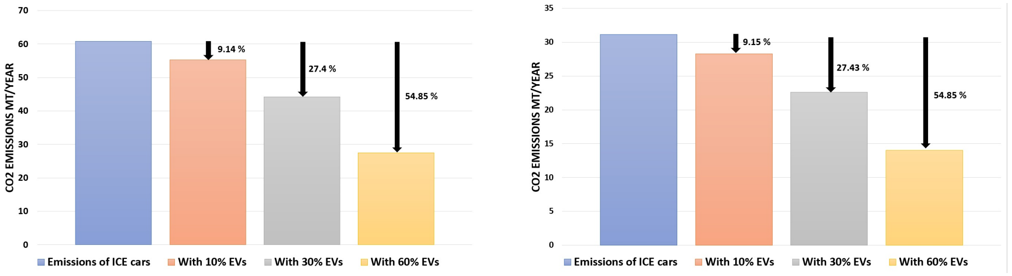


(**c**) Germany (**d**) Poland

Figure 11. Emissions with no EVs and with 10, 30, and 60% EVs for each country with current COECF.



(**a**) Switzerland (**b**) Italy



(**c**) Germany (**d**) Poland

Figure 12. Emissions with no EVs and with 10, 30, and 60% EVs for each country with new COECF.

5. Impact Assessment of COECF with NZE2050 Goals

The goals for NZE2050 have been already discussed in this study previously. If all three countries achieve the NZE2050 goals, the COECF will be reduced to approximately 57 gCO_2/kWh for all four countries. The CO_2 emissions calculated for NZE2050 with 10, 30, and 60% penetration levels of EVs are graphically represented in Figure 12. Because of the low COECF for all four countries, the impact of EVs on CO_2 emissions is positive, as even with 10% EVs, a significant fall in the emissions is noticed, and CO_2 emissions for all four countries are reduced by approximately by 9% as shown in Figure 12. For 30% and

60% EV penetration, the reduction in CO_2 emissions is significant; for 30% EVs, the CO_2 emissions reduction is 27%, and for 60% EVs, the CO_2 emission reduction is approximately 54% annually for all four countries shown in Figure 12.

6. Impact on Demand Increase

The rise in electricity demand due to the replacement of ICEPCs by 10, 30, and 60% EVs for all four countries was calculated and is presented in Table 5. This increase in electricity demand for each country was obtained with the assumption made, and has already been discussed previously in the paper. The energy demand for all the countries will increase to a high extent, as more and more ICEPCs will be replaced by EVs; and for 60% of EVs, approximately 5.384, 44.38, 54.434, and 27.872 tera-watt-hours energy will be required by Switzerland, Italy, Germany, and Poland, respectively, to charge these EVs annually. This energy demand needs to be generated from RES to make the impact of EVs more positive and significant. For 60% EVs, Figure 13 shows how CO_2 emissions can be increased or decreased depending on the RES penetration level in the power generation system. As the COECF of Switzerland is too low and the generation grid has a high percentage of RES, it is close to ideal, but if all the EVs charge in the extreme scenarios, we can see that the emissions will be more than double as compared to the current COECF. The current COECF for Poland is too high and almost matches the extreme scenario, but if we reach the ideal scenario, the emissions will be cut by almost 2/3. For Italy and Germany, both the ideal and extreme scenarios will decrease and increase the CO_2 emissions by 50% respectively as compared to the current COECF of the power generation system shown in Figure 13. Figure 13 illustrates that what impact each country will experience in reducing CO_2 emissions is dependent on the shares of RES in the power generation system to fulfill the electricity demand of charging huge fleets of EVs shortly.

Table 5. Electricity demand of each penetration level of EVs for the four countries.

EV Penetration Level	Switzerland Demand (TWh)	Italy Demand (TWh)	Germany Demand (TWh)	Poland Demand (TWh)
10% EVs	0.897	7.4	9.072	4.645
30% EVs	2.692	22.19	27.217	13.937
60% EVs	5.384	44.38	54.434	27.872

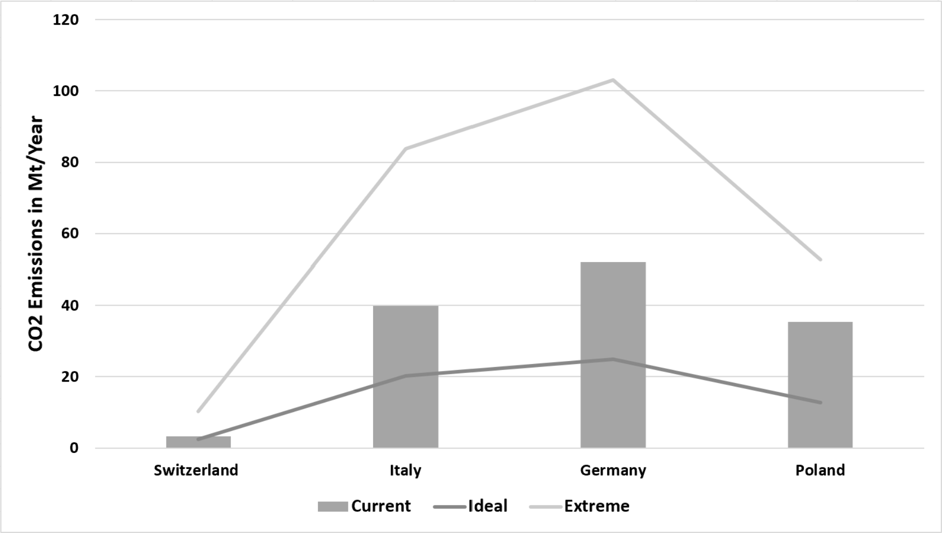


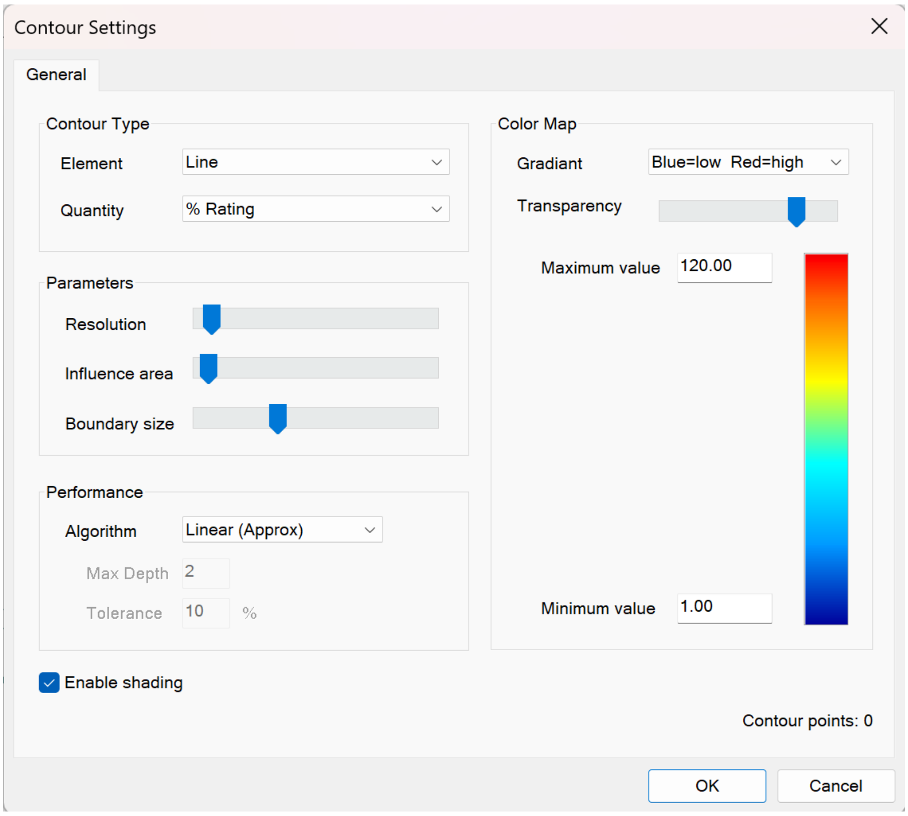
Figure 13. CO_2 Emissions in ideal, current, and extreme scenarios' COECF.

7. Results and Discussion of the Grid Impact Study

This study assumes the rapid charging capability of 100 kW for the Tesla Model Y [52]. It poses the question of, in the future, if 1% EVs out of the 60% of EVs in each region are simultaneously connected for fast charging for a brief period, what will be the resulting impact on power transmission lines? The consumption load for every city was derived from each city's per capita consumption data. This load was evenly distributed among the 13-load buses within the IEEE-14 bus system. With the existing load, all the power lines were made 50% loaded using Equation (7) [57,58]:

$$P = \frac{E_s.E_r Sin\theta}{L.x} \tag{7}$$

where P is power in MW, E_s is the sending end voltages, E_r is the receiving end voltages in kV line to line, and θ is the phase difference between the receiving and sending end voltages, L is the line length in km, and x is the reactance per km. Using the data in [57,58], the lines were made 50% loaded for each city with the current electricity consumption of the city, adjusting the lines' lengths using Equation (7). Thus, uniform initial conditions were established for all cities, with each city's simulation lines being loaded at 50% capacity based on their current electricity consumption. It was assumed that the transmission lines in each city still had 50% of their power-carrying capacity available to meet the future demand. The anticipated impact of integrating just 1% of the projected 60% electric vehicles was examined to determine the extent to which line loading would increase. In Figure 14, the color code illustrates the varying percentage loading of transmission lines in PSS®E software. Blue regions indicate that the power lines are under minimal load, greenish regions indicate approximately 50% loading, red regions signify that the lines have reached maximum capacity, and dark red regions indicate congested areas of the power lines. Given the present consumption demand of the four capital cities, the power transmission lines are made 50% loaded concerning the electricity consumption of each city as depicted in Figure 15. All four cities will exhibit identical outcomes as illustrated in Figure 15, with transmission lines loaded to 50% capacity. Also, the percentage of the loaded capacity is mentioned on each power line.


Contour Settings

General

Contour Type

Element: Line

Quantity: % Rating

Parameters

Resolution

Influence area

Boundary size

Performance

Algorithm: Linear (Approx)

Max Depth: 2

Tolerance: 10 %

Color Map

Gradiant: Blue=low Red=high

Transparency

Maximum value: 120.00

Minimum value: 1.00

☑ Enable shading

Contour points: 0

Figure 14. The color codes for percentage loading of transmission lines.

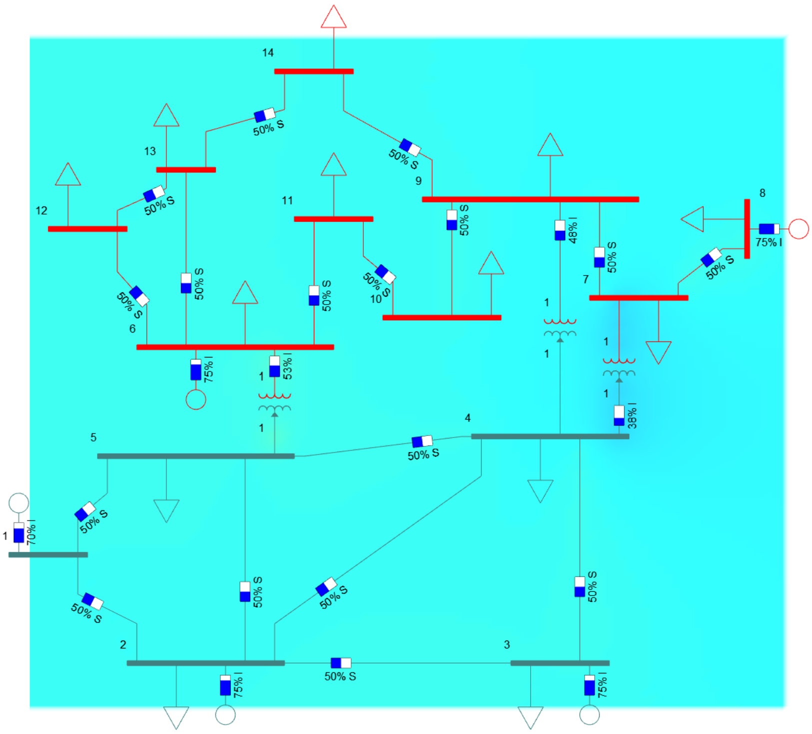


Figure 15. Simulation results with 50% loaded power lines.

7.1. Results for Rome, Italy

Rome has a population of 4.332 million and an electricity consumption of 5.27 MWh per capita. for the long-term goal, there will be 1,723,269 EVs in Rome. The assumed 1% of EVs of long-term goal EVs for Rome are connected to the existing network with power lines loaded at 50% capacity; many lines surpass the 100% loading threshold as depicted by the dark red lines in Figure 16. Given Rome's sizable population and the anticipated rise in EV numbers in the future, even a small fraction of EVs will strain the transmission and distribution lines significantly, leading to substantial congestion issues. The percentage loading of each transmission line is indicated in Figure 16.

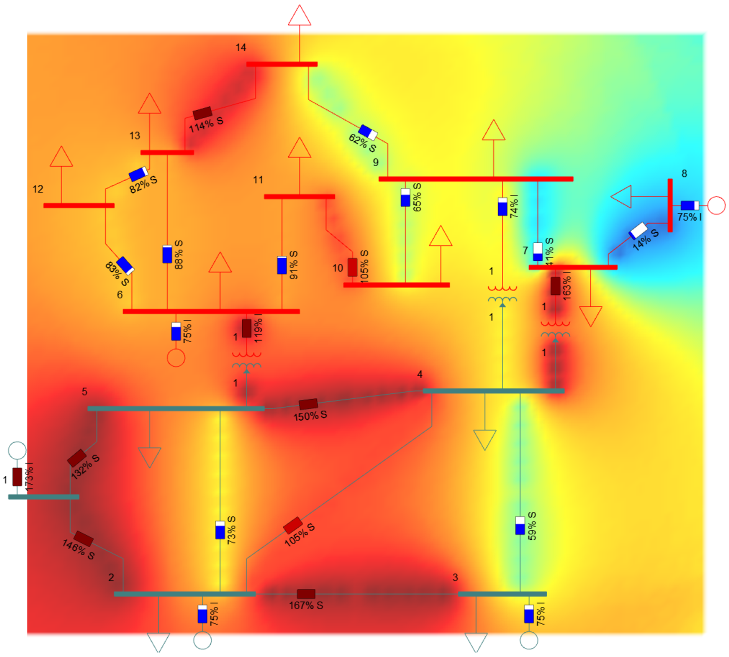


Figure 16. Results with 1% EVs fast charging for Rome.

7.2. Results for Berlin, Germany

Berlin's electricity consumption stands at 6.4 MWh per capita, with a population of approximately 3.677 million. Based on calculations, it is projected that there will be 1,279,865 EVs if 60%t of the ICEPCs are replaced by EVs. The simulation results for Berlin, Germany, depicted in Figure 15, include an added load from a fast-charging system serving 1% of the 1,279,865 EVs, connected simultaneously for a short charging period. These results emphasize the significant impact of EVs on power transmission lines, resulting in congestion. Figure 17 indicates the percentage loading of each line, revealing that most of the 33 kV lines exceed their maximum capacity due to the additional burden of EV charging. Compared to the 50% loading of the lines, this overload stems from the influx of EVs charging on the system.

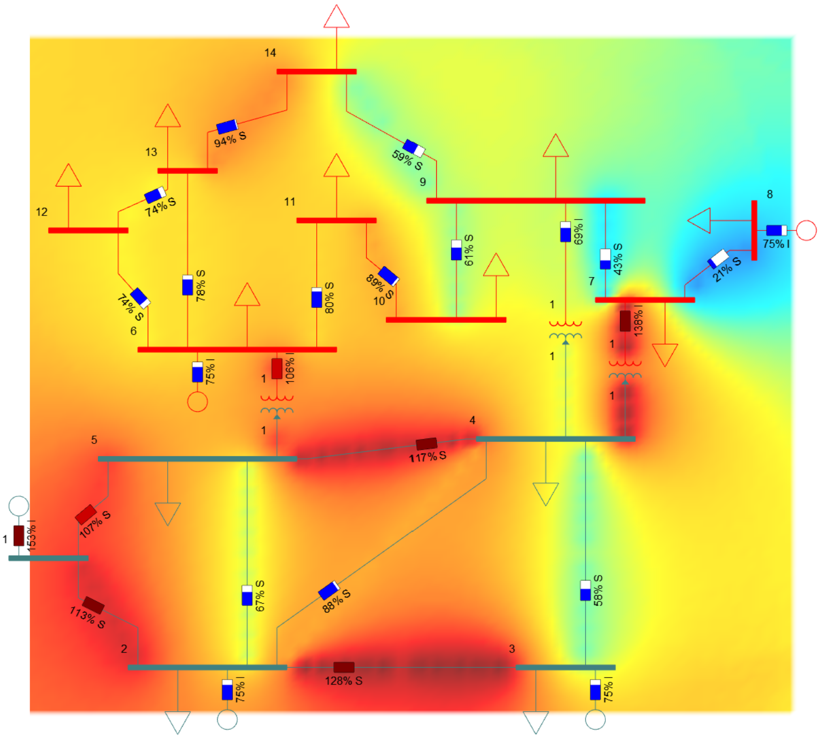


Figure 17. Results with 1% EVs fast charging for Berlin.

7.3. Results for Warsaw, Poland

Warsaw, the capital of Poland, boasts a population of 1.799 million, with an electricity consumption rate of 4.435 MWh per capita. Projections indicate that 716,721 EVs would be on the roads if 60% of ICEPCs were replaced by EVs. If only 1% of these EVs utilize fast charging at 100 kW simultaneously for a brief period, the load would surge by 716 MW. Figure 18 illustrates the consequential impact of this heightened load, showcasing the percentage increase in power line loading beyond the standard 100% operational threshold. Each line's increased percentage is detailed in Figure 18, highlighting the strain imposed by the additional EV charging load on the system.

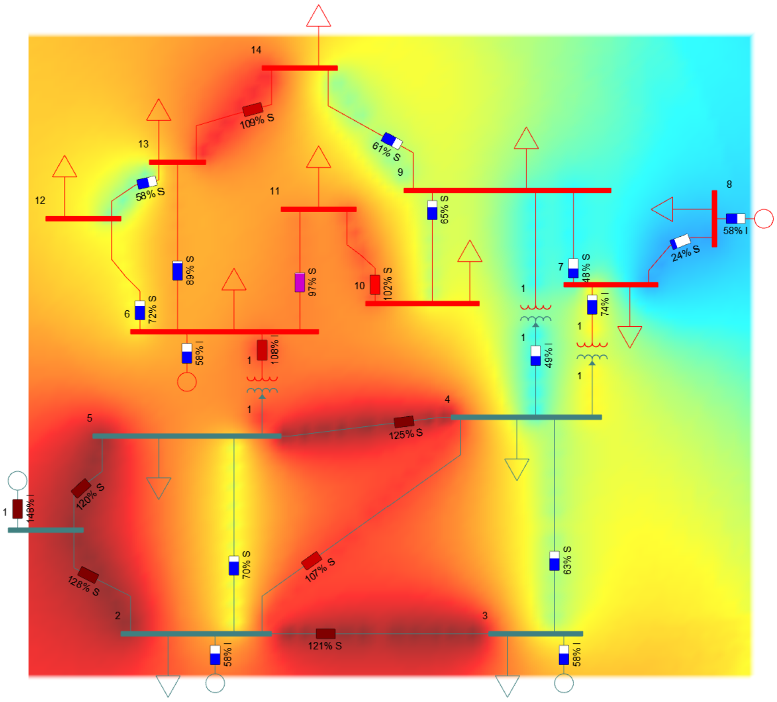


Figure 18. Results with 1% EVs fast charging for Warsaw.

7.4. Results for Bern, Switzerland

Bern, the capital of Switzerland, is home to a population of 0.445 million, with a per capita electricity consumption of 7.302 MWh. Upon replacing 60% of ICEPCs with electric vehicles (EVs), Bern is projected to host 146,850 EVs on its roads as a long-term goal. Introducing a mere 1% load from fast charging for these EVs would escalate the demand by 146 MW. Figure 19 illustrates the repercussions of this heightened load. Although no power line exceeds its maximum capacity, the loading percentage of each line experiences a significant increase. The collective impact of these results is discussed in the impact assessment section, where the outcomes for all four cities are compared.

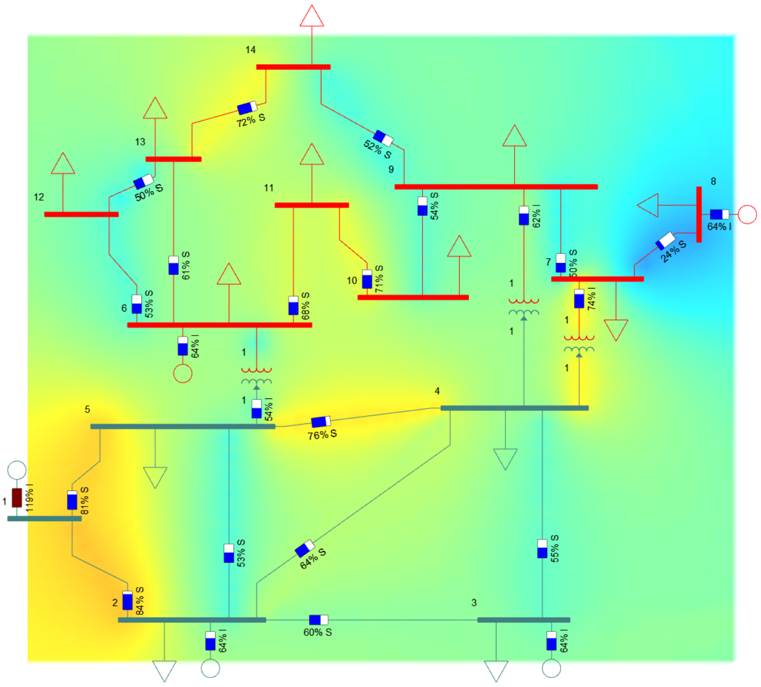


Figure 19. Results with 1% EVs fast charging for Bern.

8. Impact Assessment on Power System Lines

The simulation study has revealed that various factors, including city population, EV numbers, current electricity consumption, and the existing power-carrying capacity of transmission and distribution lines, significantly influence the power grid. In this simulation, it is assumed that all power lines are initially loaded at 50% when no EVs are integrated. However, integrating just one percent of the long-term goal of EVs into each city has resulted in substantial congestion on the power transmission lines. Fast charging stations draw a considerable amount of power in a short period, especially during peak periods, exacerbating the strain on the system.

This congestion in the distribution and transmission networks compromises grid reliability, leading to equipment failures, overheating, and potential outages. The simulation results highlight that cities with larger populations and higher numbers of EVs, such as Berlin, Rome, and Warsaw, experience more significant impacts on power line loading compared to cities with lower populations and fewer EVs, such as Switzerland. The simulation depicts the percentage loading of each line for each city, revealing that Rome, being the most densely populated, faces the greatest strain, with one power line exceeding 176% of its capacity. In contrast, Switzerland, with a lower population density, exhibits less strain, with no line surpassing 84% of its capacity. Moreover, even with power lines initially set at 50% load in the simulation, many lines in Berlin, Rome, and Warsaw exceed 150% loading. This exceeds real-world conditions, where transmission and distribution lines are typically loaded beyond 50%t. Consequently, such a system would encounter significant challenges with a high level of EV penetration in the power grid.

9. Conclusions

The journey towards a greener transportation future demands a careful examination of EVs and their impact on both CO_2 emissions reduction and power systems. Our study delved into the dynamics across four diverse European nations—Switzerland, Italy, Germany, and Poland—each bearing its own COECF profile. By 2050, the projected surge in electricity demand is staggering: 114 TWh for Switzerland, 493 TWh for Italy, 980 TWh for Germany, and 317 TWh for Poland. A 60% EV adoption rate further amplifies these figures, with demand forecasted to climb by 5.348 TWh, 44.38 TWh, 55.43 TWh, and 27.87 TWh, respectively. Meeting this escalating demand mandates strategic enhancements in grid infrastructure, coupled with a robust embrace of RES. Yet, disparities emerge, with Poland's high COECF (823 gCO_2/kWh) casting a shadow on the otherwise positive impact of EVs. Conversely, Switzerland, boasting lower COECF (152 gCO_2/kWh), witnesses remarkable reductions in CO_2 emissions of 7.46%, 23.36%, and 46.40% for 10%, 30%, and 60% EV penetration, respectively. Our findings underscore the pivotal role of RES in steering transportation towards sustainability. As we envision a zero-emission future, it is clear: the time for decisive action on renewable energy goals is now. By intertwining electrification with renewable energy, we chart a course toward a climate-resilient transportation landscape, essential for safeguarding our planet's future.

Efficiently delivering sustainably generated electricity to consumers is crucial for grid reliability, especially with the impending surge in EV charging demand. The case study of four capital cities highlights significant congestion in transmission and distribution lines due to even a small fraction of EVs being simultaneously charged. Loadings exceed 167% for Rome and 128% for Berlin and Warsaw. Upgrading existing power systems is vital to address these challenges. Strategies like increasing grid capacity, integrating distributed energy resources, implementing demand-side management practices, and deploying charging infrastructure strategically are essential for mitigating future challenges in clean transport and smart power systems. Future research could entail conducting economic analyses and assessing policy implications for grid upgrades. This would involve exploring the economic implications of necessary grid enhancements and increased adoption of renewable energy, along with identifying the policy measures required to achieve renewable energy targets.

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Abbreviations

The following abbreviations are used in this manuscript

A_{vc}	Average Number of Cars Per Person
CE_{ICE}	Emissions of Internal Combustion Engine Passenger Cars
CE_{EVs}	Total Annual Emissions From Electric Vehicles
CO_2	Carbon Dioxide
COECF	Carbon Emission Coefficient Factor
D_t	Average Distance Traveled Per Car Per Year In km
E_c	Energy Consumed by Electric Vehicle Annually
E_g	Share of Electricity Generated From Each Source
E_m	Emissions From Each Car
EU	European Union
EVs	Electric Vehicles
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
ICEPCs	Internal Combustion Engine Passenger Cars
N_{EV}	Number of Electric Vehicles
N_p	Population of Each Country
NZE2050	Net Zero Emission 2050
P_{ev}	Penetration Level of Electric Vehicles
RES	Renewable Energy Sources
SDS	Sustainable Development Scenario
T_g	Total Generation of Each Country
T_{ICE}	Total Number of Internal Combustion Engine Passenger Cars
TPVs	Traditional Passenger Vehicles

References

1. WFP Pakistan Situation Report. Available online: https://reliefweb.int/report/pakistan/wfp-pakistan-situation-report-31-october-2022 (accessed on 3 March 2023).
2. Going the Distance—Charting the Journey to Net Zero. Available online: https://sphera.com/ebook/going-the-distance-charting-the-journey-to-net-zero/ (accessed on 2 May 2024).
3. Dodman, D.; Hayward, B.; Pelling, M.; Castan Broto, V.; Chow, W.; Chu, E.; Dawson, R.; Khirfan, L.; McPhearson, T.; Prakash, A.; et al. 2022: Cities, Settlements and Key Infrastructure. In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 907–1040. [CrossRef]
4. IPCC Report 2022 AR6: Summary Part 1. Available online: https://www.fortomorrow.eu/en/blog/ipcc2022-part1 (accessed on 3 May 2024).
5. Laura, C.; Timur, G.; Stéphanie, B.; Araceli, F.P.; Christophe, M.; Laszlo, V.; Davide, D.; Thomas, S. *Net Zero by 2050 A Roadmap for the Global Energy Sector*, 4th ed.; The National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 2021; pp. 26–46.
6. IEA. *World Energy Outlook 2020*; IEA: Paris, France, 2020. Available online: https://www.iea.org/reports/world-energy-outlook-2020 (accessed on 10 March 2023).

7. CO_2 and Greenhouse Gas Emissions. Available online: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions(accessed on 10 March 2023).
8. Marion, V.; Flávia, G. *Renewable Energy Pathways in Road Transport*; Paper 13; The FIA Foundation: London, UK, 2020; pp. 2–7.
9. Mohammadi, M.; Thornburg, J.; Mohammadi, J. Towards an energy future with ubiquitous electric vehicles: Barriers and opportunities. *Energies* **2023**, *16*, 6379. [CrossRef]
10. Falchetta, G.; Noussan, M. Electric vehicle charging network in Europe: An accessibility and deployment trends analysis. *Transp. Res. Part D Transp. Environ.* **2021**, *94*, 102813. [CrossRef]
11. Electric Cars Fend off Supply Challenges to More Than Double Global Sales. Available online: https://www.iea.org/commentaries/ele\ctric-cars-fend-off-supply-challenges-to-more-than-double-global-sales (accessed on 8 March 2023).
12. IEA. *Global EV Outlook 2021*; IEA: Paris, France, 2021. Available online: https://www.iea.org/reports/global-ev-outlook-2021 (accessed on 2 May 2024).
13. Charging Ahead: Electric-Vehicle Infrastructure Demand. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/charging-ahead-electric-vehicle-infrastructure-demand (accessed on 15 December 2022).
14. SLOCAT Transport and Climate Change Global Status Report. Available online: https://tcc-gsr.com/ (accessed on 17 December 2022).
15. IEA. *The Role of CCUS in Low-Carbon Power Systems*; IEA: Paris, France, 2020. Available online: https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems (accessed on 3 May 2024).
16. Li, G.; Luo, T.; Song, Y. Climate change mitigation efficiency of electric vehicle charging infrastructure in China: From the perspective of energy transition and circular economy. *Resour. Conserv. Recycl.* **2022**, *179*, 106048. [CrossRef]
17. Ercan, T. Autonomous electric vehicles can reduce carbon emissions and air pollution in cities. *Transp. Res. Part Transp. Environ.* **2022**, *112*, 103472. [CrossRef]
18. Sathre, R.; Gustavsson, L. A lifecycle comparison of natural resource use and climate impact of biofuel and electric cars. *Energy* **2021**, *237*, 121546. [CrossRef]
19. Gai, Y. Health and climate benefits of electric vehicle deployment in the greater Toronto and Hamilton area. *Environ. Pollut.* **2020**, *265*, 114983. [CrossRef] [PubMed]
20. Ou, Y. Evaluating long-term emission impacts of large-scale electric vehicle deployment in the US using a human-Earth systems model. *Appl. Energy* **2021**, *300*, 117364. [CrossRef] [PubMed]
21. Broadbent, G. The role of electric vehicles in decarbonising Australia's road transport sector: Modelling ambitious scenarios. *Energy Policy* **2022**, *168*, 113144. [CrossRef]
22. Franzò, S.; Nasca, A. The environmental impact of electric vehicles: A novel life cycle-based evaluation framework and its applications to multi-country scenarios. *J. Clean. Prod.* **2021**, *315*, 128005. [CrossRef]
23. Moghani, M.; Archer, C.L. Impacts of replacing coal with renewable energy sources and electrifying the transportation sector on future ozone concentrations in the US under a warming climate. *Atmos. Pollut. Res.* **2022**, *13*, 101522. [CrossRef]
24. Xia, X.; Li, P.; Xia, Z.; Wu, R.; Cheng, Y. Life cycle carbon footprint of electric vehicles in different countries: A review. *Sep. Purif. Technol.* **2022**, *301*, 122063. [CrossRef]
25. Pipitone, E.; Caltabellotta, S.; Occhipinti, L. A life cycle environmental impact comparison between traditional, hybrid, and electric vehicles in the European context. *Sustainability* **2021**, *13*, 10992. [CrossRef]
26. Shafique, M.; Luo, X. Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective. *J. Environ. Manag.* **2022**, *303*, 114050. [CrossRef] [PubMed]
27. Li, P.; Xia, X.; Guo, J. A review of the life cycle carbon footprint of electric vehicle batteries. *Sep. Purif. Technol.* **2022**, *296*, 121389. [CrossRef]
28. CO_2 Emissions from New Passenger Cars in Europe: Car manufacturers' Performance in 2021. International Council on Clean Transportation. Available online: https://theicct.org/publication/co2-new-passenger-cars-europe-aug22/ (accessed on 15 January 2023).
29. Fontaras, G.; Zacharof, N.-G.; Ciuffo, B. Fuel consumption and CO_2 emissions from passenger cars in Europe–Laboratory versus real-world emissions. *Prog. Energy Combust. Sci.* **2017**, *60*, 97–131. [CrossRef]
30. Passenger Transport. Available online: https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/passenger-transport.html (accessed on 5 February 2023).
31. Sectoral Profile-Transport. Available online: https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html (accessed on 11 February 2023).
32. Electricity Maps. Available online: https://app.electricitymaps.com/map (accessed on 23 March 2023).
33. More and More Cars in Germany: Car Density Reaches New Peak. Available online: https://www.iamexpat.de/expat-info/german-expat-news/more-and-more-cars-germany-car-density-reaches-new-peak (accessed on 13 April 2023).
34. Germany Motor Vehicle Density: Per 1000 Inhabitant: Passenger Car. Available online: www.ceicdata.com/en/germany/auto-industry-statistics/motor-vehicle-density-per-1000-inhabitant-passenger-car (accessed on 13 April 2023).
35. Passenger Cars in the EU. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Transport(accessed on 12 April 2023).
36. Passenger Cars Per 1000 People in Switzerland. Available online: https://www.helgilibrary.com/indicators/passenger-cars-per-1000-people/switzerland/ (accessed on 13 April 2023).

37. Electric Vehicle Database. Available online: https://ev-database.org (accessed on 26 April 2023).
38. Energy-Charts. Available online: https://energy-charts.info/index.html?l=en&c=DE (accessed on 8 May 2023).
39. Poland-Country Commercial Guide. Available online: https://www.trade.gov/country-commercial-guides/poland-energy-sector (accessed on 8 May 2023).
40. Poland Has Increased Its Share of Wind and Solar but Still Lags behind EU Peers. Available online: https://ember-climate.org/countries-and-regions/countries/poland/ (accessed on 8 May 2023).
41. Database the Europe beyond Coal Campaign Maintains a Database with Information on All Major Coal Power Plants Covering EU-27 + UK, Turkey, and All Countries in the Western Balkans. Available online: https://beyondfossilfuels.org/database/ (accessed on 8 May 2023).
42. Terna: Significant Recovery of Electricity Consumption in 2021. Available online: www.terna.it/en/media/press-releases/detail/electricity-consumption-2021 (accessed on 10 May 2023).
43. The Portal of the Swiss Government. Available online: www.admin.ch/gov/en/start/documentation/media-releases.msg-id-88012.html (accessed on 10 May 2023).
44. Net Zero by 2050. Available online: https://www.iea.org/reports/net-zero-by-2050 (accessed on 13 May 2023).
45. Boitier, B.; Nikas, A.; Gambhir, A.; Koasidis, K.; Elia, A.; Al-Dabbas, K.; Alibas, S.; Campagnolo, L.; Chiodi, A.; Delpiazzo, E.; et al. A multi-model analysis of the EU's path to net zero. *Joule* **2023**, *7*, 2760–2782. [CrossRef]
46. Energy system of Europe. Available online: https://www.iea.org/regions/europe (accessed on 9 February 2024).
47. Germany: State and City of Berlin. Available online: https://www.citypopulation.de/en/germany/berlin/ (accessed on 9 February 2024).
48. Rome, Italy Metro Area Population 1950–2024. Available online: https://www.macrotrends.net/global-metrics/cities/21588/rome\/population (accessed on 9 February 2024).
49. Warsaw, Poland Metro Area Population 1950–2024. Available online: www.macrotrends.net/global-metrics/cities/22161/warsaw\/population (accessed on 9 February 2024).
50. Bern, Switzerland Metro Area Population. Available online: https://www.macrotrends.net/global-metrics/cities/22601/bern/\population (accessed on 9 February 2024).
51. Plugin Vehicle Share in Europe. Available online: https://cleantechnica.com/2024/02/03/24-plugin-vehicle-share-in-europe/ (accessed on 11 February 2024).
52. Tesla Model, Y. Available online: https://ev-database.org/car/1743/Tesla-Model-Y (accessed on 2 March 2024).
53. Sustainability by Numbers. Available online: https://www.sustainabilitybynumbers.com/p/public-ev-chargers (accessed on 2 March 2024).
54. Driving Mobility for Europe. Available online: https://www.acea.auto/press-release/e-mobility-only-1-in-9-charging-points-in-eu-is-fast/ (accessed on 5 March 2024).
55. Illinois Center for a Smarter Electric Grid. Available online:https://icseg.iti.illinois.edu/ieee-14-bus-system/ (accessed on 28 February 2024).
56. CO_2 Emissions per kWh of Electricity Generated in France. Available online: https://www.rte-france.com/en/eco2mix/co2-emissions (accessed on 13 May 2023).
57. Begamudre, R.D. *Extra High Voltage AC Transmission Engineering*; New Age International: New Delhi, India, 2006.
58. Kiessling, F.; Nefzger, P.; Nolasco, J.F.; Kaintzyk, U. *Overhead Power Lines: Planning, Design, Construction*; Springer: Berlin/Heidelberg, Germany, 2014.