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Electric vehicles as an emission mitigation option: expectations and reality

Esin Tetik Kollugil[1] · Kemal Sarıca[2] · Y. Ilker Topcu[1]

Abstract

Globally, the reliance on thermal power, constituting 67% of electricity generation, prompts questions for many countries regarding the viability of electric vehicles (EVs) for emission reduction in the transportation sector. This study comprehensively analyzes CO_2 emissions in the small family car segment, considering engines powered by different energy sources. The analysis is coupled with Worldwide Harmonized Light Vehicle Test Procedure driving profiles, accounting for specific ambient temperature structures representative of densely populated areas in Türkiye. The constructed model incorporates the hourly temperature of the relevant cities and the hourly electricity production mix by considering the indirect emissions and comparing the ICEVs (Internal Combustion Engine Vehicles) and EVs in different time frames from 2015 to 2020. The resulting emissions from each vehicle type in each city and driving profile, along with the ratio of instances in which EVs exhibit higher emissions than ICEVs, are presented.The findings reveal the intricate interplay between vehicle type, climate conditions, and driving profiles. While the urban driving profile emerges as superior for EVs regarding CO_2 reduction, offering a comfortable driving experience without range anxiety and mitigating local pollutants, it exhibits less significant carbon emission reductions at lower and higher speed profiles, particularly in cold climate conditions. EVs are not a silver bullet but a valuable technology for emissions reduction under specific conditions. Policymakers are urged to consider factors favoring EVs over ICEVs regarding CO_2 emissions, such as driving profiles, time and climatic conditions when formulating investment policies and subsidies.

Graphical abstract
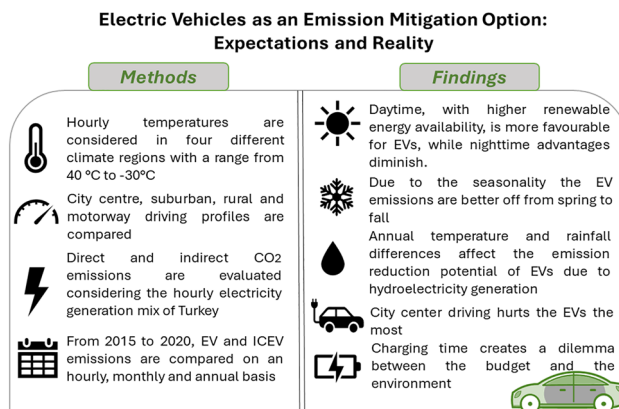
Extended author information available on the last page of the article

Introduction

The transport sector is responsible for approximately 20% of global CO_2 emissions due to high oil consumption, and the largest share depends on road transport (IEA 2017). Therefore, decarbonization toward meeting the 2 °C and 1.5 °C mitigation targets requires serious road transport actions. The substitution of electric vehicles for conventional vehicles is considered a key option for reducing the carbon footprint of road transportation in the short term (IEA 2022b). Several efforts are taken to support this option economically, such as purchase subsidies, tax exemptions and benefits, as well as installing the charging stations (IEA 2022a). The European Commission set new CO_2 emission performance standards for new passenger cars in 2020 (European Commission 2022). However, developing countries stand one step behind EV (electric vehicle) market development due to infrastructure requirements and high investment costs. In early 2023, the share of EVs was only 0.12% of the total number of passenger cars in Türkiye. The sales afterward are expected to increase due to the announced tax incentive for EV sales and the production of a new Turkish EV startup release. With the accelerating charging station investments, the sales are predicted to at least double the number of EVs in the short term.

EVs are perceived to be a sustainable means of transport that targets CO_2 reduction. However, heterogeneity in mitigation contribution exists between the top EV stock countries (Xu et al. 2021). Because the factors influencing the potential of EVs for emission reduction vary between countries, each country's parameters should be assessed individually. Moreover, considering an EV as an emission abatement solution entails at least generating fewer emissions than the replaced internal combustion engine vehicle (ICEV), even though the EV has zero tailpipe emissions. Therefore, a comparison with their ICEV counterparts under various conditions would reveal the emission performance of the EVs.

The primary determinant of EV emissions is the electricity generation fuel mix; as the sector becomes cleaner, EVs emerge as an essential tool for mitigation. However, despite the increase of renewables in recent years, most of the electricity generation depends on fossil fuels in Türkiye, where 67% of electricity was generated from thermal power in 2021, as Fig. 1 depicts. Therefore, in countries like Türkiye, careful actions are necessary for effective emission abatement through electrification.

Additionally, the driving range and associated emissions of EVs are influenced by factors beyond battery capacity and energy density (Sagaria et al. 2021). These factors include driving conditions (such as city or highway
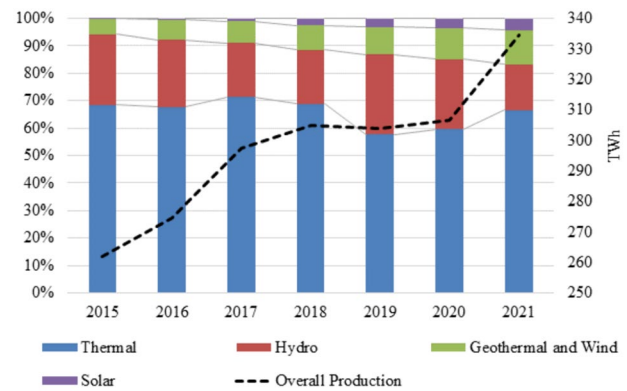

Fig. 1 Overall electricity generation (left) and breakdown of the primary energy resources (right)

driving) (Karabasoglu and Michalek 2013), temperature (Iora and Tribioli 2019; Steinstraeter et al. 2021) and the load of auxiliary systems (Iora and Tribioli 2019). Therefore, during the initial stages of vehicle electrification investment, it is essential to consider local climatic conditions and different driving conditions when assessing emissions.

This study investigates the contribution of EVs to reducing the emissions of passenger cars compared to those of conventional internal combustion engine vehicles (ICEVs) under identical driving conditions, considering Türkiye's electricity generation and environmental conditions. The emissions generated from electricity generation are comprehensively accounted for, including fuel combustion emissions, fuel extraction, infrastructure, and transmission/distribution losses, which cause additional production because of inefficiency. In addition to the electricity generation sector, the analysis considers the impact of factors that vary during vehicle use, such as driving cycle, ambient temperature, and cabin heating/cooling load, on energy consumption and, consequently, emissions from EVs. On the ICEV's side, emissions are calculated by considering fuel combustion, upstream emissions, and cabin cooling load. Different EVs and ICEVs belonging to the same segment were evaluated to strengthen the analysis. This study highlights the multidimensional aspect of EVs as an emission abatement alternative in which decision-makers can use the results to direct consumers toward rational decision-making in favor of emission mitigation efforts.

Literature review

Previous studies have compared EV emissions with those of conventional vehicles based on electricity emission intensity at the country or regional scale. Graff Zivin et al. estimated

the marginal electricity emissions for different regions and times of day in the United States (US) (Graff Zivin et al. 2014). The authors compared the emissions of PEVs (plug-in electric vehicles) with hybrid cars according to the charging time and region. One exciting result is that charging from midnight to 4 a.m. generates higher PEV emissions than the light-duty fleet average in the upper Midwest region. Donateo et al. compared the GHG (greenhouse gas) and pollutant emissions released related to EVs in Rome with limits set for conventional vehicles based on an analysis of the recharge behaviors and electricity generation mix at an hourly resolution in a particular year (Donateo et al. 2015). Even though the study did not include the temperature factor directly, to reflect the effect of seasonality, charging habits, driving conditions and vehicle specifications, the worst and best emission performances were used for comparison.

A few studies have conducted emission reduction assessments by considering factors influencing the EV range in addition to electricity emissions. Yuksel and Michalek (2015) evaluated the impact of spatial and temporal ambient temperatures on the EV range and emissions in the US using real-world data. However, the effect of speed on the driving cycles, different road conditions or cabin cooling/heating preferences are not explicitly considered, but the fleet average is assumed for all. The findings for Nissan Leaf highlighted a significant increase in energy consumption within the same state due to temperature effects. The study also emphasized the substantial influence of the grid mix, which caused a 186% difference in emissions between states, with ambient temperature contributing to a 22% increase within the same region.

In another study, Wu et al. investigated the life cycle GHG emissions of representative lightweight gasoline and electric light-duty vehicles by accounting for the combined effect of the electricity grid mix, urban/rural driving cycles and ambient temperature in US counties (Wu et al. 2019). Chantalla et al. compared EV and combustion vehicle emissions through 2030 for four US states by considering the electricity grid mix, average temperature, vehicle type and fuel economy (Challa et al. 2022). According to the analysis, unlike those in other states, EVs in New York have higher emissions than ICEVs because of replacing nuclear power plants with natural gas power plants.

Previous comparative assessment studies can be categorized as utilizing average and/or marginal electricity emission (Mehlig et al. 2022) allocation methods annually (Ma et al. 2012; Onat et al. 2015), as well as hourly (Jochem et al. 2015; Kamiya et al. 2019) temporal resolution, considering influencing factors such as location (Onat et al. 2015; Wu et al. 2019; Yuksel and Michalek 2015), temperature (Yuksel and Michalek 2015), and driving profile (Ma et al. 2012; Qiao et al. 2020; Wu et al. 2019). The novelty of this study is that it considered the combined effects of relevant factors and

the hourly temporal resolution for both ICEVs and EVs. The factors considered include the driving profile, HVAC system (heating, ventilation, and air conditioning), as well as historical national electricity emission factors and temperature at an hourly resolution coupled with the location of interest from different climatic zones. This approach is preferred for evaluating the CO_2 emission performance of different EVs compared to ICEV counterparts, allowing for identifying advantageous and disadvantageous states and providing a distinctive perspective.

The studies in the literature predominantly concentrate on the top GDP countries, including US (Challa et al. 2022; Onat et al. 2015; Wu et al. 2019; Yuksel and Michalek 2015), the UK (Mehlig et al. 2022), France (Holdway et al. 2010), Germany (Jochem et al. 2015), Canada (Kamiya et al. 2019), Italy (Donateo et al. 2015; Girardi et al. 2015) and China (Qiao et al. 2020).

To the best of the authors' knowledge, this is the first study to comprehensively assess the emission reduction performance of EVs compared to ICEV counterparts from the standpoint of environmentally conscious consumers, considering temperature coupled with spatial and temporal characteristics of Turkish cities of interest, accounted with national grid electricity generation mix, within the hourly time resolution. The impact of temperature has been assessed by considering HVAC deployment, battery performance and management systems. On top of this, WLTP driving profiles have been integrated into the what-if analysis to assess the different traffic conditions. Three different charging scenarios have been deployed to include the role of drivers in this picture: charge-and-drive, minimum emission charging and maximum emission charging. The contribution of this study is combining all these dimensions under one roof to compare expectations and reality, answering the question, "To what extent are EVs environmentally beneficial?".

Methods

A model that integrates the electricity emission factor and ambient temperature on an hourly basis, coupled with relevant driving cycles, has been developed to be used within a what-if analysis. This model utilizes distinctive climatic conditions across various cities in the country to calculate emissions related to EVs and ICEVs. This study conducts a comparative analysis based on the outputs generated by the model.

Since the performance of EVs varies between manufacturers (Sagaria et al. 2021), the emission performances of the electric vehicles Citroën ë-C4 and Nissan Leaf are compared with those of similar power counterparts conventional fuel vehicles, C4 diesel/gasoline and Volkswagen Golf-8, respectively. This analysis compared fuels within the same vehicle type and a crossmanufacturer evaluation to reveal the

energy consumption differences between EV characteristics regarding temperature, AC load, and speed.

One of the critical components of the analysis, the aggregated hourly emission factor of the electricity generated in the 2015–2020 period, is calculated as shown in Eqs. (1)–(3), by hourly electricity generation (EPIAS 2022) and power plants efficiencies based on the energy balance sheets (General Directorate of Energy Affairs 2022). For fossil fuels, direct CO_2 emission factors by fuel type (IPCC 2006) are used in the calculations, as shown in Table S1. In addition, fuel provision GHG emissions from fuel extraction to the power plant adapted to Türkiye from a life cycle assessment study overview (Turconi et al. 2013) are considered. For renewable resources, average GHG emissions from Turconi's study, which includes infrastructure (commissioning and decommissioning) emissions, are shown in Table S2. Table 1 presents the nomenclature of parameters and indexes used in these calculations.

$$FF^h = \sum_{fuel} Gen^h_{fuel} \times \left[\frac{Cons^y_{fuel}}{Gen^y_{fuel}} \times \left(Direct_{fuel} + Provision_{fuel} \right) \right] \tag{1}$$

$$RNW^h = \sum_{tech} Gen^h_{tech} \times Infrastructure_{tech} \tag{2}$$

$$EEF^h = \left[\frac{FF^h + RNW^h}{Gen^h_{fuel} + Gen^h_{tech}} \right] \times 3600 \times 10^{-9} \tag{3}$$

The average temperature in Türkiye between 1970 and 2020 was 13.2 °C, and the temperature ranged between 3.8 °C and 20.1 °C (Turkish State Meteorological Service 2021). Hourly temperature data are obtained from the MERRA-2 dataset (Global Modeling and Assimilation Office 2020). Antalya, Istanbul, Ankara and Erzurum are the selected cities for this analysis, as presented in Fig. 2. During the study period, the average annual temperatures were 18.3 °C, 15.5 °C, 12.3 °C, and 5 °C, respectively, as shown in Fig. 3b. Additionally, Fig. 3a depicts the average temperature in 2018 was significantly greater than the average temperature in these cities, especially in colder cities. This increase could be one of the reasons for the decrease in hydro generation in 2018.

The daily temperature variation is smaller in Istanbul than in the other cities, with a 10 °C difference. The temperature increases at 8 a.m. and peaks at 3 p.m., as shown in Fig. 4. Erzurum and Ankara are the colder cities on the country's middle and eastern sides. Erzurum has an average temperature below 0 °C for five months and barely reaches 20 °C in summer, while Ankara has two negative temperature months and four above 20 °C months. Besides, the average temperature does not fall below 5 °C in Istanbul or Antalya, and the

Table 1 Nomenclature of parameters and indexes for emission factor calculation

EEF^h	Emission density of the electricity generated in hour h (ton CO_2/MWh)
FF^h	Emissions derived from of fossil fuels in hour h
RNW^h	Emissions derived due to the renewable energy use in hour h
Gen^h_{fuel}	Electricity generated from each fossil fuel type in each hour h (PJ)
Gen^y_{fuel}	Electricity generated from each fossil fuel type in year y (PJ)
Gen^h_{tech}	Electricity generated from each renewable energy technology in each hour h (PJ)
$Cons^y_{fuel}$	Fossil fuel consumed to generate electricity in year y (PJ-fuel)
$Direct_{fuel}$	Combustion emission factors for each fossil fuel type (ton CO_2/PJ-fuel)
$Provision_{fuel}$	Provision emission factors for each fossil fuel type (ton CO_2-e/PJ-fuel)
$Infrastructure_{tech}$	Infrastructure emissions for each renewable energy type (ton CO_2-e/PJ-electricity)

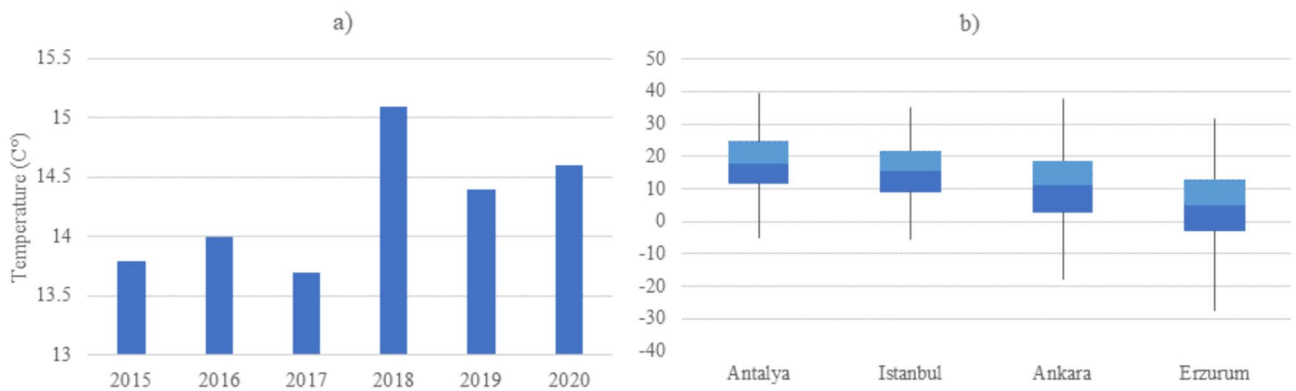**Fig. 2** Locations of the selected cities on the map of Türkiye

Fig. 3 a Annual average temperature of Türkiye (Turkish State Meteorological Service 2020) and **b** characterization of the temperature of the selected cities within the analysis period (Renewables.ninja 2020)
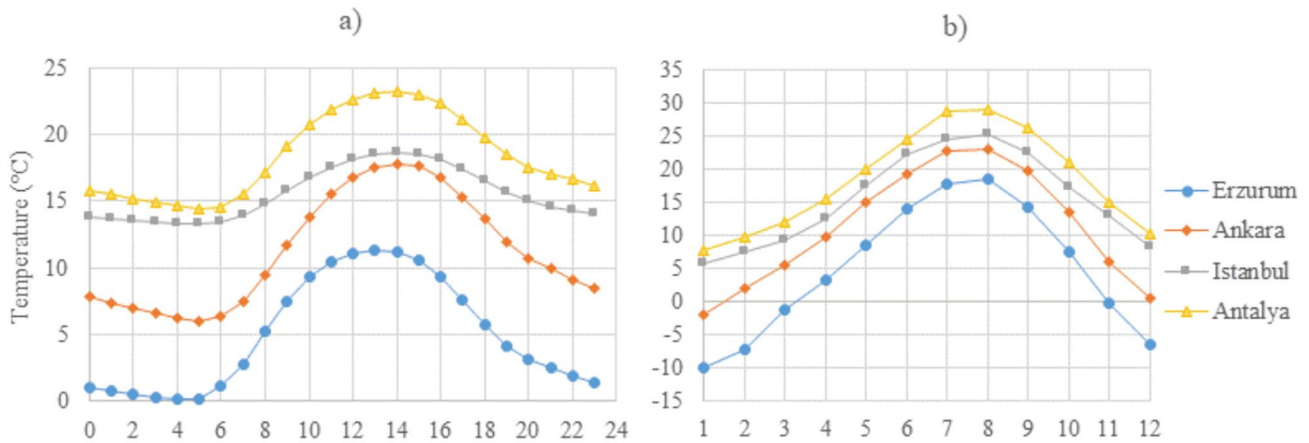

Fig. 4 Average temperatures of the selected cities for **a** hours and **b** months between 2015 and 2020

Table 2 WLTP Class 3b cycle parameters (UNECE 2021)

Driving profile	Speed phases	Max km/h	Avg. km/h with stops
Urban, city center driving	Low	56.5	18.9
Town or suburban driving	Medium	76.6	39.5
Rural driving, dual carriageway	High	97.4	56.7
Motorway driving	Extra high	131.3	92.0

southern city of Antalya has temperature values above 20 °C for six months.

The speed parameter employed in this analysis corresponds to the low, medium, high and extra high driving profiles outlined in the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) (WLTP Test Procedure 2022). These profiles are representative of city center, suburban, rural, and motorway driving, respectively. Table 2 shows the selected parameters of these driving profiles, where the average speeds with stops are used in this analysis to reflect the vehicles' performances across these driving profiles. It's worth noting that WLTP tests are performed at a fixed test temperature of 23 °C.

This analysis assumes steady-state consumption, and no cold start, which would increase the emissions at cold temperatures, is evaluated. Additionally, grid-to-motor inefficiencies (Eberhard and Tarpenning 2006), which account for a 7% loss for the charger and a 7% loss for the battery, and the transmission and distribution losses calculated from energy balance sheets (General Directorate of Energy Affairs 2022) in addition to the battery capacity, are accounted to obtain the actual specific energy consumption (SEC) of electric vehicles. Emissions related to EVs are calculated

Table 3 Nomenclature of parameters and indexes for EV emissions calculation

$Emis_{EV}^h$	Emissions related to charging and driving EV in hour h (kgCO$_2$/100km)
$BatCap_{EV}$	Battery capacity of EV (kWh)
$Range_{EV,S}^h$	Range of EV at speed profile S and ambient temperature in hour h (km)
CLoss	Charger loss ratio
BLoss	Battery loss ratio
$TLoss^y$	Transmission and distribution loss ratio of year y

as shown in Eq. (4), and the nomenclature of parameters is given in Table 3.

$$\text{Emis}_{EV}^h = \frac{\text{BatCap}_{EV}}{\text{Range}_{EV,S}^h/100} \times \frac{\text{EEF}^h}{(1 - \text{CLoss}) \times (1 - \text{BLoss}) \times (1 - \text{TLoss}^y)} \tag{4}$$

Since the EV ranges vary in real-life conditions due to other characteristics, this analysis uses the EV performance parameters announced directly by the producers instead of using data from the literature. Therefore, this analysis considers only the effects of emission factor, average speed, and temperature other than the different climate conditions such as humidity, wind and sun/shadow, road conditions, such as slope, driver effect (e.g., aggressive driving style), and cabin temperature preferences.

For the analysis, two electric vehicles and three ICEVs are selected. Citroen ë-C4, which has a 50-kWh battery and 100 kW of engine power, is chosen as one of the EVs for comparison with their counterparts, namely, Citroen C4-diesel (New C4 BlueHDi 130 SandS EAT8 8-speed automatic, 96 kW) and Citroen C4-gasoline (New C4 PureTech 130 SandS EAT8 8-speed automatic, 97 kW) (Citroën 2022b). All three vehicles are small family cars and have the same dimensions: length (4360 mm), width (2032 mm), width excluding mirrors (1800 mm), height (1525 mm), and wheelbase (2670 mm) value. Yet the kerb weight of the gasoline version is approximately 1263 kg, and that of the diesel engine is 1314 kg; however, the battery vehicle is heavier, around 1699 kg.

The manufacturer data include range estimations for ë-C4 at different speeds (30 km/h to 130 km/h) and temperatures (− 10 °C to 35 °C) with and without enabling the HVAC system (Citroën 2022a.), as shown in Fig. 5. While the maximum range values are present at the 40 km/h speed level in the HVAC-off case, the maximum range is reached at different speed levels for each temperature value in the HVAC-on case. For example, although the maximum range of ë-C4 (350 km) is reached at 20 °C and 40 km/h speed level, at − 10 °C and 35 °C, the highest available range is achieved at the 70 km/h speed level. Additionally, from − 5 to 10 °C and at 25 °C the maximum range is reached at the 50 km/h speed level. For analysis, piecewise linear functions of temperature for the given speed levels are generated with a maximum deviation of 3.3% and 1.3% for the HVAC on and HVAC off cases,
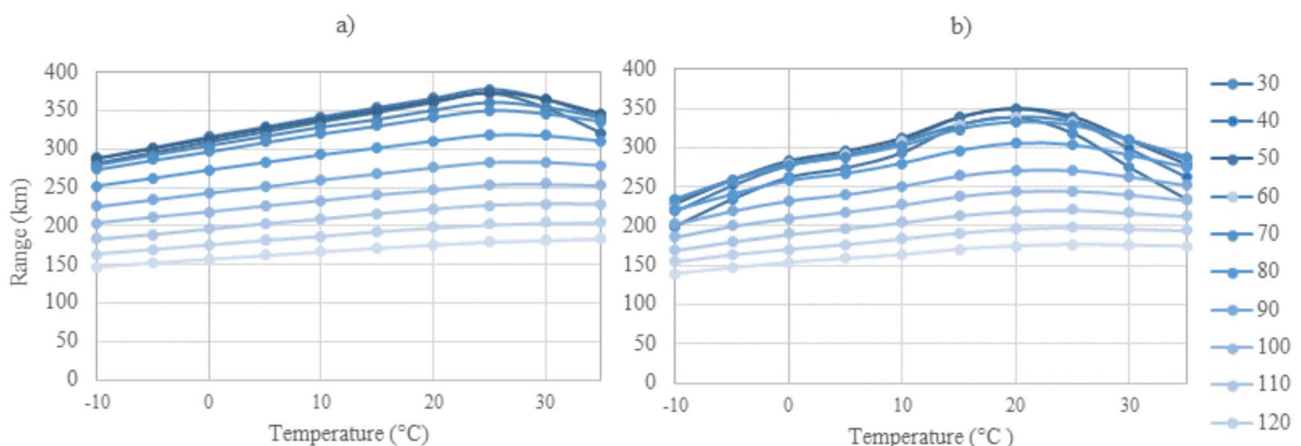
Fig. 5 Estimated ranges of Citroen ë-C4 for several average speed values when **a** HVAC is off, **b** HVAC is on (Citroën 2022a)

respectively. Convex combinations of the neighbor speed function values are calculated for other speed levels.

Secondly, a small family car, Nissan Leaf (Nissan 2022a), with a 40 kWh battery and 110 kW of maximum engine power, is selected. The dimensions of the Leaf are as follows: 4490 mm overall length, 2030 mm overall width, 1788 mm width without mirrors, 1540 mm height, and 2700 mm wheelbase. The kerb weight varies between 1518 and 1727 kg depending on the model. The Leaf is compared with a similar small family gasoline ICEV, the Golf-8 1.5 e-TSI 150PS DSG (Volkswagen 2022). Golf-8 also has a 110 kW maximum engine power, and the dimensions are as follows: 4284 mm overall length, 1789 mm width excluding mirrors, 1491 mm height, and 2619 mm wheelbase. The kerb weight is 1365 kg. The fuel consumption of Golf-8 was obtained from the producer (Volkswagen 2022) values published for each WLTP cycle.

The manufacturer provides the estimated range for a single full charge under several conditions, such as outside temperature (− 20 °C to 35 °C, by 5 °C), A/C or heater use and average speed (Nissan, 2022b). These values are for solo/couple passengers and eco mode off. The data do not reflect other factors, such as optional equipment, battery conditions, climate control, maintenance, driving behavior and weather conditions, and real-world results may vary. A heat pump is used at temperatures lower than 15 °C, and the interior temperature is set to 21–22 °C. The HVAC system automatically operates to reach that cabin temperature when on.

As shown in Fig. 6, although the peak range is achieved at the same temperature, the 32 km/h average speed shows a different dynamic than the other average speed levels, both with and without HVAC. Therefore, the joint function of speed and temperature for the range of Leaf had some drawbacks at lower speeds. Thus, distinct piecewise linear functions of the temperature were generated for each speed level, with maximum deviations of 5.4% and 1.5% for HVAC on and off cases, respectively. For the speed levels between the given values by the company, corresponding range values were linearly interpolated.

The average range of Citroen ë-C4 is announced as 350 km, and the energy consumption is 15.5 kWh/100 km. The combined WLTP range is 270 km, and the consumption
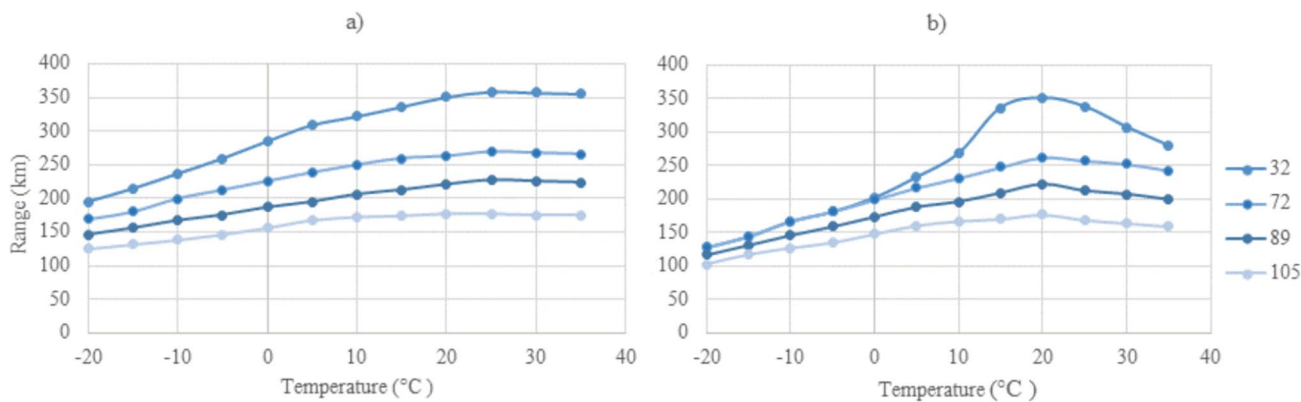

Fig. 6 Estimated ranges of Nissan Leaf at several average speed values **a** with HVAC system and **b** without HVAC system (Nissan 2022b)
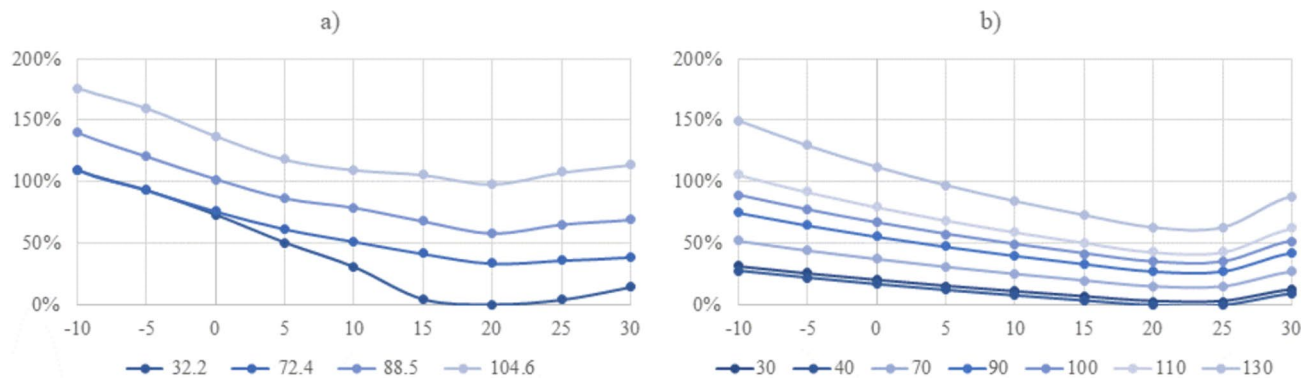

Fig. 7 Increase in the specific energy consumption of **a** Leaf and **b** ë-C4 by speed (km/h)

value is 17.1 kWh/100 km for the Leaf. Additionally, the two EVs exhibit different dynamics at varying speeds and temperatures. Figure 7 shows the increase in the SEC for each EV under various conditions derived from producer data. The difference in the behavior of EVs indicates the requirement for a complementary analysis of different EVs and ICEVs.

In general, Leaf is more sensitive to changes, especially at low temperatures; at − 10 °C, the consumption is more than double the minimum SEC at each speed. The increase in consumption is dramatic as the speed increases and the temperature decreases. On the other hand, ë-C4 is more suitable for these conditions. The consumption doubles only at very high-speed levels, above 110 km/h, at − 10 °C. Therefore, it should be noted that diesel and gasoline vehicles are compared with a competitive EV.

During the analysis period, the minimum temperature in the selected cities reached − 27 °C in Erzurum, and the maximum temperature was 38 °C in Antalya, which is beyond the temperature range that the suppliers announced. Therefore, the SEC values are assumed to increase by the piecewise linear function indicated for both EVs.

To calculate the emissions of ICEVs within the analysis, WLTP fuel consumption levels presented in Table 4 are utilized alongside gasoline/diesel emission factors. Additionally, to incorporate the additional A/C load on the ICEVs, the increase in the SEC is calculated using a regression model derived from the research findings of Weilenmann et al. (2005). The model, which excludes values of 13 °C from the previous study as they were solely used for misting the windscreen, applies the A/C effect at ambient temperatures exceeding 23 °C, consisting of the experimental conditions to keep the interior temperature at 23 °C. The model, presented in Eq. (5, incorporates parameters S for speed and T_h for the ambient temperature in time slice h, has a significance value of 4.02 e − 05 and an adjusted R-square of 95.4%. Then, the resulting ICEV emissions are calculated as shown in Eq. (6), with parameters listed in Table 5.

$$(\ln \text{ACload}^h) = -3.2632 - (0.01848 \times S) + (0.059149 \times T^h) \tag{5}$$

$$\text{Emis}^h_{\text{ICEV}} = \left\{ \begin{array}{l} T^h > 23, \ (\text{Cons}_{\text{ICEV},S} \times \text{EF}_{\text{fuel}}) \times (1 + \text{ACload}^h) \\ T^h \leq 23, \ (\text{Cons}_{\text{ICEV},S} \times \text{EF}_{\text{fuel}}) \end{array} \right\} \tag{6}$$

Table 5 Nomenclature of parameters and indexes for ICEV emissions calculation

$\text{Emis}^h_{\text{ICEV}}$	Emissions released from ICEV in hour h (kg CO_2/100km)
$\text{Cons}_{\text{ICEV},S}$	Fuel consumption of ICEV at speed profile S (lt/100 km)
EF_{fuel}	Emission factor of the fuel type (kg CO_2/lt)
ACload^h	HVAC system load factor on ICEVs in hour h

Once the emissions of EVs and ICEVs are determined, the emission differences ($\text{Emis}^h_{\text{diff}}$) between the EV and ICEV for relevant comparisons are calculated as in Eq. (7). Positive values indicate that the EV has a higher emission level at that time slice, while negative values signify that the EV has lower emissions than its ICE counterpart. The findings are summarized by the time of the day, month and year in the results and supplementary information sections. Additionally, the ratios of the number of time slices that EV has higher emissions than ICEVs ($\text{EV}^h_{\text{High}}$) are calculated as in Eq. (8) for the whole study period are presented.

$$\text{Emis}^h_{\text{diff}} = \text{Emis}^h_{\text{EV}} - \text{Emis}^h_{\text{ICEV}} \tag{7}$$

$$\text{EV}^h_{\text{High}} = \left\{ \begin{array}{l} \text{Emis}^h_{\text{diff}} > 0, \ 1 \\ \text{Emis}^h_{\text{diff}} \leq 0, \ 0 \end{array} \right\} \tag{8}$$

Fast DC charging technology is a life vest among highway drives, and frequently driven cars and fast charging stations are spreading with accelerating investments globally. Therefore, throughout the analysis, a *charge-and-drive* assumption with DC fast charging, in which electric vehicle use is uniformly distributed over a year rather than following any charging and driving pattern, has been made. It should also be noted that DC charging causes inefficient battery capacity utilization and significant range reduction due to battery aging, discharge safety margins, and a state of charge of 80% (Wager et al. 2016).

However, given the impact of the charging profile on EV emissions (Brady and O'Mahony 2016), an additional analysis has been conducted to explore the best and the worst-case scenarios. In the best-case scenario, the EV (ë-C4) is presumed to be charged during the hour with the lowest electricity emission density of each day, while the worst-case scenario assumes charging during the hour with the highest

Table 4 Fuel consumption of the selected ICEVs (lt/100 km)(Citroen 2024; Volkswagen 2022)

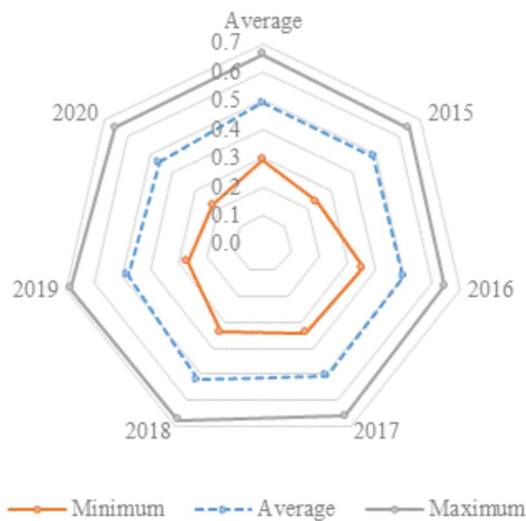| ICEV	Fuel type	Low	Medium	High	Extra high
Citroen C4 PureTech 130 SandS EAT8 8-speed auto Feel Plus	Diesel	5.7	4.8	4.3	5.4
Citroen C4 BlueHDi 130 SandS EAT8 8-speed auto Feel Plus	Gasoline	7.7	6.3	5.4	6.6
Golf-8 1.5 eTSI Gasoline DSG, 150 PS	Gasoline	7.6	5.4	4.9	5.9

emission density. Subsequently, the EV's hourly consumption has been calculated as previously described, and the resulting emissions have been compared with those of the diesel and gasoline counterparts.

Peak charging corresponds to charging when the electricity demand and price are high, and conversely, off-peak charging takes advantage of the lower price during nighttime. During peak periods, the electricity has reduced carbon intensity compared to off-peak periods. This is due to the high shares of coal combustion in the base load generation, while high demand periods rely on less carbon-intensive sources such as natural gas and dispatchable renewables (Hoehne and Chester 2016). As illustrated in Fig. 9, the highest average emission level was recorded at around 6 a.m., coinciding with the minimum demand level of the day, whereas the lowest emission level was observed at 7 p.m., corresponding to the peak hour within the analysis period. Therefore, the best and the worst-case scenarios coincide with the peak and off-peak charging profiles, respectively, which introduces an irony between being environmentally and economically conscious. Any other charging patterns would fall within the revealed range of this analysis.

Results

The annual average emission factors shown in Fig. 8 gradually increased until 2018. It reached its highest level, 0.52 tons CO_2/MWh, in 2018 and subsequently decreased to 0.46 tons CO_2/MWh in 2020, which was below the 2015–2020 period average. The minimum and maximum annual emission factors also follow similar trends. This rapid decrease was due to stationary electricity production

between 2018 and 2020, coupled with increased solar and wind generation investment, as Fig. 1 depicts. However, although the share of geothermal and wind power generation reached 11% and solar power generation was approximately 11 TWh in 2020, hydroelectricity is still the evident determinant of electricity emissions even though it does not emit any direct emissions. This is because thermal power generation compensates for decreased hydro performance due to the water regime, temperature, etc. (Isik et al. 2021).

Figure 9 shows the change in the average electricity emission factors between hours and months. The hourly distribution of the average emission factor can be distinguished as night and day since the emission factor gradually increases to 0.54 tons CO_2/MWh and decreases back to 0.5 tons CO_2/MWh between 0 a.m. and 8 a.m. and stays in the range of 0.5 tons CO_2/MWh and 0.46 tons CO_2/MWh between 9 a.m. and 11 p.m., on average. Additionally, the average monthly emission factor is compatible with hydro generation. Emission factors are above 0.5 tons CO_2/MWh between September and February and below 0.5 tons CO_2/MWh between March and August and drop to the minimum value of 0.41 tons CO_2/MWh in April, which is the month that has the highest hydro share.

ICEV emissions

Figure 10 shows the average emission levels of ICEVs during the study period to depict the baseline emissions for all the cases investigated. Compared to gasoline-C4, the GHG emission level of diesel-C4 is lower, excluding nitrogen oxides (NOx) and particulate matter (PM). The average emissions for diesel vehicle are around 16.2, 13.5, 12, and 15 kg CO_2/100 km, while gasoline vehicle emits 18.6, 15.1, 12.9, and 15.7 kg CO_2/100 km across low, medium, high, and extra high-speed profiles, respectively. However, the gasoline Golf emissions are lower than C4 gasoline emissions in all speed profiles and lower than diesel-C4 emissions except in the low-speed driving profile. The reason behind the dynamic of the Golf-8 may be contributed to better aerodynamic performance, lighter weight, and auxiliary system management.

ICEV emissions are affected by AC system use for cooling purposes above 23 °C temperatures. Consequently, the disparity in ICEV emissions across different cities is relatively narrow. Erzurum stands out with the lowest ICEV emissions due to its colder climate. The emissions increase as the average temperature of the cities rises. Compared to Erzurum, emissions in Antalya are 4% higher in the low driving profile and gradually diminish to 1% as the average speed increases. This outcome is due to the share of the AC load per km travelled, which is the highest at low-speed profile. Thus, the emissions tend to decrease as the
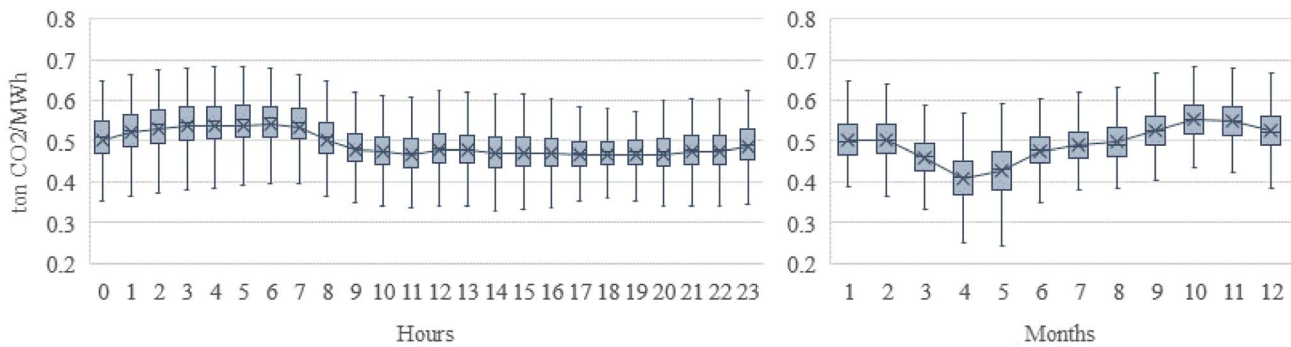
Fig. 9 Monthly and hourly distributions of the electricity emission factor during the period 2015–2020
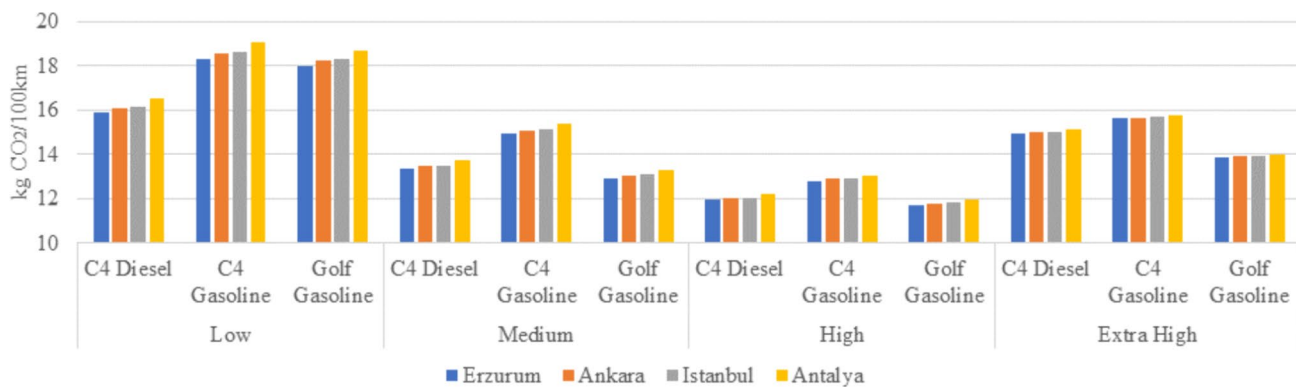

Fig. 10 Average emissions related to ICEVs during the study period

average speed increases, which the extra high driving profile reverses.

Similarly, emissions increase during the noon as the daily temperatures increase, particularly in Istanbul and Antalya, as shown in Fig. 11. The curvature of the line decreases as the average speed increases, and it tends to be a straight line in the extra high-speed driving profile, especially in Erzurum. Further details can be seen in the Supplementary Information in Figs. S2, S4, S7.

Local climatic effect

The increase in specific energy consumption of EVs under cold temperatures has been revealed via real-world driving tests in the literature (Al-Wreikat et al. 2022). In this study, the impact of ambient temperature on the emissions is compatible with these findings, and temperature is one of the key components of additional emissions due to battery performance and cabin comfort. However, other climate-related factors, such as wind, precipitation and snow, are not considered.

During the study, Antalya, characterized as the warmest city among those examined, exhibited the lowest emissions levels for EVs when the HVAC system was activated across all the driving profiles. However, as climatic conditions become colder, EV emissions gradually increase. Notably, for the Leaf, the average emission levels in Antalya and Istanbul during the study period displayed minimal
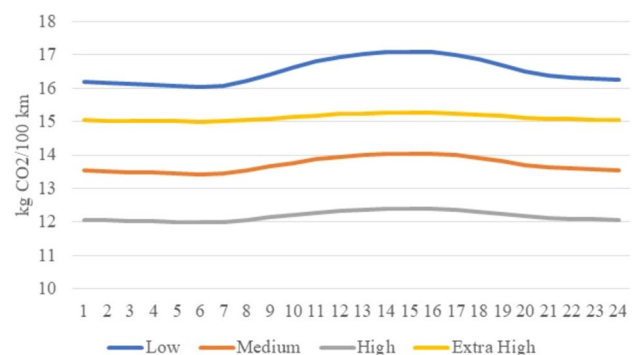

Fig. 11 Hourly average emissions of C4 diesel in Antalya during the study period

divergence, not exceeding a 2% disparity. Although the average temperature is lower in Istanbul, higher summer temperatures in Antalya increase fuel consumption due to the excessive requirement for HVAC use. In Ankara, the average emissions demonstrated a noticeable increase ranging between 6 and 15% from the extra high to low driving profiles, respectively. Besides, in Erzurum, the emissions exhibited substantial increases ranging from 15 to 33% compared to the levels observed in Antalya.

The results reveal that the trend in the performance of ë-C4 is consistent with the Leaf across all urban centers. Notably, ë-C4 exhibits a lower rate of increase in emissions, with figures indicating approximately 5% growth in Ankara and 10–16% growth in Erzurum. This phenomenon reflects the Leaf's higher increase in the SEC compared to ë-C4 in extreme temperatures, as illustrated in Fig. 7.

Consequently, the findings underscore the potential for emissions reduction with EVs in cities with milder climates across all driving profiles.

Driving profile effect

The overall study period summaries of the emission comparisons between EVs and ICEVs when the HVAC system is utilized are shown in between Figs. 12, 14. These figures suggest how often EV emissions exceed ICEV emissions in various driving profiles and locations.

In the context of the suburban (medium) driving profile, it becomes evident that EVs outperform ICEVs. Even though this driving profile represents the second-best in terms of energy consumption for ICEVs, the differences in emissions between ICEVs and EVs reach their peak level under the climatic conditions of any city. Therefore,

driving EVs under the medium speed driving profile yields the highest potential for emission reduction. Notably, ë-C4 exhibits superior emission performance in Istanbul and Antalya compared to gasoline-powered-C4 throughout the study period, as depicted in Fig. 12. Additionally, the instances where ë-C4 has higher emissions than diesel-powered C4 do not exceed 5% in these cities, and the same holds for Leaf and Golf, as depicted in Figs. 13, 14. In Ankara, the ratios are limited to 6%, 16%, and 20% of the time for EV comparisons with C4 gasoline, C4 diesel,
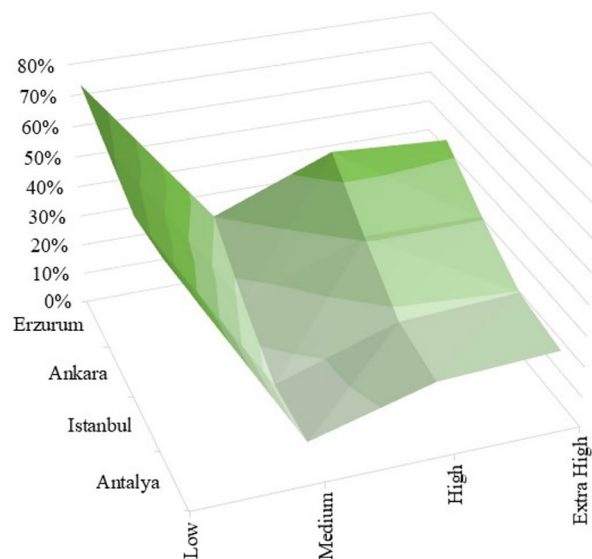

Fig. 13 The percentage of ë-C4 emissions that are higher than diesel C4 emissions across different speed profiles and cities
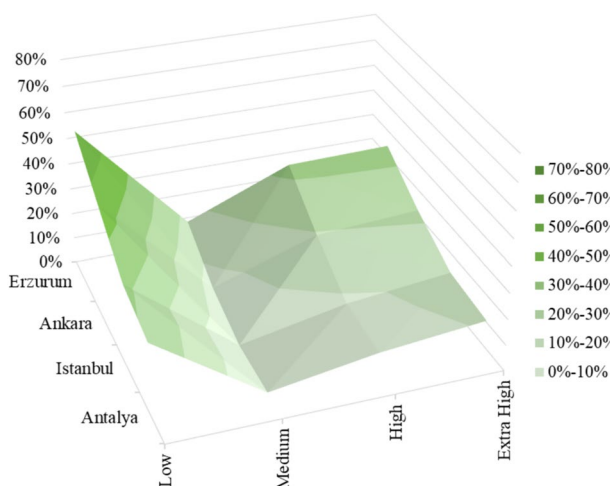

Fig. 12 The percentage ë-C4 emissions that are higher than gasoline C4 emissions across different speed profiles and cities
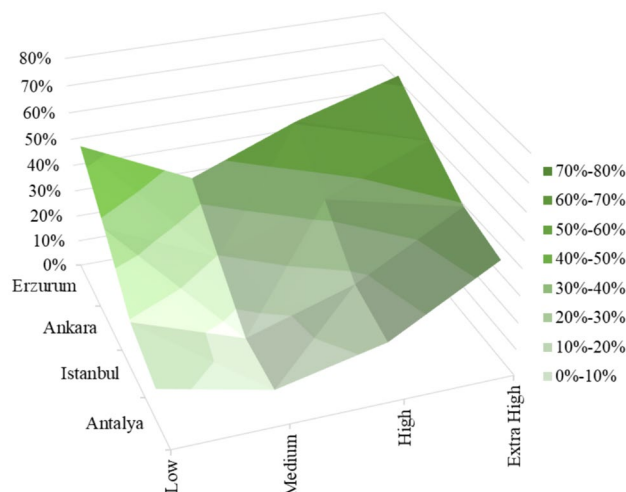

Fig. 14 The percentage of Leaf emissions that are higher than gasoline Golf 8 emissions across different speed profiles and cities

and Golf, respectively. However, these ratios increase in Erzurum, reaching 17%, 30% and 35%, respectively. Nonetheless, even with this increase, these ratios remain the lowest among all the driving profiles in the coldest city in the study.

While the medium driving profile proves to be the most favorable condition for all EVs, it is essential to acknowledge that for other driving profiles, a thorough evaluation becomes imperative. This is because vehicles exhibit distinctive responses to changes in speed and temperature, requiring careful consideration of their individual characteristics.

When comparing the emissions of the Leaf and the gasoline-powered Golf, low- and high-speed driving profiles yield similar emission performances. In the most challenging climate conditions, the Leaf emissions surpass those of the Golf in 54% and 51% of the study period in low and high driving profiles, respectively. Additionally, this ratio escalates to more than 60% in the extra high-speed profile, representing nearly twice the number of instances observed in the medium driving profile.

However, the driving dynamics differ in ë-C4, which exhibits the poorest emission performance in the low-speed profile. In Erzurum, gasoline vehicle emissions are lower than EVs 60% of the time, and the results are even more dramatic for diesel vehicle. In fact, during 80% of the study period, ë-C4 is unable to outperform diesel-C4, resulting in a substantial average emission difference that favors the diesel vehicle. Considering the entire study period, the average emissions emitted from ë-C4 surpass those of the gasoline-powered C4 only in Erzurum and Ankara within low-speed driving conditions. However, the emission gap between diesel C4 and ë-C4 remains consistent in favor of diesel vehicles across all cities, indicating that diesel vehicles emit remarkably less CO_2 under city center driving conditions. Even in Antalya, this trend persists, with ë-C4 producing higher emissions than diesel vehicle in 69% of the instances.

On the other hand, the performance of ë-C4 at high and extra high-speed profiles can be considered indifferent. In Erzurum, ë-C4 emissions exceed those of the gasoline-powered C4 in roughly 34% of the instances for both speed levels, while the ratio increases to 45% for diesel-powered C4.

HVAC effect

The utilization of HVAC systems constitutes a significant factor in the competition for emissions between vehicles and tends to favor ICEVs from an energy consumption perspective. For EVs, using an HVAC system results in increased energy consumption at temperatures other than the optimum temperature because of the additional energy requirement for cabin cooling and heating. In contrast, ICEVs benefit from the waste heat generated due to motor inefficiency, which is used for cabin heating, while the additional load is used only for cabin cooling at hot temperatures. Consequently, using HVAC systems leads to an increase in EV emissions, bringing them closer to, or in some cases, surpassing, ICEV emission levels. However, despite the additional energy requirement, comfort equipment is essential in real-life driving conditions, particularly at extremely cold and hot temperatures, to ensure driver and passenger comfort. This section analyzes the impact of HVAC systems on emissions by comparing the results with a scenario where HVAC is not used. This approach clearly demonstrates how HVAC systems influence emissions depending on the type of vehicle.

In the low-speed driving profile, the time required for each kilometer travelled; therefore, the energy consumption for HVAC usage is notably high for all types of vehicles. Consequently, in each city and for each vehicle type, activating the HVAC system leads to the highest increase in emissions in the low-speed profile, as illustrated in Fig. 15. As the speed increases, the energy required for comfort equipment decreases, resulting in a decrease in related emissions. On the other hand, the trend concerning the increase

Fig. 15 Increment of the emissions released due to the HVAC system during the overall study period
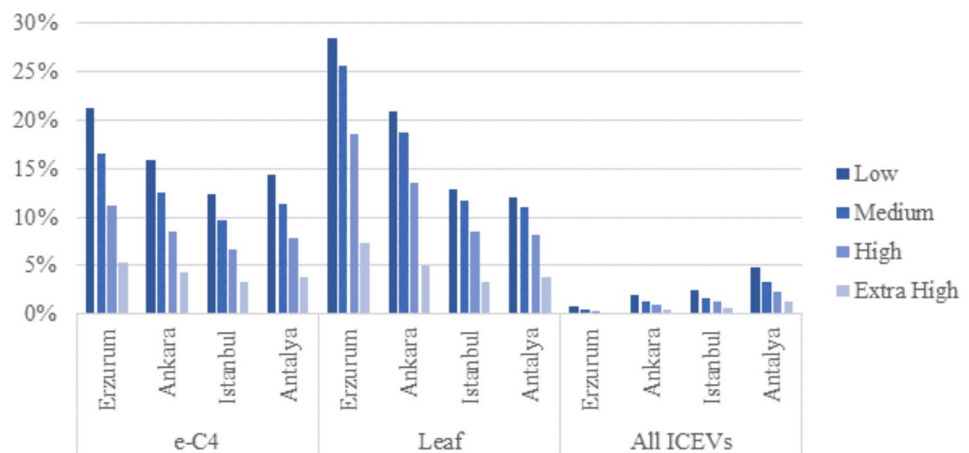
in emissions rate related to HVAC differs between ICEVs and EVs. For ICEVs, AC emissions tend to increase more as the climate becomes warmer. However, for EVs, HVAC consumption peaks in colder climates and decreases as the city's average temperature increases, reflecting the reduced need for HVAC under warmer conditions. However, for ë-C4, the increasing trend reverses in Antalya due to the extremely high temperatures prevalent in the region. A similar pattern occurs for Leaf driving at extra high speed in Antalya.

Figure 15 also highlights variations in how EVs respond to HVAC usage. While the rate of increase in emissions is higher for Leaf across all conditions, both EVs exhibit similar performances in mild climates. However, their performances differ at cold temperatures. For instance, in Erzurum, while ë-C4 emissions increase by 16% in the medium driving profile, Leaf's emissions increase by approximately 26%.

The increase in emissions due to HVAC use also corresponds to a shift upward in the frequency of instances where EV emissions surpass those of their ICEV counterparts. Figure 16 represents these fluctuations in the ratio. In line with the emission increases, for all three vehicle comparison cases, the highest increases in these ratios are observed in the cold climate cities. The additional percentage of these ratios decreases across all speed profiles as the climate becomes warmer.

Furthermore, considering that the increase in emissions from HVAC use is the highest in the Nissan Leaf, the EV exhibits the most significant change in the ratio of higher EV emissions across all three vehicle comparisons. This pattern diverges only in Erzurum and Ankara within the extra high driving profile. In these two cities, the ratio for Leaf and Golf comparison without HVAC usage is already notably high, almost twice that of the eC4 and C4 gasoline levels.

When the HVAC system is deactivated in the medium driving profile, where EVs perform best, all EV emissions become lower than those of ICEV counterparts throughout the entire study period in Istanbul and Antalya. In Ankara, although the ratios of HVAC are higher than those in mild cities, avoiding HVAC usage can reduce EV emissions to levels below those of ICEVs for almost the entire analysis period. Even in the coldest city, the number of instances where EV emissions exceed those from C4-diesel and Golf decreases significantly to just 7% from 30–35%. Additionally, compared to C4-gasoline, the EV competitor can maintain the emission advantage for the entire time in Erzurum without using an HVAC system.

For all the vehicle groups, the average difference in emissions between EVs and ICEVs decreases with HVAC use in each case. Therefore, EVs lose their emission advantage over their ICEV counterpart in cold-climate cities. The effect of the HVAC system is dramatic under driving conditions in which the EV emissions are at the highest level in both vehicle groups.

In addition to the HVAC system, auxiliary devices such as lighting, navigation and several optional comfort systems have a negligible effect on consumption (Al-Wreikat et al. 2022) and were not included in this analysis.

Hourly analysis

During the daytime, renewable energy sources have higher availability and reduced reliance on fossil fuels for electricity generation, leading to decreased electricity emissions. Consequently, electricity emissions exhibit an upward trend during the nighttime, peaking at around 5 a.m. and gradually declining after 8 a.m., as illustrated in Fig. 9. Additionally, temperature increments above the threshold, contributing to higher emissions from ICEVs, are observed during the daytime. Consequently, the potential for emission reduction with EVs is more significant during the daytime and diminishes
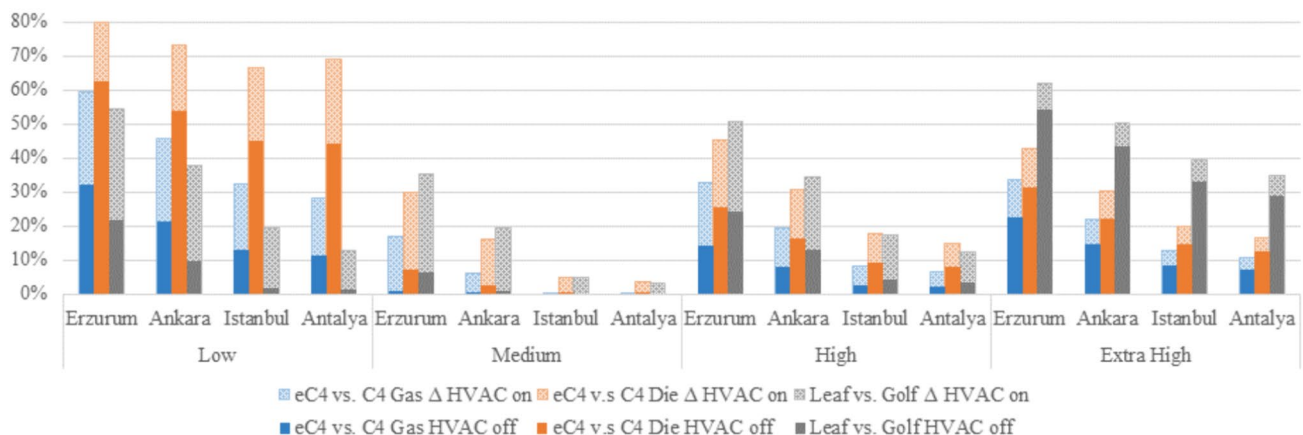

Fig. 16 Percent change in instances in which EV emissions are higher than ICEV emissions in the overall study period with HVAC use

from midnight to 8 a.m. As a result, using EVs during night-time may not provide the same emission advantages.

On the other hand, it is essential to consider that the various EVs demonstrate distinct characteristics under similar conditions, such as climate and speed level, as illustrated in Figs. S1, S6. Even though the Nissan Leaf seems more energy-consuming than the Citroen ë-C4, this general statement does not hold in all conditions. The analysis shows Leaf performs more efficiently in cities with mild climates, particularly in lower speed profiles. Hourly coverage favors the Leaf for most of the daytime uses. In contrast, the HVAC system of ë-C4 is observed to operate better under harsh climate conditions.

ë-C4 with Gasoline-C4 Comparison

As a result, ë-C4 consistently contributes to emissions reduction compared to gasoline-C4 in Antalya, Istanbul, and Ankara throughout the day, except in the low-speed profile, as shown in Fig. S3. While the reduction pattern is similar in the mild cities, with the average reduction exceeding 5 kg CO_2/100 km at medium speed between 9 a.m. and 10 p.m., it is lower at higher speed levels and during the nighttime.

In Ankara, the reductions are comparatively lower across all the speed profiles. Additionally, driving in the medium speed profile contributes to reduction even in Erzurum in all time slices. However, caution is advised for higher speed profiles due to a slight tendency to increase emissions at night.

On the other hand, the low-speed profile is strongly not recommended for nighttime use, especially in cold regions, for emission reduction purposes. Nighttime ratios of EV emissions surpassing gasoline vehicle emissions are predominant, ranging up to 90% and 77%, and cause increases in emissions of up to 5.6 and 3 kg CO_2/100 km on average in Erzurum and Ankara, respectively. Only after 9 a.m. do these ratios decrease below 50%, offering limited reduction potential, as shown in Fig. S9.

ë-C4 with diesel-C4 comparison

As the diesel emissions are lower than gasoline-C4, emission reduction of ë-C4 compared to diesel are less than those in the gasoline case. In mild climate cities, the average emission reduction persists throughout the day, yet the maximum abatement reaches only 3.7 kg CO_2/100 km in the medium speed profile, as shown in Fig. S5. Although the medium speed profile shows consistent emission avoidance in Ankara, higher speed profiles increase emissions at night. In the high and extra high-speed profiles, the EV emissions are higher than diesel, around 75% and 60%, respectively, of the time at night in Erzurum and Ankara, dropping to lower shares in the daytime. In mild climate cities, daytime EV use

at these speed profiles is highly likely (more than 90% of the time) to reduce emissions, as shown in Fig. S10.

In the low-speed profile, although the emission reduction possibility with ë-C4 compared to gasoline-C4 is more than 50% in the daytime, the mean emission difference between ë-C4 and diesel-C4 is consistently positive throughout the day in all cities. The average emissions increase to 8 kg CO_2/100 km in Erzurum at 5 a.m. since ë-C4 causes more emissions at 95% of the study time. Hence, emission reduction with ë-C4 compared to diesel is unlikely under these conditions.

Leaf and Golf Comparison

The energy consumption profile of Leaf differs from that of ë-C4 and rapidly worsens at low speeds as the ambient temperature decreases, as shown in Fig. 7. Therefore, the EV causes a significant emission increase compared to Golf in Erzurum between 6 p.m. and 9 a.m., which peaks at 6 kg CO_2/100 km. Additionally, the reduction available from morning to evening is very limited. However, the EV performance improves as the city's average temperature increases. Indeed, the highest emission reduction potential is observed in the low-speed driving profile in mild climates where it reaches 5.6 kg CO_2/100 km in Antalya, as shown in Fig. S8. The reduction rate at medium speed is close to the low driving profile and decreases as the city gets colder. In mild climate cities, the reduction is possible all day long except for the marginal increases in the extra high-speed profile at nighttime.

Additionally, caution is advised in high and extra high-speed profiles, especially at night, as EV emissions may surpass ICEV emissions, posing potential risks for emission reduction efforts. Driving Leaf in the motorway profile increases the emissions over 90% of the nighttime in Erzurum, and the ratio is 70% even in the mild climate, as shown in Fig. S11.

Monthly analysis

The electricity emissions are at their lowest level in April and increase to their maximum in November. Therefore, the opposite case holds for the emission abatement potential of EVs, and April and May offer the highest abatement levels.

The monthly emission distributions of the C4 variants and their differences are shown in between Figs. S12, S16, and the ratios of higher EV emissions are depicted in Figs. S20, S21. For ë-C4 and C4-gasoline comparison, in the medium driving profile, the emission abatement potential is spread to all months and all cities in the analysis, except for the more than 50% higher EV emission ratio of Erzurum in December and January. On the other hand, diesel vehicle regains the emission reduction advantage of ë-C4 for four months

between November and the end of February with a ratio of up to 80%.

In the city center driving profile, which is the condition that emission differences between electric and conventional fuel C4s are at the highest level, emission reduction with the EV is not possible after four months starting in October compared to the gasoline-C4, in Erzurum, and the average increase in emissions reaches 9 kg CO_2/100 km. In these months, the share of EVs that emit more emissions than the gasoline counterpart is higher than 50% in all the remaining cities. Furthermore, ë-C4 emissions are higher than diesel-C4 emissions in all the cities after nine months, starting from July, more than 50% of the time. In Erzurum, only in May do the emissions of diesel-C4 and EV meet at the breakeven point, and for the rest of the year, EV cannot be considered an abatement technology. In January, the average emission increase is 12 kg CO_2/100 km in Erzurum. Even under warm climatic conditions, only three months starting from April, EV generates less emissions than diesel vehicle more than half of the time.

Nonetheless, in the high and extra high-speed driving profiles, the EV is promising for emission abatement during all months in warm cities, compared to both C4-gasoline and C4-diesel vehicles, where the winter ratios are approximately 40%. Additionally, the emission abatement potential of the EV in cold climate cities is very close to that in warm climate cities except between October and the end of February, when EV emissions are higher than gasoline and diesel emissions, with percentages up to 80% and 90%, respectively.

The monthly emission distributions of Leaf and Golf and their differences are shown in between Figs. S17, S19, and the ratios of higher Leaf emissions are depicted in Fig. S22. While in C4 comparisons, the ratios of higher EV emissions are above 90% of the time in only the low driving profile, the ratios for Leaf emissions are higher than 90% between November and February in the low, high and extra high driving profiles in Erzurum. Even in the medium driving profile, the ratios are close to 90% in December and January. The average increase in emissions in these months is greatest in the low driving profile at 10 kg CO_2/100 km, 5.4 at extra high, 4.9 at the high driving profile and 3.6 kg CO_2/100 km in the medium driving profile in January. However, the abatement potential of Erzurum in other months gets closer to that of other cities. Ankara ratios are above or close to 90% in December and January in the low and high driving profiles, respectively, and November is added to the list in the extra high driving profile, and average incremental emissions are approximately 5.5, 3, and 2.3 kg CO_2/100 km in these driving profiles, respectively.

In the medium speed profile in Antalya, the monthly average emission differences indicate a reduction throughout the year, between 6 kg CO_2/100 km in May and 2 kg CO_2/100 km in January. According to the overall ratios, EV offers an absolute reduction between March and November. Nevertheless, the highest reduction is observed in low-speed profile at 6.8 kg CO_2/100 km in May, although the January and December average differences are at the breakeven point.

The highest average reduction in the high-speed profile is 3.9 kg CO_2/100 in May. In December and January, the average emission difference is very close to the breakeven point, even though the higher EV emission ratios are less than 40%. Still, between April and September, the high-speed profile has a rigid reduction possibility. On the other hand, in extra high-speed profile, the ratios are between 60 and 70% between October and February, and the emission differences indicate an increase in emissions of up to 1 kg CO_2/100 in December. The highest reduction in this driving profile is 3 kg CO_2/100 in April. In all the speed profiles, Istanbul follows a similar dynamic as Antalya but offers less reduction.

Annual analysis

The electricity emission factor was at its highest level in 2018; therefore, EV-related emissions also increased during that year. However, the annual average temperature is also the highest during the study period, as shown in Fig. 17. Additionally, Fig. 18 shows that, in 2018, while the number of time slices in cold temperatures around 0 °C, which increases EV's energy consumption, decreased the most, hours with warm temperatures that EVs operate at the optimum level are increasing, compared to 2015. This change generates a convenient environment for EVs, leads to more efficient battery operation, and decreases energy consumption. Therefore, although the emission reduction potential of EVs is declining because of the high emission factor, this decline is limited due to temperature changes.

In 2019 and 2020, while overall electricity production did not increase significantly due to the pandemic, the share of hydroelectricity increased, and the share of other renewable resources was on the uptrend. Therefore, EVs became advantageous in terms of emissions due to the decline in the electricity emission factor—for example, the annual average reduction of Leaf, as shown in Fig. 17b.

The annual emission reduction distributions are shown in Figs. S24, S25, and the ratios of EVs with higher emissions are shown in between Figs. S26, S28.

Charging profile analysis

Under the worst-case scenario, corresponding to off-peak charging, average diesel vehicle emissions demonstrate
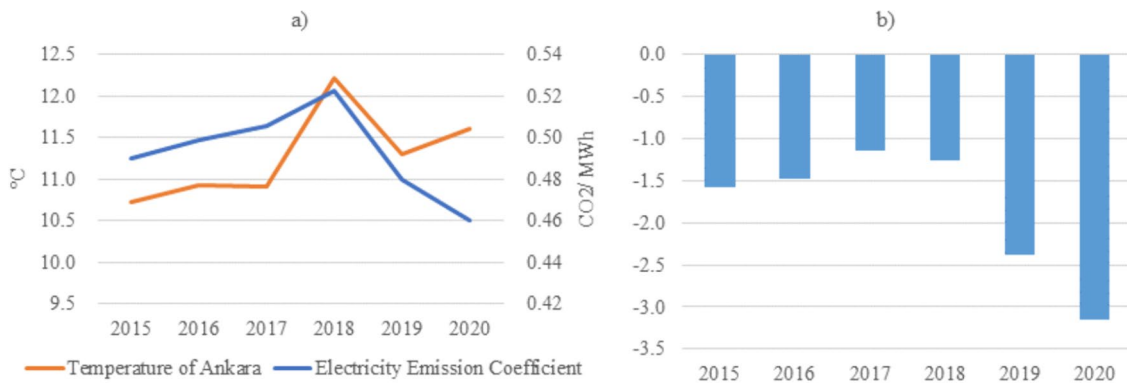
Fig. 17 **a** Annual average: electricity emission coefficient and temperature of Ankara and **b** annual average difference between Leaf and Golf emissions (kg CO_2/100 km)
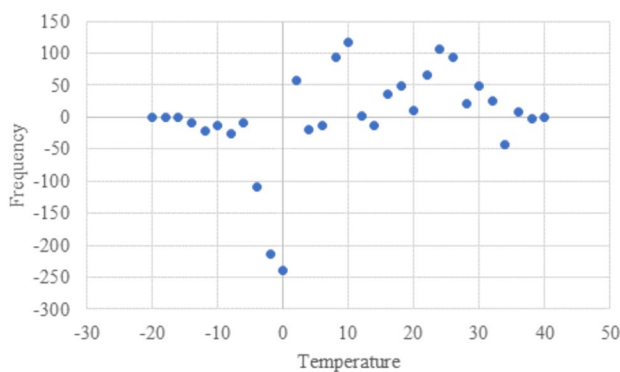

Fig. 18 Frequency of the change in temperature (°C) in Ankara from 2015 to 2018

lower values than the EV's at the low-speed profile across all cities. For the high and extra high-speed profiles, both vehicles exhibit analogous average emissions in all cities, but diesel emissions become lower only in Erzurum. Solely at medium speed, the EV manages to maintain its advantage in all cities except during nighttime in Erzurum, where the need for HVAC usage is reduced. This implies that EV driving may not offer a significant advantage over diesel vehicle in the city center or intercity transport for economical conscious charging.

Besides, when charging with the minimum emission level, average EV emissions become lower or similar to the diesel vehicle emissions in all cities (except the low speed at cold climate). However, since the minimum emission level occurs during peak hours, environmental gains are offset by higher charging costs and causes extra load on the grid. Although this analysis does not evaluate the infrastructural or financial aspects of the EV use, the findings indicate the importance of planning in the pathway of the emission reduction actions (Fig. 19).

According to a study investigating traffic density of Istanbul (AA 2020), the average speed typically hovered around 25 km/h in the morning, 30 km/h at noon and about 20 km/h in the evening from 2017 to 2019. The average speed in the evening closely aligns with the WLTP low-speed driving profile. As illustrated in Figs. 20, 21, in the best-case scenario, the emissions of both ICEVs fall within the emission range of EVs. Although the average emissions of the EV are lower than those of gasoline vehicle emissions, they remain indifferent to diesel vehicle. However, in the worst-case scenario, while the average gasoline emissions drop slightly below the average EV emissions, driving the diesel vehicle never emits more emissions than the EV average in any time slice of the day. Also, the daily average speed is reported to be around 30 km/h, which does not become close to the medium speed driving profile. This fact indicates that the drivers will not be able to use the most carbon-efficient speed range of the EVs due to city infrastructure bottlenecks most of the time.

The results of the other scenarios can be seen in supplementary information between Figs. S29, S44.

Even though the average emissions are a meaningful indicator for charging pattern comparison, one should keep in mind that the variation of the EV emissions is significant within each time slice during the study period. This demonstrates the need to carefully consider environmental factors (e.g., temperature) and driving (e.g., speed profile) conditions.

Discussion

Instead of the announced optimistic ranges, the ranges revealed in real-world driving conditions are the subject of this study to compare the actual emissions of different fuel-type vehicles. In that manner, the HVAC systems exhibit the highest power consumption among the auxiliary components, affecting EVs more than affecting ICEVs due to the efficiency
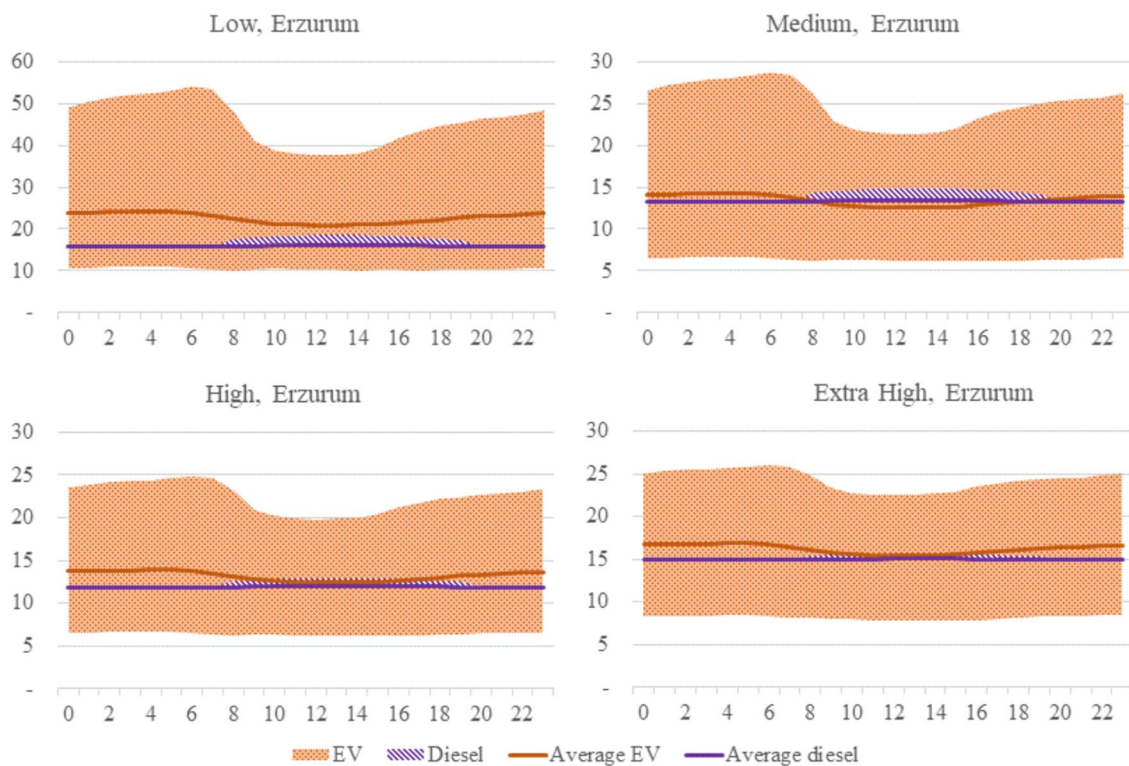
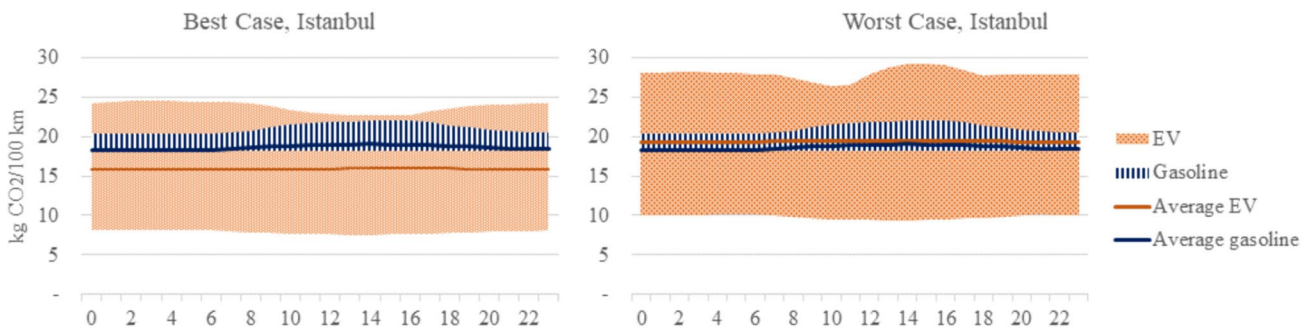**Fig. 19** Hourly emissions of ë-C4 and diesel C4 in Erzurum in the worst-case scenario

Fig. 20 Hourly emissions of ë-C4 and gasoline C4 in Istanbul at low-speed driving profile in the best- and worst-case scenarios
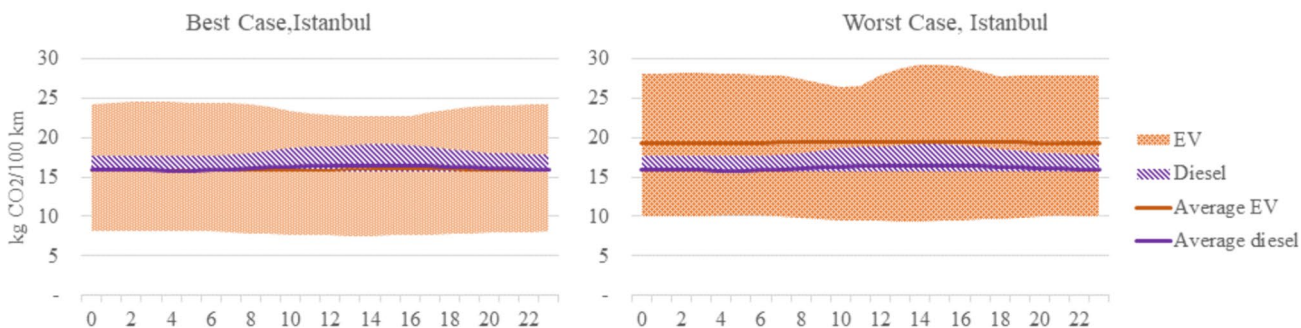

Fig. 21 Hourly emissions of ë-C4 and diesel C4 in Istanbul at low-speed driving profile in the best- and worst-case scenarios

ratios. According to Zhang et al., HVAC systems reduce the driving range of EVs by approximately 30–40%, depending on the size of the AC unit and the driving cycle (Zhang et al. 2018). Subiantoro et al. also claim that under tropic conditions, the AC system increases fuel consumption by 30% for ICEVs but decreases the range of EVs in urban driving by 40% (Subiantoro et al. 2014). In this study, the highest increase in emissions due to HVAC use is present for urban driving in Erzurum, with an overall increase of 21% for EVs, and in Antalya, with a 5% increase for ICEVs. Although the effect is not as high as that in the studies in the literature, the negative impact of HVAC on EVs is more significant than on ICEVs. Even though turning off the HVAC system seems to be a good option for increasing the ranges, when necessary, several concerns limit this approach. HVAC systems provide thermoneutral temperatures in the cabin, improving driving performance and ensuring safer driving conditions (Daanen et al. 2003). Therefore, developing alternative energy-efficient automobile AC systems that fit automobile standards and regulations is one of the challenges in this industry that would increase the ranges (Vashisht and Rakshit 2021).

The variation in EV-related emissions is mostly due to factors not primarily controlled, such as the ambient temperature, traffic conditions and renewable electricity generation (e.g., hydro). The uncertainty of hydropower is expected to cause fluctuations in electricity emissions due to the precipitation regime. In 2021, which is not included in the analysis period, overall electricity generation increased by 9.1%, around 28 TWh, while the hydropower generation decreased by 28%, approximately 22 TWh, as depicted in Fig. 1. The required energy was satisfied mainly by electricity generated from natural gas, with a 57% increase of 40 TWh to compensate for the increased demand. The increasing ratios of renewables satisfied the remaining energy needs. As a result, the average emission factor in 2021, calculated as 0.482 tons CO_2/MWh, is higher than that of 2020 and close to 2019. Additionally, the minimum emission factor throughout 2021 was increased to 0.324 tons CO_2/MWh, and the maximum value was 0.646 tons CO_2/MWh. Since 36% of the emissions are between 0.5 and 0.65 tons CO_2/MWh in 2021, the share of higher EV emissions is expected to be lower than that ratio.

On the other hand, when overall electricity production increases and the share of hydroelectricity decreases, as in 2021, the emission factor becomes the most critical parameter affecting EV emissions. Therefore, to overcome this disadvantage, the share of other renewables in the electricity generation mix should be increased to compensate for the lack of hydroelectricity in the near future.

Within the analysis period, 0.521 tons CO_2/MWh is the threshold electricity emission factor that causes EV emissions to be less than the conventional vehicle emissions for every instance under all the cases investigated. Although this value is more flexible for comparing EVs with gasoline-fueled vehicles, it must be lower for competition with diesel vehicles. On the other hand, 0.683 tons CO_2/MWh is the upper threshold observed under preferable conditions, which prevents EVs from mitigating any emissions compared to ICEVs. As expected, the maximum allowed value for electricity-related emissions is lower in Erzurum than in other cities by varying amounts, depending on the performance of the vehicles.

In the most crowded city of Türkiye, Istanbul, the CO_2 emissions released per kilometer from carrying a passenger with a metro line were reported to be 32.33 g/passenger-km in 2019, according to data from the Metro Istanbul Company (Istanbul 2021). Although the unit emissions increased to 55 g/passenger km in 2020 due to the pandemic, they are anticipated to decrease in recent years. Assuming a 1.2 occupancy rate, the minimum, average and maximum emissions released from EVs in Istanbul in 2019, considering low and medium speed profiles, are illustrated in Fig. 22. The low-speed profile corresponds to rush hours in a metropolis such as Istanbul, while the average speed may increase to medium levels during other time slices. In this comparison, even under the best conditions in a city with a mild climate, both EVs result in higher emissions than does public rail transport, especially during rush hours. Therefore, on the pathway to net zero emissions, subsidizing EVs for urban transport should be undertaken without discouraging the use of public transport.

The personal car segment is expected to experience rapid growth in the upcoming years, driven by the country's developing economy and relatively low private vehicle ownership ratio. EVs are expected to play an essential role in reducing carbon emissions in accordance with the commitments under the Paris Agreement. EVs also contribute to reduced local pollution levels. However, it is important to remember that, in some cases, even though EVs emit less CO_2 emissions than ICEVs, indicating a relative reduction in emissions due to this technology, the emissions released are not zero; they are still positive. Therefore,
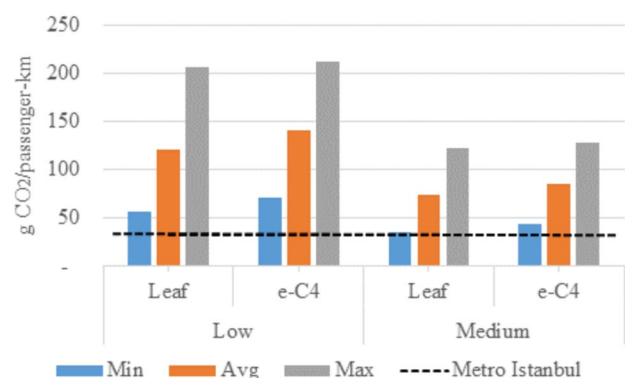

Fig. 22 CO_2 emissions released by carrying a passenger per km (g/passenger-km) with EVs at the low and medium speeds vs. metro lines in Istanbul in 2019

achieving the zero emissions target necessitates reducing the carbon intensity of the electricity grid where charging occurs. In other words, transitioning to cleaner and more sustainable electricity sources is critical to achieving net zero emissions in the transport sector, which will require capital-intensive investments. However, through this pathway, as renewable resources have limitations, demand-side management becomes a crucial factor that should not be underestimated. Balancing cleaner energy sources and effective demand-side strategies is essential for achieving long-term environmental goals in transportation.

As the adoption of EVs increases, the carbon intensity of the electricity factor can increase due to marginal demand being met by fossil fuels. In that matter, the charging patterns of EVs become a critical factor to consider. EV-related emissions have already tended to be higher than those of ICEVs at nighttime, particularly in colder regions. Hence, the greater penetration of EVs could potentially further elevate EV emissions unless strategic investments are carried out in low-carbon power generation infrastructure available during nighttime hours. Balancing the growth of EVs with a transition to cleaner energy sources is essential for mitigating the environmental impact of increased EV usage.

Despite the study's assumption of simultaneous charging and driving with fast charging, the analysis of the charging profile shows the timing of charging also plays a significant role. The analysis reveals the challenges associated with EV investments from an environmentally conscious standpoint. While cost-oriented users drop back in contribution to emission reduction, environmentally conscious users may face economic burdens. To contribute emission reduction through charging during off-peak periods, it's essential to maintain low-emission electricity production. There are two primary approaches to achieving this goal. Firstly, focusing on renewable energy sources such as wind farms and hydroelectricity, where a distributed production profile contributing to off-peak time slices can be obtained, is crucial. However, since hydroelectricity production depends on the rainfall regime, integrating wind energy into production seems to be a more promising option. Secondly, investing in storage technologies to utilize the excess solar energy production during the daytime to balance the production composition during the off-peak hours is vital for the environmentally friendly charging of EVs during off-peak periods. Prioritizing between these two options emphasizes the need to focusing wind energy for cost-effectiveness and considering the combined use of solar and storage technologies when wind energy alone is insufficient.

Several other factors pose challenges for EVs. According to Yang et al. (2018), battery degradation increases energy consumption and GHG emissions by approximately 11.5–16.2% in various US states. While this study does not account for the capacity loss effect, it is crucial to acknowledge that this factor will likely increase energy consumption and EV-related emissions over the years. In addition,

according to the Eco Best Challenge, real-world ranges of EVs operating under actual traffic conditions are lower than the WLTP ranges. In particular, the effect of the inclination can be high depending on the route used.

Moreover, an alternative analysis considering marginal electricity emissions rather than average emissions would likely result in higher emissions from EVs in Türkiye. Hence, it is reasonable to conclude that the actual CO_2 emission reduction potential of EVs might be more conservative or less optimistic than the results presented in this study. These factors emphasize the importance of considering various aspects when assessing the environmental impact and practicality of EVs.

Conclusions

This study compares CO_2 emissions from three different propellant variants of the same vehicle. Besides, two popular automobiles, one electric and the other gasoline-powered, within the small family car segment are compared. The same vehicle setup allows us to show the pure effect of engine type, and the other setup provides insights into how changes in vehicle bodies and auxiliary systems impact the parameters of interest. The constructed model is fed by hourly temperature and primary electricity generation mix data between 2015 and 2020. The analysis identifies the specific conditions and time frames in which EVs are anticipated to contribute to emissions reduction compared to ICEVs within the context of Türkiye.

Under the *charge-and-drive* assumption, local climatic conditions are critical for EV's emission reduction capabilities.

- Cold climate hits the EVs the most, reduces their driving range, and increases the energy intensity. Thus, independent of the electricity generation mix, it significantly hurts the environmentally friendly tag.
- When the sun is down, drivers should know that environmental benefits are minimized coupled with other factors.
- Winter is not the right time to drive an EV for GHG reduction; renewable generation is low, and coal and natural gas dominate, besides batteries being hurt from cold weather.
- Spring and summer are the best time for environmentally conscious driving due to the electricity generation mix and the effect of the temperature on the battery.
- Despite the expectation that EVs are always environment-friendly in all driving environments, diesel vehicles emit less carbon than their EV counterparts under heavy traffic.
- EV fits the town or suburban driving, with a 39.5 km/h average speed, the most for environmentally conscious ownership.

- For the net zero pathway, EVs are far lagging behind metro lines and are not expected to close the lap any time soon.
- The emission factor of electricity generated around 0.521 ton CO_2/MWh makes EVs identical to diesel vehicles; for gasoline, it may be higher.
- A well-designed ICEV (e.g., Golf) using advantageous technology parameters (weight, aerodynamics, auxiliary), which affect the fuel consumption in the right way, may overwhelm the EVs in the fight of emission mitigation.

In the case of *decoupled charging and driving*,

- In terms of emission intensity, the possible worst-case charging happens to be at the off-peak period, while the best-case charging is around peaking time frames.
- EV users face a trade-off between environmental concerns and their wallet.
- The worst-case charging scenario reveals that the emission mitigation potential of EVs in most cases is worse than ICEV counterparts, on average, if not nearly identical.
- The best-case charging scenario offers a brighter performance than ICEVs, but the city center driving is questionable.
- Any incentive to realize the best-case charging scenario would help the emission mitigation potential of EVs.
- Investment in wind power plants should be a priority to reduce the emission intensity of off-peak periods.
- Following solar capacity expansion, storage technology investments would be another but more expensive option that utilizes excess solar power.

In conclusion, EVs are not the panacea as widely known; however, they should be regarded as valuable technologies that can contribute to emission reduction under specific conditions. Therefore, policymakers must carefully consider factors such as charging/discharging time as well as traffic conditions and align infrastructure investments and policies accordingly. In the short term, incentivizing factors such as daytime charging and driving, mild temperature conditions, and suburban driving profiles can be essential in maximizing the effectiveness of EVs in emissions reduction. However, in the long term, the abatement potential of EVs on the pathway to net zero emissions depends on the decarbonization of the electricity grid.

Declarations

References

AA (2020) İstanbul trafik otoritmi raporu açiklandi. https://www.aa.com.tr/tr/sirkethaberleri/egitim/istanbul-trafik-otoritmi-raporu-aciklandi/660063

Al-Wreikat Y, Serrano C, Sodré JR (2022) Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle. Energy 238:122028. https://doi.org/10.1016/j.energy.2021.122028

Brady J, O'Mahony M (2016) Modelling charging profiles of electric vehicles based on real-world electric vehicle charging data. Sustain Cities Soc 26:203–216. https://doi.org/10.1016/j.scs.2016.06.014

Challa R, Kamath D, Anctil A (2022) Well-to-wheel greenhouse gas emissions of electric versus combustion vehicles from 2018 to 2030 in the US. J Environ Manag. https://doi.org/10.1016/j.jenvman.2022.114592

Citroën (2022) Yeni elektrikli citroën ë-C4. Retrieved December 26, 2022, from https://www.citroen.com.tr/araclar/c4/c4-elektrik.html

Citroen (2022) Passenger vehiclesprice list. https://www.citroen.co.uk/content/dam/citroen/uk/b2c/tools/brochure/pdf/price-lists/Citroen-Car-Price-List.pdf

Citroen (2024) Citroen eC4 and C4 prices and specifications. https://indd.adobe.com/view/5454d815-8c37-4471-9e86-64695e6fcedc

European Commission (2022) CO_2 emission performance standards for cars and vans. Retrieved December 22, 2022, from https://climate.ec.europa.eu/eu-action/transport-emissions/road-transport-reducing-co2-emissionsvehicles/co2-emission-performance-standardscarsand-vans_en

Daanen HAM, Van De Vliert E, Huang X (2003) Driving performance in cold, warm, and thermoneutral environments. Appl Ergon 34(6):597–602. https://doi.org/10.1016/S0003-6870(03)00055-3

Donateo T, Licci F, D'Elia A, Colangelo G, Laforgia D, Ciancarelli F (2015) Evaluation of emissions of CO2 and air pollutants from electric vehicles in Italian cities. Appl Energy 157:675–687. https://doi.org/10.1016/j.apenergy.2014.12.089

Eberhard M, Tarpenning M (2006) The 21st century electric car tesla motors.

EPIAS (2022) EXIST Transparency Platform. Retrieved December 21, 2022, from https://seffaflik.epias.com.tr/transparency/uretim/gerce klesen-uretim/gercek-zamanli-uretim.xhtml

General Directorate of Energy Affairs (2022) Energy balance sheets. Retrieved December 23, 2022, from https://enerji.gov.tr/eigm-raporlari

Girardi P, Gargiulo A, Brambilla PC (2015) A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. Int J Life Cycle Assess 20(8):1127–1142. https://doi.org/10.1007/s11367-015-0903-x

Graff Zivin JS, Kotchen MJ, Mansur ET (2014) Spatial and temporal heterogeneity of marginal emissions: implications for electric cars and other electricity-shifting policies. J Econ Behav Organ 107:248–268. https://doi.org/10.1016/j.jebo.2014.03.010

Hoehne CG, Chester MV (2016) Optimizing plug-in electric vehicle and vehicle-to-grid charge scheduling to minimize carbon emissions. Energy 115:646–657. https://doi.org/10.1016/j.energy.2016.09.057

Holdway AR, Williams AR, Inderwildi OR, King DA (2010) Indirect emissions from electric vehicles: emissions from electricity generation. Energy Environ Sci 3(12):1825. https://doi.org/10.1039/c0ee00031k

IEA (2017) World energy balances database. http://data.iea.org

IEA (2022a) Electric vehicles. https://www.iea.org/reports/electric-vehicles

IEA (2022b) World energy outlook 2022. https://www.iea.org/reports/world-energy-outlook-2022

Iora P, Tribioli L (2019) Effect of ambient temperature on electric vehicles' energy consumption and range: model definition and sensitivity analysis based on nissan leaf data. World Electric Vehicle J 10(1):2. https://doi.org/10.3390/wevj10010002

IPCC (2006) Guidelines for national greenhouse gas inventories, energy, stationary combustion. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

Isik M, Ari I, Sarica K (2021) Challenges in the CO2 emissions of the Turkish power sector: evidence from a two-level decomposition approach. Utilities Policy 70:101227. https://doi.org/10.1016/j.jup.2021.101227

Istanbul M (2021) Surdurulebilirlik raporu. https://www.metro.istanbul/Dosyalar/efqm/surdurebilirlik_raporu.pdf

Jochem P, Babrowski S, Fichtner W (2015) Assessing CO 2 emissions of electric vehicles in Germany in 2030. Transportation Research Part a: Policy and Practice 78:68–83. https://doi.org/10.1016/j.tra.2015.05.007

Kamiya G, Axsen J, Crawford C (2019) Modeling the GHG emissions intensity of plug-in electric vehicles using short-term and long-term perspectives. Transp Res Part D: Transp Environ 69:209–223. https://doi.org/10.1016/j.trd.2019.01.027

Karabasoglu O, Michalek J (2013) Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains. Energy Policy 60:445–461. https://doi.org/10.1016/j.enpol.2013.03.047

Ma H, Balthasar F, Tait N, Riera-Palou X, Harrison A (2012) A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. Energy Policy 44:160–173. https://doi.org/10.1016/j.enpol.2012.01.034

Mehlig D, ApSimon H, Staffell I (2022) Emissions from charging electric vehicles in the UK. Transp Res Part D: Transp Environ 110:103430. https://doi.org/10.1016/j.trd.2022.103430

Nissan. (2022) Leaf brochure. Retrieved December 22, 2022, from https://www-europe.nissan-cdn.net/content/dam/Nissan/gb/brochures/Vehicles/Nissan_Leaf_UK.pdf

Nissan (2022) Range calculator. Retrieved December 22, 2022, from https://leaf-range-calculator.nissan.co.uk/en_uk/uk/autonomy

Onat NC, Kucukvar M, Tatari O (2015) Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. Appl Energy 150:36–49. https://doi.org/10.1016/j.apenergy.2015.04.001

Qiao Q, Zhao F, Liu Z, Hao H, He X, Przesmitzki SV, Amer AA (2020) Life cycle cost and GHG emission benefits of electric vehicles in China. Transp Res Part D: Transp Environ 86:102418. https://doi.org/10.1016/j.trd.2020.102418

Renewables.ninja (2020) Weather, air temperature, MERRA-2 dataset

Sagaria S, Neto RC, Baptista P (2021) Modelling approach for assessing influential factors for EV energy performance. Sustain Energy Technol Assess 44:100984. https://doi.org/10.1016/j.seta.2020.100984

Steinstraeter M, Heinrich T, Lienkamp M (2021) Effect of low temperature on electric vehicle range. World Electric Vehicle J 12(3):115. https://doi.org/10.3390/wevj12030115

Subiantoro, A., Ooi, K. T., and Stimming, U. (2014). Energy saving measures for automotive air conditioning (AC) system in the tropics. http://docs.lib.purdue.edu/iracc

Turconi R, Boldrin A, Astrup T (2013) Life cycle assessment (LCA) of electricity generation technologies: overview comparability and limitations. Renew Sustain Energy Rev 28:555–565. https://doi.org/10.1016/j.rser.2013.08.013

Turkish State Meteorological Service (2020) State of the Turkey's climate in 2020. https://www.mgm.gov.tr/eng/yearly-climate.aspx?year=2020

Turkish State Meteorological Service (2021) Average temperature of Turkey.

UNECE (2021) UN regulation no. 154 - worldwide harmonized light vehicles test procedure (WLTP). https://unece.org/sites/default/files/2021-08/R154e.pdf

Vashisht S, Rakshit D (2021) Recent advances and sustainable solutions in automobile air conditioning systems. J Cleaner Prod 329:129754. https://doi.org/10.1016/j.jclepro.2021.129754

Volkswagen (2022) The Golf 8. Retrieved December 25, 2022, from https://www.volkswagen.co.uk/en/new/golf.html

Wager G, Whale J, Braunl T (2016) Driving electric vehicles at highway speeds: the effect of higher driving speeds on energy consumption and driving range for electric vehicles in Australia. Renew Sustain Energy Rev 63:158–165. https://doi.org/10.1016/j.rser.2016.05.060

Weilenmann MF, Vasic A-M, Stettler P, Novak P (2005) Influence of mobile air-conditioning on vehicle emissions and fuel consumption: a model approach for modern gasoline cars used in Europe. Environ Sci Technol 39(24):9601–9610. https://doi.org/10.1021/es050190j

WLTP Test Procedure (2022) Retrieved December 22, 2022, from https://en.wikipedia.org/wiki /Worldwide_harmonised_light_vehicles_test_procedure

Wu D, Guo F, Field FR, De Kleine RD, Kim HC, Wallington TJ, Kirchain RE (2019) Regional heterogeneity in the emissions benefits of electrified and lightweighted light-duty vehicles. Environ Sci Technol 53(18):10560–10570. https://doi.org/10.1021/acs.est.9b00648

Yang F, Xie Y, Deng Y, Yuan C (2018) Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation. Nat Commun 9(1). https://doi.org/10.1038/s41467-018-04826-0

Xu B, Sharif A, Shahbaz M, Dong K (2021) Have electric vehicles effectively addressed CO2 emissions? Analysis of eight leading countries using quantile-on-quantile regression approach. Sustain Prod Consum 27:1205–1214. https://doi.org/10.1016/j.spc.2021.03.002

Global Modeling and Assimilation Office (2020) MERRA-2

Yuksel T, Michalek JJ (2015) Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States. Environ Sci Technol 49(6):3974–3980. https://doi.org/10.1021/es505621s

Zhang Z, Wang J, Feng X, Chang L, Chen Y, Wang X (2018) The solutions to electric vehicle air conditioning systems: a review. Renew Sustain Energy Rev 91:443–463. https://doi.org/10.1016/j.rser.2018.04.005

Authors and Affiliations

Esin Tetik Kollugil[1] · Kemal Sarıca[2] · Y. Ilker Topcu[1]

✉ Esin Tetik Kollugil
 tetikes@itu.edu.tr

[1] Department of Industrial Engineering, Istanbul Technical University, Istanbul, Türkiye

[2] Department of Industrial Engineering, Gebze Technical University, Kocaeli, Türkiye