Energy Reports 12 (2024) 5834–5845

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Determining the share of renewable electricity in electric vehicle charging in Europe

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ARTICLE INFO

Keywords:
Plug-in electric vehicles
Renewable energy
Home charging
Work charging
Public charging

ABSTRACT

Plug-in electric vehicles (PEVs) are considered a promising option to reduce greenhouse gas (GHG) emissions in transport. The electricity used for charging is decisive for the environmental assessment of PEVs. Most studies on the environmental performance of PEV assume carbon intensity according to the average electricity grid mix for charging. This article provides a systematic overview of existing studies on charging shares at home, work, and public charging points and provides new empirical and statistical data on the contracted renewable electricity shares at these locations. As a result, we obtain a contracted share of 57 – 66 % of renewables in the charged electricity for PEVs in Europe in 2022 with 61 % as most likely value, i.e. higher than the total contracted share of 49 % in the electricity mix. The data used covers 94 % of the European PEV market. Our results show that the actual share of renewables in electricity contracts for home, work and public charging is higher than in the European grid mix. Despite discussions around the methodological use of contracted renewable electricity, our findings imply that many previous studies underestimate the share of renewable electricity in PEV charging which implies underestimation of well-to-wheel life-cycle benefits of PEV in parts of the literature. Future research should analyse charging behaviour and renewable usage in PEV charging more broadly empirically.

1. Introduction

1.1. Motivation and contribution

Plug-in electric vehicles (PEVs) including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) can offer noteworthy greenhouse gas (GHG) emission reduction on a life-cycle basis compared to internal combustion engine vehicles (ICEVs). A key prerequisite for this is that the PEVs are mainly charged from renewable energy sources, i.e., renewable electricity (RE) (IEA – International Energy Agency., 2024, Cox et al., 2018, Märtz et al., 2021).

In the passenger car segment of the European Union, the share of PEVs in new registrations has increased from around 3 % in 2019 (BEVs 1.9 % and PHEVs 1.1 %) to over 22 % in 2023 (BEVs 14.6 % and PHEVs 7.7 %) (EAFO – European Alternative Fuels Observatory., 2024). Even if the figures are currently slightly decreasing, around one in five newly registered passenger cars has been a PEV since 2022. However, the share of PEVs in the total fleet of passenger cars in the EU is still low with 3 % by end of 2023 (EAFO – European Alternative Fuels Observatory., 2024). So far, there is hardly any information available on the share of renewable electricity in the charging volumes for these vehicles.

Existing studies show that life-cycle PEV emissions are impacted by the electricity used for charging (Yuksel et al., 2016, Märtz et al., 2021, Tamayao et al., 2015, Nordelöf et al., 2014). However, these studies either use current electricity production mixes or exogeneous assumptions in the analyses but little is known about the use of private solar photovoltaics (PV) or the use of renewable electricity contracts despite some evidence that some PEV users use private PV for charging (Scherrer et al., 2019). Further studies analyse the share of charging at different locations (at home, at work and at public charging stations) but do not combine it with the information on type of electricity used for charging. Likewise, actual measurements or information on the electricity volumes charged at different locations, however, are rare (e.g. Dodson and Slater, 2019, Gardien et al., 2020 and Duurkoop et al., 2021). Thus, despite the importance of electricity used for charging PEV at different locations, a systematic and empirical analysis for Europe is still missing.

Here, we empirically estimate ranges for the share of renewable electricity used for charging PEVs in Europe. Specifically, we look at the European Union (EU) with its 27 member states (EU27) as well as the

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https://doi.org/10.1016/j.egyr.2024.11.044
Received 2 August 2024; Received in revised form 31 October 2024; Accepted 16 November 2024
Available online 27 November 2024
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United Kingdom (UK), Norway (NO) and Iceland (IS). We combine publicly available data from existing reports and supplement this with new data from our own surveys.

The aim of the present study is to identify upper and lower boundaries for the RE share of PEV charging in Europe. We estimate the range of the RE share in PEV charging over all countries of the EU27 + UK, NO, IS. Therefore, we do not limit ourselves to the countries for which a sufficient data basis is available, but also discuss approaches to close remaining data gaps and their impact on the range of the RE share for all European countries mentioned.

The present work differs from previous research in several aspects. First, it provides a systematic overview of the existing literature on the characteristics of PEV charging in Europe - differentiating between home, work, and public charging. Second, we present new survey data including PEV from several European countries but also include fleet managers regarding the contracted electricity for work charging. Thirdly, we make an empirical estimate for a plausible range of the contracted RE share in PEV charging in Europe that is more robust than the prevailing assumption of the physical grid mix. Thus, we go beyond existing studies by gathering new empirical data in unified fashion for thirteen European countries and provide new data on RE in charging for future life-cycle assessments of PEV.

The outline of the present paper is as follows. Section 1.2 provides an overview of the existing literature on the relevance of RE use for the carbon footprint of PEVs in general and the characteristics of PEV charging in Europe in particular. In Section 2, we describe the data used for our study, i.e. the results of our newly conducted surveys and the data used from statistical publications and existing literature. In Section 3, we present our findings on the share of renewable electricity in the charging volumes of the PEV fleet in Europe. Our results are discussed in Section 4 and we present our conclusions in Section 5.

1.2. Existing literature

Past studies have shown that life-cycle PEV emissions depend heavily on the assumed electricity mix and usage conditions (Yuksel et al., 2016, Märtz et al., 2021, Tamayao et al., 2015, Nordelöf et al., 2014). Yuksel et al. (2016) focus on the marginal grid mix, ambient temperature and driving behaviour. They find the GHG emission benefit of PEV (compared to ICEV) strongly depends on the source of electricity used for charging. Tamayao et al. (2015) compare different grid mixes without future changes in the carbon intensity. Xu et al. (2020) consider the emissions from the whole PEV life-cycle by a Life Cycle Assessment (LCA) and combined this with a sophisticated consideration of charging times in the European energy system. Kim et al. (2016) discuss cradle-to-gate emissions of commercial BEV and compared the cradle-to-gate GHG emissions to an ICEV. Märtz et al. (2021) also include the future evolution towards more RE in the energy systems in Europe and globally, leading to an improved outlook on PEV life-cycle GHG emission benefits. Cox et al. (2018) highlight the importance of changes in the electricity sector in PEV life-cycle GHG emissions and find electricity used for charging is the most important factor in GHG emission results. Similarly, based on the analysis of 44 electric vehicle LCA studies, Marmiroli et al. (2018) conclude that despite the large scale and numerous variables, the electricity mix explains 70 % of the variability in the results in electric vehicle LCA studies.

Despite being the single most important variable in PEV GHG assessment, the electricity used for charging has received limited attention in the literature. The share of RE in electricity generation mix varies among the European countries with an average of about 45 % (AIB – Association of Issuing Bodies., 2023). For Germany, as the biggest, European car market, survey-based studies find a share of contracted RE of 60 % (Römer and Steinbrecher, 2021) and 58 % (Frenzel et al., 2015) for charging at home. The latter survey is not very recent but contains a large sample and includes an analysis of work charging quantities, thus, a contracted RE share of 53 % for work charging was determined (Frenzel et al., 2015). We add more recent data to Germany and other key markets with an additional new survey to be presented below. In addition, a survey of 35 retail chains in Germany concluded that approximately 68 % of the charging stations in their parking lots are powered from RE contracts (EHI Retail Institute e. V e. V., 2021). Despite the scope of this study, it only covers a specific segment of public charging and only a small share of the publicly accessible charging infrastructure in Germany. As the share of contracted RE for PEV charging has hardly been published so far, we conducted a survey on the contracted renewable electricity shares for PEV charging in the 12 countries with the most PEV registrations and Poland (cf. Section 2.2). In this context, we also collected current data on charging frequency at the various charging locations of PEV users by applying the same methodology for all countries investigated. We thus add to the existing literature with new empirical data on contracted RE in PEV charging and the importance of different charging locations across Europe. We obtain a share of 57 – 66 % of renewables in the charged electricity for PEVs in Europe with 61 % as most likely value, i. e. higher than the total contracted share of 49 % in the electricity mix that is commonly used in the literature. The results of the surveys are presented below.

A second group of studies analysed the characteristics of PEV charging in the EU or individual European countries, focusing on the share of charging at different locations (at home, at work and at public charging stations). Some studies based on empirical data from PEV user surveys provide information on charging location preferences (e.g. Wolff and Madlener, 2019, Avere France and Ipsos, 2020, Enedis, 2021) or the proportion of charging frequency at these locations (e.g. Scherrer et al., 2019, Plötz et al., 2020, Höfling and Römer, 2019, Römer and Steinbrecher, 2020, Figenbaum and Kolbenstvedt, 2016, Figenbaum and Nordbakke, 2019, Helmus et al., 2020, NewMotion, 2020, Visaria et al., 2022, Anderson et al., 2022, EAFO – European Alternative Fuels Observatory., 2022). Other studies use modelling of charging behaviour (McKinsey, 2018, Baresch and Moser, 2019, Nicholas and Wappelhorst, 2021) or expert estimates (T&E 2020). Actual measurements or information on the electricity volumes charged at different locations, however, are very rare (e.g. Dodson and Slater, 2019, Gardien et al., 2020 and Duurkoop et al., 2021). The results of all studies show that charging at home (still) clearly dominates. An overview of the published data is given in Section 2.

Concerning existing literature, we reviewed the English and German literature published since 2015. We found 51 publications that contained data on the two parameters we were looking for, i.e., the distribution of charging processes across different charging locations and the contracted renewable electricity supplies for these locations. Most studies focused on selected European countries or the EU.

Data on the shares of charging across different locations is available in 21 existing publications (see Table 1 for data of the top 5 countries regarding PEV registrations and for EU). A wide range of data can be seen in the published studies, even within individual countries. However, home charging has by far the largest share in all countries with a trend to decrease in more recent studies in favour of charging at public charging points. This can be explained by the ongoing expansion of the public charging infrastructure, which makes more frequent partial charging on the way possible. In addition, it can be assumed that households without a private charging point are also increasingly using a PEV.

For Europe, studies estimated between 55 % and 61 % of home charging among all PEV users, yet with higher shares in multi-family homes (MFH) where PEV owners have less easily access to home charging. The estimated share of work-place charging ranges between 14 % and 27 %.

In summary, many of the existing studies emphasize the importance of the electricity used in charging PEV. But what is the proportion of renewable electricity used for PEV charging in European countries? Studies analysing the behaviour of PEV users provide information for

Table 1
Overview of published shares of use of charging locations for selected European countries.*.

Region	Source	Method & Sample	PEV types	Home	Work	Public
DE	Wolff and Madlener, (2019)	Choice survey, N = 4000 non-EV users	BEV	80 %	12 %	8 %
	Plötz et al. (2020)	Survey, N = 74	PHEV	64 %	22 %	12 % (slow), 1 % (fast)
	Scherrer et al. (2019)	Survey, N = 432	BEV+PHEV	55 %	26 %	12 % (slow), 6 % (fast)
	Höfling/Römer, (2019)	Survey, N = 48	BEV+PHEV	49 %	24 %	25 % (+2 % other)
	Römer/Steinbrecher, (2020)	Survey, N = 87	BEV+PHEV	54 %	19 %	27 %
	Anderson et al. (2022)	Survey, N = 2641	BEV	66 %	17 %	15 % (slow), 2 % (fast)
		Survey, N = 1531	PHEV	80 %	15 %	5 % (slow), 0 % (fast)
	EAFO – European Alternative Fuels Observatory., (2022)	Survey, N = 57	BEV	48 %	22 %	20 % (slow), 10 % (fast)
UK	Dodson and Slater, (2019)	8 million charging events	BEV	71 %	14 %	10 % (slow), 5 % (fast)
			PHEV	78 %	16 %	6 % (fast)
NO	Figenbaum and Kolbenstvedt, (2016)	Survey, N = 3111	BEV	71 %	25 %	4 % (slow), 1 % (fast)
	Figenbaum and Nordbakke, (2019)	Survey, N = 3659	BEV	76 %	20 %	4 %
FR	Avere France & Ipsos 2020	Survey, N = 3643	BEV+PHEV	55 %	12 %	29 % (slow), 4 % (fast)
	Enedis, (2021)	Survey, N = 708	BEV+PHEV (SFH)	89 %	5 %	5 % +1 % other)
		Survey, N = 96	BEV+PHEV (MFH)	54 %	16 %	26 % (+4 % other)
	EAFO – European Alternative Fuels Observatory., (2022)	Survey, N = 58	BEV	61 %	11 %	21 % (slow), 7 % (fast)
NL	Helmus et al. (2020)	Survey, N = 502	BEV	51 %	12 %	26 % (slow), 11 % (fast)
	Gardien et al. (2020)	Survey, N = 1618	BEV+PHEV	47 %	19 %	23 % (slow), 11 % (fast)
	Duurkoop et al. (2021)	Survey, N = 1697	BEV+PHEV	59 %	11 %	22 % (slow), 8 % (fast)
	EAFO – European Alternative Fuels Observatory., (2022)	Survey, N = 55	BEV	47 %	18 %	26 % (slow), 9 % (fast)
EU	McKinsey, (2018)	Simulation & Scenarios	BEV+PHEV (SFH)	74 %	16 %	4 % (slow), 5 % (fast)
			BEV+PHEV (MFH)	52 %	16 %	28 % (slow), 4 % (fast)
	T&E 2020	Expert interviews	BEV	61 %	15 %	17 % (slow), 7 % (fast)
			PHEV	61 %	15 %	24 % (slow), 1 % (fast)
	NewMotion, (2020)	Survey, N = 4500	BEV	58 %	27 %	10 % (slow), 5 % (fast)
	EAFO – European Alternative Fuels Observatory., (2022)	Survey, N = 1378	BEV	55 %	14 %	24 % (slow), 7 % (fast)

Notes: SFH: Single-family houses, MFH: Multi-family houses. *The different data from the studies on the proportion of charging location usage (e.g. shares of charging volumes, frequency of use or usage preference) were adequately harmonized for better comparability.

some European countries on the proportion of charging at different types of location, indicating that home is the most important charging location. However, so far there is no comprehensive overview of the use of renewable electricity for PEV charging in Europe.

2. Data and methods

The present section introduces the methods used in the present paper and the data. We first explain our approach in calculating RE shares including the cluster analysis method and secondly introduce the general data on county specific RE shares as well as the new empirical data we collected for the present study.

2.1. Methods

The aim of the present study is an empirical estimate for a plausible range of the contracted RE share in PEV charging in Europe that is more robust than the prevailing assumption of the physical grid mix. Of course, the share of RE in electricity generation provides a valuable first estimate of RE in PEV charging but some existing studies (e.g., Scherrer et al., 2019, EAFO – European Alternative Fuels Observatory., 2022) indicate that PEV owners are more likely to own PV and use it for charging than the general population and that many CPOs have contracted 100 % RE for the operation of their charging stations. Thus, the aim of the present study is to use new empirical data on contracted RE of PEV owners combined with PEV stock per European country and the share of PEV charging at different locations (with varying information on the contracted RE share for each location) type to provide more accurate estimate for the overall share of RE in PEV charging. Methodologically, we will combine new empirical survey data on contracted RE for thirteen European countries with cluster analysis to transfer the survey results to the remaining European countries.

A first approximation to estimate the RE share in PEV charging is to combine country specific PEV registrations and the respective national electricity mix. Please note that the “share of RE” can be operationalised in different ways: as share of contracted RE, share of production or generation mix RE, or share of supplier mix. We present a first estimate for the share of RE in PEV charging from the respective national electricity mix at the beginning of Section 3 below. We look at the electricity production mix on the one hand and the total supplier mix on the other hand. The country’s electricity production mix results from the types of primary energy sources used for the power plants that feed into the national electricity grid. Even if the electricity production mix does not consider the cross-border exchange of electricity and therefore only approximates the real grid mix, it can be used to estimate the share of RE consumption at national level from a physical point of view. However, as all power plants simultaneously always maintain the grid frequency depending on the current electricity demand, it is not possible to assign a specific power source to a specific power sink. This also means that it is not possible to differentiate between the RE shares used for individual customer groups, such as PEV users (if they are connected to the public grid).

To obtain a more differentiated picture of RE used in PEV charging, detailed information on charging characteristics is required. The reason is that home, work and public charging can differ substantially in the share of actual or contracted RE share. For example, many private PEV owners use their own PV systems to charge their PEV at home, indicating an above average share of RE in the PEV charging at home compared to charging, e.g., at work where the employer is more likely to have grid mix electricity contract (Scherrer et al., 2019, EAFO – European Alternative Fuels Observatory., 2022). Likewise, many CPOs use 100 % contracted RE for their charging stations, possibly to make sure PEV charging is environmentally friendly or because charging station funding programmes require it (BMVI, 2021). We perform a literature review on the distribution of charging processes with respect to different charging locations (home, work, public) and added new primary data from newly conducted surveys as well as evaluations of further statistical data.

2.1.1. Clustering of the European PEV market

To fill the remaining data gaps for share of charging location and contracted RE in PEV charging, we conducted a cluster analysis to find

similarities between countries to ultimately transfer the available data from one country to other countries in the same cluster. The cluster analysis allows us to make empirically based statements about Europe even though our new empirical data covers only a limited set of countries. This clustering does not come without uncertainty, of course, and we treat the uncertainty explicitly by deriving upper and lower bounds for our estimated shares of contracted RE oin PEV charging. Similar clustering approaches have recently been applied to successfully in the literature on European PEV markets and PEV charging (Straka and Buzna, 2019, Möring-Martínez et al., 2024, Hajhashemi et al., 2024, Genov et al., 2024).

For the cluster analysis, we applied a hierarchical procedure using the Ward method, the Euclidean distance, and a z-standardization. We included the following variables as relevant for the research question in the cluster analysis:

- Share of low emission electricity (renewables and nuclear) on the national grid mix (BP, 2020)
- Share of PEV on the country-specific registration of cars (EAFO – European Alternative Fuels Observatory., 2022)
- Share of public charging points on the available charging points in Europe (EAFO – European Alternative Fuels Observatory., 2022)
- Attitude toward protecting the environment within the country's general population (i.e., percentage of the population answering "very important" to the question "How important is protecting the environment for you personally?" (Special Eurobarometer, 2020)
- Share of (semi-)detached houses in the country (Eurostat, 2018)
- Share of small photovoltaic plants (< 20 kW) on the total amount of photovoltaic plants in the country (Eurostat, 2019)
- Share of house/apartment owners living in their property (Eurostat, 2020)

We selected these variables for clustering as they present factors influencing the share of RE for PEV charging (e.g., about one third of German PEV users also have a photovoltaic system, Scherrer et al., 2019). Since the data on these cluster variables were not available for all European countries, we were able to include only 13 countries in the cluster analysis: Austria, Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Norway, Portugal, Spain, Sweden, and the UK. However, these countries account for 86 % of the European PEV market in 2020 (EAFO – European Alternative Fuels Observatory., 2022), thus related data presents a valid data basis.

2.2. Data

2.2.1. PEV by country and electricity mix

For weighting country specific estimates of the share of RE in the charging volumes, we start with available country-specific data from statistics on PEV registrations and national electricity mixes. This is based on the simplified assumption that charging volumes per vehicle are similar in all countries. This assumption of similar kWh charged per year and PEV across the countries is based on high similarities in average annual distances travelled of passenger cars in the countries in Europe (Pasaoglu et al., 2014). It is assumed that BEV and PHEV have approximately the same average annual mileage (Plötz et al., 2017).

Fig. 1 shows the country specific PEV registrations in Europe by the end of 2022 (passenger cars, data from EAFO – European Alternative Fuels Observatory., 2023). It shows that Germany, France, the United Kingdom, Norway, and the Netherlands account for most registrations. Around 70 % of all PEV in Europe were registered in these top five countries. Taken together, the top ten countries accounted for 90 % of all registered PEV in Europe. The PEV registrations per country are used below to obtain PEV stock size weighted averages for the share of contracted RE in PEV charging. Without stock size weighting, all countries would have similar weight in calculating an average RE share in PEV charging for Europe not properly reflecting the large differences in PEV stock among the countries.

A specific type of electricity generation can only be allocated to a specific electricity supplier or consumer via a certification system, e.g. through the trading of guarantees of origin. The Association of Issuing Bodies (AIB) prepares an annual balance sheet that adequately records certificate trading and the distribution of uncertified electricity volumes in Europe. As a result, the total supplier mix is determined for each country, which reflects the allocation of certified and remaining electricity generation in Europe to the electricity consumers (AIB – Association of Issuing Bodies., 2023).

Fig. 2 compares the electricity generation mix with the total supplier mix and shows the differences between the generation and supplier RE share in the national electricity mixes for each country. We will use both values per country below to estimate the share of RE in PEV charging where data on contracted RE shares at different charging location types (home, work, public) is not available.

2.2.2. New primary survey data

The share of contracted RE for PEV charging has hardly been published in the research landscape so far: We could not identify existing studies over and above the published results mentioned in Section 1. Thus, we identified gaps in the share of PEV charging location for some European countries and a major gap regarding the share of contracted RE in PEV charging. Moreover, the existing studies applied different methodologies (e.g., focusing on PHEV or BEV users only, assessing multi-family or single-family homes only, assessing the charging frequency vs. charging preference). For these reasons, our study conducted its own surveys on the contracted renewable electricity shares for PEV

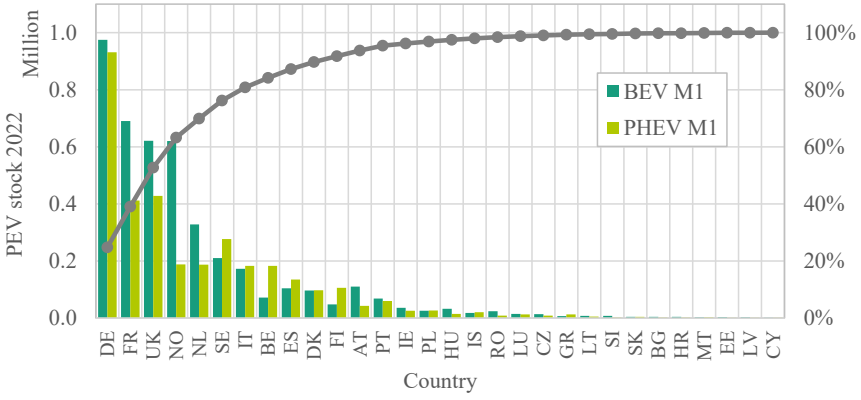


Fig. 1. Registered PEV per country in 2022 in size M1 (passenger cars): Total number of PEV (left y-axis) as well as cumulated share of the PEV in stock in EU, UK, NO, and IS (right y-axis).

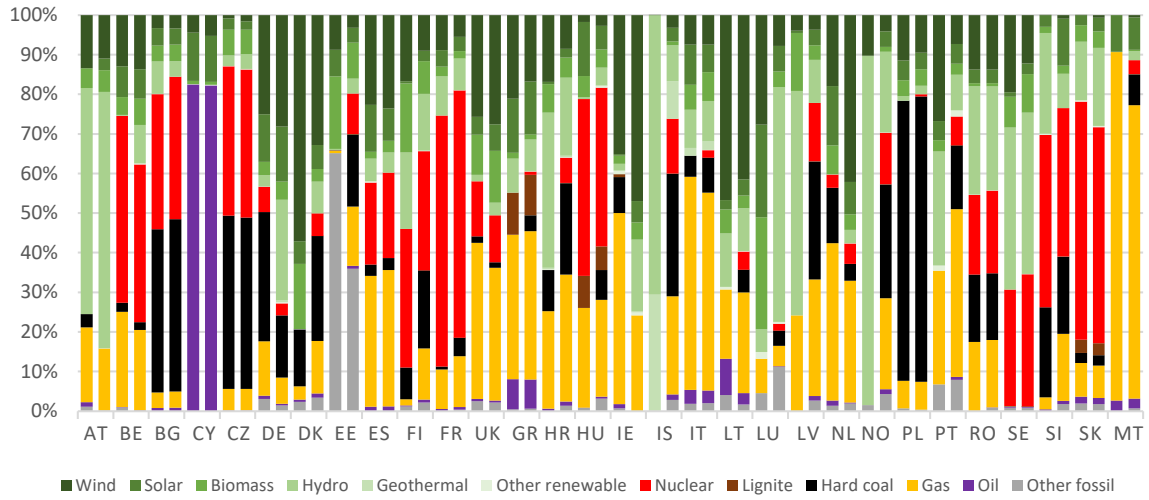


Fig. 2. Electricity generation mix (left bars) and total supplier mix (right bars) 2022 by country and energy source (colors) in %.

charging in the 12 countries with the most PEV registrations and Poland (which is a significant European Car market and has one of the most CO_2 intense generation mixes in Europe). In this context, we also collected current data on charging frequency at the various locations (see the following section).

To data gaps regarding charging location and share of contracted RE, we conducted two surveys. Here we present the method, the recruitment strategy, and the samples of both surveys (1) with PEV users and (2) with fleet managers. The method was largely the same for both surveys. To obtain the target data regarding home charging, we asked private PEV users in the first survey where they usually charge their PEV and whether they have a RE tariff for home charging supplemented by further questions not relevant to this study. The two most important questions for this study were:

- "Please estimate: How often do you charge your PEV on average per months… at home / at work / at public slow charging stations / at public fast charging stations?" – integer values for each field.
- "Do you have a 100 % renewable electricity tariff for charging your electric vehicle?" –"Yes" / "No" / "I do not know" options to select.

The option "I don't know" in surveys is used to ensure differentiated response behaviour. Experience shows that without this option, any of the predefined answers (in our case "yes" or "no") will be chosen if the respondent is not sure. We will use two ways to incorporate the "I don't know" answers to derive a lower and upper bound for the share of contracted RE in PEV charging in the results section. For the lower bound, we assume that all "I don't know"-respondents have not concluded a RE contract. It can be assumed that this interpretation underestimates the real situation, as some of the unsure respondents may have a RE contract. For the upper bound, on the other hand, the "I don't know" responses are ignored. This implicitly assumes that this "I don't know"-group is subject to the same yes-no-split as the respondents who answered this question. Here, the "yes" share may be somewhat overestimated, as having a RE contract is usually a conscious decision that is often associated with higher costs.

In the second survey, we contacted fleet managers on the share of contracted RE for work charging (i.e., asking whether they have a 100 % RE tariff at their company). Additionally, we collected data on socio-demographic characteristic of the PEV users and characteristics of the company, respectively. Data collection was completely anonymous and took place in October and November 2023.

To recruit PEV users for the first survey, we were supported by a market research institute and collected data in 13 countries, namely, Belgium, Austria, Denmark, Spain, Italy, Germany, France, UK, Sweden, Norway, the Netherlands, Finland, and Poland. These countries were pre-determined, to cover EU countries with a high share of PEV registrations. A total of 3438 participants fully completed the survey. The spread of participants across countries and the socio-demographic characteristics of the sample in each country are presented in Table 2.

Table 2
Sociodemographic characteristics of the surveyed PEV users, per country.

Country (number of respondents)	Age range (Mean, SD)	Share men vs. women*	Share with academic degree	Share with high income
Belgium – BE (n = 273)	18–74 (M = 39.5, SD = 12.9)	57 % vs. 41 %	56 %	32 %
Austria – AT (n = 245)	18–77 (M = 43.0, SD = 13.7)	49 % vs. 51 %	43 %	44 %
Denmark – DK (n = 250)	18–81 (M = 54.0, SD = 16.2)	49 % vs. 51 %	48 %	76 %
Spain – ES (n = 338)	18–72 (M = 39.4, SD = 10.4)	63 % vs. 37 %	61 %	58 %
Italy – IT (n = 251)	21–78 (M = 45.7, SD = 11.9)	57 % vs. 43 %	63 %	46 %
Germany – DE (n = 342)	18–87 (M = 48.4, SD = 13.4)	52 % vs. 48 %	51 %	53 %
France – FR (n = 248)	22–85 (M = 48.8, SD = 13.7)	50 % vs. 50 %	63 %	38 %
United Kingdom – UK (n = 281)	20–88 (M = 46.5, SD = 13.9)	51 % vs. 48 %	72 %	52 %
Sweden – SE (n = 249)	19–89 (M = 50.7, SD = 15.9)	45 % vs. 55 %	56 %	67 %
Norway – NO (n = 257)	18–90 (M = 51.4, SD = 16.3)	52 % vs. 48 %	66 %	55 %
The Netherlands – NL (n = 251)	18–80 (M = 49.4, SD = 14.7)	58 % vs. 41 %	49 %	68 %
Finland – FI (n = 197)	18–84 (M = 48.9, SD = 15.9)	54 % vs. 46 %	51 %	51 %
Poland – PL (n = 256)	18–76 (M = 42.7, SD = 13.5)	46 % vs. 54 %	69 %	39 %

The average age of PEV users who responded to our survey varies between 39 years (in Spain and Belgium) and 51–54 years (in Norway and Denmark). Across countries, there is a relatively equal gender balance between men and women who use PEV and responded to the survey. Only in some countries, there were more men (e.g., in the Netherlands, Italy and Belgium) or more women (e.g., in Sweden and Poland). In general, most respondents across countries have an academic degree and thus can be viewed as highly educated. Regarding their income, between one third and three quarters of respondents (in Belgium and Denmark) reported to live (very) comfortably on their current income. Overall, these results on the sociodemographic characteristics of PEV users demonstrate that PEV users are still of higher age and highly educated (see also Plötz et al., 2014; Scherrer et al., 2019), however, this seems to shift slightly towards a broader group of the population that uses PEV (e.g., as demonstrated by the gender balance).

To recruit fleet managers with PEV in the company, two different approaches were used. First, we contacted European PEV associations and service providers in the e-fleet sector. We asked them whether they are willing to share our questionnaire with the relevant target group of fleet managers in their associations. Second, we contacted the biggest companies (by number of employees) in European countries as well as companies that were explicitly mentioned in online forums, magazines, or newspapers about e-fleets and PEV. In addition, for the recruitment of fleet managers in Germany, we used established contacts to individual fleet managers from previous studies on PEV. Overall, we shared the second survey link with a total of 384 European associations and companies (of which 85 were individual contacts to fleet managers in Germany). In a second round of recruitment, we called over 40 fleet managers via phone in Europe (mainly in Italy, Denmark, and the UK). This additional recruitment effort led to only few additional answers per country. Reasons for no answers varied but were mainly (i) language barriers or (ii) repeated unavailability of the fleet manager responsible.

A total of 103 fleet managers completed the respective survey for fleet managers on work charging. The database for the contracted RE share in work charging looks as follows: One fleet manager answered the questionnaire for a Slovenian company, three fleet managers came from Denmark and four from Italy; all other fleet managers were from Germany ($n = 95$) accounting for 6451 PEV. Hence, only for Germany, we received a valid database to analyse the share of RE in PEV work charging. Regarding the relevant question on the use of a 100 % renewable electricity tariff, 70 of the 95 German fleet managers answered this question (the other 25 people preferred the provided option not to answer the question). The 70 fleet managers answering this question accounted for 5476 PEV.

2.2.3. Statistical data on RE in the German public charging infrastructure

The survey data present an adequate data basis regarding contracted RE shares for home charging in the most relevant European countries as well as for work charging in Germany. However, no data from our survey or published studies is available on the share of contracted RE in public charging in any European country. Although this share is still small compared to other charging locations, it may become more important for the future (see Section 2). To fill this gap, at least for Germany, we analysed official registers on the public charging infrastructure and supplemented them with data from further research to determine the minimum share of renewable energy that is achieved with public charging. The methodology is outlined below.

All public charging points in Germany must be registered with the Bundesnetzagentur (BNetzA). By the end of 2022, approximately 84,200 publicly accessible charging points were in operation, including about 71,600 slow charging points (< 50 kW) and 12,600 fast charging points (≥ 50 kW), managed by over 4400 CPOs (BNetzA – Bundesnetzagentur., 2024). The National Charging Infrastructure Control Center (Leitstelle) records the charging volumes of publicly accessible charging points that have received federal funding, which mandates their operation with contracted RE to meet the funding conditions (BMVI, 2021). In 2022, more than 600 CPOs reported charging volumes for nearly 19,500 charging points (NLL., 2023). These data cover 23 % of all public charging points in Germany registered with the BNetzA.

The number of charging points in the registers of the Leitstelle and the BNetzA is available by NUTS1 region. This serves as the database for our analysis. First, the total charging volume at public charging points in Germany is estimated by extrapolating the data reported to the Leitstelle. The average volumes for fast and slow public charging recorded for each NUTS1 region are multiplied by the respective number of charging points. This means that the charging volumes (with 100 % contracted RE) reported to the control centre account for around 28 % of the total charging volume at public charging points in Germany.

To capture the use of RE at non-subsidized charging points, large CPOs (> 100 charging points) were identified through website research and short telephone interviews. All of them operate all their charging points with 100 % RE. By comparing this data with the register of the Leitstelle at the NUTS1 level, the number of charging points for which the CPO reported data was subtracted from the total number of charging points operated by the respective CPO. This approach, in addition to the Leitstelle data, identified 20,500 additional public slow charging points and 6275 public fast charging points operated with 100 % contracted RE. Combined with the Leitstelle data, this covers 52 % of public slow charging points and 72 % of public fast charging points in Germany. Based on the extrapolated charging volumes, this results in a contracted RE share of 56 % for public slow charging and 77 % for public fast charging. These contracted RE shares represent a lower bound, as it is assumed that several of the more than 4300 smaller CPOs (< 100 charging points) also utilize RE.

3. Results

Assuming that the use of PEVs is similar in European countries and that all of them charge the national electricity mix on average, we arrive at a first estimate for the RE share in PEV charging by weighting the respective electricity mix with the country specific PEV registrations (combining Figs. 1 and 2 in a scalar product). Weighting by PEV stock is necessary as countries differ substantially in PEV stock and otherwise countries with virtually no PEV would have gotten the same weight in PEV charging estimate as countries with larger stock. In this case, the electricity production mix approach and the total supplier mix approach arrive at the same RE share of 49 % across all countries (EU27 + UK, NO, IS) for 2022. The 49 % are obtained as scalar product of RE share in generation mix and PEV stock per country. The value of 49 % RE in PEV charging provides a first rough estimate for overall RE in PEV charging in Europe, not for a country specific value.

In the following two sections we present and discuss our results for estimating a plausible range of the share of renewable electricity used for charging PEVs in the EU27 + UK, NO and IS. For this purpose, we use the primary data collected as part of this study, which were described in Section 2. In Section 3.1, we close the remaining data gaps for individual countries using our cluster approach. These country-specific usage shares are then used in Section 3.2 to weight the charging location-specific RE shares of the individual countries to determine the total share of RE for PEV charging across all the countries considered.

3.1. Usage shares of charging location types

In the following, we include information on the country-specific charging characteristics in the analysis, specifically the different charging locations (home, work, public) and the contracted green electricity supplies at each location, to obtain a more differentiated picture of the share of RE used in PEVs.

We start with the survey results on PEV charging locations by country. We computed a mean of the share of charging locations across all participants per country who answered the question of the charging location (see Fig. 3). Results vary between the countries. Overall and in

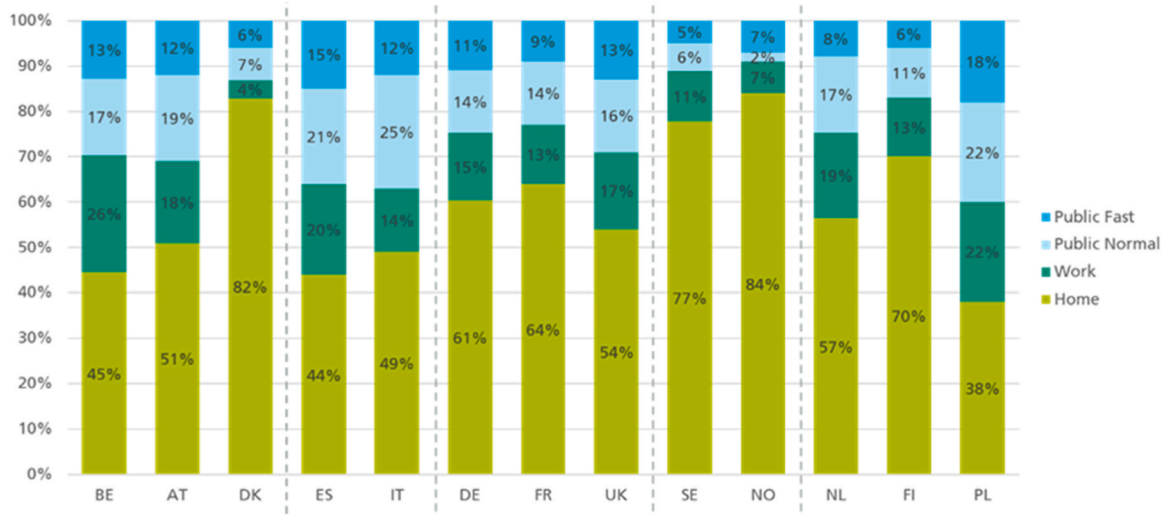


Fig. 3. Share of charging frequency at the different charging locations based on survey data (missing values to 100 % due to rounding).

line with existing literature, the share of charging at home is the largest, with 38 % in Poland and 84 % in Norway. Results show that between 4 % and 26 % of all charging processes are performed at work, 2–25 % of the charging occasions are performed at public slow charging stations, and 5–18 % at public fast charging stations. It is noteworthy that the percentages represent the charging frequencies (not the charging amount or preferences).

Regarding the share of contracted RE in home charging, the survey with PEV users showed the following results: The share of contracted RE tariffs for home PEV charging differs largely across countries (see Fig. 4). While the share is very low with 16 % in Norway as well as in Finland and with 21 % in Denmark, it is highest in Germany (59 %), Austria (58 %), Spain (56 %), the UK (51 %), and Belgium (50 %). In the latter countries, more than half of the responding PEV users reported to charge their PEV at home with a 100 % RE tariff. It is noteworthy that we also included the share of respondents who did not know the answer to this question. This share of "I do not know"-responses is especially high in Norway (65 %), the Netherlands (46 %), Finland (37 %), and Denmark (34 %), indicating that people do not pay special attention to the contracted electricity tariffs (in general and) for PEV charging in those countries.

For work charging, we analysed the survey data completed by fleet managers. Due to the low response rate, only the data for Germany can be analysed. In Germany, 70 fleet managers (responsible for 5476 PEV) knew the electricity tariff they provide for charging PEV at work. Of these, 59 % reported to have a 100 % RE tariff. Importantly, about one third did not know whether the electricity tariff for work charging was a 100 % RE tariff or not, and only 11 % of the German fleet managers who answered the questions stated that they knew that their tariff was not a 100 % RE tariff.

In the last step in this section, we use cluster analysis to fill data gaps for specific countries by cluster analysis. As described in Section 2.4, we use Ward hierarchical clustering with Euclidean distance, and a z-standardization with variables on the shares of low emission electricity, of PEV in car registration, of public charging points, of detached houses, of small PV systems, of housing ownership, and the attitude toward the environment. We cluster 13 countries (Austria, Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Norway, Portugal, Spain, Sweden, UK) that account for 86 % of the European PEV market in 2022.

The results of the four obtained clusters are shown in Fig. 5. Due to the similarity of the countries within each cluster on all outlined cluster variables, it appears appropriate to transfer the data from one country of a cluster to the other countries in the same cluster, allowing to fill the remaining data gaps.

We use the share of PEV registrations (sum of BEV and PHEV) of the year 2022 in the EU to weight the cluster data in subsequent calculations

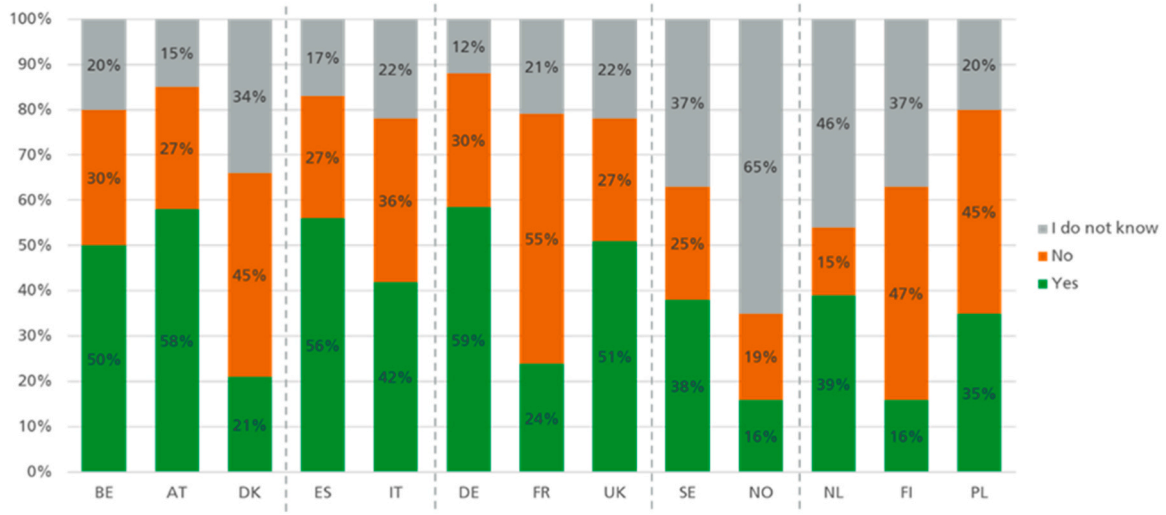


Fig. 4. Survey results on the share of 100 % RE tariffs for PEV home charging per country.

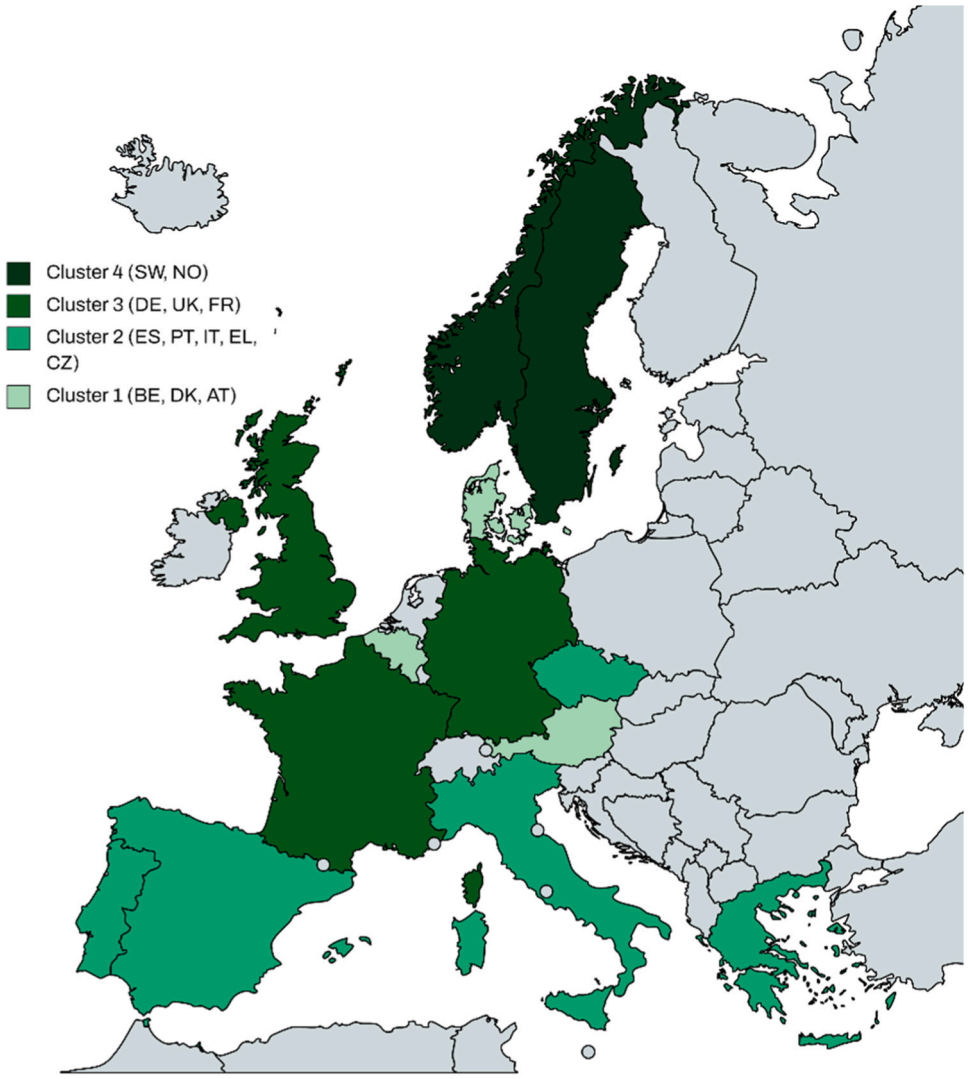


Fig. 5. Results of the cluster analysis presenting the four clusters of countries including only those countries for which data to all cluster variables were available.

of the European-wide RE share in charging electricity. The identified clusters cover the following share of the European PEV market (including EU, UK, NO, IS):

- Cluster 1 (Belgium, Austria, and Denmark): 8 %
- Cluster 2 (Spain, Portugal, Italy, Greece, and Czech Republic):10 %
- Cluster 3 (Germany, France, and the UK): 53 %
- Cluster 4 (Sweden and Norway): 17 %
- Cluster 5 (all other countries, with 9 % for NL, FI, and PL):13 %

As an example, when combining these results from the cluster analysis with the results from the PEV user survey, the data on the share of charging location of one country can be transferred to other countries in the same cluster. Hence, remaining data gaps regarding the share of charging locations can be filled with the substitute data from another country in the same cluster. This means that the cluster-specific shares for the different PEV charging locations can be calculated by averaging the available survey data in each cluster and weighting the country-specific values with the country-specific PEV share within each cluster. The results of this calculation are shown in Table 3. Consequently, the average of the survey data from our Spanish and Italian sample can also be considered representative for all other countries in Cluster 2 (i.e., Portugal, Greece, and the Czech Republic). The same applies for the average results of the Netherlands, Finland, and Poland, and its transfer to the remaining countries in Cluster 5.

Table 3
Cluster-specific and total shares of charging by location.

	Share of PEV	Home	Work	Public slow	Public fast
Cluster 1 (AT, BE, DK)	8 %	58 %	17 %	14 %	11 %
Cluster 2 (CZ, ES, GR, IT, PT)	10 %	47 %	17 %	23 %	13 %
Cluster 3 (DE, FR, UK)	53 %	60 %	15 %	14 %	11 %
Cluster 4 (NO, SE)	17 %	82 %	8 %	4 %	6 %
Cluster 5 (other)	13 %	58 %	18 %	16 %	8 %
Total (EU, UK, NO, IS)	**100 %**	**62 %**	**14 %**	**14 %**	**10 %**

Our survey data of PEV users covers the most relevant countries in which more than 94 % of PEVs in Europe were registered at the end of 2022. Regarding the usage shares of the charging location types, complete data sets are available for these countries. To close the remaining data gaps for the non-surveyed countries in Cluster 2 and 5, we use the average values of the available survey results as proxy data for the respective cluster. For Cluster 2, these are the available data from Spain and Italy, which together represent almost 78 % of the PEVs registered

in this cluster. For Cluster 5, the cluster average is formed with the data from the Netherlands, Finland and Poland, which together account for 73 % of the PEVs in the cluster. Even if our cluster approach is subject to a degree of uncertainty, the impact on the result is therefore only marginal. The complete country-specific data set on the utilisation shares of different charging locations is shown in Table 4 with own survey results (in bold) and cluster-specific average values of the available survey data as proxy for remaining gaps (in italics).

By combining existing studies with our new primary survey data and the cluster analysis, we obtained reliable values for the share of charging at home, at work and publicly fast and slow for all countries have Europe. These will be used in the following for an improved estimate of the share of contracted RE in PEV charging in Europe.

3.2. Share of contracted RE in PEV charging

For the contracted RE shares, the survey with PEV users provides results for charging at home in the countries covered. RE shares for charging at work and in public were determined, at least for Germany, with the help of the survey with fleet managers and publicly available statistics. In the following, we will present upper and lower bounds for the share or RE in PEV charging in Europe by combining the survey results with additional assumptions.

The simplest RE share estimate is to use the electricity production mix or the total supplier mix and take the PEV stock share weighted estimate for Europe. Both mixes lead to a total 49 % RE share in PEV charging in Europe for 2022. However, the existing literature and our survey results indicate that the actual share should be higher as many PEV users, companies and CPOs have 100 % RE contracts. In the following, we will replace the total supplier mix assumption for individual countries by direct survey results for that country or by transfer from other countries within a cluster.

Table 4
Total shares of charging by location. Own survey results in bold, cluster-specific averages in italics.

Cluster	Country	Share of PEV	Home	Work	Public slow	Public fast
1	AT	1.98 %	**51 %**	**18 %**	**19 %**	**12 %**
	BE	3.31 %	**45 %**	**25 %**	**17 %**	**13 %**
	DK	2.52 %	**82 %**	**4 %**	**7 %**	**6 %**
2	CZ	0.29 %	*47 %*	*17 %*	*23 %*	*13 %*
	ES	3.11 %	**44 %**	**20 %**	**21 %**	**15 %**
	GR	0.24 %	*47 %*	*17 %*	*23 %*	*13 %*
	IT	4.61 %	**49 %**	**14 %**	**25 %**	**12 %**
	PT	1.66 %	*47 %*	*17 %*	*23 %*	*13 %*
3	DE	24.76 %	**61 %**	**15 %**	**13 %**	**11 %**
	FR	14.31 %	**64 %**	**13 %**	**14 %**	**9 %**
	UK	13.63 %	**54 %**	**17 %**	**16 %**	**13 %**
4	NO	10.50 %	**84 %**	**7 %**	**2 %**	**7 %**
	SE	6.32 %	**77 %**	**11 %**	**6 %**	**5 %**
5	BG	0.08 %	*58 %*	*18 %*	*16 %*	*8 %*
	CY	0.02 %	*58 %*	*18 %*	*16 %*	*8 %*
	EE	0.05 %	*58 %*	*18 %*	*16 %*	*8 %*
	FI	2.00 %	**70 %**	**13 %**	**11 %**	**6 %**
	HR	0.07 %	*58 %*	*18 %*	*16 %*	*8 %*
	HU	0.61 %	*58 %*	*18 %*	*16 %*	*8 %*
	IE	0.79 %	*58 %*	*18 %*	*16 %*	*8 %*
	IS	0.50 %	*58 %*	*18 %*	*16 %*	*8 %*
	LT	0.16 %	*58 %*	*18 %*	*16 %*	*8 %*
	LU	0.36 %	*58 %*	*18 %*	*16 %*	*8 %*
	LV	0.04 %	*58 %*	*18 %*	*16 %*	*8 %*
	MT	0.07 %	*58 %*	*18 %*	*16 %*	*8 %*
	NL	6.69 %	**57 %**	**19 %**	**17 %**	**8 %**
	PL	0.68 %	**38 %**	**22 %**	**22 %**	**18 %**
	RO	0.41 %	*58 %*	*18 %*	*16 %*	*8 %*
	SI	0.12 %	*58 %*	*18 %*	*16 %*	*8 %*
	SK	0.11 %	*58 %*	*18 %*	*16 %*	*8 %*
Total (EU, UK, NO, IS)		**100 %**	**62 %**	**14 %**	**14 %**	**10 %**

The next simple estimate uses the specific country data from our surveys wherever available, i.e. the share of contracted RE for home charging in Belgium, Austria, Denmark, Spain, Italy, Germany, France, the UK, Sweden, Norway, the Netherlands, Finland, and Poland, as well as work and public charging for Germany, and the total supplier mix for the remaining charging locations in these countries and the remaining countries. The PEV stock share weighted average of the total contracted RE shares for PEV charging in Europe is 61 %. This is our central estimate and central result. In the following we will add lower and upper bound to this central estimate. Please note that our surveys provide results for the contracted RE share in PEV charging for several European countries. However, we chose to report mainly a weighted average for all of Europe as Europe is second largest global PEV market and empirical results for smaller countries will remain scarce such that European averages can be expected to be used frequently. Additionally, many EU policies rely on low LCA emissions of PEV for which are results provide decisive input.

For the upper and lower bound, we transfer the survey results from one country within a cluster to the other cluster members and vary two of the assumptions in filling gaps in the country specific data. For the lower bound, we omit the “I don’t know” answers concerning the type of contracted electricity and treat the “No 100 % RE contract” as 0 % RE electricity. We do this within the countries of each cluster and obtain a lower bound 57 % for the share of RE in PEV charging in Europe. For the upper bound, we use the country-specific electricity mix for other than “100 % contracted RE electricity” answers in the surveys and obtain 66 % for the share of RE in PEV charging in Europe. If several countries within one cluster had a survey, we use the average of the survey countries for the other non-surveyed countries in the cluster. The resulting individual values for RE shares in charging at home, at work, and in public are shown by cluster and country in Table 5.

The difference between the lower and upper bound for the total European share of RE for PEV charging is 9 percentage points. It stems for the uncertainty surrounding the “I don’t know” responses. For the lower bound, we assume that all "I don’t know"-respondents have not concluded a RE contract. For the upper bound, on the other hand, the "I don’t know" responses are ignored. This implicitly assumes that this "I don’t know"-group is subject to the same yes-no-split as the respondents who answered this question. The lower and upper bounds thus reflect the uncertainty concerning the respondents’ knowledge of their contract and allow us to quantify the accuracy of our empirical estimate.

4. Discussion

Overall, the present study provides an estimate for the share of RE at different PEV charging locations in Europe and a total RE share in PEV charging. We analysed the contracted RE share per country as well as the country-specific total supplier mix. Our study goes beyond existing literature and results as we do not only use the national electricity grid mixes but incorporate new primary survey data on the share of 100 % RE tariffs at home charging for 13 European countries (covering 94 % of the European PEV market) as well as work and public charging RE shares for Germany. As a result, we obtain a share of 57 – 66 % of RE in the charged electricity for PEVs in Europe with 61 % as most likely value, i.e. higher than the total contracted share of 49 % in the electricity mix.

Our results come with some uncertainties. The new samples cover between 200 and 350 BEV users per country. The standard error for binomial shares from survey due to the finite sample size per country is thus about 2.5 – 3.5 percentage points. Accordingly, there is uncertainty around the share of RE tariffs in the countries, yet the individual country results are multiplied with the share of PEV of that country among all European PEV and furthermore the large share of RE in the total supplier mix alleviate reduces the effect of sample size uncertainty. Future research should aim at collecting further and larger samples of contracted RE in PEV charging and including countries that are not covered

Table 5
Shares of RE in charging at home, work and in public by country for central estimate, lower, and upper bound.

Cluster	Co.	PEV Share	Central estimate				Lower bound				Upper bound			
			Home	Work	public		Home	Work	public		Home	Work	Public	
					slow	fast			slow	fast			slow	fast
1	AT	1.98 %	93 %	84 %	84 %	84 %	58 %	84 %	84 %	84 %	95 %	84 %	84 %	84 %
	BE	3.31 %	69 %	38 %	38 %	38 %	50 %	38 %	38 %	38 %	76 %	38 %	38 %	38 %
	DK	2.52 %	61 %	50 %	50 %	50 %	21 %	50 %	50 %	50 %	66 %	50 %	50 %	50 %
2	CZ	0.29 %	14 %	14 %	14 %	14 %	48 %	14 %	14 %	14 %	65 %	14 %	14 %	14 %
	ES	3.11 %	73 %	40 %	40 %	40 %	56 %	40 %	40 %	40 %	81 %	40 %	40 %	40 %
	GR	0.24 %	40 %	40 %	40 %	40 %	48 %	40 %	40 %	40 %	76 %	40 %	40 %	40 %
	IT	4.61 %	62 %	34 %	34 %	34 %	42 %	34 %	34 %	34 %	70 %	34 %	34 %	34 %
	PT	1.66 %	26 %	26 %	26 %	26 %	48 %	26 %	26 %	26 %	70 %	26 %	26 %	26 %
3	DE	24.76 %	89 %	89 %	88 %	94 %	59 %	59 %	56 %	77 %	91 %	96 %	88 %	94 %
	FR	14.31 %	38 %	19 %	19 %	19 %	24 %	59 %	56 %	77 %	44 %	87 %	65 %	82 %
	UK	13.63 %	76 %	51 %	51 %	51 %	51 %	59 %	56 %	77 %	83 %	92 %	78 %	89 %
4	NO	10.50 %	41 %	30 %	30 %	30 %	16 %	30 %	30 %	30 %	62 %	30 %	30 %	30 %
	SE	6.32 %	79 %	65 %	65 %	65 %	38 %	65 %	65 %	65 %	86 %	65 %	65 %	65 %
5	BG	0.08 %	16 %	16 %	16 %	16 %	34 %	16 %	16 %	16 %	66 %	16 %	16 %	16 %
	CY	0.02 %	18 %	18 %	18 %	18 %	34 %	18 %	18 %	18 %	67 %	18 %	18 %	18 %
	EE	0.05 %	20 %	20 %	20 %	20 %	34 %	20 %	20 %	20 %	68 %	20 %	20 %	20 %
	FI	2.00 %	45 %	34 %	34 %	34 %	16 %	34 %	34 %	34 %	51 %	34 %	34 %	34 %
	HR	0.07 %	36 %	36 %	36 %	36 %	34 %	36 %	36 %	36 %	74 %	36 %	36 %	36 %
	HU	0.61 %	18 %	18 %	18 %	18 %	34 %	18 %	18 %	18 %	67 %	18 %	18 %	18 %
	IE	0.79 %	76 %	76 %	76 %	76 %	34 %	76 %	76 %	76 %	90 %	76 %	76 %	76 %
	IS	0.50 %	26 %	26 %	26 %	26 %	34 %	26 %	26 %	26 %	71 %	26 %	26 %	26 %
	LT	0.16 %	60 %	60 %	60 %	60 %	34 %	60 %	60 %	60 %	84 %	60 %	60 %	60 %
	LU	0.36 %	78 %	78 %	78 %	78 %	34 %	78 %	78 %	78 %	91 %	78 %	78 %	78 %
	LV	0.04 %	22 %	22 %	22 %	22 %	34 %	22 %	22 %	22 %	69 %	22 %	22 %	22 %
	MT	0.07 %	11 %	11 %	11 %	11 %	34 %	11 %	11 %	11 %	65 %	11 %	11 %	11 %
	NL	6.69 %	74 %	58 %	58 %	58 %	39 %	58 %	58 %	58 %	88 %	58 %	58 %	58 %
	PL	0.68 %	48 %	20 %	20 %	20 %	35 %	20 %	20 %	20 %	55 %	20 %	20 %	20 %
	RO	0.41 %	44 %	44 %	44 %	44 %	34 %	44 %	44 %	44 %	78 %	44 %	44 %	44 %
	SI	0.12 %	23 %	23 %	23 %	23 %	34 %	23 %	23 %	23 %	70 %	23 %	23 %	23 %
	SK	0.11 %	28 %	28 %	28 %	28 %	34 %	28 %	28 %	28 %	71 %	28 %	28 %	28 %
Total (EU, UK, NO, IS)			**61 %**				**57 %**				**66 %**			

in our additional data collection (see Section 2.2).

The lower and upper bound estimates for the share of RE in PEV charging use the cluster results with additional assumptions. They vary in (1) their treatment of "I don't know" responses about the electricity tariff for home charging and (2) in the assumption of total supplier mix percent RE or 0 % RE for the "I don't know". Other, more extreme bounds could, e.g. treat the "I don't know" and no RE tariff answers as 0 % RE, resulting in only 46 % of RE charging in Europe, or ignore the "I don't know" answers and apply the supplier mix for all "no 100 % RE" answers, resulting in 72 % for PEV charging in Europe. However, these estimates are too extreme.

The lower bound used here is a conservative estimate. This is due to the assumption that PEV users without a specific RE contract do not use any RE components in their charging electricity when charging at home. To date, not all RE volumes generated have been traded via guarantees of origin. Standard electricity contracts also increasingly include renewable shares. These non-certified RE quantities are included in the total supplier mix and the estimates therefore analyses the extent to which the total RE share in the investigated countries changes if the RE share of the total supplier mix is assumed for the load quantity shares without RE contracts instead of 0 %. The RE contracts surveyed are still considered as 100 % RE. Correctly, the latter would have to be deducted from the RE share of the TSM for this procedure, as they are also included in the total supplier mix. However, the share of electricity consumption for charging PEVs is still marginal compared to the remaining electricity consumption. Hence, this double counting is not significant for our results.

Furthermore, as current PEV owners have above average income and are more likely to own a house than the average car-owning population (Hardman et al., 2018), future shares of non-home charging are likely somewhat higher than those in present surveys.

From a psychological point of view, it is not surprising that PEV users charge more RE than grid mix: Following cognitive dissonance theory, people tend to behave in a consistent manner being led by their beliefs and attitudes, including their pro-environmental beliefs; thus, PEV users are likely to have a RE tariff (Wietschel et al., 2019, but see literature on rebound effects, spillover and compensatory green beliefs, e.g. Dütschke et al., 2021; Capstick et al., 2019).

5. Summary and conclusion

This study derived a lower bound for the share of contracted renewable electricity in plug-in electric vehicle (PEV) charging in Europe. Since the charged electricity presents a large part of the carbon footprint of PEVs, this information is essential to calculate the well-to-wheel GHG emissions of PEVs. Here, we present new primary data as well as an evaluation of existing secondary data and used a stepwise methodology applying scientific standards to close existing data gaps. Supporting previous studies, our results indicate that PEVs are mostly charged at home, followed by charging processes at work and a smaller share of charging processes on public slow or public fast charging points. Thus, focusing on the use of RE at home presents an important element to reduce the carbon footprint of PEVs. We find that a high percentage of PEV users charge their PEV based on RE contracts across all charging location; this share is above the often assumed European or country-specific electricity grid mix for the calculation of GHG. We obtain a total share of 61 % contracted RE charging for Europe across all charging locations compared to 49 % using the same calculations with the electricity grid mix, i.e., the balanced total supplier mix for 2022.

Further research should focus on extending the data collection through surveys in all European countries especially for charging at work and at public charging points to receive a valid data basis for Europe. Due to the rapid PEV developments, we suggest updating the data on a regular basis. It is noteworthy that the survey data on the share

of RE in charging electricity present RE without ensuring the actual additionality from the RE production.

To conclude, this paper presents recent data which closes gaps regarding shares of charging locations and shares of RE for PEV charging in Europe. Our approach presents a scientific methodology to combine existing and newly collected survey and statistical data to ultimately arrive at the currently best available data basis for a European-wide calculation of the GHG emissions for PEV charging. We extend existing studies with new empirical data for most large European countries, show that PEV life-cycle CO_2 emission benefits are larger than previously thought and provide a starting point for future empirical PEV charging surveys and PEV life-cycle assessments.

Our findings will be useful for the academic and sustainability discourse of plug-in electric vehicles CO_2 emissions benefits as our findings demonstrate that the actual electricity used for charging has lower carbon content than grid mix. More generally our findings could provide useful input for companies assessing the sustainability of their vehicle fleets. In addition, some public debates still question the environmental benefits of plug-in electric vehicles based on the electricity used for charging and our analysis could be helpful in these discussions as we empirically show the actual electricity used for charging is "cleaner" than the grid mix.

CRediT authorship contribution statement

Robert Kunze: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Martin Wietschel:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Patrick Plötz:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Jakob Zwirnmann:** Software, Formal analysis, Data curation. **Sabine Preuß:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sabine Preuss reports financial support was provided by Volkswagen AG. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge funding from the Volkswagen AG (Germany) as well as great support in data collection by Aline Scherrer and Alexandra Rummel.

Data availability

Data will be made available on request.

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