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An Updated Data-Driven Greenhouse Gas Emission Rate Analysis for Vehicle Comparisons Applied to Europe

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Abstract

This study presents a data-driven lifecycle assessment (LCA) framework for evaluating greenhouse gas (GHG) emissions from passenger vehicles across European electricity systems. The analysis compares battery electric vehicles (BEVs), full hybrid electric vehicles (FHEVs), and internal combustion engine vehicles (ICEVs) using both conventional average electricity emissions factors and time-resolved marginal emissions, referred to as real charging emissions (RCE). Hourly generation and interconnector/cross-border flow data for 2023 from 29 European countries are processed to estimate consumption-based marginal emissions rates that account for grid dispatch behavior and cross-border electricity flows. The approach is applied to two vehicles where multiple powertrains are available on the same platform, the 2024 Hyundai Kona (available as a BEV, FHEV, and ICEV) and Peugeot 2008 (available as a BEV and ICEV), to isolate drivetrain-related lifecycle differences. Results show substantial divergence between average and marginal emissions estimates, with a mean absolute difference in BEV–FHEV lifecycle emissions of 31–36 g CO_2 eq/km across Europe. In several countries with carbon-intensive marginal generation, including Poland and Cyprus, BEVs may exhibit higher lifecycle emissions than comparable hybrids, while low-carbon grids such as Norway, Sweden, and France provide large BEV advantages. Sensitivity analyses demonstrate the importance of transmission losses, temperature effects, electricity imports, and charging timing. These findings highlight the limitations of average grid emissions factors in vehicle LCAs and underscore the importance of geographically and temporally resolved data-driven electricity emissions when assessing electrified vehicle climate impacts.

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Introduction

As the global powertrain fleet becomes more diversified, methods for comparing the environmental impact of different types of vehicles become ever more important. When it comes to climate change, the importance of reducing greenhouse gas (GHG) emissions from the vehicle fleet is vital. Today, almost all regulations specify the measurement of emissions at the vehicle tailpipe [1]. This made sense, historically, when the vast majority of emissions came from the tailpipe. However, today, many vehicles, such as Battery Electric Vehicles (BEV), do not have a tailpipe, yet still have emissions associated with them. Indeed, for some vehicles with tailpipes, such as Full Hybrid Electric Vehicles (FHEV) and Internal Combustion Engine Vehicles (ICEV), non-exhaust emissions are higher than their exhaust emissions [2].

In order to fairly compare vehicle's environmental impact, life cycle analysis (LCA) has become the dominant method. Although LCA is not considered in legislation today, it is likely that it will be in the future. For example, the European Commission [the executive arm of the European Union (EU)], in 2021, stated that it was uncertain that a standard approach could be developed for a regulatory environment [3]; however, it issued a call for evidence in 2024, indicating that it was considering modifying its legislation to include LCA [4] and committing to publishing a methodology for calculating it by the end of 2025 [5]. Similarly, the United Nations Economic Commission for Europe (UNECE) is working on a methodology for LCA, which would be a foundation upon which legislation could be built [6].

A typical LCA considers the emissions produced by the following stages of the vehicle's life: fuel production and distribution (sometimes referred to as well-to-tank), raw materials sourcing, material processing, vehicle production, vehicle use (tank-to-wheel), and disposal/recycling. This is not the only approach, and recently alternatives have been proposed to radically simplify the assessment of the environmental impact of vehicles [7]; however, LCA is regarded as the most accurate method, although subject to some uncertainty.

The uncertainty in LCA often occurs due to challenges associated with evaluating the emissions associated with the raw materials sourcing, car production, and recycling and disposal phases of a vehicle's life [8]. Many of the emissions from both production and use of a vehicle are associated with electricity production. Therefore, the electricity emission rate is possibly the term that requires the highest accuracy in the calculation of total GHG emissions for an LCA [9].

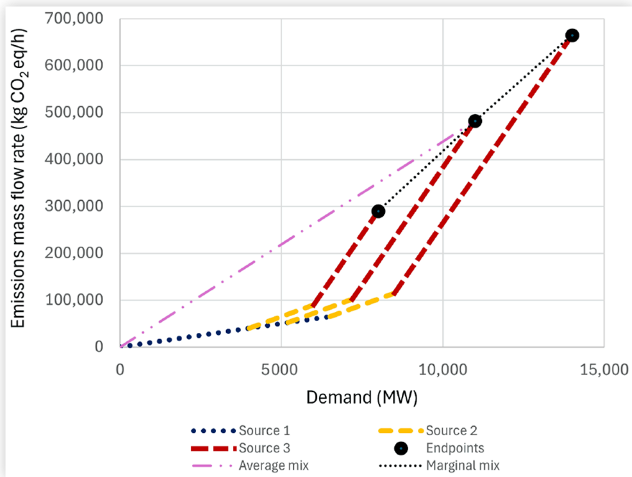
Most LCAs adopt the so-called average emissions rate. This rate takes the emissions rates for each individual source on a grid and averages them weighted by their relative production on that grid over some time period (usually a year). This method is attractive because of its simplicity and ease of calculation. This approach is usually used in LCAs when accounting for the emissions associated with BEVs [10, 11]. This approach assumes that a grid is of fixed composition and that all loads on the grid receive the average emissions; however, this is not how grids actually work. In reality, sources are turned on and off to match supply and demand. The order in which different sources are turned on and off depends primarily on their cost (known as economic dispatch), but also on their ramp-rate (the speed at which they can come on- and offline, known as dispatch) [12]. Economic dispatch, for many sources such as gas (whether CCGT or a gas peaker plant), is often determined by a combination of spark spread (similar terms such as dark spread, quark spread, and bark spread exist for sources other than gas) and power plant efficiency [13]. An alternative approach to calculating emissions rates is to consider the specific emissions of the power source added to the grid in order to meet a new demand. This approach is often known as the marginal emissions rate, or more recently real charging emissions (RCE).

The marginal emissions rate can either be calculated in the abstract (for example, answering the question "what if a BEV were charged by solar power or coal power?") by using the emissions rate for a specific power source [14]. Use of marginal emissions can result in markedly different results compared to average emissions. For example, Garcia et al. found that using a marginal calculation method resulted in a BEV having more than double the LCA emissions compared to an average method [15]. Alternatively, today, high temporal resolution data about what sources are actually online on a particular grid at any given time are now available, such that this data can be used to obtain geographically and temporally resolved marginal emission rates that capture the real-world carbon emissions associated with present-day use of any particular grid. This approach was pioneered by many of this study's authors in a previous work [16]. That study, which compared FHEV and BEV versions of the 2020 Hyundai Ioniq and Kia Niro in all 48 continental US states, found that the FHEV is more likely to achieve a GHG emissions benefit in comparison to a BEV when using 2020 marginal emission rates, but there are substantial regional and vehicle model dependencies.

RCE rates are the rate of change of emissions mass flow with respect to demand. While there isn't a direct correlation between demand and carbon intensity of the generation source, it is frequently the case that the average emissions rate is either substantially higher or lower than the marginal emissions rate depending on the source that meets the marginal demand (e.g., gas or hydro). In almost all cases, the average and marginal emissions rates are not the same. This difference can clearly be seen in Figure 1. This gives an example of how the marginal emissions rate differs from the average emissions rate when considering three different electricity sources.

The three endpoints correspond to total demand at the same hour on different days. The total emission mass

FIGURE 1 Graphical comparison of marginal and average emissions rates.



flow rate, also indicated by the endpoints, is the sum of the emissions mass flow rates produced by each of the three sources, which add up to the total demand. The gradient of the line connecting the endpoints (labeled as "marginal mix") is equal to the marginal emissions rate, whereas the average emissions rate is the gradient of the pink dash–dot line (labeled as "average mix") between the origin and the average endpoint. In this example, the marginal emissions rate is greater than the average emissions rate, because most of the increase in demand is being met by Source 3, which has a higher emissions rate (steeper gradient) than the other two sources. It is important to note that in reality, the end points may not fall onto a straight line, and instead a line of best fit would be used for the marginal mix; this example is used to make the comparison with the average mix clearer.

There are clearly a large number of factors that determine the LCA emissions of a particular vehicle, whether a BEV, FHEV, or ICEV. The uncertainty in evaluating the emissions associated with the raw materials sourcing, vehicle production, and recycling/disposal phases can be eliminated by adopting an "apples-for-apples" comparison of cars of the same model that come with different choices of powertrain. The key assumption in this approach is that the only difference between the production and recycling/disposal emissions of each variant of the model is due to the emissions of the different-sized battery installed (i.e., all other emissions associated with raw materials sourcing, materials processing, production, and disposal are assumed to be equal for each model, be that a BEV, FHEV, or ICEV version). A similar method was used in Raugei et al. [8], in which the production process of a BEV was treated as a retrofit of a battery into an ICEV version of the same car. This method allows a relative comparison of each type of drivetrain and greatly reduces the uncertainty in the LCA. While this does not produce a definitive value for the lifetime emissions of a particular car model, it provides an accurate estimate of emissions between powertrain types. This was also the approach used in Burton et al. [16].

The aim of this LCA is to perform a data-driven comparison of lifecycle emissions rates from three different powertrain types for BEVs, FHEVs, and ICEVs, by applying the method from Burton et al. [16] (which only considered the USA), to countries in Europe. The European grid network is substantially different from the USA's, with substantially more wind generation (17% vs 10%) and less coal generation, as well as greater interconnectivity. Two different vehicles, available in all three powertrain configurations on the same platform, will be tested: the 2024 Hyundai Kona Advance and the 2024 Peugeot 2008.

Methodology

Countries Considered

The countries considered in this work are the countries of the EU, Norway, Switzerland, and the UK. Due to a lack of data, Malta was excluded, and so its interconnector with Italy may slightly affect the results in this work for Italy. However, Malta is sufficiently small that this is not expected to have a material impact. Please note that references to Ireland combine Northern Ireland and the Republic of Ireland. They are treated as having the same emissions rates, owing to the fact that there is one combined grid [the Single Electricity Market (SEM)] that provides electricity on the island of Ireland. Due to Northern Ireland's inclusion in the data for Ireland, the rest of the UK is considered Great Britain.

Data Processing

Data Sources Data for this work was taken for the calendar year 2023. The majority of the electricity generation data is downloaded from the ENTSO-E transparency platform's [17] API, with two exceptions: the data for Great Britain (which comes from BM Reports (BMRS) [18]) and Cyprus (which comes from TSOC [19]). All of the data for interconnector and cross-border flows comes from the ENTSO-E transparency platform's API. For some countries (particularly Ireland), data for some hours in 2023 on the ENTSO-E website are missing. The EU ETS Registry also provides plant-specific emissions data (emissions produced over a whole year), which can be used in conjunction with the generation data provided by ENTSO-E to determine a more accurate estimate of the emissions factors for these particular power plants [20]. Depending on the type of emissions rate being calculated, different methods have been used to clean the data.

The data was initially cleaned by checking for erroneous spikes or drops. This was carried out for each type of generation, each import, and each export, for every country. Any data point that was (a) a 30% change from the previous hour, (b) more than 1 standard deviation above the mean value, and (c) more than 2% of total generation for that hour was inspected. If the value appeared to be incorrect in the context of several values before and after it in the dataset, it was replaced by the mean of the two adjacent values.

Additional Data Processing—Netherlands One of the names for generation sources on ENTSO-E is "Other," which in most cases is a small fraction of overall generation. The typical approach to deal with this is to assume the worst case from an emissions perspective, and assign this generation an emissions factor of 700 kg CO_2 eq/MWh, as if it were a mixture of coal, gas, and oil. However, in the case of the Netherlands, "Other" accounts for roughly 30% of total generation. By plotting this generation source against time, it is clear that a large portion of it is coming from solar generation, despite the fact that the Netherlands submits solar generation data separately as well. To determine a rough estimate for the amount of generation from solar, the data was processed as follows: For every day of the year, determine the first and last hours when solar energy is being generated from the solar generation data. Then, find the values for generation of "Other" at these times, on that day. Any generation from "Other," which is above the average of the two values (corresponding to the first and last hours of solar generation) is then assumed to be produced by solar. This method identified 23% of the generation by "Other" to be from solar generation.

Calculating Average Emissions

Average emissions are calculated by taking a weighted sum of the different sources of energy multiplied by their respective emissions rates, and then dividing by the sum of the total energy being supplied. Additionally, it is necessary to perform electricity flow tracing in the cases where countries transmit electricity to one another via interconnectors or cross-border connections. This method is equivalent to that used in a 2014 report by the IPCC [21]. The first step in calculating average emissions rates is to determine all of the emissions produced by local generation in each country, by use of a simple weighted sum as shown in Equation 1:

$$AER_{locat,c,h,d} = \frac{\sum_{u \in U_c} G_{u,c,h,d} F_{u,c}}{\sum_{u \in U_c} G_{u,c,h,d}} \quad (1)$$

where $AEM_{local,c,h,d}$ is the local average emissions rate of country c, at hour h, on day d; U_c is the set of electricity generation sources in country c; $G_{u,c,h,d}$ is the electricity generated by source u, with units of MWh; and $F_{u,c}$ is the emissions factor of source u, in country c, with units of g CO_2 eq/kWh.

Any instances of missing generation data were estimated because there were very few hours in 2023 when every country reported generation data for every single source of generation. Linear interpolation was performed if a missing value was in between two recorded values. For cases with two or more consecutive missing values, the values were set to the average value for the corresponding hour of the day.

Once the local average emissions rates have been calculated (for each hour, and for each country), the average emissions rate of the electricity, which is actually being *consumed* in a given country, can then be calculated using flow tracing. This involves determining the origin of all of the electricity that is used in a given country, by accounting for interconnector or cross-border flows at the time of use. This is done using the method proposed by Bialek [22]. Note that at this stage the electricity network is assumed to be lossless, and that there is perfect mixing of all electricity flows that enter a country. The losses due to transmission and distribution are accounted for later on in the LCA.

The average emissions rates of the countries considered in this study for 2023 are shown in Table 1.

Calculating Marginal Emissions

Marginal emissions rates are calculated using the statistical method from Burton et al. [16] to determine which sources of electricity are likely to respond to increases in demand. This can then be used to evaluate the expected emissions rate of an additional unit of electricity being added to the grid demand. Grid inertia requirements (spinning reserves) are not considered; this analysis only considers how any particular grid balances total power demand against generation.

The total demand in a particular country can be written as

$$D_{c,h,d} = \sum_{u \in U_c} G_{u,c,h,d} + \sum_{q \in C_c} I_{q,c,h,d} \quad (2)$$

where $D_{c,h,d}$ is total demand in country c at hour h, on day d; $G_{u,c,h,d}$ is generation from source u; $I_{q,c,h,d}$ is the import into country c, from country q (which is always non-negative); U_c is the set of all generation sources in country c; C_c is the set of all countries which have interconnectors or cross-border connections with country c. The generation sources and imports that respond to increases in demand for electricity are determined by regressing each, individually, with total demand, to generate a linear model:

$$G_{u,c,h,d} = \alpha^G_{u,c,h} + \beta^G_{u,c,h} D_{c,h,d}$$
or
$$I_{q,c,h,d} = \alpha^I_{q,c,h} + \beta^I_{q,c,h} D_{c,h,d} \quad (3)$$

TABLE 1 2023 average emissions rates for countries considered in this work.

Country	Average emissions rate (g CO_2 eq/kWh)
Austria	174
Belgium	175
Bulgaria	397
Croatia	289
Republic of Cyprus	765
Czechia	465
Denmark	143
Estonia	261
Finland	78
France	51
Germany	391
Great Britain	220
Greece	385
Hungary	256
Ireland	415
Italy	342
Latvia	189
Lithuania	181
Luxembourg	289
Netherlands	284
Norway	33
Poland	791
Portugal	151
Romania	297
Slovenia	243
Slovakia	242
Spain	155
Sweden	25
Switzerland	82

Initially, a source or import will be deemed to be marginal if its linear regression produces a gradient, $\beta^{G}_{u,c,h}$ or $\beta^{I}_{q,c,h}$, which is positive and greater than 0.01, with a p-value less than 5%—with the exception of nuclear, which cannot respond to changes in demand and is always taken to be non-marginal [16]. Once this is done, the marginal sources are combined to create an initial estimate for marginal demand, and then re-regress each marginal source/import with this provisional marginal demand. If any source/import that was originally determined to be marginal now has a gradient less than 0.01, or a p-value more than 5%, it is no longer considered marginal. Once all of the marginal sources have been re-regressed with the initial estimate for marginal demand, a new estimate for marginal demand is calculated from the remaining marginal sources. This re-regression is repeated iteratively until no more non-marginal sources/imports are discovered. In most cases, $\sum\beta^{G}_{u,c,h} + \sum\beta^{I}_{q,c,h} = 1$, but if this is not the case, each β will be normalized by this sum.

Once the marginal sources and imports have been determined for each hour of the day for each country, it is possible to determine the local marginal emissions rate by evaluating how local emissions vary with a change in marginal demand. Marginal demand is calculated as follows:

$$X_{c,h,d} = \sum_{u\in U^{M}_{c,h}} G_{u,c,h,d} + \sum_{q\in C^{M}_{c,h}} I_{q,c,h,d} \tag{4}$$

where $X_{c,h,d}$ is the marginal demand of country c, at hour h, on day d; $U^{M}_{c,h}$ is the set of all marginal generation sources in country c, at hour h; and $C^{M}_{c,h}$ is the set of countries that provide marginal imports to country c at hour h. Equation 5 can then be used to evaluate the corresponding local emission mass flow rate:

$$Y^{G}_{c,h,d} = \sum_{u\in U^{M}_{c,h}} G_{u,c,h,d} F_{u,c} \tag{5}$$

where $Y^{G}_{c,h,d}$ is the emissions mass flow rate resulting from the electricity generated by the marginal sources. A linear regression is performed between $Y^{G}_{c,h,d}$ and $X_{c,h,d}$ to determine the local emissions produced in response to increased marginal demand:

$$Y^{G}_{c,h,d} = \alpha^{Y}_{c,h} + \beta^{Y}_{c,h} X_{c,h,d} \tag{6}$$

The local marginal emissions rate, $MER_{local,c,h}$ can be determined by dividing $\beta^{Y}_{c,h}$ by the sum of the gradients of the marginal sources, $\sum\beta^{G}_{u,c,h}$—this is the fraction of marginal demand being met by local sources. $MER_{local,c,h}$ is not used in any further calculations, however $\beta^{Y}_{c,h}$ is.

It is important to note that when performing the regressions described by Equations 3 and 6, it was assumed that the gradient (the β term) was the same across the whole year (roughly the same response to demand/marginal demand), while the intercept (the α term) was allowed to vary from month-to-month to capture the seasonal variability in base level of the dependent variables, as per the method in Burton et al. [16], and in line with Zivin et al. [23].

To determine a consumption marginal emissions rate, then, it is necessary to consider how the total emission mass flow rate increases with a small increase in marginal demand (i.e., how do the emission mass flow rates change domestically, as well as in other countries). The total emissions mass flow rate, $Y_{c,h}$, is given in Equation 7, which is due to all of the marginal sources and imports for country c, at hour h.

$$Y_{c,h} = Y^{G}_{c,h} + \sum_{q\in C^{M}_{c,h}} Y^{I}_{q,h} \tag{7}$$

where $Y^{I}_{q,h}$ is the emissions mass flow rate in a country q from which country c is importing electricity.

Then, the expected change in total emissions mass flow rate, $\Delta Y_{c,h}$, corresponding to a change in marginal demand, Δx, is evaluated as follows:

$$\begin{aligned}\Delta Y_{c,h} &= \left(E\left[Y_{c,h}\big|_{X_{c,h}=x+\Delta x} \right] - E\left[Y_{c,h}\big|_{X_{c,h,d}=x} \right] \right) \\ &= E\left[\left(Y^{G}_{c,h} + \sum_{q\in C^{M}_{c,h}} Y^{I}_{q,h} \right)\Bigg|_{X_{c,h}=x+\Delta x} \right] - \\ &\quad E\left[\left(Y^{G}_{c,h} + \sum_{q\in C^{M}_{c,h}} Y^{I}_{q,h} \right)\Bigg|_{X_{c,h}=x} \right]\end{aligned} \tag{8}$$

Because $E[\ ]$ is a linear operator, Equation 8 can be separated into two parts:

$$\begin{aligned}&E\left[Y^{G}_{c,h}\big|_{X_{c,h}=x+\Delta x} \right] - E\left[Y^{G}_{c,h}\big|_{X_{c,h}=x} \right] \\ &= \left[\alpha^{Y}_{c,h} + \beta^{Y}_{c,h}\left(x+\Delta x \right) \right] - \left[\alpha^{Y}_{c,h} + \beta^{Y}_{c,h} x \right] = \beta^{Y}_{c,h}\Delta x\end{aligned} \tag{9}$$

$$\begin{aligned}&E\left[\sum_{q\in C^{M}_{c,h}} Y^{I}_{q,h} \Bigg|_{X_{c,h}=x+\Delta x} \right] - E\left[\sum_{q\in C^{M}_{c,h}} Y^{I}_{q,h} \Bigg|_{X_{c,h}=x} \right] \\ &= \sum_{q\in C^{M}_{c,h}} \beta^{I}_{q,c,h} \left(E\left[Y_{q,h}\big|_{X_{q,h}=x+\Delta x} \right] - E\left[Y_{q,h}\big|_{X_{q,h}=x} \right] \right)\end{aligned} \tag{10}$$

Hence, combining Equations 9 and 10, Equation 8 can be rewritten as

$$\begin{aligned}\Delta Y_{c,h} &= \beta^{Y}_{c,h}\Delta x + \sum_{q\in C^{M}_{c,h}} \beta^{I}_{q,c,h}\Delta Y_{q,h} \\ \text{or} \qquad MER_{c,h} &= \beta^{Y}_{c,h} + \sum_{q\in C^{M}_{c,h}} \beta^{I}_{q,c,h} MER_{q,h}\end{aligned} \tag{11}$$

where $MER_{c,\,h}$($=\Delta Y_{c,\,h}/\Delta x$) is the consumption marginal emissions rate for country c at hour h. Similar to the case for calculating average emissions, this forms a system of coupled equations which can be solved via a matrix method:

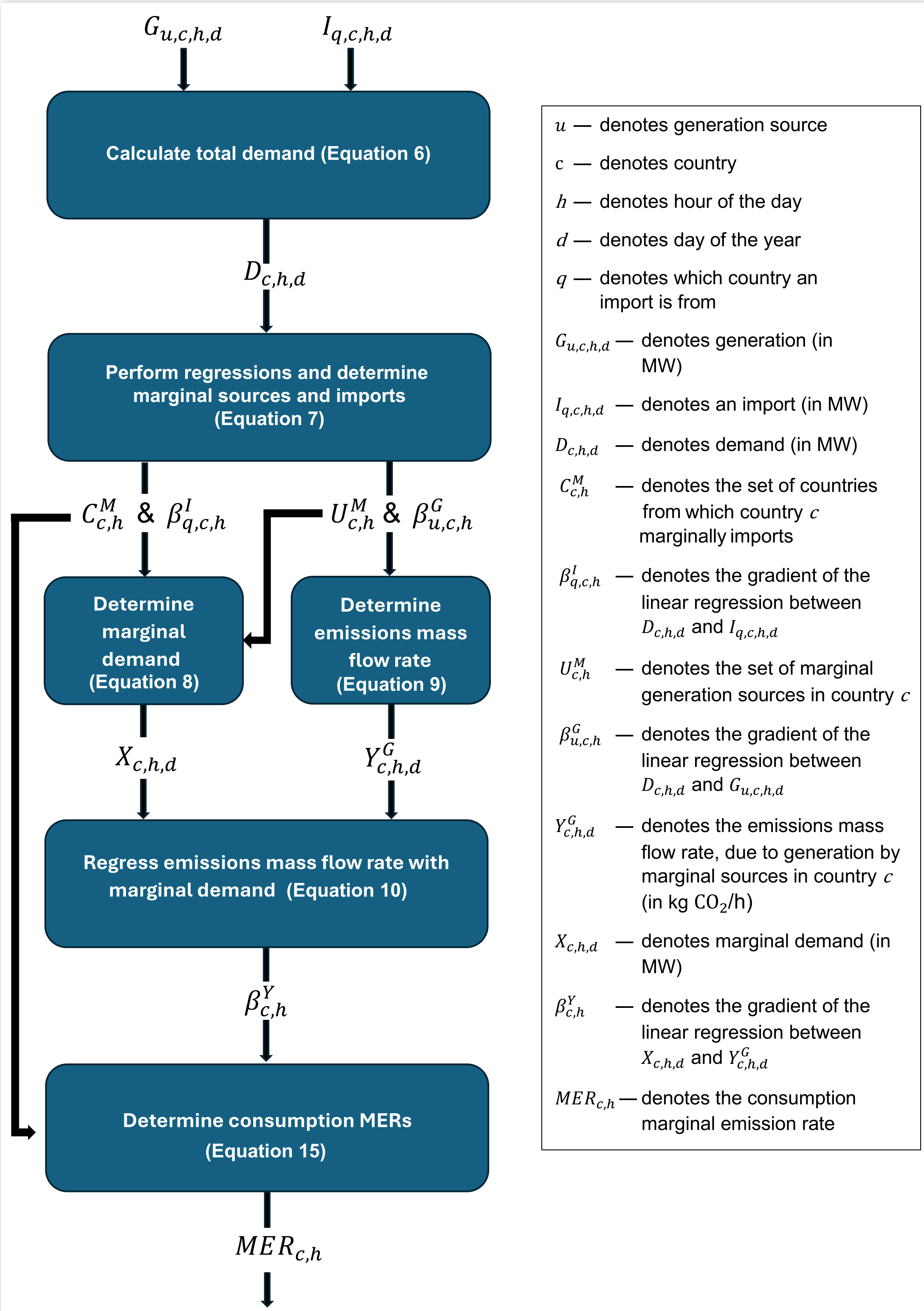
$$B_h\left[MER \right]_h = \beta^{Y}{}_{h} \text{ where } \left[B_h \right]_{ij} = \begin{cases} 1 & \text{if } i = j, \\ -\beta^{I}_{j,i,h} & \text{if } j \in C^{M}_{i,h}, \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where $[MER]_h$ and $\beta^{Y}{}_{h}$ are vectors, each with one element corresponding to each country and B_h is a square matrix. The consumption marginal emissions rates for each country can hence be determined by pre-multiplying each side of the equation by B_h^{-1}. Unlike the average emissions case, where this matrix method had to be applied to each hour of the year individually, this method is only applied 24 times—once for each hour of the day. The whole process for calculating consumption marginal emissions rates is displayed as a flowchart in Figure 2. From now on, any reference to marginal emissions rate will be referring to this consumption marginal emissions rate.

Similar to the average rate calculation, if generation data was missing from any source, or any interconnector/cross-border data was not recorded, the values for that hour were not considered in the regression. With the exception of Belgium and Ireland, the regressions for each country, for every hour of the day, had more than 360 data points. In Belgium, the minimum number of data points was 330, which is still a reasonable size. In Ireland, however, the number of valid data points for each regression ranged from 17 to 22 (due to frequently unreported generation data, for multiple sources). This lack of data does not impact any other countries, because for Great Britain—the only country Ireland had any interconnectors (or cross-border connectivity) with—imports from Ireland are non-marginal. Examples of the complete calculation can be found in Bialek [22].

Differences to Previous Work While this work aims to apply Burton et al.'s work in the USA [16] for countries in Europe, exact application of that method is not possible due to differences in data reporting. As noted, emissions mass flow rates in this LCA are calculated using Equation 5, which involves summing the products of the generation from each source and its respective emissions factor. In the USA, however, the Environmental Protection Agency (EPA) provides generation and emissions data for individual plants [24], which can be reconciled with data from the Energy Information Administration (EIA) [25], to calculate real-time emissions mass flow rates on an hourly basis. Burton et al. used this data to achieve a much more accurate estimate of how emissions vary with demand. While some of the emissions factors used in this LCA are different for specific countries, these do not account, in real time, for additional emissions resulting from: plants operating at partial loads; inefficiencies associated with start-up/shutdown; nor energy which is used to power the plants themselves. Furthermore, the emissions from small capacity "peaker" plants, which both have a strong response to demand and tend to have high emissions rates, are incorporated into Burton et al.'s emissions estimates, whereas the emissions factors used in this LCA which are country-specific are based on data from large power plants (the plants which submit data to ENTSO-E have an installed capacity of at least 100 MW, whereas plants in the USA with capacity exceeding 25 MW have

FIGURE 2 Process for calculating marginal emissions rates.



to submit data to the EPA). If there were equivalent data in Europe, more accurate estimates for emissions mass flow rates and therefore marginal emissions rates could be evaluated.

In addition, a second type of marginal emissions rate is evaluated in Burton et al. [16], using an "Emitting Source" classification to identify marginal sources. The difference between this classification and that which is used in this work is that nuclear, wind, solar, and hydro (excluding pumped hydro) generation are assumed to be non-marginal. While this is a reasonable assumption for the USA, where these renewables typically account for a small percentage of generation, in many European countries, this is not the case, with renewables (particularly wind) often being statistically significant marginal sources, however. As an example, Finland's only marginal source or import, for every hour of the day, is wind, which would mean that this "Emitting Source" classification adopted previously would not work. It is therefore not adopted in this study.

Calculating Vehicle Emissions Rates

Vehicles Considered Two vehicles were considered, which were available in multiple powertrain options, but otherwise were the same car in order to ensure as fair an LCA comparison as possible. These are the 2024 Hyundai Kona and the 2024 Peugeot 2008. The 2024 Hyundai Kona is available in BEV, FHEV, and ICEV versions.

Here, the lifecycle emissions of the BEV and FHEV will be compared. The BEV comes with two battery pack options of 48 and 65 kWh, with Worldwide Harmonised Light Vehicles Test Procedure (WLTP) maximum ranges of 377 and 515 km, respectively. The FHEV comes with a 1.56 kWh battery pack and a 1.6 L petrol engine. The WLTP combined cycle fuel consumption of the FHEV is 4.7 L/100 km. The manufacturer's recommended prices of the 48 kWh and 65 kWh BEVs are £34,995 and £38,595, respectively, and the FHEV is priced at £30,025 at the time of writing. For the BEVs, the battery pack warranty is 100,000 miles or 8 years (whichever comes first), and hence the worst- and best-case battery lives will be taken to be 168,000 and 256,000 km. The FHEV doesn't have a warranty specifically for the battery, so the battery lives are assumed to be the same as that of the BEV. While the 48 kWh version has a shorter range, its WLTP electrical energy consumption is slightly lower (0.145 kWh/km, as opposed to 0.149 kWh/km) and the battery production emissions are lower. Consequently, this model has a lower emissions rate per km and will be used for the best-case scenario for the BEV drivetrain option in this vehicle comparison, while the 65 kWh version will be used for the worst-case scenario. For this best- and worst-case comparison, it is assumed that the battery packs for the FHEV and BEV could be made in different countries.

The 2024 Peugeot 2008 comes with either a BEV or ICEV drivetrain. There are several petrol ICEV versions which will be compared to the BEV versions in order to present a most and least BEV-favorable scenario, as was done for the Hyundai Kona. The BEV options all come with a 54 kWh battery pack, with a WLTP maximum range of 307–332 km. The petrol ICEVs each have a 1.2 L engine, and their WLTP combined fuel consumption ranges from 5.4–6.8 L/100 km. The WLTP electric energy consumption of the BEVs is 0.174–0.184 kWh/km. The manufacturer's recommended retail prices for the BEV models range from £36,500 to £41,750, while the ICEVs are priced between £24,170 and £31,170. The battery warranty of the Peugeot is the same as that of the Hyundai, and hence the minimum and maximum battery lives in this comparison are the same as before.

Production Emissions This LCA is performed on a relative basis, which assumes the emissions from raw material sourcing, the production stage (besides battery production), and the disposal/recycling stage are the same for different drivetrain versions of the same car model. This leads to a fair comparison and removes a large portion of the uncertainty that would result if all stages were accounted for. Having calculated the marginal emissions rates for the countries of interest, it is possible to determine the relative emissions rates of BEVs, compared to FHEVs and ICEVs.

The following equation is used to evaluate the relative life cycle emissions associated with a BEV [16]:

$$ER_{BEV} = EC \cdot TC \cdot \frac{MER}{1 - TDL} + \frac{BPCO_2}{BL} \tag{13}$$

where ER_{BEV} is the emissions rate in g CO_2 eq/km; EC is the electricity consumption rate in kWh/km; TC is a temperature correction factor; MER is the marginal emissions rate of electricity in g CO_2 eq/kWh; TDL is the transmission and distribution losses as a fraction of total energy transferred on the grid; $BPCO_2$ is the battery pack production emissions measured in g CO_2 eq/kWh; and BL is the battery life in km. The values of EC, $BPCO_2$, and BL will be the same in each country. Similarly, the emissions rate for a FHEV can be calculated using Equation 14:

$$ER_{FHEV} = FC \cdot TC \cdot (CER + UER) + \frac{BPCO_2}{BL} \tag{14}$$

where FC is fuel consumption in L/km; CER is the combustion emissions rate of petrol, which for this case study in Europe is taken to be 2.24 kg CO_2 eq/L [26]; UER is the upstream emissions resulting from the production, refining, and transportation of petrol, which is taken to be 0.68 kg CO_2 eq/L [26]. The equation for an ICEV is the same as that of the FHEV, without the consideration of a battery.

This LCA aims to provide a best- and worst-case scenario for the relative emissions impact of a BEV.

Consequently, there will be an upper and lower value calculated for the temperature correction factor, the battery pack production emissions, and the battery life. The best-case scenario for the BEV will involve a comparison of the lowest value for the BEV emissions rate with the highest emissions rate for the FHEV/ICEV version of the car, and vice versa for the worst-case scenario.

Fuel Economy The standard procedure used in the EU to determine fuel consumption of cars is the WLTP. This consists of four different speed phases—Low, Medium, High, and Extra high—which collectively simulate realistic driving, with varied speeds, accelerations, and time spent stationary. This test is operated at 23°C, and consequently temperature correction factors are required to get a fuel economy (FE) that is country-specific. In this LCA, the overall FE across all four phases is used. The WLTP data used is drawn from the UK's Vehicle Certification Agency website [27].

Temperature Correction The amount by which FE varies with temperature is highly dependent on the drivetrain being used. Roughly 30% of the energy used by ICEs is released as heat [28], and as a result heating requirements at low temperatures have less of an impact on the FE of ICEV/FHEVs because this heat can be used for heating directly. In the case of BEVs (or PHEVs operating in charge-depleting mode), heating requirements have a greater effect on electricity use. Additionally, the amount of energy that can be recuperated by regenerative braking tends to decrease with temperature [29], and this affects BEVs, PHEVs, and FHEVs, to varying degrees. In the case of BEVs, regenerative braking can account for more than 35% of the total energy requirement of the traction system [29]. Ranges for the extent to which fuel economies vary for ICEVs and FHEVs were determined using data from the US EPA website [30]. The cars selected from the EPA dataset were chosen because they had FE data for both the "City" driving test cycle at the standard temperature range of 68–86°F (20–30°C), as well for the "Cold" test cycle, which is the same as the city driving test, except that it is instead carried out at 20°F (−7°C) [31]. Table 2 shows the FE for the two temperatures for the selected vehicles, and also indicates that the smallest and largest increases in fuel consumption (the inverse of the FE) for ICEVs were 11% and 26%, and for the case of FHEVs it was 9% and 41%. These values will be used for the minimum and maximum possible temperature correction factors for the FE of the corresponding drivetrain technologies. Given that the average temperature in the EPA city test cycle is roughly the same as that of the WLTP, a linear relationship was assumed (between −6.7°C (20°F) and 23°C) to determine the extent to which the temperature correction factor is applied, based on a representative ambient temperature in each country, which is an average between 1991 and 2020 [32]. These are calculated using a weighted sum of the minimum, mean, and maximum daily temperatures in each country with the following weightings: 0.5 to minimum temperature, 0.4 to mean temperature, 0.1 to maximum temperature. These were chosen because most driving takes place at temperatures below the mean daily temperature (i.e., rush hours are in the early morning and late afternoon).

The temperature correction approach for BEVs used is not the same, because the limited number of BEVs in the EPA dataset provides too large a range of values to extract a meaningful upper bound for the increase in electricity consumption at low temperatures. For some cars, such as the Tesla Model Y, the EPA data suggests more than a 400% increase in electricity consumption at 20°F, which would likely invalidate the use of a linear interpolation. This significant reduction in FE at 20°F is most likely due to the fact that regenerative braking in Teslas reportedly stops working at low temperatures [29]. Instead, the range of 40%–75% is used, based on data from a 2019 report by the American Automobile Association (AAA) [33].

Transmission and Distribution Losses The TDLs are largely taken from [34], with the exception of Romania [35], Bulgaria [36], and Switzerland [36]. TDLs associated with electricity that is imported from neighboring countries are not accounted for in this work, despite inevitable losses that will occur in interconnectors.

Battery Production Emissions The process of determining the emissions associated with the life cycle of the lithium-ion batteries (LIBs) that go into FHEVs, PHEVs, and BEVs carries a great deal of uncertainty. Estimates of greenhouse gas emissions from different LIB LCAs vary

TABLE 2 Effect of temperature on ICEV and FHEV fuel consumption.

Car brand	Model	Drivetrain	City FE (in mpg)	Cold FE (in mpg)	FC % increase
VW	GTI	ICEV	29.85	23.7	26
Audi	A4 Quattro	ICEV	32.85	26.5	24
Kia	K5	ICEV	29.7	26.75	11
Hyundai	Venue	ICEV	37.9	33.15	14
Hyundai	Tucson	FHEV	50.15	37.05	35
Honda	Civic	FHEV	26.45	24.3	9
Kia	Sportage Hybrid	FHEV	53.83	38.3	41
Toyota	RAV4 Hybrid	FHEV	56.15	40.85	37

considerably depending on the assumptions made in the LCA, most notably the location from which materials are mined/extracted, the energy mix used in the production process, the scale of production, and the chemistry of the battery being produced [37]. This leads to a wide variety of values cited in review papers in the literature: 56–494 kg CO_2 eq/kWh [38], 61–106 kg CO_2 eq/kWh [39], and 42–125 kg CO_2 eq/kWh [40].

The most important factor to consider from an emissions perspective is the location(s) in which the production of the battery cells occurs. In 2020, 77% of global LIB production capacity was in China; however, by 2025 Europe's share is expected to rise to 25% [41]. In light of this, this work assumes that the final production stage for batteries occurs in Europe. It is possible to create a lower and upper bound for the carbon emissions contribution from production of LIBs in Europe using the marginal emissions rates calculated. The countries in Europe with the highest and lowest marginal emissions rates (accounting for TDL) that are current/future homes of gigafactories are Poland (a 35+ GWh/year factory owned by LG Chem Ltd. is currently operational) and Norway (Morrow, Freyr, and Beyonder) with marginal emissions rates of 951 and 26 g CO_2 eq/kWh, respectively. Production in these locations would therefore contribute emissions of 57.06 kg CO_2 eq/kWh and 1.56 kg CO_2 eq/kWh, respectively, to the LIB's total emissions. Adding this to the 59 kg CO_2 eq/kWh for all of the other processes leads to upper and lower bounds of 116.06 and 60.56 kg CO_2 eq/kWh for LIBs whose production stage occurs in Europe. This is very similar to the range provided by Emilsson et al. [39], as well as the two cases considered in Chordia et al. [42]. If average emissions rates are used instead, the countries with the highest and lowest average emissions rates (accounting for TDL), which have LIB gigafactories, are Sweden (Northvolt operates a 60 GWh/year cell production factory) and Poland, with rates of 26 g CO_2 eq/kWh and 839 g CO_2 eq/kWh, respectively. This results in a range of cell production emissions of 1.56–50.34 kg CO_2 eq/kWh. Hence, the upper and lower bounds of the total production of LIBs in the average emissions case would be 109.34 CO_2 eq/kWh and 60.56 CO_2 eq/kWh.

The lower and upper bounds for the battery life are taken to be 105% and 160% of the battery's warranty, in kilometers [16]. Hence, the best-case scenario for a BEV will involve the lower value for battery pack emissions being amortized over the upper value for battery life.

Results and Discussion

Comparison of Average and Marginal Emissions Rates

Figure 3 graphically demonstrates the difference between average and marginal emissions rates for the countries considered. A positive value in Figure 3(b) indicates that the marginal emissions rate is higher than the average emissions rate. In 12 countries, the marginal emissions rates were lower than their respective average emissions rates. Excepting Ireland (which had data quality issues as previously discussed), the largest drop from average to marginal emissions rate occurred in Germany, where the average rate is 391.2 g CO_2 eq/kWh, and the marginal rate is only 72.2 g CO_2 eq/kWh. This drop largely results from Germany's frequent excess generation of renewable energy—particularly wind. 18 countries had marginal emissions rates higher than their respective average emissions rates. The most extreme example of this was Slovakia, where the average rate was 242.3 g CO_2 eq/kWh, whereas the marginal rate was 821.5 g CO_2 eq/kWh. This is due to Slovakia's marginal demand being met almost entirely by imports from Poland and the

FIGURE 3 Marginal and average emissions rates comparison.

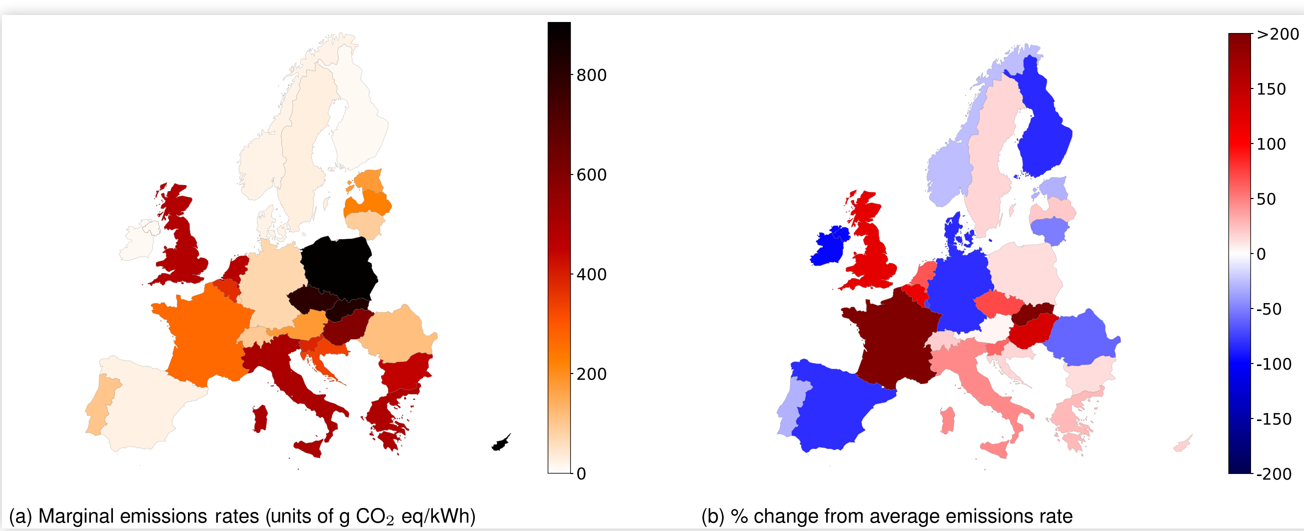
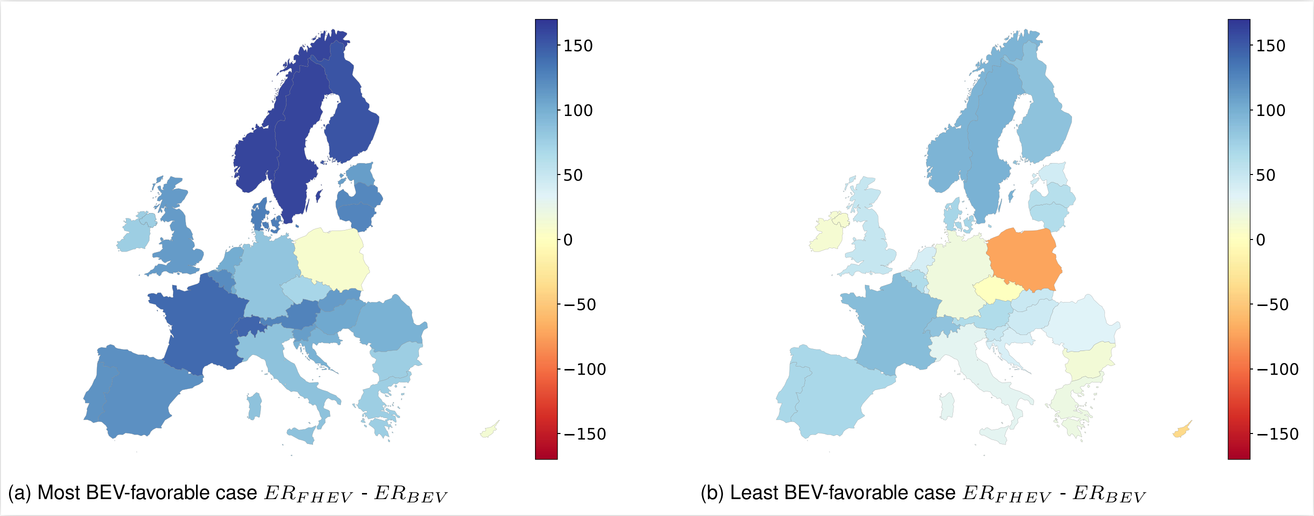


FIGURE 4 Hyundai Kona—average emissions case (units of g CO_2 eq/km).



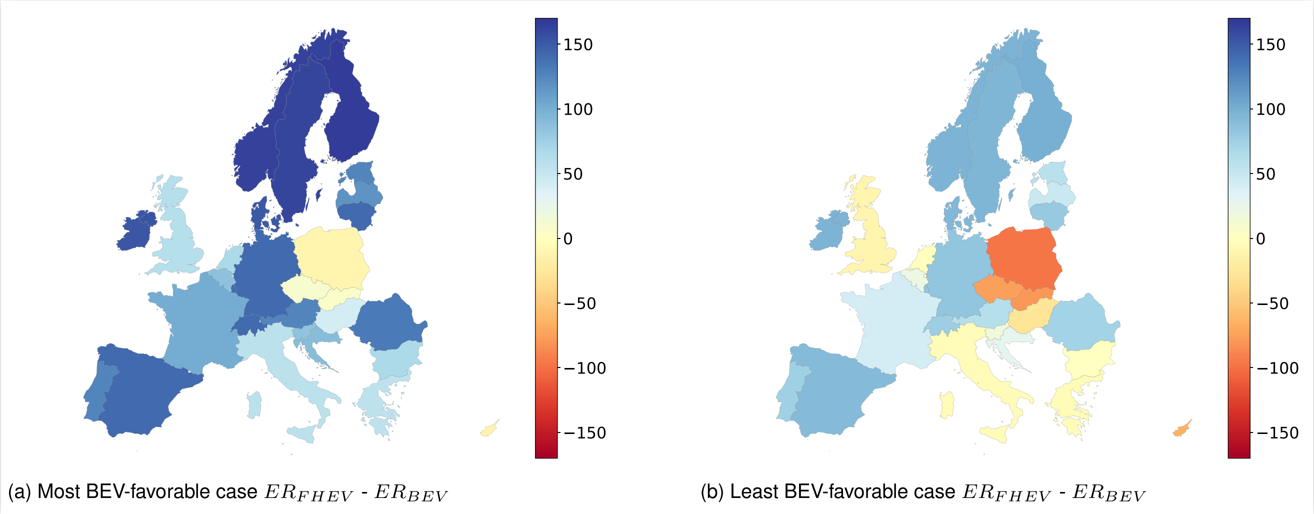
Czech Republic, whose marginal emissions rates are the 2nd and 4th highest, respectively. A more detailed breakdown of each country's dominant marginal sources/imports and their hourly marginal emissions rates is presented in Tables A.1–A.6 in the Appendix.

Vehicle Comparison

The results of the LCA for the Hyundai Kona in the average and marginal emissions cases are displayed in Figures 4 and 5, respectively. In the marginal emissions scenario, the contribution of battery pack production to the lowest and highest BEV emissions rates is 11.4 and 45 g CO_2 eq/km. For the FHEV, the equivalent contributions are 0.37 and 1.08 g CO_2 eq/km.

Comparing the results from evaluating the lifecycle emissions on a marginal emissions basis to an average emissions basis, some countries, such as Austria, Norway, and Sweden, display very little change in the emissions rate reduction ($ER_{FHEV} - ER_{BEV}$). However, for most countries, the average emissions case gave quite a different result to the marginal emissions case in terms of emissions rate reduction, particularly in the least BEV-favorable case. The mean absolute difference in $ER_{FHEV} - ER_{BEV}$ across all the countries between the average and marginal emissions cases was 31 g CO_2 eq/km for the most BEV-favorable case and 36 g CO_2 eq/km for the least BEV-favorable case. For 11 countries, the emissions rate reduction increased (i.e., the apparent emissions benefit of driving a BEV improved) when going from average emissions analysis to marginal emissions analysis, in both

FIGURE 5 Hyundai Kona—marginal emissions case (units of g CO_2 eq/km).



the most and least BEV-favorable scenarios. Besides Ireland, the greatest improvements were seen in Germany, Luxembourg, and Romania. For 18 countries, the opposite was true, with Slovakia, the Czech Republic, and Hungary seeing the largest decreases in $ER_{FHEV} - ER_{BEV}$. Using average emissions rates to analyze lifecycle vehicle emissions leads to very different results when compared to using marginal emissions rates, and there is no clear mapping between the two.

According to the marginal emissions analysis, in the most BEV-favorable case, the lifecycle emissions resulting from driving a FHEV over a BEV will be lower in only two countries—Cyprus and Poland. But in the least BEV-favorable case, the Czech Republic, Great Britain, Greece, Hungary, Italy, the Netherlands, and Slovakia also fall into that category (with Bulgaria coming close to doing so as well). This LCA indicates that a marginal emissions rate of 450 g CO_2 eq/kWh is a conservative cutoff below which the BEV becomes the preferable option, even in the least BEV-favorable case. In several countries such as Norway, Sweden, and Denmark, the marginal emissions rates are below 30 g CO_2 eq/kWh, which is the ideal scenario. So, it is worth noting that if a country is just below the cutoff of 450 g CO_2 eq/kWh, there is still an opportunity to avoid a large portion of emissions. Considering that the Hyundai Kona BEV's WLTP energy consumption is 0.145–0.149 kWh/km, reducing marginal emissions from 450 g CO_2 eq/kWh down to 30 g CO_2 eq/kWh would avoid more than 60 g CO_2 eq/km, before accounting for temperature correction or transmission losses. Overall, it can be concluded that for Cyprus and Poland there is no rationale in driving a BEV today purely from an emissions perspective. In the remaining cases—any of the countries which appear to be blue even in the least BEV-favorable case—a BEV drivetrain is most likely the preferable option for a passenger vehicle in terms of lifecycle emissions. To provide some context to the results, Figures 5 and 6 show the breakeven distance for a BEV in each country. This indicates how many thousands of kilometers the BEV must be driven for before the additional production emissions, due to the larger battery pack, are offset by the lower emissions rate for the in-use phase, when compared to the FHEV. In some countries, there is no breakeven distance, because the emissions rate for the in-use phase of the BEV is higher than that of the FHEV. The limit on the distance scale is capped at 250,000 km, as this is the assumed upper limit for the battery life.

The LCA emissions comparisons for the average and marginal emissions cases for the Peugeot 2008 are presented in Figures 7 and 8. The battery pack's contributions to the emissions rates of the BEVs are in the best- and worst-case 12.8 and 37.3 g CO_2 eq/km, respectively.

Comparing Figures 5 and 8, the results are fairly similar, except there is a greater range of results at the positive end of the scale. In the most BEV-favorable case, none of the countries analyzed suggest driving an ICEV Peugeot 2008 would be preferable from an emissions perspective over a BEV. In the least BEV-favorable case, there are six countries which indicate greater lifecycle emissions resulting from a BEV. Figure 9 gives the breakeven distances for the Peugeot 2008 BEV. The values are close to but lower than those in Figure 6, for all countries (with the exception of Hungary in the least BEV-favorable case). While the optimal decision about whether or not to buy a BEV in each country is quite similar to the Hyundai Kona, these results would suggest that if the choice is instead between an ICEV and an FHEV, the lifecycle emissions of the FHEV will almost certainly be lower. In fact, comparison of the FHEV version of the Hyundai Kona (in its least favorable scenario) with the ICEV version of the Hyundai Kona (in its most favorable scenario) indicates lower emissions in every country—the results of this comparison are displayed in the Appendix, in Figure 17.

FIGURE 6 Hyundai Kona—marginal emissions case (units of '000s of km).

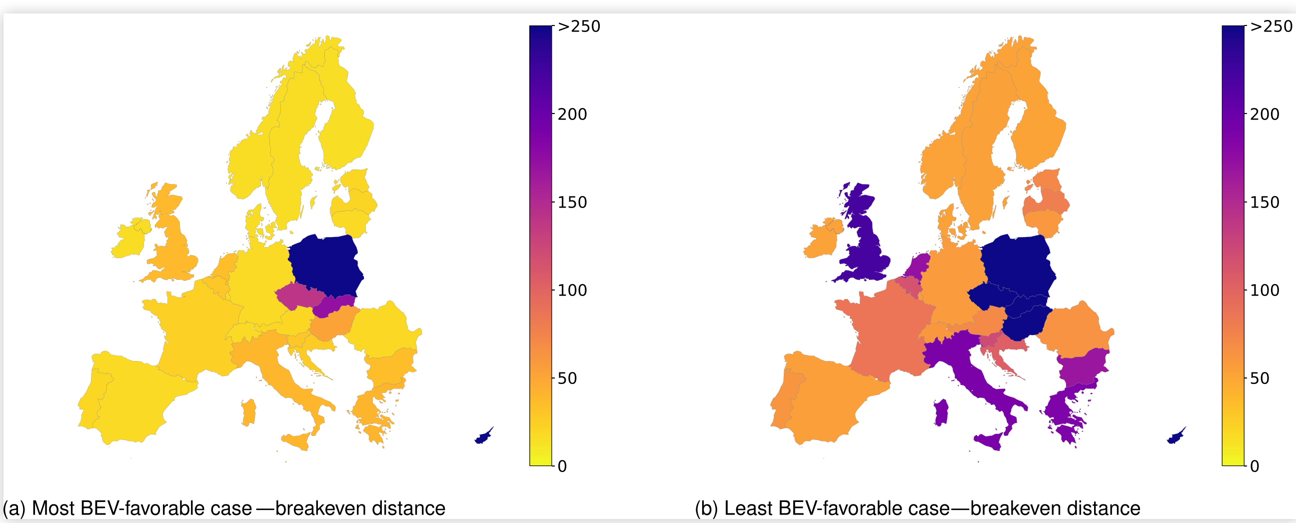
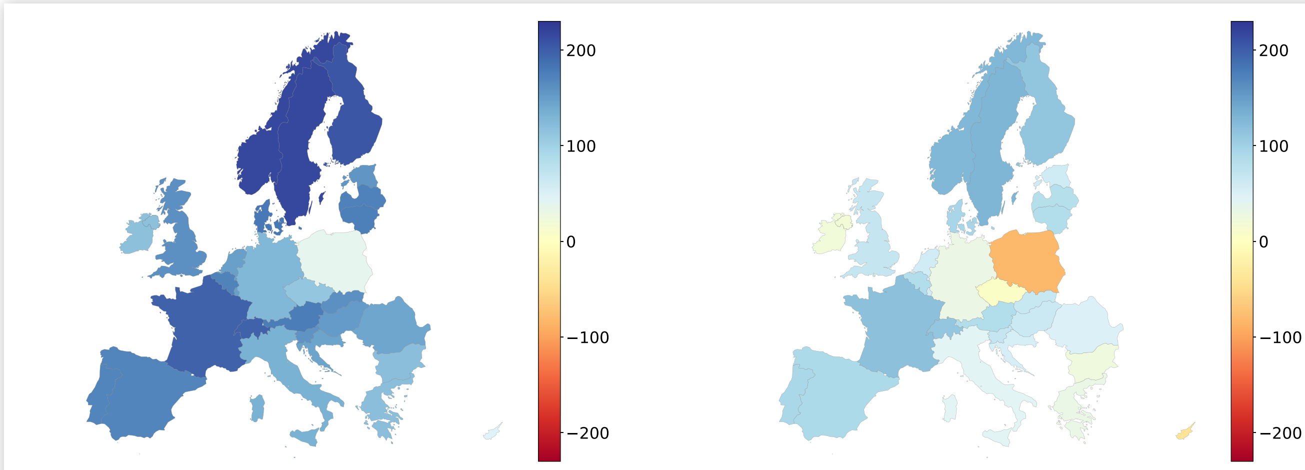
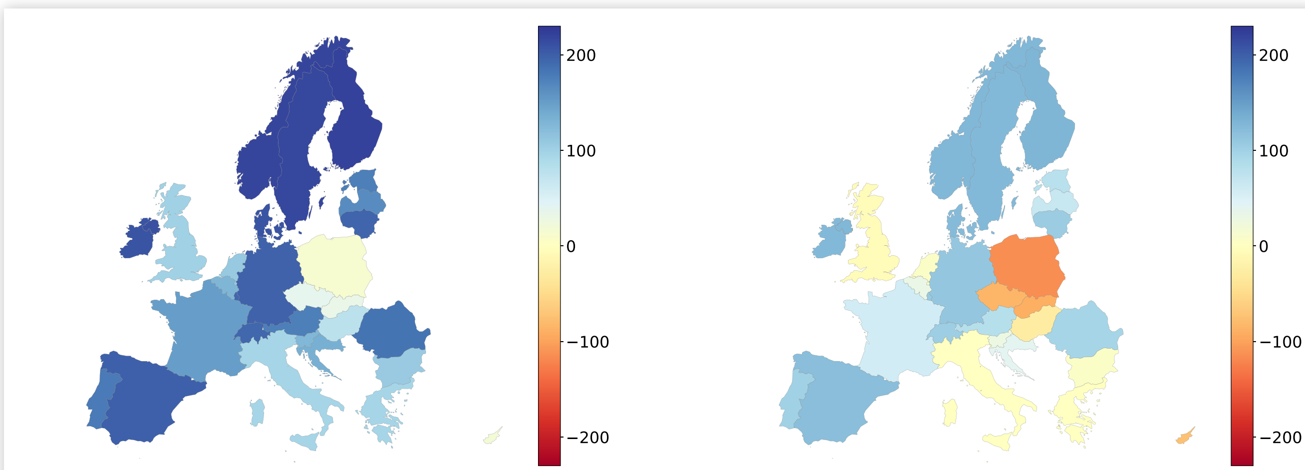


FIGURE 7 Peugeot 2008—average emissions case (units of g CO_2 eq/km).



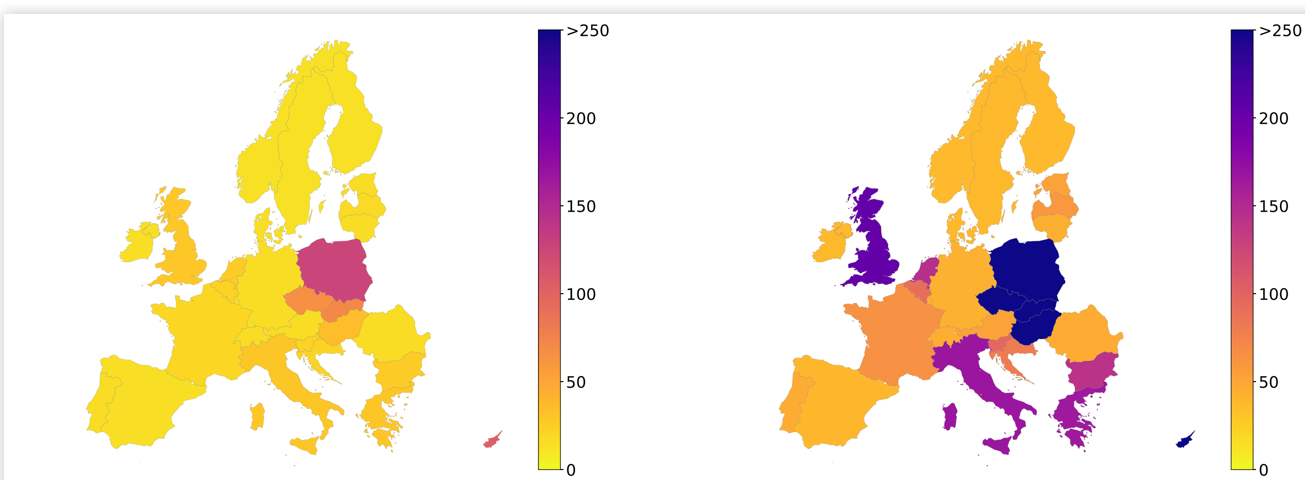
(a) Most BEV-favorable case ER_{ICEV} - ER_{BEV} (b) Least BEV-favorable case ER_{ICEV} - ER_{BEV}

FIGURE 8 Peugeot 2008—marginal emissions case (units of g CO_2 eq/km).



(a) Most BEV-favorable case ER_{ICEV} - ER_{BEV} (b) Least BEV-favorable case ER_{ICEV} - ER_{BEV}

FIGURE 9 Peugeot 2008—marginal emissions case (units of '000s of km).



(a) Most BEV-favorable case—breakeven distance (b) Least BEV-favorable case—breakeven distance

Overall, while a BEV may not be the best option in every country from a lifecycle emissions perspective, a FHEV will almost always be better than an ICEV of the same model (assuming they both use the same fuel type).

Sensitivity Analysis

The sensitivity of the results to four parameters is explored. These are the effect of TDLs, the temperature correction, imports and exports, and charging patterns. Each parameter will be compared for the BEV and FHEV versions of the Hyundai Kona, in the marginal emissions case.

Transmission and Distribution Losses Figure 10 shows the change in $ER_{FHEV} - ER_{BEV}$ in the event that TDLs are neglected. In all countries, the BEV appears to improve on a relative basis, with the countries with higher marginal emissions rates seeing the biggest changes—in Poland, ignoring TDLs causes up to 12.6 g CO_2 eq/km (from the BEV) to be unaccounted for. In this scenario, Great Britain, Greece, Italy, and the Netherlands would now favor the BEV over the FHEV, even in the least BEV-favorable case. So, while these changes aren't large, this failure to consider energy loss on electricity grids does have the potential to change the conclusions of the LCA.

Temperature Correction The effect of temperature correction for the BEV and FHEV models is displayed separately to indicate the differential impacts for these two types of powertrain. Comparing Figure 11(b) with Figure 12(b), when the temperature correction factor is high, the increase in the FHEV emissions rate due to a temperature correction factor is on average higher, and mostly varies according to the local temperature of the country, whereas the BEV emissions rates are most affected in the countries with high marginal emissions rates. Countries such as Norway and Sweden, despite having large reductions in vehicle range due to low temperatures, see very little change in BEV emissions rate, because their marginal emissions rates are so low. To consider temperature correction factors' effects on the vehicle comparisons, the most BEV-favorable scenario is compared in Figures 11(b) and 12(a), and hence removing this correction would result in an apparent benefit for the FHEV. In the least BEV-favorable case, on average, the reverse is true. Generally, the removal of temperature correction factors would result in a narrower range of results. In terms of how this would affect the overall conclusion, the result is the same as when TDLs are ignored, with Great Britain, Greece, Italy, and the Netherlands no longer favoring the FHEV in the least BEV-favorable case. It can be observed that temperature correction factors, in a BEV emissions LCA, are especially important in countries/regions with high marginal emissions rates. In the case of FHEV emissions LCAs, temperature correction factors are always important and should not be neglected.

Imports and Exports Local marginal emissions rates indicate how emissions from domestic generation vary with changes in marginal demand. Figure 13 shows the change from Figure 5 that occurs when using the mean *local* marginal emissions rates (i.e., neglecting the effect of imports). For some hours, in some of the countries analyzed in this LCA, there are no marginal sources. This is because all of the marginal demand is met by imports. In these instances, the hour without a local marginal emissions rate is removed from the calculation of the mean local marginal emissions rate. The effect on the battery pack emissions is ignored, as the most important consideration is the effect on in-use emissions. The countries that appear in blue in Figure 13 indicate that using the local marginal emissions rate results in an emissions rate

FIGURE 10 Change in $ER_{FHEV} - ER_{BEV}$ (units of g CO_2 eq/km)—relative to Figure 5.

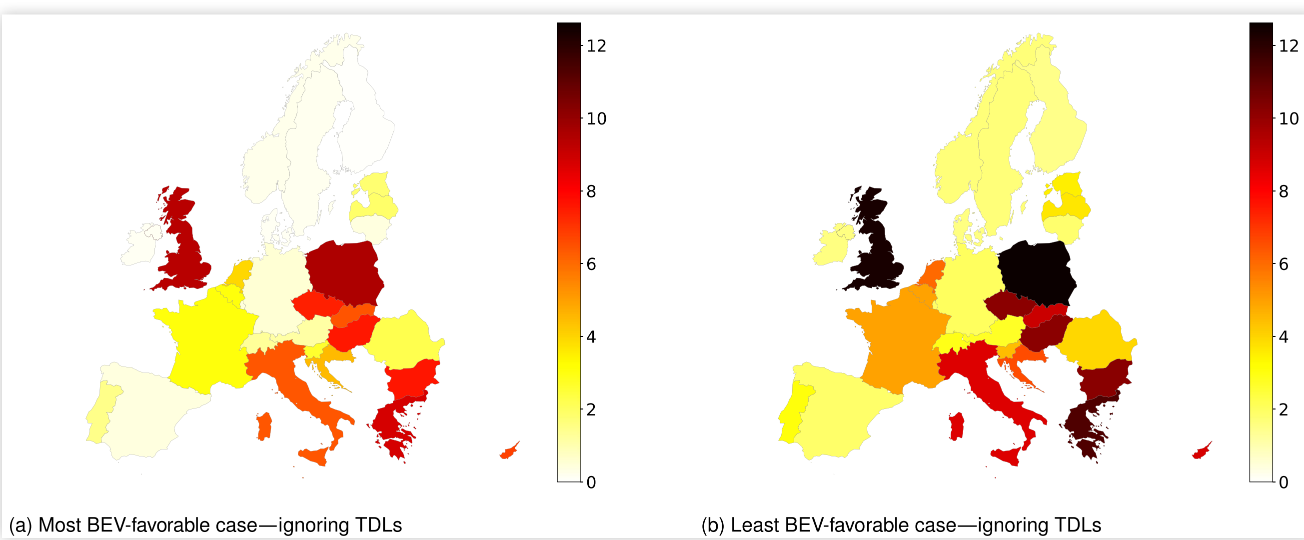


FIGURE 11 Applying temperature correction—change in ER_{FHEV} (units of g CO_2 eq/km).

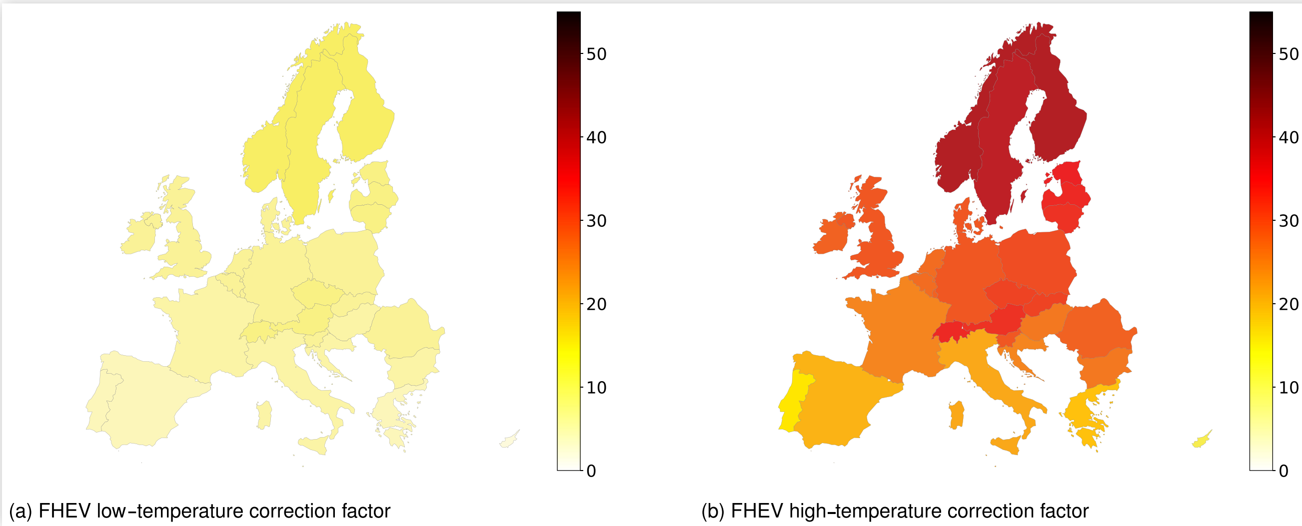


FIGURE 12 Applying temperature correction—change in ER_{BEV} (units of g CO_2 eq/km).

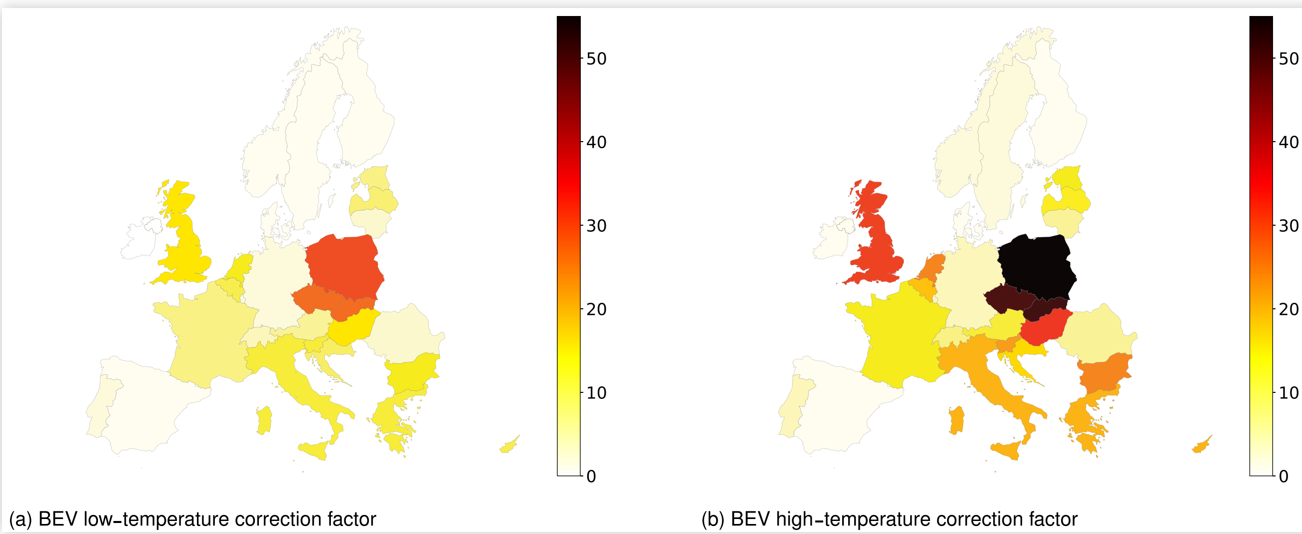
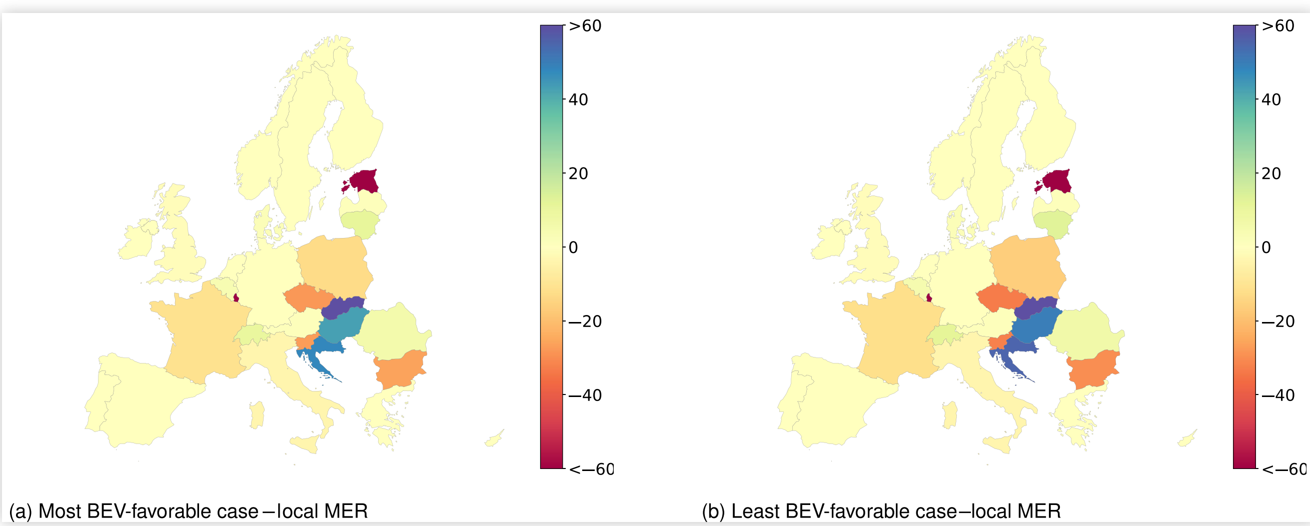


FIGURE 13 Change in $ER_{FHEV} - ER_{BEV}$ (units of g CO_2 eq/km)—relative to Figure 5.



improvement for the BEV, which would indicate that these countries marginally import from other countries with dirtier electricity grids. The most extreme case is Slovakia, whose consumption marginal emissions rate is 84% higher than its local marginal emissions rate. The countries in red show a relative improvement in the FHEV emissions rate, with Luxembourg and Estonia seeing the largest changes. Estonia's local marginal emissions rate is 784 g CO_2 eq/kWh, which is 341% higher than its consumption marginal emissions rate. This is due to 78% of Estonia's marginal demand being met by imports from the country with the lowest marginal emissions rate: Finland.

Looking at the most BEV-favorable scenario, driving a FHEV in the Czech Republic now appears to reduce emissions, and in the least BEV-favorable case, Bulgaria, Estonia, Luxembourg, and Slovenia now indicate the FHEV is the better option, while Hungary and Slovakia now favor the BEV. This is a clear indication of how important it is to consider the effect of imports and exports on emissions associated with charging BEVs.

Charging Patterns Unlike TDLs, temperature correction, and imports and exports, charging patterns were not previously considered in this LCA. Instead, it was assumed that cars would be charged at the mean marginal emissions rate. When considering Tables A.2, A.4, and A.6, the effect of charging at different times of day in different countries can clearly be seen. For example, in Finland (FI) and Norway (NO) the hourly consumption marginal emissions rates are effectively independent of the hour of the day, however in a number of countries, such as Poland (PL), Bulgaria (BG), and Greece (GR), for example, there is a large (576 g CO_2 eq/kWh) difference in maximum and minimum hourly consumption marginal emissions rates over the course of the day. In these and many other countries, overnight charging would give substantially lower emissions compared to peak hours (morning or evening) charging. If it takes about 8 h to charge an electric vehicle (assuming a 50–60 kWh battery with 7 kW charging), then the highest and lowest-emitting charging windows can be evaluated for each country by finding the 8-h period with the lowest and highest mean marginal emissions rates. Figure 14 is the same as Figure 5, except that Figure 14(a) uses the mean marginal emissions rate from the optimal 8-h windows, and Figure 14(b) uses the worst 8-h windows. As a result, this presents more extreme upper and lower bounds than in Figure 5. In the most BEV-favorable case, only Cyprus indicates that a FHEV would produce lower emissions, while in the least BEV-favorable case, 11 countries appear to favor the FHEV over the BEV.

Unlike the first three examples, it cannot be definitively said that charging patterns should or should not be ignored in an LCA. While the upper and lower bounds were affected, and for some countries the conclusions altered, the validity of assuming charging patterns with marginal emissions rates is uncertain. If every electric vehicle owner began charging at the hours with the lowest marginal emissions rates, there could be a substantial increase in demand at those times, and the reverse would then be true for the hours with high marginal emissions rates. This in turn could result in the marginal sources (and hence emissions rates) changing at those times. Hence, charging patterns were not implemented in this vehicle comparison LCA, but are shown here for completeness.

Light Bulb Comparison

There are several countries on the borderline when it comes to deciding which drivetrain option leads to lower lifecycle emissions. To provide some context to the difference in emissions rates, the emissions saving of the BEV drivetrain can be represented as the number of light bulbs

FIGURE 14 Best and worst charging $ER_{FHEV} - ER_{BEV}$ (units of g CO_2 eq/km).

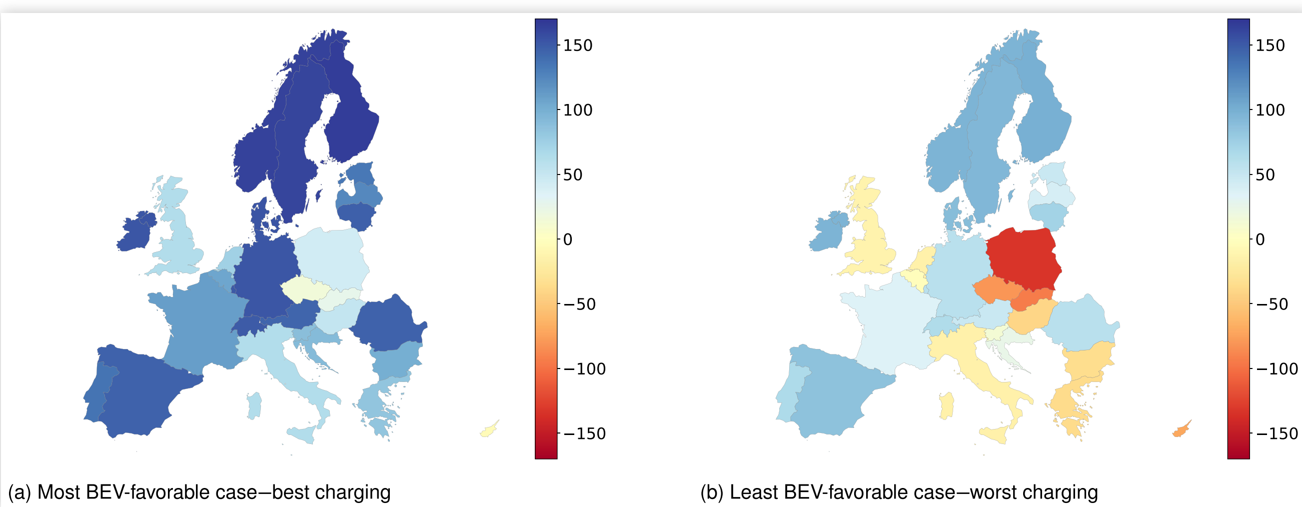


TABLE 3 Emissions reduction in most BEV-favorable case.

Country	Number of LEDs
Bulgaria	18
Czech Republic	1
Great Britain	15
Greece	13
Hungary	9
Italy	14
Netherlands	18
Slovakia	1

that would need to be replaced by LEDs to provide the same benefit. If a 60 W incandescent light bulb is replaced by a 7 W LED bulb, and assuming that it is switched on for 8 h a day, this will save 155 kWh of electricity per year. In Slovakia, the marginal emissions rate (accounting for TDLs) is 858 g CO_2 eq/kWh, and the emissions rate saving from the BEV in Figure 5(a) is 5.6 g CO_2 eq/km. Hence, if the BEV is driven 20,000 km in 1 year, the emissions avoided by driving a BEV equates to 112 kg CO_2 eq, whereas the purchase of the LED saves 133 kg CO_2 eq. So, the emissions benefit of driving a BEV in Slovakia, in the best-case scenario, can be achieved by instead driving a FHEV and replacing one light bulb with an LED. In the case of the Hyundai Kona Advance, the FHEV costs at least £4970 less than either of the BEV models, whereas the price of an LED bulb is under £10 (and this cost would be recouped several times over by the energy saving). The same calculations have been performed for several other countries which offer a relatively small emissions reduction in the most BEV-favorable case and these are summarized in Table 3.

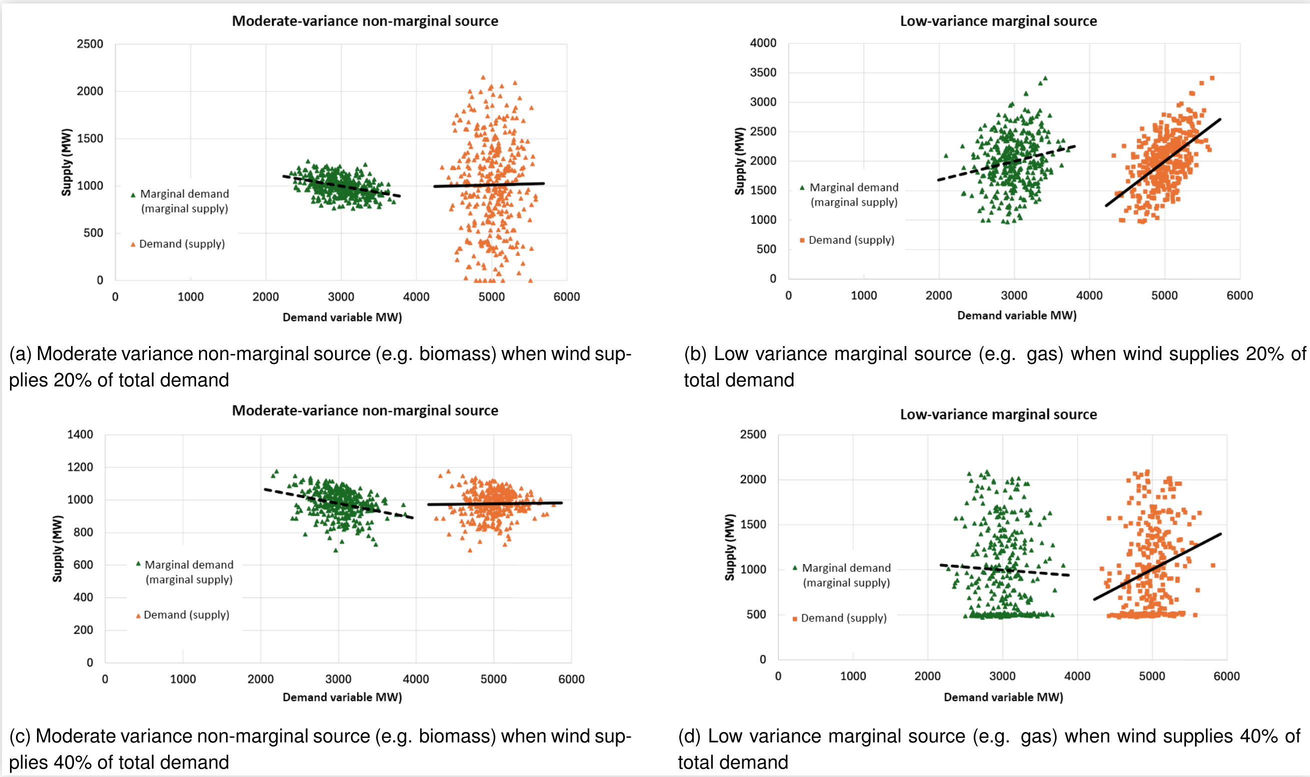
The purpose of this comparison is not to diminish the benefit offered by BEVs, but instead to outline that in certain countries, there are much more cost-effective methods to reduce emissions. The trade-off between the emissions benefit and the additional cost of a BEV will strongly influence consumer decisions when choosing a new car, and for the countries in Table 3, LEDs offer a cheaper way to avoid a similar amount of emissions. In countries with lower marginal emissions rates (below about 450 g CO_2 eq/kWh), the emissions saved by using LEDs decreases, and the emissions avoided by driving a BEV increase, so the number of LEDs required can increase substantially.

German Grid

Germany is arguably the most important of all the countries analyzed in this LCA. It has the largest population, largest number of passenger cars (49 million [43]), and its size and central location means that it has the greatest number of interconnectors and cross-border flows: 11. In 2023, seven countries marginally imported electricity from Germany, each doing so for at least 6 h of the day. The average emissions rate in Germany is relatively high (391 g CO_2 eq/kWh), given the country's heavy utilization of coal—26% of local generation in 2023. However, 59% of local generation is produced by renewable sources, with more than half of this coming from wind energy. In 2023, generation from low-carbon energy (wind, solar, and nuclear) in Germany exceeded demand (excluding exports) for 3.3% of the hours of the year. Excluding wind energy, this did not occur. Consequently, in this LCA, wind is a marginal source for every hour of the day in Germany and as a result, Germany's marginal emissions rate, 71 g CO_2 eq/kWh, is relatively low.

In addition, several countries can exhibit negative marginal emissions rates (Germany included), which is generally due to fossil fuel generation being negatively correlated with renewable energy production—i.e., when renewable output is predicted to increase, coal or gas plants are turned off. In a simple Monte Carlo simulation, supply and demand profiles can be created to illustrate this. Using four source types [low-variance non-marginal (e.g., nuclear), moderate-variance non-marginal (e.g., biomass), high-variance renewable (e.g., wind), and low-variance marginal (e.g., gas)] it is possible to show that the marginal source will demonstrate a positive slope when regressed with demand (which here is the supply) and a negative slope when regressed with marginal demand (which here is marginal supply). This occurs when the moderate-variance non-marginal source is negatively correlated with the high-variance renewable source. This is most likely the situation that is found in these countries, where planning for variation in wind supply on the grid requires adjustments to another source to maintain grid stability. This is illustrated in Figure 15, where two cases are shown. One where wind comprises 20% of the total supply (upper) and the other where the wind is 40% of the total supply (lower). The linear trendlines (representative of the regressions) are shown for the low-variance marginal source and the moderate-variance non-marginal source, the latter of which was negatively correlated with the high-variance renewable source for the purposes of this demonstration. Figure 15 shows that the initially positive slope of the marginal source (right) with supply converts to a negative slope when re-regressed (i.e., against marginal supply) when wind is at 40%. However, when the wind is at 20%, both slopes are positive. The moderate-variance non-marginal source (left) initial regression does not produce a statistically significant positive slope in either scenario, so is classified as non-marginal in the analysis. Upon re-regression, a source like the low-variance marginal source in the 40% wind case would be removed due to its negative slope, leaving only wind as the marginal source. But, wind is not a marginal source because it cannot respond to demand. To address this, a few alternative approaches are suggested.

FIGURE 15 Trendlines (representative of the regressions) from the Monte Carlo simulation for various sources regressed against marginal demand and demand for two cases, one where wind is 20% of the total supply and another when wind is 40% of the total supply.



(a) Moderate variance non-marginal source (e.g. biomass) when wind supplies 20% of total demand

(b) Low variance marginal source (e.g. gas) when wind supplies 20% of total demand

(c) Moderate variance non-marginal source (e.g. biomass) when wind supplies 40% of total demand

(d) Low variance marginal source (e.g. gas) when wind supplies 40% of total demand

Renewable sources could be removed before re-regressing, (i.e., using the "emitting source" classification), as has been done in previous studies [16]. In Germany, the "emitting source" marginal emissions rate is 935 g CO_2 eq/kWh. But given that the previous method indicated that more than 90% of marginal demand was met by wind generation, using this value is inappropriate.

An alternative method is to avoid using Equation 6. Instead, the local marginal emissions rate can be calculated using Hawkes's Method [44] (regressing total generation with total emissions mass flow rate, for a given country, for a given hour of the day), and then $\beta^{Y}_{c,h}$ can be evaluated by multiplying the local emissions rate by the sum of the gradients of the marginal sources, $\sum \beta^{G}_{u,c,h}$. In this way, the effect of marginal imports is still included, and the marginal emissions rate captures the change in emissions in response to a change in demand. Using this method, Germany's marginal emissions rate is estimated to be 316 g CO_2 eq/kWh. However, when extending this to other countries, some, such as Spain, exhibit negative marginal emissions rates, which indicates that this method does not provide meaningful results.

Another possible approach is to evaluate the marginal sources and imports, and rather than re-regressing, assume that each respond to a fraction of marginal demand. This fraction is calculated by normalizing the marginal source's gradient from Equation 3 $\left(\beta^{G}_{u,c,h}\right)$ by the sum of all of the marginal sources/imports (i.e., use the remaining marginals by a proportion of their capacity). Alternatively, the slopes from the first regression could be normalized and used as if they resulted from the re-regression. This fraction (from either approach) is then used in a weighted sum of the emissions factors for that country, to calculate a new estimate for $\beta^{Y}_{c,h}$, as shown in Equation 15:

$$\beta^{Y}_{c,h} = \frac{1}{\beta_{total}} \sum_{u \in U^{M}_{c,h}} \beta^{G}_{u,c,h} F_{u,c}$$
$$\text{where} \quad \beta_{total} = \sum_{u \in U^{M}_{c,h}} \beta^{G}_{u,c,h} + \sum_{q \in C^{M}_{c,h}} \beta^{I}_{q,c,h} \qquad (15)$$

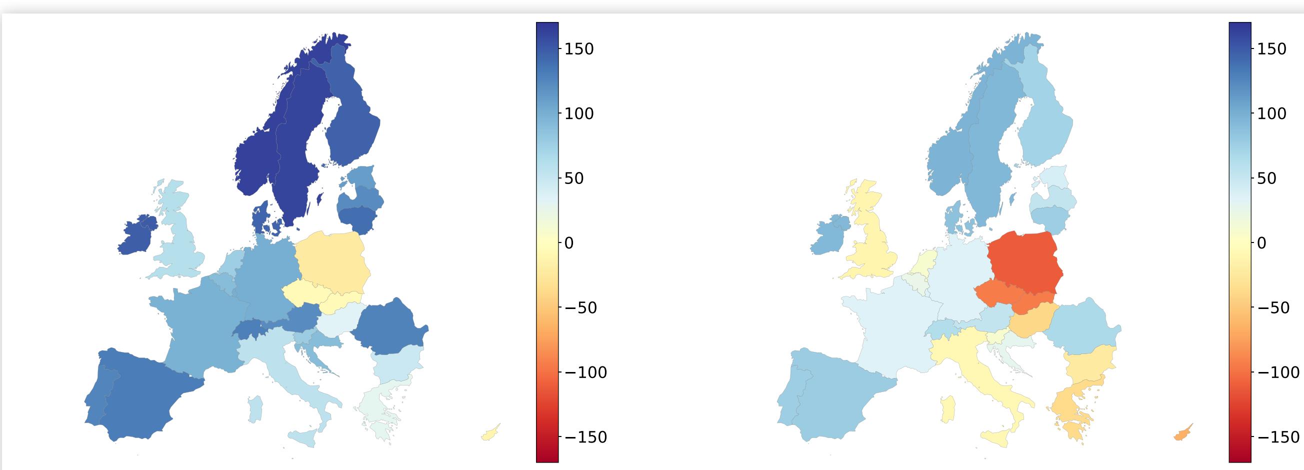
In this work, the marginals were used by a proportion of their capacity to obtain the fraction (although it should be noted that in this case, using the slopes from the first regression gave similar results). For Germany, the advantage of this method over previous work [16] is that it avoids the dominant effect of renewables in the re-regressing process, which otherwise causes the removal of fossil fuel sources which do, in fact, respond to demand. The advantage over Hawkes's Method is that this method ensures all of the marginal emissions rates are positive, for every country. This method evaluates the responses of generation sources in isolation, whereas the previous methods analyze the simultaneous responses of multiple sources by combining them into one regression (such as in Equation 6). It could therefore be argued that this means the grid is not treated as a dynamic system; however, it avoids the issues presented in the re-regression process for the cases where some marginal sources are negatively correlated with other, more dominant, marginal sources. While the point made here has been about ensuring that the contribution of fossil fuels to the marginal emissions rate will be included in a grid such as Germany's, which is dominated by renewables, it should also increase the likelihood that the response of renewables will be represented in a grid dominated by fossil fuel sources. This method is, effectively, considering the probability that a source will respond to increased demand and uses that as a weighting factor to determine the marginal emissions rate. All sources which appear to respond to demand are included, and hence this may be the most appropriate process for countries in Europe, where renewable sources, particularly wind, are dominant marginal sources. This method indicates that Germany's marginal emissions rate is 299 g CO_2 eq/kWh, and the result of performing the LCA with these marginal emissions rates for the Hyundai Kona is represented in Figure 16. This new method changes some of the LCA's conclusions for the BEV–FHEV comparison. In the most BEV-favorable case, the Czech Republic and Slovakia have switched to favoring the FHEV, and in the least BEV-favorable case, Bulgaria now favors the FHEV, whereas the Netherlands favors the BEV.

Conclusions

In this work, average and data-driven marginal emissions comparisons have been used to conduct an LCA for two otherwise identical vehicles propelled by different powertrains. This applies a method previously developed by Burton et al. to the USA [16] and modifies and adopts it for countries in Europe. The key takeaways of this LCA are as follows:

1. Comparing powertrain options for passenger vehicles, purely on greenhouse gas emissions, BEVs are the preferable option for most countries in Europe. As per Figure 5, the lifecycle emissions rate of a Hyundai Kona BEV is lower than that of the FHEV version in 21 out of the 30 countries analyzed, even in the least BEV-favorable case. It ought to be noted, however, that the validity of results for one region—Ireland—is limited due to poor data quality.
2. When comparing the BEV and FHEV, seven countries indicate that the powertrain technology with the lowest emissions rate differs in the most and least BEV-favorable scenarios. In these countries, the benefit of an all-electric fleet is more limited, and the middle ground of a PHEV may be the optimal choice.
3. Marginal emissions rates, assuming they can be calculated, give the most realistic indication of the lifecycle emissions which result from deciding to drive a BEV instead of a FHEV/ICEV. The use of average emissions rates can cause misleading conclusions to be drawn about which powertrain produces fewer emissions, either by exaggerating or diminishing the benefit of driving a BEV.

FIGURE 16 Hyundai Kona—marginal emissions case—evaluating marginal sources responding to a fraction of marginal demand (units of g CO_2 eq/km).



(a) Most BEV-favorable case ER_{FHEV} - ER_{BEV}

(b) Least BEV-favorable case ER_{FHEV} - ER_{BEV}

4. The sensitivity analysis clearly indicates that neglecting factors such as interconnector and cross-border flows and temperature correction can cause a change in the LCA's conclusions. As a result, any LCA that fails to consider these effects could introduce bias into its results.
5. For countries with significant renewable energy capacity, particularly if those countries use negative pricing to curtail production of renewable energy, an alternative method for calculating marginal emissions rates is developed and applied.
6. A marginal emissions rate of 450 g CO_2 eq/kWh is approximately the cutoff below which the BEV becomes the preferable powertrain option on an emissions basis in this analysis. However, it is important to bear in mind that just below this cutoff there is still significant scope to reduce vehicle emissions further.

Europe as a whole appears to be in a good position to reap the potential benefits offered by BEVs. That being said, for about a third of the countries analyzed the emissions rate saving is limited or nonexistent. Hence, in these countries, choosing a BEV over a hybrid may not be the most cost-efficient way to reduce greenhouse gas emissions today. A consumer's choice of powertrain technology will ultimately come down to cost and amenity, and while a BEV may be too expensive in many cases, choosing a hybrid over an ICEV presents a more affordable method of reducing vehicle emissions.

Declaration of AI-Assisted Technologies

The authors declare that no generative AI technologies were used in the preparation and writing of this article. In doing so, the authors take full responsibility for the authenticity and scientific integrity of this article.

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Definitions, Acronyms, Abbreviations

AAA - American Automobile Association

API - Application Programming Interface

BEV - Battery Electric Vehicle

BMRS - Balancing Mechanism Reporting Service

CO_2 - Carbon Dioxide

CO_2 eq - Carbon Dioxide Equivalent

EIA - Energy Information Administration

ENTSO-E - European Network of Transmission System Operators for Electricity

EPA - Environmental Protection Agency

ETS - Emissions Trading Scheme

EU - European Union

FHEV - Full Hybrid Electric Vehicle

GHG - Greenhouse Gas

ICEV - Internal Combustion Engine Vehicle

IPCC - Intergovernmental Panel on Climate Change

LCA - Life Cycle Analysis

LED - Light-Emitting Diode

LIB - Lithium-Ion Battery

PHEV - Plug-in Hybrid Electric Vehicle

SEM - Single Electricity Market

TDL - Transmission and Distribution Losses

TSOC - Transmission System Operator Cyprus

UNECE - United Nations Economic Commission for Europe

USA - United States of America

WLTP - Worldwide Harmonised Light Vehicles Test Procedure

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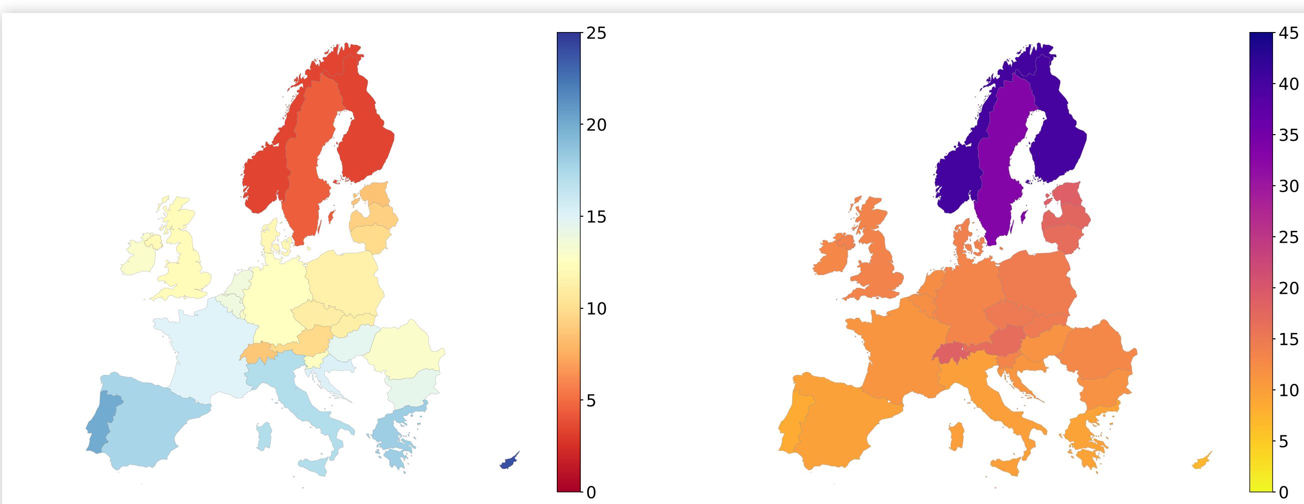
Appendix: Detailed Breakdown of Country’s Dominant Marginal Sources/Imports and Hourly Emissions Rates

FIGURE 17 Hyundai Kona advance—FHEV-ICEV comparison—least FHEV-favorable case.



(a) $ER_{ICEV} - ER_{FHEV}$ (units of g CO_2 eq/ km)

(b) Breakeven distance (units of ’000s of km)

TABLE A.1 Top three marginal sources/imports (1/3).

Code	Country	Marginal sources/imports
AT	Austria	Wind (37.6%), gas (21.7%), pumped hydro (20.9%)
BE	Belgium	Gas (39.9%), Netherlands (28.9%), wind (12.1%)
BG	Bulgaria	Coal (36.8%), Romania (27.2%), hydro (12.4%)
CH	Switzerland	Hydro (23.52%), Germany (23.2%), pumped hydro (22.1%)
CY	Cyprus	Oil (94.8%), wind (3.6%), solar (1.6%)
CZ	Czech Rep.	Coal (56.1%), Poland (15.6%), Germany (14.3%)
DE	Germany	Wind (90.3%), coal (3.5%), solar (2.3%)
DK	Denmark	Wind (80.7%), Germany (19.3%)
EE	Estonia	FI (78.5%), oil shale (15.5%), wind (2.6%)
ES	Spain	Wind (86.8%), solar (7.5%), gas (2.1%)

TABLE A.2 Hourly consumption marginal emissions rates (units of g CO_2 eq/kWh) (1/3).

Hour	AT	BE	BG	CH	CY	CZ	DE	DK	EE	ES
0	67.0	235.1	247.7	154.1	953.6	758.2	12.6	12.6	171.1	12.6
1	70.8	186.9	243.3	159.9	953.6	758.3	16.9	13.6	168.3	12.6
2	68.9	259.2	235.0	169.6	885.6	756.3	17.4	13.7	162.2	12.6
3	33.4	384.9	248.2	174.2	867.8	770.9	18.1	13.9	151.6	12.6
4	154.9	481.3	310.6	146.8	859.4	754.8	20.0	14.1	169.3	12.6
5	219.7	514.7	738.7	45.7	874.1	797.5	267.3	56.4	153.3	15.4
6	247.8	504.2	591.8	46.4	953.6	810.1	341.3	68.6	164.4	93.6
7	239.2	504.0	542.9	46.0	953.6	829.8	315.5	72.0	150.2	120.5
8	232.2	406.8	504.4	87.6	953.6	868.4	292.6	69.3	136.3	96.2
9	212.5	317.0	472.9	110.1	953.6	876.7	241.9	61.1	121.7	74.2
10	228.4	312.1	283.5	87.2	891.7	788.9	16.7	13.6	134.2	15.9
11	222.1	286.5	283.6	121.9	900.2	791.9	17.0	13.7	147.0	15.4
12	213.1	284.2	296.3	104.4	893.5	783.8	16.6	13.7	163.3	15.0
13	220.3	165.4	434.5	101.9	891.2	765.6	12.6	12.6	173.3	14.9
14	224.8	184.3	686.8	55.6	840.3	751.1	12.6	12.6	175.4	15.5
15	232.8	117.4	657.3	51.1	814.1	762.2	12.6	12.6	177.1	15.8
16	246.1	400.4	666.5	57.4	835.8	792.8	12.6	12.6	197.0	15.1
17	244.3	489.2	686.8	54.5	861.1	825.4	12.6	12.6	216.5	14.0
18	251.1	534.2	701.9	47.3	953.6	827.4	12.6	12.6	238.0	13.4
19	251.4	534.6	661.9	63.6	953.6	858.2	12.6	12.6	300.9	12.6
20	193.1	538.5	400.5	59.3	953.6	829.2	12.6	12.6	243.0	12.6
21	130.3	536.5	363.2	93.4	907.7	822.8	12.6	12.6	209.5	12.6
22	64.2	544.5	291.7	158.7	902.7	783.9	12.6	12.6	201.6	12.6
23	62.8	247.1	263.1	142.9	900.2	734.9	12.6	12.6	194.1	12.6

TABLE A.3 Top three marginal sources/imports (2/3).

Code	Country	Marginal sources/imports
FI	Finland	Wind (100%)
FR	France	Gas (38.5%), hydro (19.0%), Spain (10.4%)
GB	Great Britain	Gas (90.4%), biomass (5.5%), coal (3.0%)
GR	Greece	Gas (45.8%), wind (18.8%), coal (16.0%)
HR	Croatia	Bosnia (34.4%), wind (21.9%), Serbia (18.9%)
HU	Hungary	Slovakia (64.8%), Austria (24.3%), solar (7.6%)
IE/NI	Ireland	wind (100%)
IT	Italy	Gas (72.6%), other (6.2%), wind (4.8%),
LT	Lithuania	Wind (44.8%), Sweden (36.0%), Belarus (9.2%)
LU	Luxembourg	Germany (99.4%), gas (0.5%), biomass (0.1%)

TABLE A.4 Hourly consumption marginal emissions rates (units of g CO_2 eq/kWh) (2/3).

Hour	FI	FR	GB	GR	HR	HU	IE/NI	IT	LT	LU
0	12.6	301.6	478.3	267.1	353.0	519.8	12.6	482.9	115.3	12.6
1	12.6	298.9	479.5	278.4	360.7	529.3	12.6	469.1	112.8	19.1
2	12.6	305.7	479.0	260.9	360.7	535.1	12.6	465.9	114.0	17.4
3	12.6	314.1	459.0	314.0	345.3	551.4	12.6	480.4	111.0	20.8
4	12.6	318.9	461.8	379.7	325.9	610.7	12.6	514.3	69.0	20.0
5	12.6	297.2	468.4	611.6	318.4	680.5	12.6	493.8	298.9	267.3
6	12.6	269.6	478.1	537.4	329.1	690.4	12.6	465.8	58.3	341.3
7	12.6	254.4	484.5	504.3	345.2	723.0	12.6	457.4	86.0	317.8
8	12.6	259.7	490.8	464.3	351.9	638.2	12.6	461.1	132.0	295.2
9	12.6	273.9	490.1	434.8	357.1	525.2	12.6	463.4	110.5	241.9
10	12.6	274.0	486.9	432.8	355.3	478.4	12.6	463.7	61.7	23.0
11	12.6	286.8	486.3	447.5	352.6	495.0	12.6	471.9	61.7	23.2
12	12.6	294.1	487.0	493.1	339.6	519.1	12.6	495.7	63.1	22.8
13	12.6	297.3	486.8	544.7	326.7	554.2	12.6	494.8	71.3	19.4
14	12.6	53.9	487.5	589.7	318.5	654.1	12.6	490.1	73.1	19.3
15	12.6	51.5	488.3	636.8	302.9	661.7	12.6	502.8	73.2	18.7
16	12.6	255.8	492.4	631.9	330.2	667.6	12.6	529.6	76.6	19.3
17	12.6	266.4	495.7	638.3	337.0	670.4	12.6	540.4	61.5	19.5
18	12.6	274.6	495.4	641.4	335.7	676.5	12.6	564.5	57.9	18.2
19	12.6	273.3	493.1	640.3	334.1	708.0	12.6	579.3	52.7	12.6
20	12.6	299.3	490.8	652.3	331.9	617.4	12.6	579.4	56.3	12.6
21	12.6	307.6	489.7	694.4	317.3	578.9	12.6	572.4	52.8	12.6
22	12.6	308.6	484.1	374.4	317.2	513.0	12.6	507.0	86.0	12.6
23	12.6	264.7	479.9	291.8	339.0	484.2	12.6	483.2	106.2	12.6

TABLE A.5 Top three marginal sources/imports (3/3).

Code	Country	Marginal sources/imports
LV	Latvia	Hydro (43%), gas (31%), Estonia (18.4%)
NL	Netherlands	Gas (63.5%), coal (12.8%), solar (10.0%)
NO	Norway	Hydro (95.9%), pumped hydro (4.1%)
PL	Poland	Coal (70.7%), wind (14.2%), gas (7.0%)
PT	Portugal	Wind (58.5%), gas (16.7%), hydro (14.0%)
RO	Romania	Wind (68.7%), hydro (15.7%), Bulgaria (7.0%)
SE	Sweden	Hydro (50.6%), wind (31.1%), Norway (11.8%)
SI	Slovenia	Croatia (49.8%), hydro (16.9%), coal (16.7%)
SK	Slovakia	Czech Rep. (66.8%), Poland (32.0%), gas (1.0%)

TABLE A.6 Hourly consumption marginal emissions rates (units of g CO_2 eq/kWh) (3/3).

Hour	LV	NL	NO	PL	PT	RO	SE	SI	SK
0	186.5	432.4	24.3	535.1	12.6	42.6	27.4	361.8	680.7
1	190.5	330.8	24.2	521.8	12.6	42.3	27.5	359.9	676.2
2	183.4	315.3	24.2	543.9	12.6	44.3	27.4	357.7	683.1
3	183.6	318.5	24.2	621.3	12.6	39.2	27.3	356.8	720.5
4	183.4	555.3	24.3	783.4	12.6	73.4	27.7	373.8	764.2
5	200.0	545.3	24.3	1063.3	135.4	165.4	29.1	407.8	882.9
6	228.0	533.1	24.4	1079.6	155.5	198.4	28.9	431.5	874.9
7	243.5	514.8	24.4	1083.6	144.4	206.7	28.2	437.8	903.5
8	236.3	504.4	24.4	1046.9	141.5	196.4	27.7	411.2	933.4
9	239.7	345.5	24.3	1045.3	121.4	183.0	26.7	389.0	925.1
10	245.9	438.6	24.3	1027.1	113.3	153.8	26.3	374.3	860.4
11	238.0	417.3	24.3	1024.7	117.5	153.5	25.6	377.1	858.6
12	240.0	413.9	24.3	1029.5	108.8	151.6	25.8	357.7	853.6
13	247.0	431.2	24.3	1031.3	108.6	153.6	26.9	347.8	845.8
14	250.0	466.7	24.3	1031.3	61.0	167.9	29.2	341.1	833.7
15	255.2	518.4	24.4	1062.4	108.7	129.6	31.0	364.7	851.7
16	272.7	543.5	24.5	1079.5	130.4	132.5	32.2	392.2	865.9
17	283.3	427.4	24.5	1097.8	196.1	136.4	33.3	418.7	879.2
18	284.7	570.9	24.5	1089.0	216.0	113.9	33.9	426.2	892.2
19	286.4	568.6	24.4	1073.2	193.1	94.9	34.0	427.3	923.8
20	233.8	572.0	24.4	821.0	158.7	62.9	33.4	412.5	826.7
21	204.8	562.7	24.4	730.1	118.3	47.8	31.5	470.6	793.9
22	195.4	575.6	24.3	586.3	118.2	47.6	25.0	358.1	721.0
23	185.7	449.2	24.3	522.6	27.8	46.7	28.0	361.4	665.2