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Notes

Abstract

Plug-in electric vehicles (PEV) are widely considered a promising option to reduce greenhouse gas (GHG) emissions in transport. The electricity used for charging is decisive for the environmental assessment of PEV. Most studies assume the average grid mix for charging. A study in 2021 showed that the share of renewables in charging electricity of PEV in Europe was above the grid mix. The present study provides an update of this study to further refine the database and to compare the results from 2021 and 2023. In addition, small methodological adjustments were implemented to improve the estimate of renewable electricity in PEV charging across Europe. Therefore, this article presents results of an extensive survey with over 3,400 PEV users in 13 countries across the EU. Results reveal that PEV users still charge their PEV mostly at home. However, the share of renewable charging tariffs for home charging decreased compared to the results from 2021. When considering all charging locations (home, work and public charging), the respective share of renewable contracted electricity, and the number of PEV per EU country, the share of renewables in the charging electricity of PEV has further increased and is still above the European grid mix (i.e., balanced total supplier mix). We discuss reasons for this finding by outlining differences between the results of the study from 2021 and the present one.

Contents

1 Introduction

Plug-in electric vehicles (PEV) present an efficient way to reduce carbon emissions in the transport sector and ultimately help to mitigate climate change. PEV can offer noteworthy greenhouse gas (GHG) emission reductions on a life-cycle base compared to internal combustion engine vehicles (ICEV) – if they are mainly charged with renewable energy sources, i.e., renewable electricity (RE) (IEA 2021, Cox et al. 2018, Märtz et al. 2021). One study from 2021 showed that the contracted RE in PEV charging in Europe was higher than grid mix (Preuß et al. 2021). Besides this study, only few studies have analysed the actual electricity contracted for PEV charging, including the different charging locations such as home, work, and public fast and public slow charging. Moreover, since 2021, the number of PEV has been continuously rising in Europe. Hence, this article presents an update of the 2021 study: In the present study, we have collected and analyse new, extensive survey data from PEV users of 13 EU countries to derive (1) the share of PEV charging at different charging locations (home, work, public slow and public fast charging) and (2) the share of contracted RE in PEV charging (at these locations). We then combine both shares in a careful and conservative manner to avoid an overestimation of contracted RE share across charging locations and across European countries, to ultimately obtain a lower bound for the share of contracted RE in PEV charging in Europe.

The structure of this paper is as follows. The remainder of Section 1 summarises the existing literature on the electricity assumed for PEV charging as well as the contribution of our study regarding the share of different charging locations. Section 2 describes our method and data sources, including the collected survey data. Section 3 contains the results of the surveys carried out, the calculated results to fill all data gaps, and the total share of contracted RE at different locations in different countries. A comparison of the results of the 2021 study and the current study is described in Section 4. The discussion of the results is presented in Section 5, followed by a summary and conclusions in Section 6. Additional details on the data and methods are provided in the Supplementary Material.

1.1 Contribution

The aim of this paper is to obtain an updated lower bound for RE in PEV charging in Europe. To this end, we (1) analyse the share of PEV charging at different locations (i.e., home, work, public slow charging < 50kW, and public fast charging ≥ 50kW) and (2) combine it with the share of contracted RE at these locations. We aim to obtain a conservative estimate (i.e., a lower bound) for the share of contracted RE in PEV charging in Europe and compare it with today's RE share in the electricity grid mix (i.e., country-specific balanced total supplier mix; AIB 2023).

This research presents an update of the study conducted in 2021 and differs from previous research in the following aspects: First, it closes existing data gaps (beyond the data of the 2021 study) with new survey data including over 3,400 PEV users from 13 countries (for home charging and the share of charging locations) and understudied fleet managers from Germany (regarding the contracted RE for work charging). Second, the article outlines minor adjustments in the methodological approach to estimate the lower bound for contracted RE in PEV charging, given the broader database with new survey data. Third, this research provides an updated empirical lower bound for the overall share of contracted RE in PEV charging in Europe that is more precise than assuming the grid mix and shows differences and delevopments in PEV charging between 2021 and 2023.

1.2 Existing literature

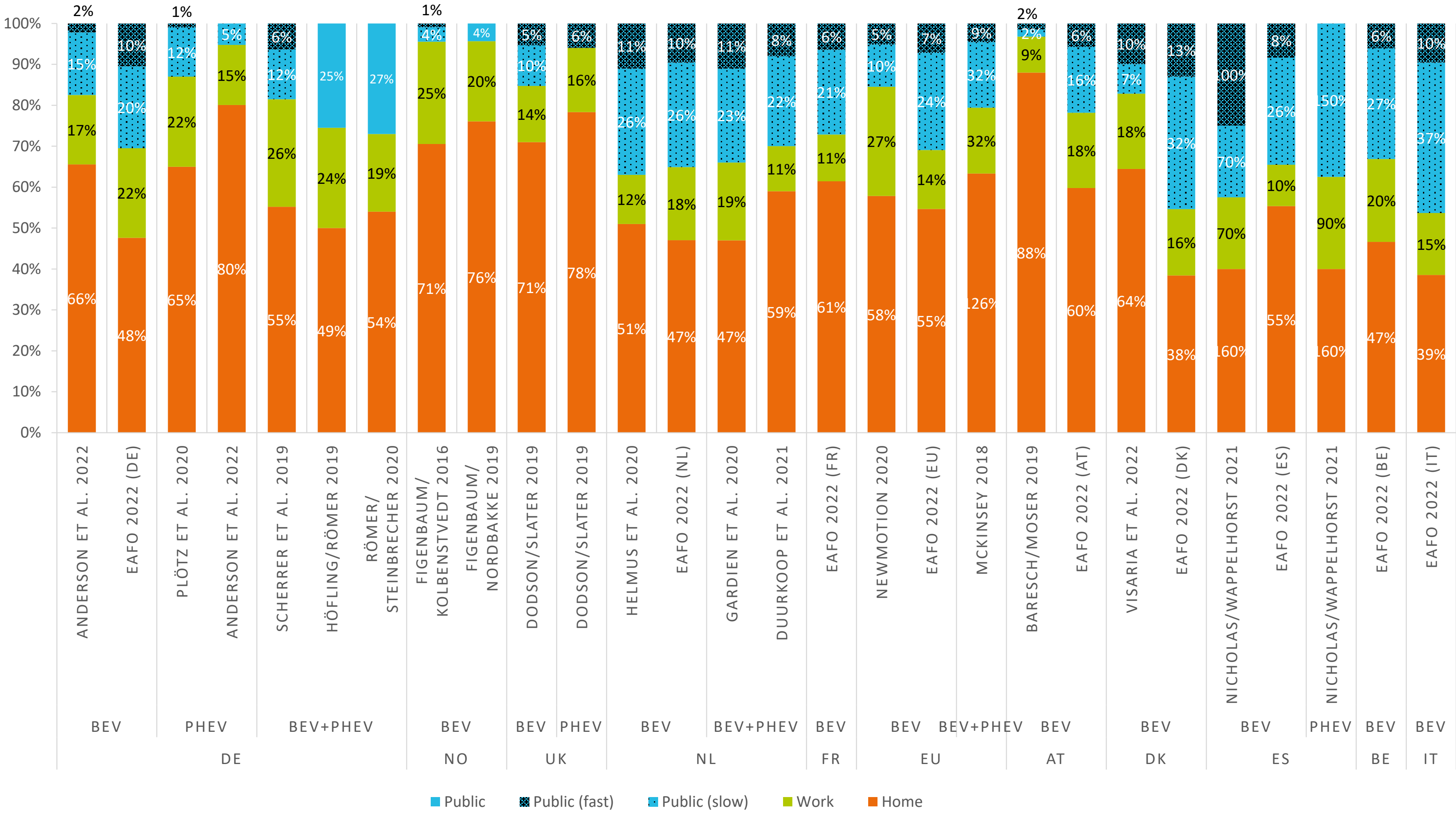
Past studies have shown that life-cycle PEV emissions depend heavily on the assumed electricity mix and usage conditions (Yuksel et al. 2016, Märtz et al. 2021, Tamayao et al. 2014, Nordelöf et al. 2015). Yuksel et al. (2016) find that the GHG emission benefit of PEV strongly depends on the source of electricity used for charging. 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 that 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 intensity of the electricity mix explains 70% of the variability in the results in electric vehicle LCA studies. In summary, many studies emphasise the importance of the electricity used in PEV charging but none of these studies consider that many PEV users (at home or at work) and charging point operators (CPO) have specific RE contracts. Hence, to estimate the share of RE contracts for PEV charging, the share of charging location (home, work, public slow and public fast) is required.

The share of electricity charged at different locations in European countries (at home, at work, public slow and public fast charging) has already been analysed in various studies focused on Europe or some selected European countries. Compared to our last study from 2021, the literature search was expanded to include four additional publications published in 2022 or later. In total, 21 studies have now been analysed, providing data with shares for the different charging locations.

Studies based on empirical data from PEV user surveys provide information on charging preferences (e.g. Wolff & Madlener 2019, Avere France & Ipsos 2020, Enedis 2021) or the share of charging frequency (e.g. EAFO 2022, Visaria et al. 2022, Anderson et al. 2022, Scherrer et al. 2019, Plötz et al. 2020, Höfling & Römer 2019, Römer & Steinbrecher 2020, Figenbaum & Kolbenstvedt 2016, Figenbaum & Nordbakke 2019, Helmus et al. 2020, NewMotion 2020) at different charging locations. Other studies use modelling of charging behaviour (McKinsey 2018, Baresch & Moser 2019) or expert estimates (T&E 2020). Actual measurements or information on the electricity charged at different locations are scarce (e.g. Nicholas 2021, Dodson & Slater 2019, Gardien et al. 2021 and Duurkoop et al. 2021). An overview of the published data based on charging quantity or charging frequency is given in Figure 1.

Very few studies have so far examined the use of RE for PEV charging. Our updated literature review revealed no new studies in this regard published in 2021 or later for Europe. For Germany, survey-based studies find a share of contracted RE of 60% (Römer & Steinbrecher 2021) and 58% (Frenzel et al. 2015) for charging at home. The latter study also includes an analysis of charging at work, resulting in a 53% share of contracted RE for charging at work (Frenzel et al. 2015). In addition, a survey of 35 retail chains in Germany found that around 68% of the charging stations in their parking lots are powered by RE contracts (EHI 2021). Despite the scope of this study, it only covers a certain segment of public charging and overall, only a small part of the publicly accessible charging infrastructure in Germany. Beyond this study, no information is available on the share of RE in the public charging infrastructure in Germany. Hence, there is no study available that assesses the share of RE in Europe. To the authors' knowledge, the study by Preuß et al. (2021) is the first study that considers and examines the share of charging on different charging locations in combination with the RE share at these locations.

Figure 1: Overview of published shares of charging at different locations for different European countries



1.3 Scope of the present research

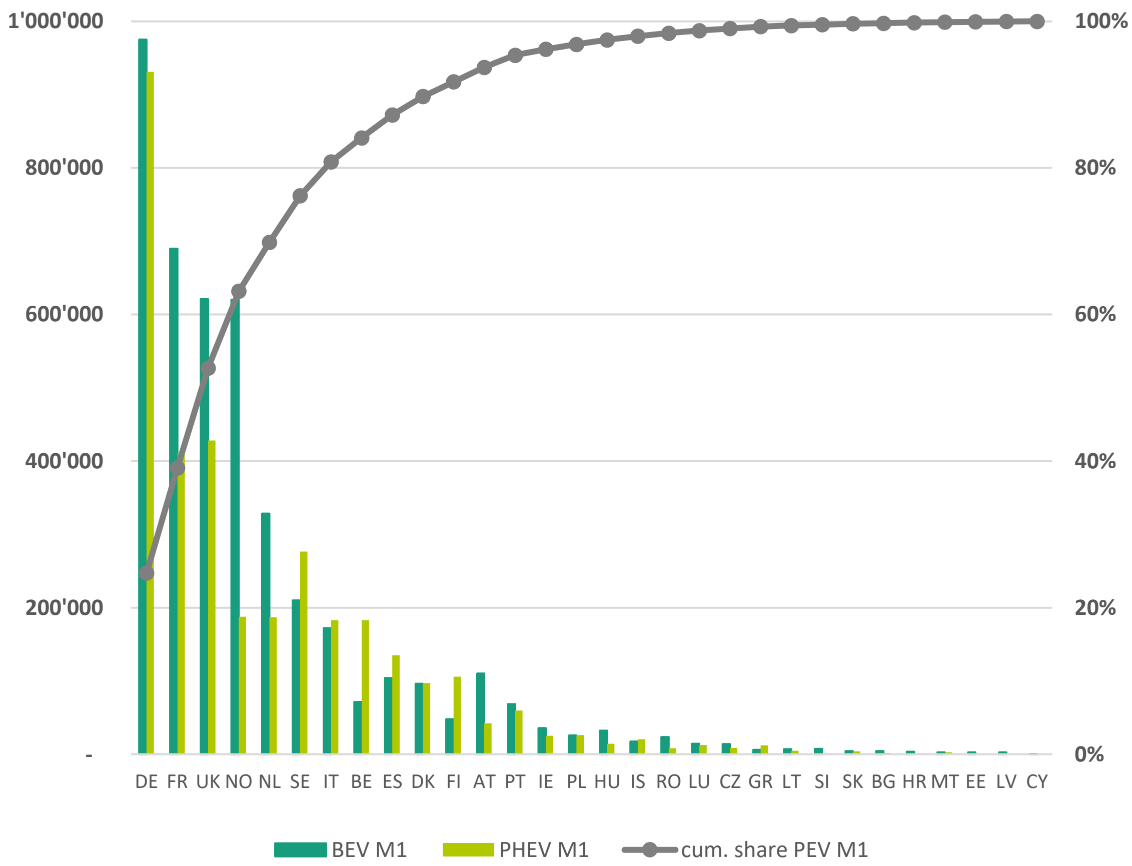
When looking at the latest data on the PEV shares in European countries, the PEV share is changing rapidly (EAFO 2023), including plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV). This makes an update of the data from the study in 2021 crucial to estimate a reliable share of RE in PEV charging across Europe: Currently, Germany, France, the UK, Norway and the Netherlands account for most PEV registrations (see Figure 2). These top five countries in terms of PEV registrations currently represent nearly 70% of the total European PEV market (compared to 72% in 2020) with about 5.38 million PEV (compared to 2.18 million in 2020). In 2022, notable PEV registrations also included Sweden, Italy, Belgium, Spain, Denmark, Finland, Austria and Portugal. This middle group in terms of absolute PEV registrations currently represents about 1.96 million PEV (compared to 720,000 in 2020), or about 25% (compared to 24% in 2020) of the European PEV market. The remaining 5% of the EU-wide PEV market is distributed among all remaining EU27 countries and Iceland, with none of these countries having more than approximately 62,000 PEV registrations (compared to 15,000 in 2020).

The geographical scope of this paper covers all 27 EU-countries as well as the United Kingdom (UK), Norway, and Iceland. Based on the methodological approach of the study by Preuß et al. (2021), we apply the same methodological approach including the country clustering based on seven selected clustering variables (see Supplementary Material, Figure 10).

Consequently, given the identified clusters in the study from 2021, the current share for the year 2022 of the European PEV market is the following (including EU27, Iceland, Norway, and the UK):

- Cluster 1 (including BE, AT, DK): 8% (7% in 2020)
- Cluster 2 (including ES, PT, IT, GR, CZ): 10% (9% in 2020)
- Cluster 3 (including DE, FR, UK): 53% (48% in 2020)
- Cluster 4 (including SE, NO): 17% (21% in 2020)
- Cluster 5 (all other countries): 13% (14% in 2020)

Figure 2: Total number of PEV (separately for BEV, dark green, and PHEV, light green) for all EU-27 countries plus Island, Norway, and the United Kingdom (UK) in 2022 (left y-axis) and share of PEV market in these countries (right y-axis).



Note: Vehicle category M1 includes passenger cars with no more than eight seats in addition to the driver seat (Source: EAFO 2023).

2 Methods and data

2.1 Overview

As in the study conducted in 2021, to answer the two outlined questions relevant for the calculation of PEV emissions (share of charging location and contracted RE at each location), we aimed to collect data to complete Table 1. Thus, we performed different surveys to update and refine the database of the study in 2021, to ultimately close more data gaps leading to a more reliable database. Hence, we ran two survey studies in Europe, one with PEV users and one with fleet managers. Moreover, we conducted an analysis of the data and transformed them with the help of the results of the cluster analysis (Preuß et al., 2021; see also Supplementary Material, Figure 10) and existing databases to obtain the target data for Europe. We aimed to use the latest data to generate a lower estimate of the share of charging locations and the share of (contracted) RE in PEV charging for 2022/2023.

Table 1: Targeted data structure regarding charging locations and RE charging for PEV in Europe (including EU27, Iceland, Norway and the UK).

	Home	Work	Public slow	Public fast	Total
Share of charging processes at this location	??%	??%	??%	??%	100%
Share of contracted renewable electricity	??%	??%	??%	??%	??%

2.2 Home and work charging survey

To update and refine the database regarding charging location and share of RE, we conducted two surveys in Europe – one addressing PEV users and one addressing fleet managers. The method did not differ largerly between the two surveys. To obtain the target data regarding home charging, , we asked private PEV users in the first survey where they usually charge their PEV ("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?") and whether they have a RE tariff ("Do you have a 100% renewable electricity tariff for charging your electric vehicle?"), supplemented by further questions not relevant to this study. In the second study, we surveyed fleet managers to obtain data on the share of RE for work charging (i.e., asking whether they have a 100% RE tariff at their company). Additionally, we collected data on sociodemographics of the PEV users and characteristics of the company, respectively. Data collection of both surveys was completely anonymous to comply with general data protection regulations and took place in October and November 2023.

2.2.1 PEV user survey on home charging

For the recruitment of PEV users, we were supported by a market research institute (NORSTAT), aiming to receive at least 200 PEV users in each of the 13 pre-determined countries, to cover EU countries with a high share of PEV users and to ensure a good coverage of all clusters. A total of 3,438 participants fully completed the survey, leading to 768 participants for Cluster 1, 589 participants for Cluster 2, 871 participants for Cluster 3, 506 participants for Cluster 4 and 704 participants for Cluster 5 - the latter including all remaining EU-27 countries and Iceland (see Table

2). While the snowballing technique for recruitment in 2021 led to a database of 1,467 PEV users, the adjusted recruitment strategy involving a market research institute led to more than double of the responses from PEV users. Moreover, instead of covering two countries (in 2021), this time, over 3,400 responses from PEV users were spread quite equally across 13 countries. The socio-demographic characteristics of the sample in each country are presented in the Supplementary Material, Table 6.

Table 2: Total number of participants (PEV users) in the EU-27 plus Norway, Iceland, and the UK, including the responses per cluster and the responses in the 2021 study.

Country	Cluster	Total no. of Participants per Cluster in 2023	Home Charging Survey in 2023	Home Charging Survey in 2021
BE	1	N = 768	n = 273	(n = 9)
AT	1		n = 245	(n = 45)
DK	1		n = 250	(n = 6)
ES	2	N = 589	n = 338	n = 609
PT	2		---	(n = 1)
IT	2		n = 251	(n = 3)
GR	2		---	---
CZ	2		---	---
DE	3	N = 871	n = 342	n = 867
FR	3		n = 248	(n = 21)
UK	3		n = 281	(n = 18)
SE	4	N = 506	n = 249	(n = 17)
NO	4		n = 257	(n = 6)
NL	5	N = 704	n = 251	(n = 1)
FI	5		n = 197	(n = 1)
PL	5		n = 256	(n = 1)
TOTAL		**N = 3438**	**N = 3438**	**N = 1467**

Note: Numbers in brackets were too small to receive reliable results for this country.

2.2.2 Fleet manager survey on work charging

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, including those who participated in the study in 2021 and agreed to be re-contacted (to comply with general data protection guidelines). Overall, we shared the survey link for work charging with a total of 384 European associations and companies (of which 85 were individual contacts to fleet managers in Germany, see Table 3). 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.

Table 3: Recruitment of fleet managers: Overview of number of contacted associations and companies in Europe (without individual contacts from Germany).

PEV associations and service providers	Companies (contacted via personal contact)	Companies (contacted via general inquiries addresses)	Total
18	136	145	299

A total of 103 fleet managers completed the respective survey for fleet managers on work charging. The database for the 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 6,451 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 persons preferred the provided option not to answer the question). The 70 fleet managers answering this question accounted for 5,476 PEV. In summary, the survey data can be analysed for Germany, but the database is too small for other countries. Consequently, we were not able to fill the gaps regarding the share of RE in work charging for the other European countries with the help of this survey.

2.3 Method to close data gaps

With the survey data, an appropriate database for the share of charging locations is available for the following 13 EU countries: Belgium, Austria, Denmark, Spain, Italy, Germany, France, the UK, Sweden, Norway, the Netherlands, Finland, and Poland. This database covers at least the two countries in each cluster with the highest share of PEV in the EU PEV market (or even more countries). More specifically, Clusters 1, 3 and 4 are completely covered; only in Cluster 2 and Cluster 5 with the remaining countries (having a very small share of the European PEV market), data gaps remain.

Due to the similarity of the countries within each cluster on all selected cluster variables, it appears appropriate to transfer the data from one country of a cluster to the other countries in the same cluster. This allows to fill the remaining data gaps (see Supplementary Material, Figure 10). The share of registered PEV (sum of BEV and PHEV, see Figure 2) in the EU in 2022 is used to weight the cluster data in subsequent calculations of the European-wide RE share in charging electricity.

Regarding contracted RE shares, the survey data present an appropriate database for home and work charging in Germany and for home charging in the above mentioned 13 EU countries. However, only for Germany, data is available on the share of contracted RE in public charging. For Germany, official registers on *public* charging infrastructure are evaluated and supplemented with data from further desk research to determine the minimum share of RE achieved in public charging, as in the 2021 study (Preuß et al., 2021). The methodology is outlined below.

All operating public charging points in Germany need to be registered at the Bundesnetzagentur (BNetzA). At the end of 2022, a total of almost 84,200 publicly accessible charging points – including around 71,600 slow charging points (< 50kW) and 12,600 fast charging points (≥ 50kW) – were operated by more than 5,000 CPO in Germany (BNetzA 2023). The National Charging Infrastructure Control Center (Leitstelle) records the charging volumes of publicly accessible charging points that have received federal funding and, thus, need to be operated with RE to meet the funding conditions. More than 600 CPO have reported charging volumes for nearly 19,500 charging points in 2022 (see Table 7 in the Supplementary Material). These data cover 23% of all operated public charging points in Germany (see Figure 9 in the Supplementary Material) registered at the BNetzA.

The number of charging points in the registers of the Leitstelle and the BNetzA is available per NUTS1 region[1]. We use this as database for our estimation. First, the total charging volume at public charging points in Germany is estimated by extrapolation using the data reported to the Leitstelle. Hence, the average volumes for fast and slow public charging recorded for each NUTS1 region are multiplied by the respective number of charging points. This analysis shows that the charging volumes with 100% RE reported to the Leitstelle cover approximately 28% of the total charging volume at the public charging points in Germany.

To also record the use of RE at non-subsidised charging points, the following procedure has been applied. Initially, large CPO (with more than 100 charging points) that operate all their charging points with 100% RE are identified through website research and short telephone interviews. By comparing the data with the register of the Leitstelle at NUTS1 level, the number of charging points for which the CPO reported data to the NLL is deducted from the total number of charging points operated by the respective CPO. In addition to the Leitstelle data, this approach makes it possible to identify 20,500 additional public slow charging points and 6,275 public fast charging points that are operated with 100% RE. Together with the Leitstelle data, 52% of public slow charging points and 72% of public fast charging points in Germany are thus covered. Based on the extrapolated charging volumes, this results in a RE share of 56% for public slow charging and 77% for public fast charging. These RE shares present a lower bound, as it can be assumed that several of the more than 4,000 smaller CPO (with less than 100 charging points) also use RE electricity.

To summarise the database, for 13 European countries, a data set regarding the share of charging locations and the contracted RE shares for home charging is available. In addition, shares for the use of RE in work charging as well as public slow and fast charging for Germany are available. The available data for the shares of charging locations are made usable for extrapolation to other countries within the framework of the cluster analysis which is described in the Supplementary Material. To close the remaining data gaps regarding the RE share in charging locations, we will use the RE shares of the balanced total supplier mix as substitute data for each country (AIB 2023).

[1] NUTS (Nomenclature des unités territoriales statistiques): hierarchically structured system of territorial units for the statistics of the European Union. NUTS 0 = national level (e.g. Germany), NUTS1: regional level 1 (e.g. in Germany, 16 federal states).

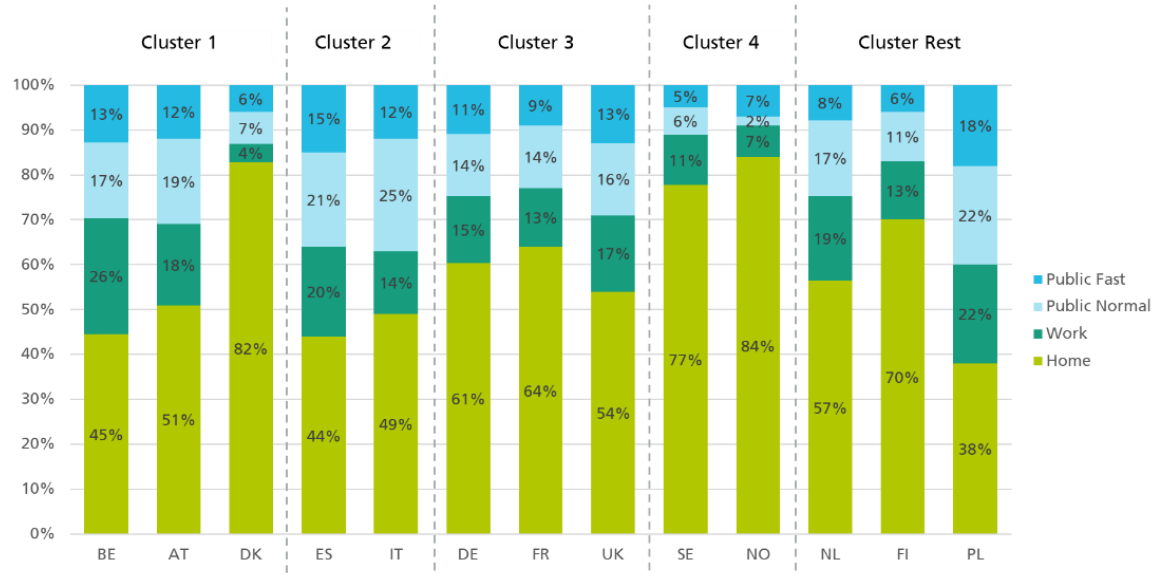
3 Results

The following section presents the results of our research. First, we outline the results regarding the share of charging locations. Second, the results regarding the share of contracted RE in charging electricity for PEV are presented. In each of these two subsections, we focus on the survey results first, followed by combining the newly collected survey results with existing data and the cluster analysis. Finally, we arrive at the aimed data structure (as shown in Table 1).

3.1 Share of charging locations

Based on the survey data of PEV users, we were able to fill the gaps on charging locations for 13 EU countries. We computed a mean of the share of charging locations across all participants per country who answered the question of the charging location (see Figure 3). Overall, 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% to 25% of the charging occasions are performed at public slow charging stations, and 5% to 18% at public fast charging stations. Results vary between the countries, especially in Cluster 1 and Cluster 5 (other countries). It is noteworthy that the percentages represent the charging frequencies (not the charging amount). For the share of charging locations with 95%-confidence intervals and the number of responses per country see Table 8 in the Supplementary Material.

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



Combining these results from the PEV user survey and the results from the cluster analysis in 2021, the data on the share of charging location of one country can be transferred to other countries in the same cluster. Remaining data gaps regarding the share of charging locations are filled with the substitute data. This means that the cluster-specific shares for the different PEV charging locations were 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 result of this calculation is shown in Table 4. Consequently, the average of the survey data from our Spanish and Italian sample is also 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. The resulting country-specific data set is shown in Table 9 in the Supplementary Material.

Table 4: Cluster-specific and total shares of charging by location.

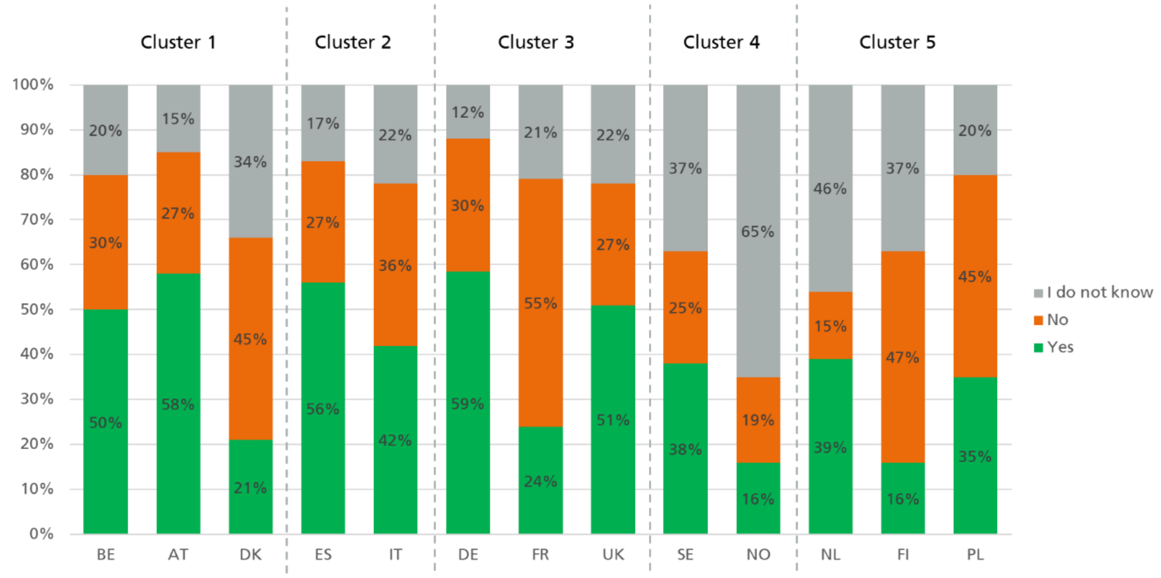
Cluster	Share of PEV in EU27 + UK, NO, IS	Home	Work	Public slow	Public fast
1	8%	58%	17%	14%	11%
2	10%	47%	17%	23%	13%
3	53%	60%	15%	14%	11%
4	17%	82%	8%	4%	6%
5 (other)	13%	58%	18%	16%	8%
Total (EU27 + UK, NO, IS)	**100%**	**62%**	**14%**	**14%**	**10%**

In all country clusters, most people charge their PEV at home (47-82%). This is usually followed by charging at work (8-18%), public slow charging (4-23%), and finally public fast charging (6-13%). However, in Cluster 2, the share of public slow charging is higher than the share of charging at work (23% vs. 17%). In Cluster 4, since the share of home charging is above 80%, the shares of the other charging locations in Cluster 4 is smaller than in the other clusters. This is not surprising, given that Cluster 4 contains Norway and Sweden which can have large stretches between cities where most public charging is available. This leaves less option for public charging and makes home charging most suitable in these countries. In Cluster 4, the share of public fast charging is also larger than the share of public slow charging. Reasons may be large distances between cities and a high number of fast charging points in combination with a small population per km^2 (compared to other EU countries).

3.2 Share of contracted RE in PEV charging

Regarding 100% renewable electricity, the survey with PEV users showed the following results for home charging: The share of contracted RE tariffs for home PEV charging differs largely across countries and clusters (see Figure 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 results with 95%-confidence intervals, see Supplementary Material, Table 11 (home charging) and Table 12 (work charging).

Figure 4: Results from the home charging survey 2023 with PEV users on the share of 100% RE tariffs for PEV home charging.



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 (as in 2021). In Germany, 70 fleet managers (responsible for 5,476 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.

To estimate the overall share of RE in PEV charging, we applied the following procedure which slightly differs from the approach in the 2021 study: For the share of "yes"-responses, we calculated a 100% RE tariff (as indicated by the responses); for the rest (i.e., share of "I do not know"- and "no"-responses), we assume the balanced total supplier mix (i.e., grid mix, AIB, 2023) containing the country-specific RE share in electricity consumption. The assumption for the rest is more realistic than assuming a RE share of 0% (as in the 2021 study), although the balanced total supplier mix includes RE certified by guarantees of origin (GOO) because GOO are used mostly in RE tariffs but less in non-RE tariffs. However, the balanced total supplier mix also includes country-specific uncertified RE shares that are part of general electricity tariffs. At the same time, it is worth noting that the share of charging electricity in relation to the total electricity consumption in each country is still very low. Hence, if there are no data available on the RE share based on the surveys conducted and our desk research, we use only the share of RE in the country-specific balanced total supplier mix (i.e., grid mix) to calculate the RE estimate across the EU. To the best of our knowledge, this leads to the most realistic but still conservative estimate of the RE share in PEV charging across Europe. Various approaches that can be used to calculate the estimate of the RE share across Europe are presented in the Supplementary Material (see Figure 11).

Consequently, for work and public charging in all countries except Germany, the RE share in the country-specific balanced total supplier mix is used as the share of RE in the charging electricity. The country-specific data set resulting from this calculation is presented in Table 10 in the Supplementary Material. Based on this data set, the cluster-specific RE shares of the charging locations listed in Table 5 are calculated by weighting the country-specific values with the country-specific EU PEV share within each cluster.

Table 5: Cluster-specific and total shares of contracted RE by charging location.

Cluster	Share of PEV per cluster	Home	Work	Public slow	Public fast
1	8%	72%	53%	53%	53%
2	10%	57%	34%	34%	34%
3	53%	72%	60%	60%	62%
4	17%	55%	43%	43%	43%
5 (other)	13%	60%	49%	49%	49%
Total (EU27 + UK, NO, IS)	**100%**	**66%**	**53%**	**52%**	**54%**

The values shown in Table 4 and Table 5 allow the calculation of a **total contracted RE share of at least 61% of the total PEV charging in 2022 in the EU27, the UK, Norway and Iceland**. For this purpose, all shares of charging locations in Table 4 are multiplied with the corresponding RE share and the PEV share of the EU PEV market of the corresponding cluster in Table 5. The RE share of 61% for the total PEV charging results from the sum of those multiplications. For comparison, **calculating and weighting only the national balanced total supplier mix for electricity in the same manner results in a RE share of 49% – 12 percentage points lower** than the more elaborated, but conservative RE share developed in this study using novel survey results based on current individual contracts.

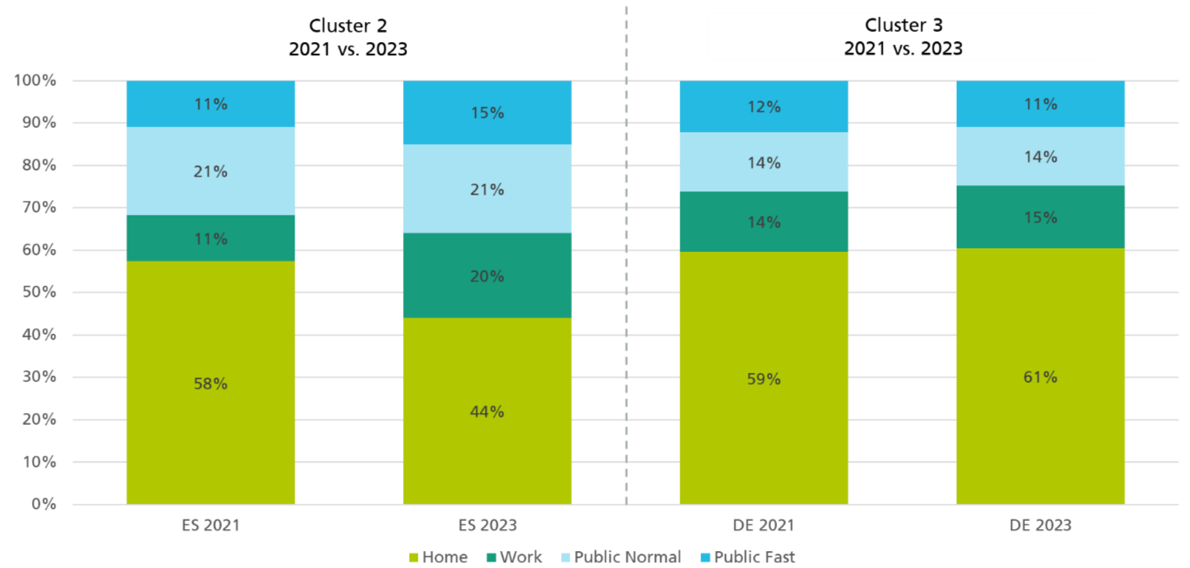
4 Comparison of results from 2021 and 2023

The developments between 2021 and 2023 may provide first insights for potential future developments. While the share of PEV in Europe has increased, the increase has been quite evenly distributed across the clusters (see share of PEV on the European PEV market, which has remained quite stable in Section 1.2): Whereas the share of PEV in Clusters 1 to 3 increased slightly (by 1 to 5 percentage points), the share decreased slightly in Clusters 4 and 5.

Taking a look at the survey data that were collected in the 2021 study compared to the present research, we observe the following changes: The results can only be compared for Spain and Germany since the database for all other countries in 2021 was too small for reliable results. In the present study, the database was greatly improved by covering 13 EU countries with the survey on charging locations and contracted RE in home charging. This led to a more solid database for the estimate.

Regarding the share of charging at different locations, the shares have remained very similar for Germany between 2021 and 2023 (see Figure 5). There were only small changes of 1-2 percentage points in Germany. In contrast, the results for Spain show that the share of work charging increased from 11% in 2021 to 20% in 2023. Also, the share of charging at fast public charging stations increased slightly in Spain (11% in 2021, 15% in 2023), while the share of home charging decreased from 58% in 2021 to 44% in 2023 in Spain. A reason for this development may be the influence of the COVID-19 pandemic, which may have led to a higher share of home charging in 2021. Another reason may be an increase of charging stations for work and public charging.

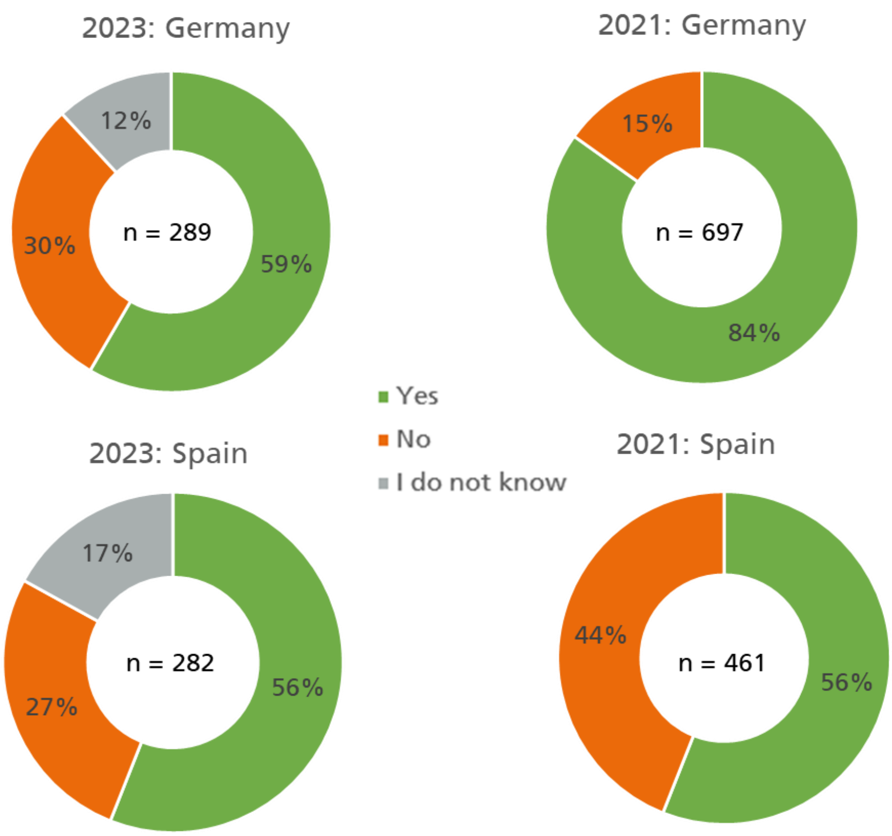
Figure 5: Comparison of the 2021 and 2023 survey results regarding the share of charging at different charging locations (missing to 100% due to rounding).



Regarding the share of contracted RE in home and work charging based on the survey data, results revealed the following developments: In 2021, we received a reliable database from the PEV user survey on home charging for Spain and Germany. Although we have extended the database for the 2023 study to 13 countries, we can only compare the results for these two countries (Germany and Spain). In the current 2023 study, 59% of 289 participants in Germany reported to have a 100% renewable electricity tariff to charge their PEV at home – compared to 84% of 697 participants in

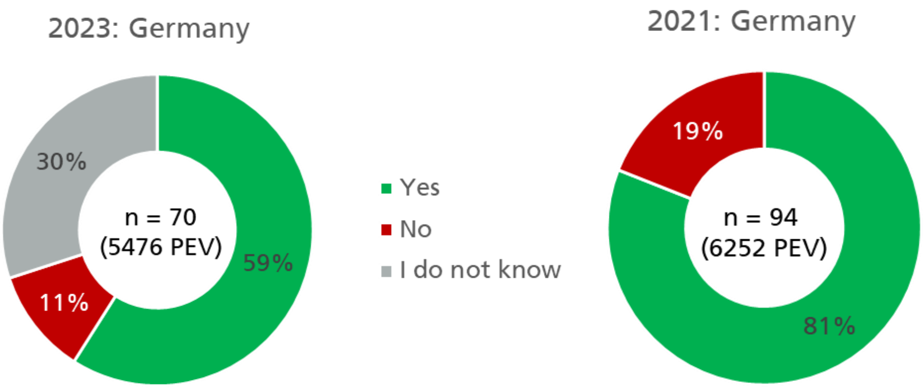
2021. In Spain, 56% of 282 participants reported having a 100% renewable electricity tariff to charge their PEV at home – compared to 56% of 461 participants in 2021. Thus, while there is no change in contracted RE share in Spain in home charging, there is a large decrease of contracted RE share in Germany of 25 percentage points (see Figure 6). It is noteworthy that the 2023 results include “I do not know” responses in the calculation of the RE share for home charging; this was not the case in 2021, where "I do not know" responses were excluded and the other two options made up the final 100%.

Figure 6: Home charging survey: Share of contracted RE in PEV charging at home in Germany (upper panel) and Spain (lower panel), compared for the years 2021 and 2023.



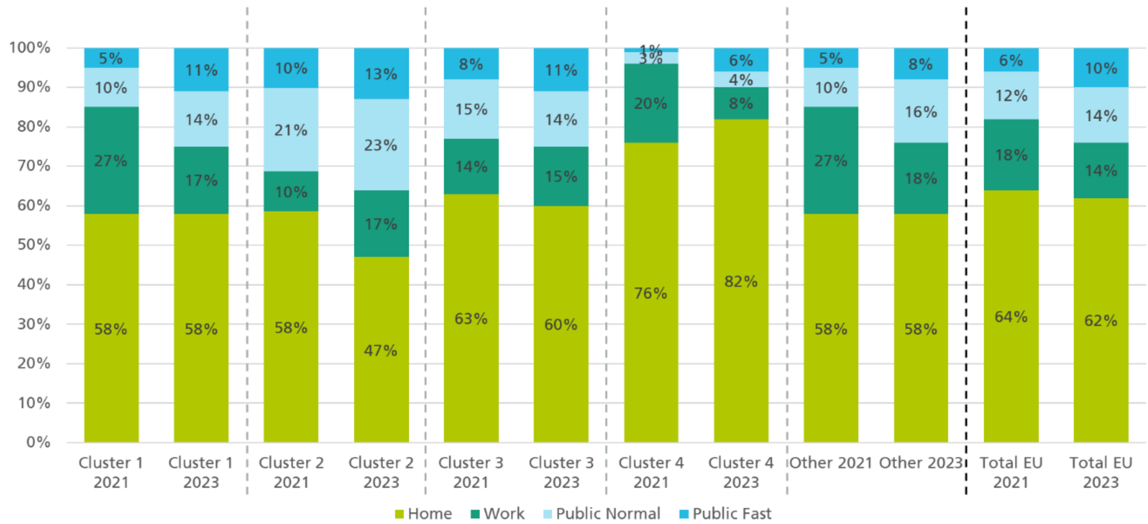
For the share of contracted RE in work charging, we can only compare the 2021 and 2023 results for Germany because Germany was the only country for which we received a solid database of work charging data from the surveys with fleet managers in both years. Comparing 2021 and 2023, results reveal that the share of contracted RE in work charging greatly decreased. Whereas in 2021, 81% of 94 fleet managers (responsible for 6,252 PEV) reported having a 100% renewable electricity contract, in 2023 only 59% of 70 German fleet managers (responsible for 5,476 PEV) reported the same (see Figure 7). Again, a slight methodological change needs to be noted by considering the answer option “I do not know” for the 2023 results regarding RE share in work charging.

Figure 7: Work charging survey: Comparison of share of contracted RE charging in PEV work charging for Germany.



When comparing the calculated results on a cluster level, by closing all data gaps with the methodology outlined in Section 2.3, it can be noted that the share of charging locations changed only slightly between 2020/2021 and 2022/2023 (see Figure 8).

Figure 8: Changes in the share of charging locations at cluster-level and across the EU, comparing the results from 2020/2021 and 2022/2023.



When comparing the results on the cluster level regarding RE share in PEV charging, we see that in almost each cluster (except Cluster 3) the share of contracted RE in home charging increased between 2021 and 2023: Across all clusters, it increased from 63% in 2021 to 66% in 2023 (see Table 5). The same pattern applies for work charging: In almost all clusters (except Cluster 3), the share of contracted RE in work charging increased. However, the increase in work charging in the clusters is marginal while the decrease in the largest cluster, Cluster 3, is large (from 81% in 2021 to 60% in 2023). Hence, across all countries, the share of RE in work charging decreased from 60% in 2021 to 53% in 2023. For public charging, the share of contracted RE increased. This applies for each cluster as well as for the share across clusters. For public slow charging across all clusters, the share of contracted RE increased from 44% in 2021 to 52% in 2023 and, for public fast charging, it increased from 46% in 2021 to 54% in 2023. However, the share of charging at different charging locations differs (with home charging holding 62% and public charging holding 14% for public slow and 10%

for public fast charging, see Table 4). Since these results are used when calculating the European RE share in PEV charging, we see the following development.

When we take a look at the estimations to fill all data gaps for Europe, there are differences in the estimated contracted share of RE in PEV charging between 2021 and 2023: **In the present study, the share of contracted RE in PEV charging for Europe lies at 61% (compared to 58% in 2021) and, thus, still above the balanced total supplier mix of 49% (compared to 46% in 2021).** Interestingly, both values, the balanced total supplier mix and the RE estimate increased between 2021 and 2023 by 3 percentage points.

Reasons for this result are discussed in the following section. Moreover, there are slight methodological adjustments between the study in 2021 and the present research to derive a realistic but conservative estimate of the contracted RE share in PEV charging in Europe (see also Supplementary Material, Table 13). These methodological adjustments are also outlined in the following section.

5 Discussion

The aim of the present paper was to develop an elaborated but conservative estimate of the share of contracted RE in PEV charging in Europe – separately for the different charging locations (home, work, public slow, and public fast charging). Thus, we determined the shares of charging locations as a first step with the help of survey data from 13 European countries. Following our step-wise methodology to close as many data gaps as possible with available and most recent data, our results support previous studies that most PEV users charge their PEV at home, followed by charging processes at work, and a smaller share of charging processes on public slow or fast charging points. However, country-specific differences occur.

To calculate the share of RE in PEV charging, recent research has mostly used the national (or European) electricity grid mix. In this regard, our analysis and data differ from existing results since we include new survey results from up to 13 EU countries on the share of contracted RE in PEV charging. Moreover, we apply a slightly adapted methodology for the estimate compared to the study conducted in 2021 (for details see below). Our analysis indicates that the share of RE in charging electricity still lies above the grid mix: 61% of European PEV users charge their PEV with RE – across all charging locations and countries (compared to a balanced total supplier mix of 49%). In 2021, the share of contracted RE in PEV charging was above grid mix with 58% (compared to a balanced total supplier mix, i.e., grid mix of 46%). Reasons for the results will be outlined in the following.

To ensure a lower bound for the estimate of RE share in European PEV charging, we applied the following methodological adjustments in the present research compared to the study in 2021: Next to the update of the survey data, we also included more countries and defined a lower threshold of responses with 200 PEV users per country. This led to a broader, more country-specific and thus more reliable database for Europe. The defined threshold (of 200 PEV users per country) was considered in the recruitment process of the PEV user survey on home charging, which was performed with the help of a market research institute. Since the study results from 2021 showed that home charging accounts for the largest share of charging and provides the data for the share of charging locations, setting a focus on the PEV user survey appeared valuable. Hence, we improved the recruitment strategy from a snowballing technique (via email, contacts and mouth-to-mouth sharing) to a recruitment with a panel sample in each country led by the market research institute. Since the panels are largely representative for the country's population, the responses also came from more diverse PEV users than in the 2021 study.

Another methodological adjustment is the inclusion of "I do not know"-responses regarding the question whether the PEV users have a 100% RE tariff at home. Past experiences showed that survey participants usually choose a response if they are forced to, whether they know the answer or not. Thus, based on good social science practises, we included the "I do not know"-option in the survey and also considered it in the analyses when calculating the share of RE in PEV charging. Hence, PEV users who selected "I do not know" regarding their electricity tariff were treated as people who reported to not have a 100% RE tariff at home for PEV charging, to arrive at a conservative estimate for Europe. One reason for this adjustment is the fact that PEV users who explicitly choose a 100% RE tariff are usually aware of their electricity tariff (if they are the person in the household who is responsible for selecting the electricity tariff). For a comparison of results including vs. excluding the "I do not know"-responses see Table 13 in the Supplementary Material. Moreover, the share of "I do not know"-responses varies across countries. In the study from 2021, the results were mostly driven by the survey results from Germany and Spain. The extension to 11 additional countries in the 2023 study showed that Germany has the smallest share of "I do not know"-responses in the examined European countries with 12% and Spain was also at the lower end with 18% of "I do not know"-responses. Hence, excluding these values in the 2021 study was a sensible choice but no longer reasonable for a conservative estimate in 2023, given that other countries reached high shares of "I do not know"-responses (e.g., up to 65% in Norway). Excluding "I do not know"-response would have led to an invalid database in some countries. Moreover, Germany is also the country with the highest RE share in PEV home charging (59%). Consequently, the larger database covering 13 countries in the 2023 study presents a more accurate estimate of the share of RE in PEV charging.

Other minor methodological adjustments include the following: For the share of charging locations, we prioritised the use of the survey data from the PEV user survey over results from the literature. We justify this with the fact that the PEV user survey presented in this research applies the same methodology for all countries (surveying the charging frequencies including all types of respondents with PHEV or BEV, multi-family homes or single-family homes), while the results from the literature do not cover 13 countries at the same time using the same methodology (i.e., some studies survey only single-family homes, others use interviews, some focus only on PHEV users instead of PEV users etc.).

By using the PEV user survey as a justified and reliable main database covering 13 countries, we also had to slightly adjust the methodology for the estimate for countries with data gaps. It is important to note that the database covers the countries with the highest share of the European PEV market and thus the estimated share for the countries without data is small and has a minimal impact on the result of RE share in Europe. Our adjustment was differed for filling the data gaps regarding the charging location and regarding the RE share. First, we describe the procedure of how we filled the data gaps regarding the charging location: Instead of implementing the results from the literature (as in the 2021 study), we calculated the average of the results from the countries in the same cluster and applied this to the cluster countries without data. The advantage of this approach is the fact that the research in the literature may have implemented different methodologies, while in the present research, the same methodology has been applied to all surveyed countries (for details see paragraph above). In summary, the slight methodological modifications between the study in 2021 and the present research lead to more reliable results and a more conservative estimate of the RE share of PEV charging in Europe. Second, for filling the data gaps regarding the RE share, we adjusted the methodology as follows: Instead of assuming 0% RE for "no"- or "I do not know"-responses (as in the 2021 study), we applied the balanced total supplier mix. This leads to a more realistic estimate of the RE share in PEV charging since the total balance supplier mix increased between 2021 and 2023. However, at the same time, we also adjusted the methodology to still arrive at a conservative estimate: Instead of using the cluster analysis and transferring the RE results from one country to other countries in the same cluster (as in the 2021 study), we filled the gaps for countries without data based on our survey and desk research solely with the country-specific total supplier mix. For options to calculate the RE share across Europe are outlined in the Supplementary Material (see Figure 11). Advantages and disadvantages of each option (including the applied approach) will be discussed in detail in a journal publication.

On a different note, one needs to consider external factors influencing the data collection. In 2021, data were collected during the COVID-19 pandemic, therefore, the answers might be affected by phenomena like an increased number of working from home (which could have led to an increased share of home charging compared to work charging). In 2023, post-effects of the energy crisis and the wars in Ukraine and Israel might have affected the results. Nonetheless, we do not assume large effects of these external events on our results. However, it highlights the importance of continuously and regularly updating and improving the database.

Regarding the work charging results, we would like to highlight that the survey sample is not representative. The lack of a representative sample is caused by the fact that information about the entire population of PEV fleet managers in Europe and in the different European countries are missing. Consequently, we used a snowballing technique for work charging to reach as many European fleet managers as possible. In addition, we only analysed survey data if a statement for more than 150 PEV in one European country was possible. This procedure was applied to avoid results that are not reliable. Thus, we believe that our survey results are reliable and valid, also given the fact that 95 German fleet managers (accounting for more than 6,400 PEV) completed the questionnaire. Generally, the success of recruiting fleet managers varied greatly across countries. It depended mostly on the willingness of large, often national-wide newsletters and related associations to share our survey link.

Moreover, the use of the cluster analysis and transferring the results from one country within a cluster to another one in the same cluster can be seen critically. For instance, one might wonder whether the results regarding work charging from Germany (with very little to no nuclear power) can be transferred to France (with a high share of nuclear power). Germany and France share a cluster because one of the selected cluster variables is the share of low emission electricity in the national grid mix – combining RE with nuclear electricity. However, we have included seven different cluster variables within the cluster analysis that contribute to the final clusters – to ensure a statistical reliable and non-arbitrary clustering of the countries. Moreover, the shares of work charging in Germany and France are at 15 and 13%. Hence, changes in the RE share of work charging would lead to only small changes in the overall result for Europe. Nonetheless, we slightly adapted the methodology from the 2021 study to avoid using the cluster analysis for the transfer of RE shares within one cluster (as outlined above). In general, we made sure that the applied procedures were strict and we were careful to arrive at conservative values for a realistic bound of the share of RE at the different charging locations in European PEV charging.

The present study provides a realistic but still conservative bound for the share of RE in PEV charging in Europe. It is noteworthy that we only analyse the contracted RE share as well as the RE share in the country-specific balanced total supplier mix. We did not analyse the physical share of RE and whether the electricity is produced in newly built plants that aim to meet the electricity demand of PEV (additionality criterion). However, this is a reasonable approach given that (1) electricity cannot be physically labelled, and that (2) most European distribution grids are highly interconnected. Due to the developments between 2021 and 2023, we strongly recommend a continuous and regular update of the study on a biannual basis.

6 Summary and further research

This article presents an update of the study from 2021 to derive a most recent, realistic but conservative estimate of (i) the share of charging locations and of (ii) the share of contracted renewable electricity (RE) for plug-in electric vehicles (PEV) charging in Europe (EU27, Iceland, Norway, the UK). By implementing two surveys – one on home charging and the charging location of PEV users and one on work charging with fleet managers – we achieved a larger and updated database compared to 2021: The PEV user survey was implemented in 13 countries (Belgium, Austria, Denmark, Spain, Italy, Germany, France, the UK, Sweden, Norway, the Netherlands, Finland, and Poland), covering more than 94% of the EU PEV market, while the fleet manager survey covered Germany. For public slow and public fast charging, we applied the same methodology as in 2021 by merging different data from registers in Germany and additional desk research.

These data are essential to calculate the GHG emissions of PEV because charging presents a large part of the carbon footprint of PEV. Drawing on the outlined data, we used a step-by-step methodology applying scientific standards to further close existing data gaps and arrive at values for all European countries. More specifically, focusing on countries with high shares in the PEV market as well as applying the identified clusters from the 2021 study with relevant cluster variables enabled us to transfer data from one country to other countries within the same cluster for the charging location. Supporting previous studies, our results indicate that PEV are predominantly charged at home in most countries, followed by charging processes at work. Thus, focusing on the use of RE at home presents an important element to reduce the carbon footprint of PEV.

Based on the conducted PEV survey, we achieved a reliable database for the share of RE in PEV charging at home (about 200 responses per country and more than 500 responses per cluster). Slight methodological adjustments compared to the 2021 study led to a more realistic and still conservative estimate of RE share across Europe. We found that the share of PEV charged with contracted RE across all charging locations is still above the often-assumed European electricity grid mix (i.e., the balanced total supplier mix); this confirms the results from 2021. With the introduced methodology in 2021 and slight methodological adjustments, we retrieved a total share of 61% contracted RE charging for Europe across all charging locations with the updated and enlarged database (compared to 49% using the same calculations with the electricity grid mix, i.e., the balanced total supplier mix for 2022/2023).

Data collection for public charging appeared more challenging than expected and may be extended for studies updating this research. The survey results on work charging are mainly driven by answers from German fleet managers, with Germany presenting one of the main PEV markets in Europe. For countries without accessible data on RE share in work charging, we applied the common approach of integrating the balanced total supplier mix. Further research should focus on extending the data regarding work and public charging to receive a continuously updated database for Europe.

The country- and cluster-specific data present a valuable database for further research and related analyses. We plan to outline pros and cons of different methodological approaches with this dataset in another publication. In addition, due to the rapid PEV developments and the differences in the results of 2021 and 2023, we suggest to update the data on a regular basis. To conclude, this paper presents recent data that further close identified gaps regarding shares of charging locations and respective shares of RE for PEV charging in Europe. At the same time, this research shows developments in shares of charging locations and RE share in PEV charging from 2021 to 2023. Our approach presents an updated, realistic, conservative, scientific methodology including survey data to ultimately arrive at the currently best available database for a European-wide calculation of the GHG emissions for PEV charging.

7 Acknowledgements

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8 List of figures

9 List of tables

10 References

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11 Supplementary Material

Sociodemographic characteristics of the survey respondents using PEV

Table 6: Sociodemographic variables of the surveyed PEV users, per country.

Country (number of responses)	Age range (Mean, SD)	Share of men vs. women*	Share with academic degree	Share with (very) comfortable income
Belgium – BE (n = 273 responses)	18-74 (M = 39.54, SD = 12.91)	57% vs. 41%	56%	32%
Austria – AT (n = 245 responses)	18-77 (M = 42.98, SD = 13.71)	49% vs. 51%	43%	44%
Denmark – DK (n = 250 responses)	18-81 (M = 54.03, SD = 16.20)	49% vs. 51%	48%	76%
Spain – ES (n = 338 responses)	18-72 (M = 39.35, SD = 10.37)	63% vs. 37%	61%	58%
Italy – IT (n = 251 responses)	21-78 (M = 45.67, SD = 11.85)	57% vs. 43%	63%	46%
Germany – DE (n = 342 responses)	18-87 (M = 48.40, SD = 13.35)	52% vs. 48%	51%	53%
France – FR (n = 248 responses)	22-85 (M = 48.77, SD = 13.69)	50% vs. 50%	63%	38%
United Kingdom – UK (n = 281 responses)	20-88 (M = 46.53, SD = 13.90)	51% vs. 48%	72%	52%
Sweden – SE (n = 249 responses)	19-89 (M = 50.71, SD = 15.91)	45% vs. 55%	56%	67%
Norway – NO (n = 257 responses)	18-90 (M = 51.40, SD = 16.30)	52% vs. 48%	66%	55%
The Netherlands – NL (n = 251 responses)	18-80 (M = 49.42, SD = 14.67)	58% vs. 41%	49%	68%

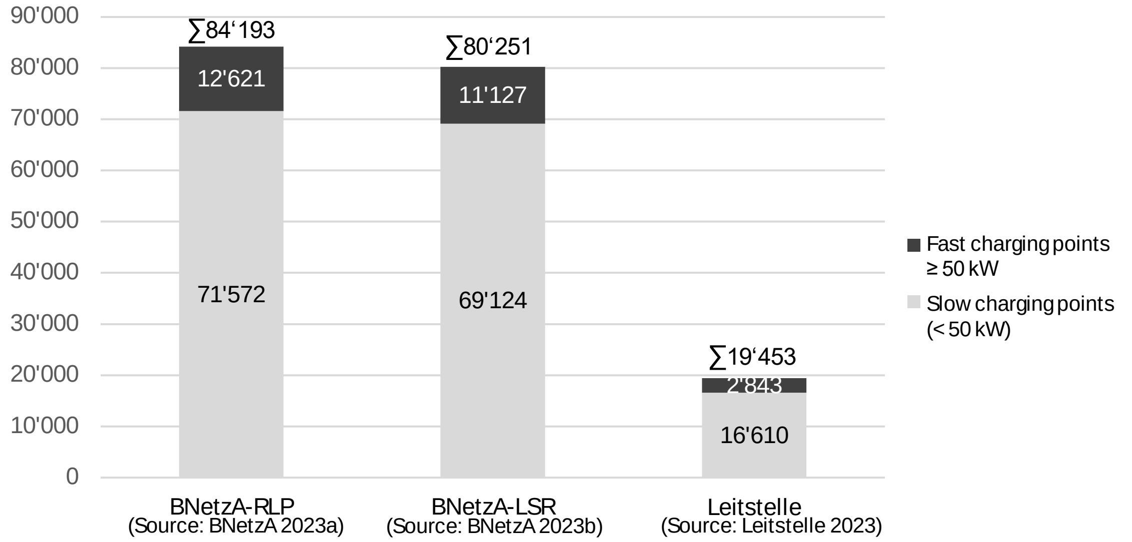
Country (number of responses)	Age range (Mean, SD)	Share of men vs. women*	Share with academic degree	Share with (very) comfortable income
Finland – FI (n = 197 responses)	18-84 (M = 48.94, SD = 15.93)	54% vs. 46%	51%	51%
Poland – PL (n = 256 responses)	18-76 (M = 42.67, SD = 13.47)	46% vs. 54%	69%	39%

Note: * Numbers do not add up to 100% since we do not report if "third gender / non-binary / gender-queer" or "I do not feel like belonging to any of the categories mentioned above" was selected by respondents.

The average age of PEV users who responded to our survey varies between 39 years (in Spain and Belgium) and 51 or even 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 women (e.g., in Sweden and Poland). In general, the majority of respondents across countries has 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 sociodemographics 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).

Registered public charging points in Germany

Figure 9: Amount of registered public charging points for the year 2022 in Germany in different registers



BNetzA-RLP: Public charging points registered with the Bundesnetzagentur in Germany with commissioning by 31/12/2022.
BNetzA-LSR: Public charging points listed in the BNetzA's charging point register with the consent of the CPO, with commissioning by 31/12/2022. The difference of nearly 4,000 charging points between the RLP and LSR data is due to the fact that the LSR register only publishes charging point data that the CPO has agreed to publish.
Leitstelle: Subsidized charging points with 100% RE electricity requirement in operation in 2022, which have reported charging volumes to the National Centre for Charging Infrastructure.

Table 7: **Reported numbers and charging volumes for 2022 of subsidised public charging points in Germany and average charging volumes calculated from these for NUTS1 regions.**

Region (NUTS 1)	Public slow (< 50 kW) Number of charging points (CP)	Public slow (< 50 kW) Reported charging volumes (kWh)	Public slow (< 50 kW) Average volumes (kWh per CP and day)	Public fast (≥ 50 kW) Number of charging points (CP)	Public fast (≥ 50 kW) Reported charging volumes (kWh)	Public fast (≥ 50 kW) Average volumes (kWh per CP and day)
Baden-Württemberg	3,257	14,050,311	13.8	432	5,552,293	46.4
Bavaria	2,995	9,278,921	11.6	468	5,540,172	41.5
Berlin*	48	178,263	14.9	19	613,766	(110.4)*
Brandenburg	500	1,439,425	10.3	85	1,255,764	57.4
Bremen	143	872,640	23.9	16	349,743	68.7
Hamburg	489	5,073,688	30.5	69	1,235,034	74.5
Hessen	1,089	3,669,074	12.0	183	3,994,090	81.9
Mecklenburg-Vorpommern	165	686,040	13.5	25	309,566	53.9
Lower Saxony	1,926	5,901,638	10.0	341	4,759,356	46.5
North Rhine-Westphalia	2,557	11,550,630	14.4	480	10,905,064	74.6
Rhineland-Palatinate	1,017	3,636,692	11.9	273	4,468,423	52.9
Saarland	283	1,095,841	12.0	27	497,761	52.5
Saxony	770	1,782,604	7.9	156	1,672,850	37.2

Region (NUTS 1)	Public slow (< 50 kW) Number of charging points (CP)	Public slow (< 50 kW) Reported charging volumes (kWh)	Public slow (< 50 kW) Average volumes (kWh per CP and day)	Public fast (≥ 50 kW) Number of charging points (CP)	Public fast (≥ 50 kW) Reported charging volumes (kWh)	Public fast (≥ 50 kW) Average volumes (kWh per CP and day)
Saxony-Anhalt	294	764,590	9.1	83	1,067,904	55.1
Schleswig-Holstein	768	3,328,711	13.8	95	1,718,465	65.0
Thuringia	309	875,272	8.9	91	737,749	27.7
Germany (NUTS 0)	**16,610**	**64,184,339**	**12.8**	**2,843**	**44,678,000**	**54.7**

Source: Leitstelle 2023. * The value for fast charging in Berlin appears to be biased due to the low reported number of charging points. For the extrapolation, the average charging quantities for Germany are therefore used for fast public charging in Berlin.

Cluster Analysis

To fill the remaining data gaps for share of contracted RE in PEV charging, we conducted a cluster analysis to find similarities between countries to ultimately transfer the data from one country to the other countries in the same cluster. For the cluster analysis, we used a hierarchical procedure using the Ward method, the Euclidean distance, and a z-standardization. Details of the cluster analysis are available from the first author upon request. Within our research team, we identified the following variables as relevant for the research questions and the related 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 (data from 2020; EAFO 2021)
- Share of public charging points on the available charging points in Europe (data from 2020; EAFO 2021)
- 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 (data from 2016; Eurostat 2018)
- Share of small photovoltaic plants (< 20 kW) on the total amount of photovoltaic plants in the country (data from 2017; Eurostat 2019)
- Share of being an owner of the house/appartment they are living in (data from 2019; Eurostat 2020)

We selected these cluster variables because there is evidence suggesting that these factors influence 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 was not available for all European countries, we were only able to include the following countries: Austria, Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Norway, Portugal, Spain, Sweden, and the UK.[2] However, these countries account for 86% of the European PEV market in 2020, therefore, related data presents a valid data basis. The results of the cluster analysis are presented in the following Figure 10. Due to the similarity of the countries within each cluster on all selected cluster variables, it appears approriate to transfer the data on the share of charging location from one country of a cluster to the other countries in the same cluster. This allows to fill the remaining data gaps for the different charging locations.

[2] For Norway, data on the attitudes toward protecting the environment as well as the share of small photovoltaic plants was not available. However, given the other data of the other cluster variables, Norway clearly belonged to Cluster 4 being associated with Sweden. This was confirmed by the same cluster analysis excluding the two variables for which we could not find available data for Norway.

Figure 10: **Results of the cluster analysis presenting the four clusters of countries, including only those countries for which data were available for all cluster variables.**

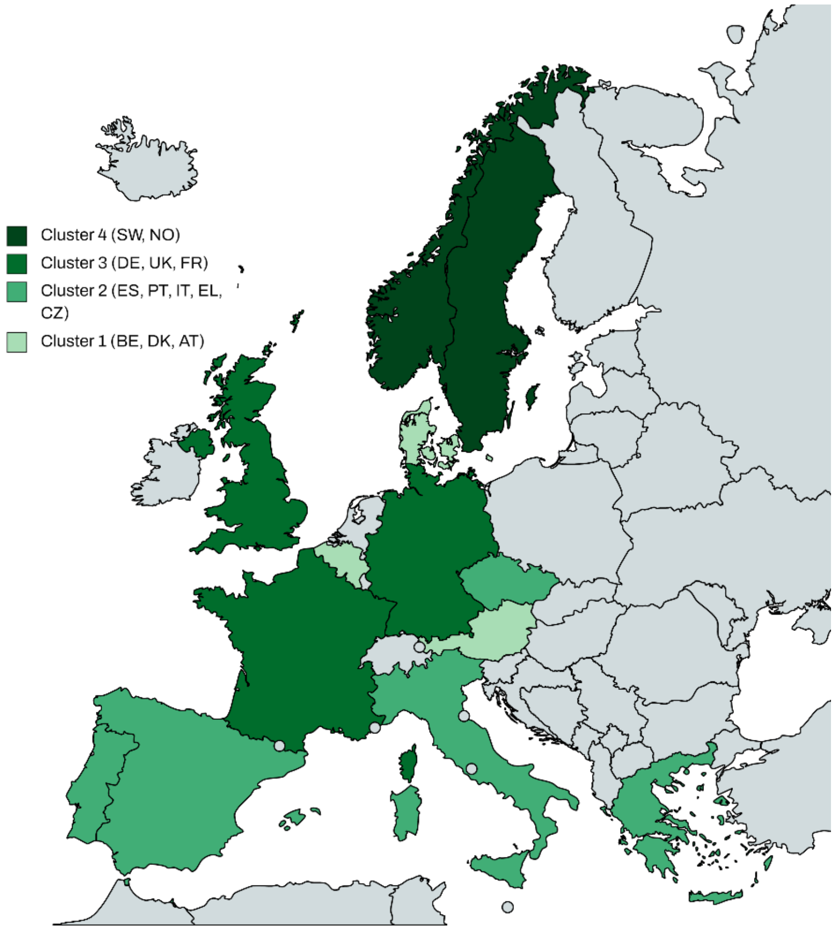


Table 8: **Shares of charging frequency at different locations for each country based on survey data – including 95%-confidence intervals.**

	Home charging	Work charging	Public slow charging	Public fast charging
Belgium – BE (n = 211 responses)	45 ± 7%	26 ± 6%	17 ± 5%	13 ± 5%
Austria – AT (n = 157 responses)	51 ± 8%	18 ± 6%	19 ± 6%	12 ± 5%
Denmark – DK (n = 164 responses)	82 ± 6%	4 ± 3%	7 ± 4%	7 ± 4%
Spain – ES (n = 290 responses)	44 ± 6%	20 ± 5%	21 ± 5%	15 ± 4%
Italy – IT (n = 200 responses)	49 ± 7%	14 ± 5%	25 ± 6%	12 ± 5%

	Home charging	Work charging	Public slow charging	Public fast charging
Germany – DE (n = 288 responses)	61 ± 6%	15 ± 4%	14 ± 4%	11 ± 4%
France – FR (n = 211 responses)	64 ± 6%	13 ± 5%	14 ± 5%	9 ± 4%
United Kingdom – UK (n = 211 responses)	54 ± 7%	17 ± 5%	16 ± 5%	13 ± 5%
Sweden – SE (n = 155 responses)	77 ± 7%	11 ± 5%	7 ± 4%	5 ± 3%
Norway – NO (n = 174 responses)	84 ± 5%	7 ± 4%	2 ± 2%	7 ± 4%
The Netherlands – NL (n = 179 responses)	57 ± 7%	19 ± 6%	17 ± 6%	8 ± 4%
Finland – FI (n = 131 responses)	70 ± 8%	13 ± 6%	11 ± 5%	6 ± 4%
Poland – PL (n = 172 responses)	37 ± 7%	22 ± 6%	22 ± 6%	18 ± 6%

Table 9: Data used for the share of charging volumes by location.

Country	Cluster	Number of PEVs	Home	Work	Public slow	Public fast
AT	1	152,514	**51%**	**18%**	**19%**	**12%**
BE	1	254,647	**45%**	**25%**	**17%**	**13%**
DK	1	193,766	**82%**	**4%**	**7%**	**6%**
CZ	2	22,646	*47%*	*17%*	*23%*	*13%*
ES	2	239,373	**44%**	**20%**	**21%**	**15%**
GR	2	18,575	*47%*	*17%*	*23%*	*13%*
IT	2	355,164	**49%**	**14%**	**25%**	**12%**
PT	2	128,049	*47%*	*17%*	*23%*	*13%*
DE	3	1,906,232	**61%**	**15%**	**13%**	**11%**
FR	3	1,101,686	**64%**	**13%**	**14%**	**9%**
UK	3	1,049,563	**54%**	**17%**	**16%**	**13%**
NO	4	808,256	**84%**	**7%**	**2%**	**7%**
SE	4	486,700	**77%**	**11%**	**6%**	**5%**
BG	5	6,300	*58%*	*18%*	*16%*	*8%*

Country	Cluster	Number of PEVs	Home	Work	Public slow	Public fast
CY	5	1,220	*58%*	*18%*	*16%*	*8%*
EE	5	3,633	*58%*	*18%*	*16%*	*8%*
FI	5	154,043	**70%**	**13%**	**11%**	**6%**
HR	5	5,485	*58%*	*18%*	*16%*	*8%*
HU	5	47,197	*58%*	*18%*	*16%*	*8%*
IE	5	61,031	*58%*	*18%*	*16%*	*8%*
IS	5	38,408	*58%*	*18%*	*16%*	*8%*
LT	5	12,288	*58%*	*18%*	*16%*	*8%*
LU	5	27,456	*58%*	*18%*	*16%*	*8%*
LV	5	3,400	*58%*	*18%*	*16%*	*8%*
MT	5	5,317	*58%*	*18%*	*16%*	*8%*
NL	5	515,242	**57%**	**19%**	**17%**	**8%**
PL	5	52,064	**38%**	**22%**	**22%**	**18%**
RO	5	31,795	*58%*	*18%*	*16%*	*8%*
SI	5	9,220	*58%*	*18%*	*16%*	*8%*
SK	5	8,743	*58%*	*18%*	*16%*	*8%*

Data used from our own surveys are written in bold. Available country-specific data within a cluster from own surveys are carried forward as substitute data for the countries within the same cluster (written in italics) as weighted average within each cluster based on the country-specific number of PEV, to fill data gaps for the share of charging locations.

Table 10: Data used for the renewable electricity shares in the total charging volumes (by charging location)

Country	Cluster	Number of PEVs	Home	Work	Public slow	Public fast
AT	1	152,514	**93%**	*84%*	*84%*	*84%*
BE	1	254,647	**69%**	*38%*	*38%*	*38%*
DK	1	193,766	**61%**	*50%*	*50%*	*50%*
CZ	2	22,646	*14%*	*14%*	*14%*	*14%*
ES	2	239,373	**73%**	*40%*	*40%*	*40%*
GR	2	18,575	*40%*	*40%*	*40%*	*40%*
IT	2	355,164	**62%**	*34%*	*34%*	*34%*
PT	2	128,049	*26%*	*26%*	*26%*	*26%*
DE	3	1,906,232	**89%**	**89%**	**88%**	**94%**
FR	3	1,101,686	**38%**	*19%*	*19%*	*19%*

Country	Cluster	Number of PEVs	Home	Work	Public slow	Public fast
UK	3	1,049,563	**76%**	*51%*	*51%*	*51%*
NO	4	808,256	**41%**	*30%*	*30%*	*30%*
SE	4	486,700	**79%**	*65%*	*65%*	*65%*
BG	5	6,300	*16%*	*16%*	*16%*	*16%*
CY	5	1,220	*18%*	*18%*	*18%*	*18%*
EE	5	3,633	*20%*	*20%*	*20%*	*20%*
FI	5	154,043	**45%**	*34%*	*34%*	*34%*
HR	5	5,485	*36%*	*36%*	*36%*	*36%*
HU	5	47,197	*18%*	*18%*	*18%*	*18%*
IE	5	61,031	*76%*	*76%*	*76%*	*76%*
IS	5	38,408	*26%*	*26%*	*26%*	*26%*
LT	5	12,288	*60%*	*60%*	*60%*	*60%*
LU	5	27,456	*78%*	*78%*	*78%*	*78%*
LV	5	3,400	*22%*	*22%*	*22%*	*22%*
MT	5	5,317	*11%*	*11%*	*11%*	*11%*
NL	5	515,242	**74%**	*58%*	*58%*	*58%*
PL	5	52,064	**48%**	*20%*	*20%*	*20%*
RO	5	31,795	*44%*	*44%*	*44%*	*44%*
SI	5	9,220	*23%*	*23%*	*23%*	*23%*
SK	5	8,743	*28%*	*28%*	*28%*	*28%*

Data from our own surveys plus the calculated share of RE in the balanced total supplier mix for the "no"- and "I do not know"-responses are written in bold. Substitute data are written in italics, i.e., for the remaining data gaps, the country-specific balanced total supplier mix (AIB 2023) is used as substitute data (in italics) for the RE shares in charging volumes. The combination of the survey value for home charging and the balanced RE share for the other charging locations can be justified because PEV charging volumes have accounted for a only very small share of the total national electricity demand so far.

Results from the surveys on Home and Work Charging with confidence intervals

Table 11: Home Charging: Shares of renewable energy charging tariffs for home charging in each country based on survey data from PEV users – including 95%-confidence intervals.

	PEV users: Do you have a 100% RE tariff?		
	Yes	No	I do not know
Belgium – BE (n = 225 responses)	50 ± 7%	30 ± 6%	20 ± 5%
Austria – AT (n = 171 responses)	58 ± 7%	27 ± 7%	15 ± 5%
Denmark – DK (n = 223 responses)	21 ± 5%	45 ± 7%	34 ± 6%
Spain – ES (n = 282 responses)	56 ± 6%	27 ± 5%	17 ± 4%
Italy – IT (n = 183 responses)	42 ± 7%	36 ± 7%	22 ± 6%
Germany – DE (n = 289 responses)	59 ± 6%	30 ± 5%	12 ± 4%
France – FR (n = 215 responses)	24 ± 6%	55 ± 7%	21 ± 5%
United Kingdom – UK (n = 235 responses)	51 ± 6%	27 ± 6%	22 ± 5%
Sweden – SE (n = 210 responses)	38 ± 7%	25 ± 6%	37 ± 7%
Norway – NO (n = 251 responses)	16 ± 5%	19 ± 5%	65 ± 6%
The Netherlands – NL (n = 159 responses)	39 ± 8%	15 ± 6%	46 ± 8%
Finland – FI (n = 178 responses)	16 ± 5%	47 ± 7%	37 ± 7%
Poland – PL (n = 175 responses)	35 ± 7%	45 ± 7%	20 ± 6%

Table 12: Work Charging: Share of renewable energy charging tariffs for work charging in Germany based on survey data from fleet managers of PEVs – including 95%-confidence intervals.

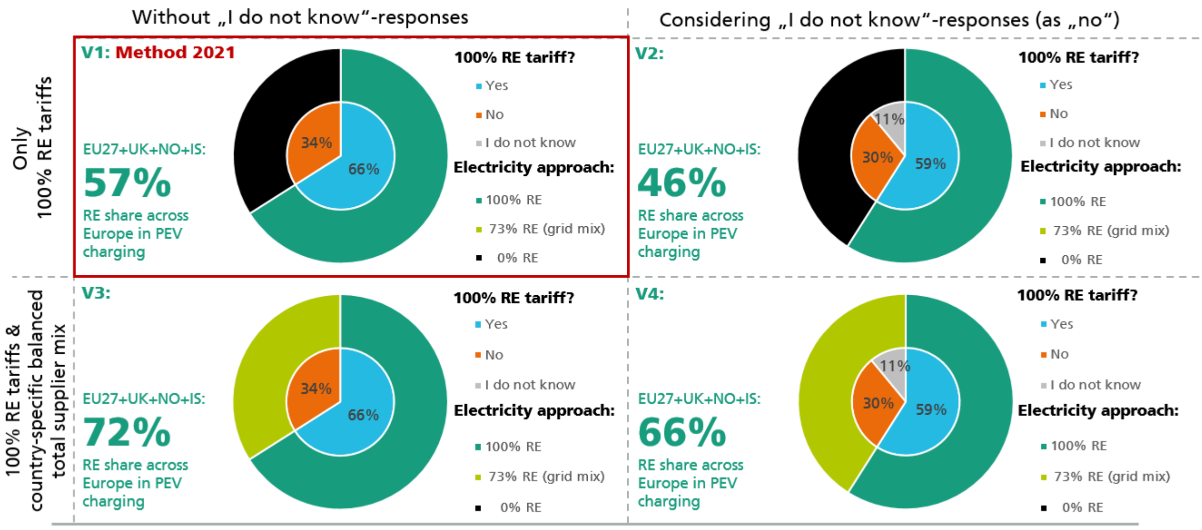
	Fleet managers: Do you have a 100% RE tariff?		
	Yes	No	I do not know
Germany – DE (n = 70 responses)	59 ± 12%	11 ± 7%	33 ± 11%

Comparison of results from 2023 (with and without respondents who stated “I do not know”)

Table 13: Comparison of cluster-specific and total shares of contracted RE by charging location from 2023 (including vs. excluding the responses from PEV users who did not know whether or not they have a 100% RE charging tariff, in the calculation of the percentages)

Cluster	Share of PEV in EU27 + UK, NO, IS	Home without "I do not know" responses	Home considering "I do not know"	Work without "I do not know" responses	Work considering "I do not know"	Public slow	Public fast
1	8%	78%	72%	53%	53%	53%	53%
2	10%	63%	57%	34%	34%	34%	34%
3	53%	76%	72%	63%	60%	60%	62%
4	17%	71%	55%	43%	43%	43%	43%
5 (other)	13%	69%	60%	49%	49%	49%	49%
Total (EU27 + UK, NO, IS)	**100%**	**73%**	**66%**	**54%**	**53%**	**52%**	**54%**

Figure 11: Comparison of results when applying various methodological approaches to calculate the estimate of the RE share across Europe.



This matrix with two dimensions shows four additional options to calculate the RE share of PEV charging in Europe. The large numbers written in green present the results across Europe. The diagrams show an example, i.e., the results for home charging in Germany. The dimension of the matrix are (1) considering "I do not know"-responses vs. not considering them and (2) considering only 100% RE tariffs as indicated by the survey responses and our desk research vs. considering the

100% RE tariffs and for the "no"- and "I do not know"-responses, respectively, the country-specific balanced total supplier mix (presented as "grid mix" in the chart). In all four approaches, the cluster analysis has been used to transfer the results from one country to other countries in the same cluster. This last aspect differentiates these approaches from the used approach described in the main text.