Working Paper Sustainability and Innovation
No. S 11/2021

Sabine Preuß
Robert Kunze
Jakob Zwirnmann
Jonas Meier
Patrick Plötz
Martin Wietschel

The share of renewable electricity in electric vehicle charging in Europe is higher than grid mix

Fraunhofer ISI

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. This article provides a systematic overview of existing studies and additional data on the electricity contracts of users and charge point operators (CPO) as well as the share of renewables in the charged electricity for PEV in Europe. We combine survey data with existing studies and cover a noteworthy share of the European PEV market and CPO. Our results show that the actual share of renewables in electricity contracts for home and work charging as well as for public CPO 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 underestimated the well-to-wheel life-cycle benefits of PEV.

Table of Contents

Page

1 Introduction 1

1.1 Background: Existing literature 1

1.2 Contribution 3

2 Methods and data 3

2.1 Overview 3

2.2 Data from available studies 4

2.3 Home and work charging survey 7

2.3.1 PEV user survey 8

2.3.2 Fleet manager survey 8

2.4 Method to close data gaps 9

2.5 Clustering of the European PEV market 11

3 Results 14

3.1 Share of charging locations 15

3.2 Share of contracted RE in PEV charging 16

4 Discussion 18

4.1 Methodological discussion 19

4.2 Further discussion of RE and related aspects 20

5 Summary and further research 22

6 Acknowledgements 24

7 References 24

8 Supplementary Material 28

List of Figures

Figure 1: Overview of published shares of charging modes for different European countries 5

Figure 2: Results of the cluster analysis presenting the four clusters of countries including only those countries for which data to all cluster variables were available. 13

Figure 3: Registered BEV and PHEV per country in 2020: Total number of PEV (left y-axis) as well as cumulated share on the EU27 + UK, NO, IS PEV market (right y-axis). 14

Figure 4: Amount of registered public charching points for the year 2020 in Germany in different registers.* 29

List of Tables

Table 1: Targeted data structure regarding charging location and RE charging for PEV in Europe (EU27 + UK, NO, IS). 4

Table 2: Quality assessment of available studies on shares of charging location. 6

Table 3: Share frequency of charging processes at the different charging locations in Germany and Spain based on survey data including 95% confidence intervals (missing to 100% from rounding). 15

Table 4: Cluster-specific and total shares of charging by location. 16

Table 5: Cluster-specific and total shares of contracted RE by charging location. 17

Table 6: Applied criteria with related characteristics for the quality assessment of available studies. 28

Table 7: Reported numbers and charging volumes for 2020 of subsidized public charging points in Germany and average charging volumes calculated from these for NUTS1 regions.* 30

Table 8: Data used for the share of charging volumes by location. 31

Table 9: Data used for the renewable electricity shares in the total charging volumes (by charging location)* 32

Table 10: Associations and companies contacted for recruiting (upper part for PEV user survey, lower part for fleet manager survey). 33

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. Currently, the numbers of PEV are rising in Europe with over 15% sales share by mid 2021 including plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) (EAFO 2021). PEV can offer noteworthy greenhouse gas (GHG) emission reduction on a life-cycle base compared to internal combustion engine vehicles (ICEV) if mainly charged with renewable energy sources, i.e., renewable electricity (RE) (IEA 2021, Cox et al. 2018, Märtz et al. 2021). However, only a few studies have analysed the actual electricity contracted for charging including the different charging locations such as home, work, and public charging. Here, we combine new survey data with a systematic overview of existing studies to derive (1) the share of PEV charging at different locations and (2) the share of contracted RE in charging (at these location). We then combine both shares in a carefull and conversative manner to avoid an overestimation and to obtain a lower bound for the share of contracted RE in PEV charging in Europe.

The outline of the present paper is as follows. The remainder of Section 1 summarises the existing literature on the electricity assumed in PEV charging as well as the contribution regarding the share of different charging locations. Section 2 describes our method and data sources, i.e. the survey data and existing data in literature sources. Section 3 contains the results from the surveys performed, the existing values from the literature and the total share of contracted RE at different locations in different countries. The discussion is presented in Section 4 and followed by our conclusions in Section 5. Additional details on the data and methods are given in the Supplementary Material.

1.1 Background: 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) focus on the marginal grid mix, ambient temperature and driving behaviour. They find the GHG emission benefit of PEV strongly depends on the source of electricity used for charging. Tamayao et al. (2014) compare different grid mixes without future changes in the carbon intensity. Xu et al. (2020) considered 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 commercial BEV and compared the cradle-to-gate GHG emissions to an ICEV. Märtz et al. (2021) also include the future evolution towards more RES 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 intensity of the electricity mix explains 70% of the variability in the results in electric vehicle LCA studies. In summary, many studies emphasize the importance of the electricity used in charging PEVs but none of these studies take into account 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 charging PEV, the share of charging location (home, work, public slow and fast) is required.

This is considered in a second group of studies which analysed the share of electricity charged at different locations in European countries – some of these studies making a statement on the use of RE. For Germany, survey-based studies find a share of contracted RE of 60% (Römer/Steinbrecher 2021) and 58% (Frenzel et al. 2015) for home charging. The latter survey also includes an analysis of work charging quantities, thus, a contracted RE share of 53% for work charging was determined (Frenzel et al. 2015). In addition, a recent 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 2021). Despite the scope of this study, it only covers a specific segment of public charging and overall only a small share of the publicly accessible charging infrastructure in Germany. In addition, no information is available on RE shares in public charging in Germany.

A few studies based on empirical data from PEV user surveys provide information of the charging preferences (e.g. Wolff/Madlener 2019, Avere France/Ipsos 2020, Enedis 2021) or the share of charging frequency (e.g. 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 location types. 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. Dodson/Slater

2019, Gardien et al. 2021 and Duurkoop et al. 2021). An overview of the published data is given in

Figure 1 below.

In summery, some pieces of information of charging at different locations are published in the literature for some European countries, indicating that home is the most important charging location. However, the available results show a considerable variation *between* the countries as well as also *within* one country. Apart from the dominant share of home charging, it is hardly possible to derive general trends from the comparison of the data for the analyzed countries. In contrast, the data basis on the RE shares in charging is even smaller: There is no comprehensive overview regarding the share of RE for all charging locations for any European country so far.

1.2 Contribution

The aim of the present paper is to obtain a lower bound for RE in PEV charging in Europe. To this end, we analyse the share of PEV charging at different locations (i.e., home, work, public slow charging < 50kW, and public fast charging ≥ 50kW) and combine it with the share of contracted RE at these locations. With the assumption of today's average RE share in the grid mix for each country, we obtain a lower bound for the share of contracted RE in PEV charging in Europe.

This work differs from previous research in several aspects. First, it provides a systematic overview of existing literature on PEV charging locations and contracted RE shares. Second, it closes existing data gaps with survey data including hitherto less studied fleet managers regarding the contracted electricity for work charging. Third, it provides an empirical lower bound for the overall share of contracted RE in PEV charging in Europe that is more precise than assuming the grid mix.

2 Methods and data

2.1 Overview

To answer the two outlined questions relevant for the calculation of PEV emissions, we aimed to collect data to complete Table 1. Thus, we performed three steps: Firstly, we selected existing data from the literature review based on various quality criteria, leading to the identification of data gaps. Secondly, we performed different surveys to fill these data gaps. Hence, we ran two studies in Europe, one with PEV users and one with fleet managers. Thirdly, we conducted an analysis of the data and transformed them with the help of a cluster analysis and existing data bases to receive the targeted data for Europe. The geographical scope of the present paper contains all 27 EU-countries as well as the United Kingdom (UK), Norway, and Iceland. We aimed to use the latest data to generate an estimate of share of charging locations and share of (contracted) RE in PEV charging for 2020.

Table 1: Targeted data structure regarding charging location and RE charging for PEV in Europe (EU27 + UK, NO, IS).

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

2.2 Data from available studies

For the present study, we screened the available English and German literature and included 41 publications published since 2015 that included country-specific data regarding our research questions (share of charging location and share of contracted RE for PEV charging). The evaluation shows that the use of RE for PEV charging has hardly been considered in the research landscape so far. Data with shares for the different charging locations (home, work, public slow, public fast) are available in 17 of the 41 publications. These studies focused on Europe or a few selected European countries.

Figure 1 shows an overview of shares of charging location in the published data that we have identified.

In order to make an adequate selection of the data to be used from the range of available studies regarding the share of charging location, the studies were assessed in an evaluation matrix using three categories for the data's quality (higher vs. medium vs. lower) along different criteria. The result of this evaluation matrix is shown in Table 2.

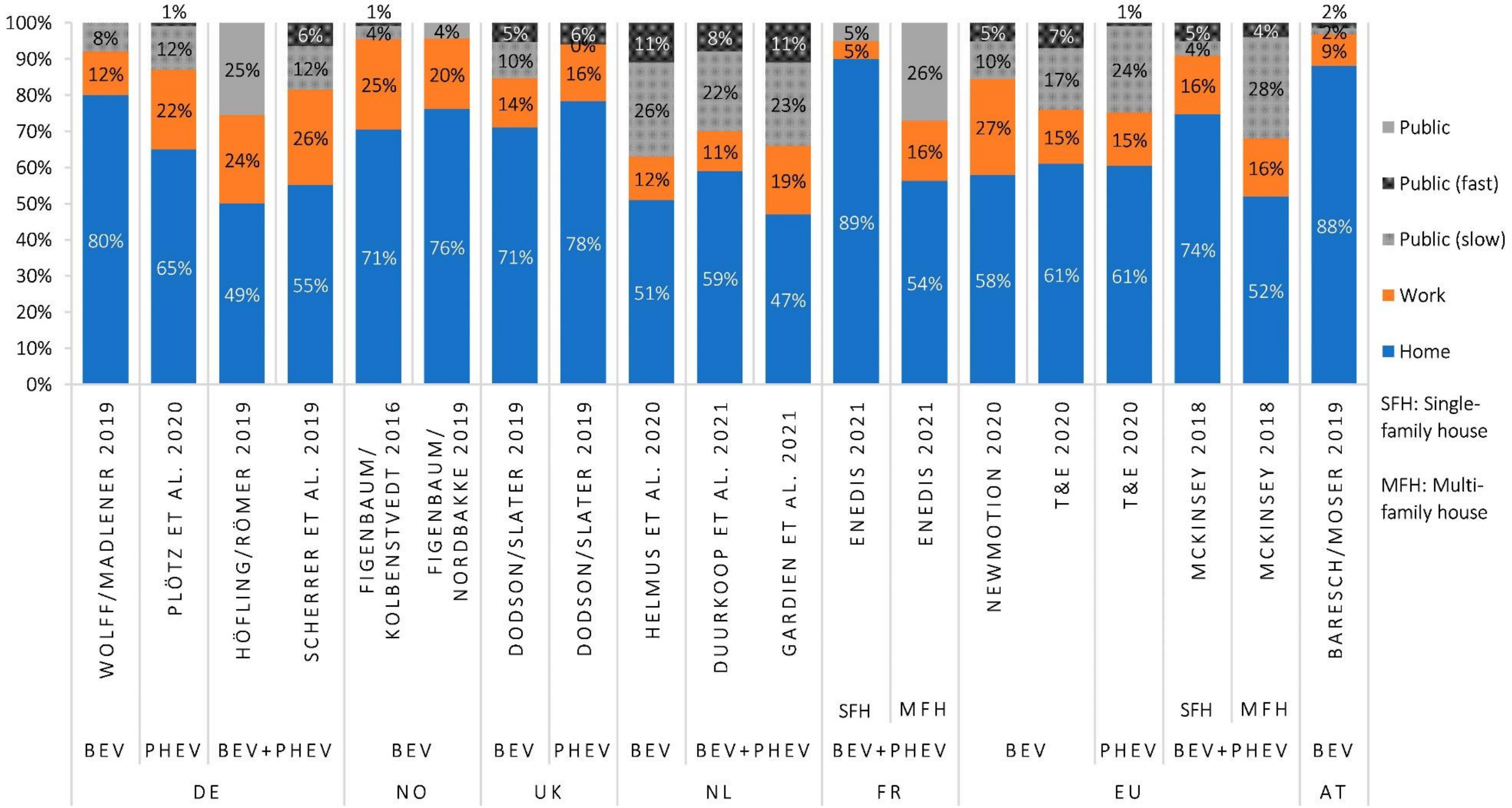

Figure 1: Overview of published shares of charging modes for different European countries

Table 2: Quality assessment of available studies on shares of charging location.

Region	Source	Type of source	Method-ology	Represen-tativity	Values collected	Recency	Type of PEV considered
DE	Wolff/Madlener 2019	lower	higher	lower	lower	not clearly specified	medium
	Scherrer et al. 2019	medium	higher	higher	medium	higher	medium
	Höfling/Römer 2019	medium	higher	lower	medium	higher	medium
	Römer/Steinbrecher 2021	medium	higher	lower	medium	higher	medium
	Plötz et al. 2020	medium	higher	higher	medium	medium	lower
UK	Dodson/Slater 2019	medium	higher	higher	higher	higher	higher
NO	Figenbaum/Kolbenstvedt 2016	medium	higher	higher	medium	medium	medium
	Figenbaum/Nordbakke 2019	medium	higher	higher	medium	higher	medium
FR	Avere France/Ipsos 2020	medium	higher	higher	lower	higher	medium
	Enedis 2021	medium	higher	medium	lower	higher	medium
NL	Helmus et al. 2020	lower	higher	higher	medium	higher	medium
	Gardien et al. 2021	medium	higher	higher	higher	higher	medium
	Duurkoop et al. 2021	medium	higher	higher	higher	higher	medium
AT	Baresch/Moser 2019	medium	medium	lower	medium	not clearly specified	medium
EU	McKinsey 2018	medium	lower	not clearly specified	higher	medium	medium
	T&E 2020	lower	lower	lower	higher	not clearly specified	higher
	NewMotion 2020	medium	higher	medium	medium	higher	medium

■ higher ■ medium ■ lower ■ not clearly specified

To evaluate the data quality of the studies, the main evaluation criteria are the type of source (official statistics vs. peer-reviewed article vs. other paper, etc.), the methodology of data generation (empirical vs. model or expert survey) and the degree to which the data are representative (highly representative vs. partly representative vs. not representative). Other criteria include the type of values that were collected (charging volumes/quantity vs. charging processes/ frequency vs. charging preferences) and the year of survey or data collection. Due to the currently high dynamics in the PEV market, more recent data are rated higher than older ones. In addition, we also rated the studies based on the extent to which the data covered BEV and PHEV separately or in sum or only one of them. The complete list of evaluation criteria with their characteristics for the data quality assessment is shown in Table 6 in the Supplementary Material. The evaluation along these criteria presents an orientation of the studies' data quality.

Regarding the share of RE in PEV charging, we could not identify existing studies over and above the published results mentioned in Section 1.1. Thus, we identified gaps in the share of PEV charging location for some European countries and a majoy gap regarding the share of RE in PEV charging.

2.3 Home and work charging survey

To start filling the identified data gaps regarding charging location and share of RE, we conducted two surveys in Europe – one including PEV users and one including fleet managers. The method did not differ largerly between the two surveys: Among other questions not relevant for the purpose of the present research, we asked private PEV users 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?") to obtain data regarding home charging. In the second study, we surveyed fleet managers to receive data on the share of RE for work charging (i.e. asking whether they have a RE tariff at their company). Additionally, we collected data on socio-demographics 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 2021.

2.3.1 PEV user survey

To recruit PEV users, we contacted PEV associations, newsletters and mailing lists, magazines, online forums as well as social media groups in European countries (for details see Supplementary Material Table 10). A total of 2032 participants completed the survey. Due to selection criteria (see Supplementary Material), we analysed data of 1608 participants. For these, 867 were from Germany, 609 from Spain and 132 from other European countries (including Norway, Iceland, and the UK). Except for Germany and Spain, the sample size per country was too small to analyse the data separately by country (n < 50).

The German sample (n = 867) consisted of mainly male participants (89%). The age in the German sample ranged between 18 and 85 years (mean M = 53.82; standard deviation SD = 12.72) with 77% having a high level of education (n = 512 earned a university degree, n = 155 completed the university entrance level). In the Spanish sample (n = 609), the distribution was similar: 90% of respondents were male, and the educational level was rather high with 73% having a university degree and/or the qualification for university entrance. In the Spanish sample, age ranged between 20 and 88 years (M = 48.23, SD = 9.39). In both subsamples, the majority (approximately 90%) owned a BEV (the other 10% owned a PHEV) and only 5% in each sample owned both, a BEV and a PHEV. These sample characteristics fit existing research on early adopters of PEV (Plötz et al. 2014; Scherrer et al. 2019).

2.3.2 Fleet manager survey

To recruit fleet managers with PEV, we contacted PEV associations, magazines, online forums as well as social media groups in European countries (for details see Supplementary Material Table 10). A total of 250 fleet managers completed the respective survey. After applying the relevant selection criteria (see Supplementary Material), 170 answers from fleet managers in Europe remained, leading to the following database: One fleet manager each answered the questionnaire for a Norwegian and Belgian company; all other fleet managers were from Germany (n = 168) accounting for 8621 PEV. Of the 168 German fleet managers, 4% made a break but fully completing the questionnaire (given the option to choose not to answer for almost all question). Thus, the survey data can be analysed for Germany, but the database is too small for other countries. Hence, we were not able to fill the gaps regarding work charging for the other European countries with the help of this survey.

For the share of RE in PEV public charging (slow and fast), we also aimed to conduct a survey with CPO of public charging points. Thus, we contacted a total of 210 CPO (66 large to medium-size European CPO and all German CPO providing more than 37 charging points each) with a survey link and asked for the requested answers. However, the response rate was very low (n = 11 across countries), thus this data does not present an adequate basis that can be analysed.

2.4 Method to close data gaps

As an interim summary, the collected survey data can fill some of the data gaps identified in Section 1.2 – but not all of them. With the survey data, an adequate data basis for the share of charging locations is only available for Germany and Spain. The existing data from already published studies can help to fill the gaps regarding the share of charging location for the other European countries. Based on the results of the evaluation matrix (see Table 2), for the present study, the country-specific results regarding the shares of charging locations from Dodson/Slater (2019), Figenbaum/Nordbakke (2019), Avere France/Ipsos (2020) and as a EU-wide dataset the results from NewMotion (2020) will be used.

Regarding contracted RE shares, the survey data present an adequate data basis for home and work charging in Germany and for home charging in Spain, however no data is available on the share of contracted RE in *public* charging in any European country. In addition, no studies were identified to fill the data gaps regarding share of contracted RE in any European country. Thus, for no European country, a complete data set regarding the share of charging locations *and* the contracted RE shares is available so far, when combining the existing data and the survey data.

As a next step to fill these gaps, we draw on registers regarding public charging infrastructure. Thus, we can fill at least one country-specific gap regarding the share of contracted RE in public charging, to achieve a complete data set at least for Germany, which is currently the largest PEV market in the EU in terms of the absolute numbers of registered PEV (EAFO, 2021). For Germany, the combined evaluation of official, publicly accessible registers on public charging infrastructure offers the possibility to determine a reliable value for the still missing RE share in public charging. Figure 4 in the Supplementary Material shows the results of the register evaluation for the charging points recorded in each case. The methodology for deriving the RE share is briefly presented in the following. For all other data gaps, adequate substitute data have to be defined, which will be presented afterwards.

In Germany, public charging points must be registered at the Bundesnetzagentur (BNetzA). The number of charging points is available per NUTS 1 region.[1] In total, just over 43,400* publicly accessible charging points were installed at the end of 2020 (BNetzA 2023). This is compared with the data from the National Centre for Charging Infrastructure (Leitstelle). The Leitstelle records the charging volumes of the publicly accessible charging points that have received federal funding every six months over a period of six years. The basic requirement for the funding approval is that the charging points are operated exclusively with RE during this period. In 2020, charging power volumes for nearly 11,200* charging points were reported to the Leitstelle (see Table 7 in the Supplementary Material). For the year 2020, the Leitstelle data thus cover about 26%* of all slow public charging points and 25%* of all fast public charging points in Germany.

The Leitstelle data are also available at NUTS1 level. From the number of reporting charging points and the reported charging volumes, specific average charging quantities per fast and slow charging point per operating day are calculated for each NUTS 1 region (see Table 7 in the Supplementary Material). These average charging quantities are multiplied by the respective NUTS 1 charging point number from the BNetzA data to estimate the total charging volumes for Germany. The time of commissioning of the charging points must be taken into account. For charging points that were only commissioned in the course of 2020, only pro rata charging quantities are taken into account in the extrapolation according to their commissioning date. This extrapolation results in a total charging volume of approx. 61 GWh* with a RE share of at least 29%* at public slow charging points and of just approx. 31 GWh* with a RE share of at least 31%* at public fast charging points.

In order to also take into account RE usage at unsubsidized charging points, it must first be ensured that these charging points are not already recorded in the Leitstelle data. Therefore, information is available on the number of charging

1 NUTS (Nomenclature des Units Territoriales Statistiques): Hierarchically structured system of territorial units for the statistics of the European Union. NUTS 0 = national level (e.g. Germany), NUTS 1: regional level 1 (e.g. in Germany 16 federal states).

* An earlier version of the paper reported different numbers; the modification was necessary due to a revision of the database.

points reported to the NLL (differentiated by CPO, NUTS 1 region and fast and slow charging).

Based on this register matching, a number of charging points are identified that were operated in 2020 and were not recorded in the Leitstelle data. The websites of larger CPO and short telephone interviews were used to find out whether these charging points were operated with contracted RE. To arrive at a conservative estimate, the following CPO were excluded:

- CPO for which, due to the current dynamics in the German CPO market (spin-offs, mergers, changing company names), there were doubts during the register comparison as to whether their charging points were already included in the Leitstelle data.
- CPO for which no information was available on the use of renewable electricity at their charging points or which do not operate all their charging points with 100% renewable electricity.

The contracted RE shares determined in this way were added to the RE shares based on the Leitstelle data. This results in a total contracted RE share of at least 49%* at public slow charging points and a RE share of at least 52%* at public fast charging points for Germany. Thus, with this methodology, we were able to fill the gap regarding the share of contracted RE for public charging in Germany, however, the data gaps for the other European countries remain.

As next steps, to close the data gaps regarding the RE share in charging locations, we will use the RE shares of the balanced country mix as substitute data for each country (AIB 2021). Additionally, the available data for the shares of charging locations are made usable for extrapolation to other countries within the framework of a cluster analysis which is described in the following.

2.5 Clustering of the European PEV market

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

* An earlier version of the paper reported different numbers; the modification was necessary due to a revision of the database for public charging.

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 they might 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 only able to include the following countries: Austria, Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Norway, Portugal, Spain, Sweden, and the UK.[3] However, these countries account for 86 % of the European PEV market (see Figure 3), thus related data presents a valid data basis. The results of the cluster analysis are presented in

Figure 2. Due to the similarity of the countries within each cluster on all selected cluster variables, it appears approriate 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.

---

3 For Norway, data on the attitude 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.

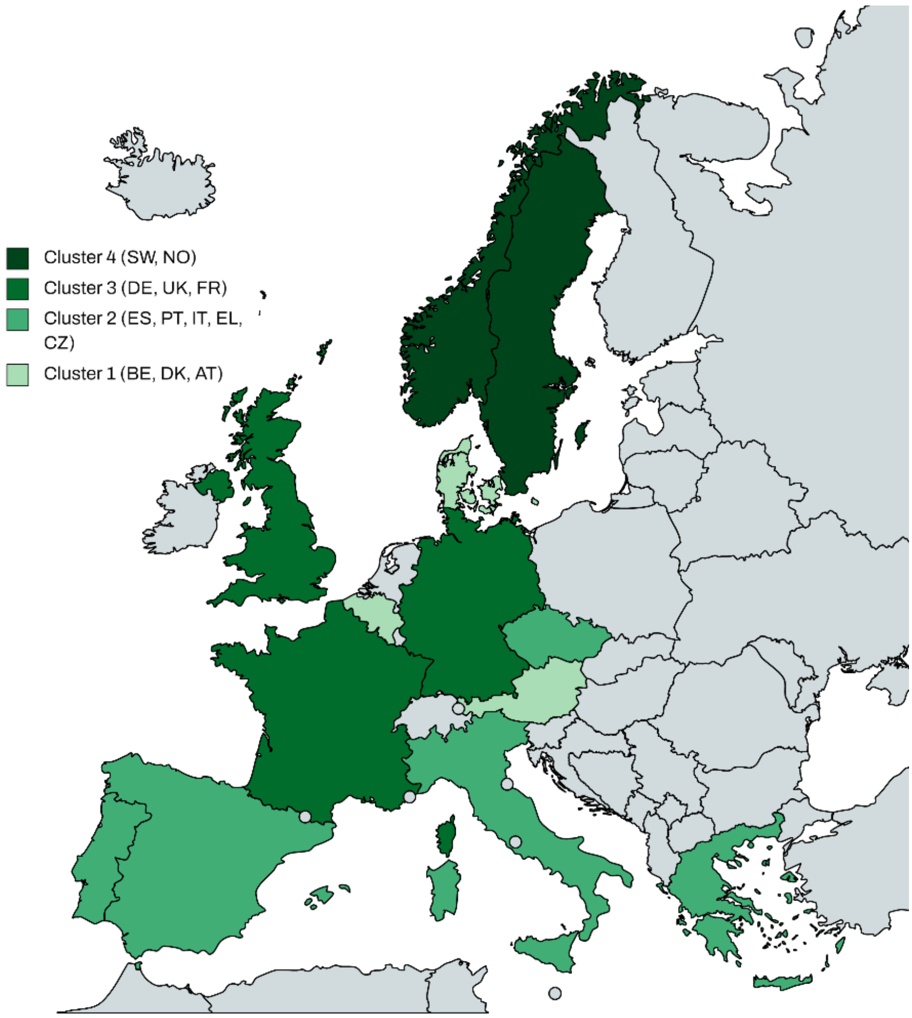

Figure 2: Results of the cluster analysis presenting the four clusters of countries including only those countries for which data to all cluster variables were available.

The share of PEV registrations (sum of BEV and PHEV) of the year 2020 in the EU is used to weight the cluster data in subsequent calculations of the European-wide RE share in charging electricity (see Figure 3). Germany, Norway, the UK, France, and the Netherlands account for most PEV registrations. These top five countries in terms of PEV registrations currently represent about 72% of the total European PEV market with about 2.18 million PEV. In 2020, notable PEV registrations also included Sweden, Belgium, Italy, Spain, Portugal, Denmark, Austria and Finland. This middle group in terms of absolute PEV registrations currently represents about 720 thousand PEV, or about 24% of the European PEV market. The remaining 4% of the EU-wide PEV market is distributed among all remaining EU27 countries and Iceland, with none of these countries having more than about 15 thousand PEV registrations. Consequently, the identified cluster cover the following share of the European PEV market (including EU27 + UK, NO, IS):

- Cluster 1 (including Belgium, Austria, Denmark): 7%
- Cluster 2 (including Spain, Portugal, Italy, Greece, Czech Republic): 9%
- Cluster 3 (including Germany, France, the UK): 48%
- Cluster 4 (including Sweden, Norway): 21%
- Not clustered (all other countries with 9% accounting for the Netherlands): 14%

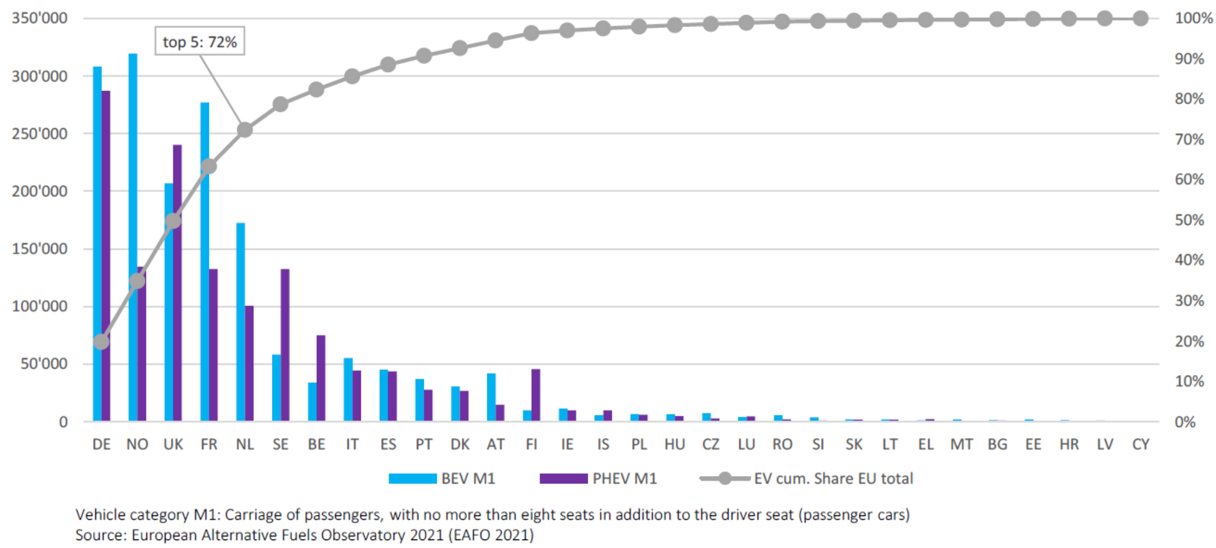

Figure 3: Registered BEV and PHEV per country in 2020: Total number of PEV (left y-axis) as well as cumulated share on the EU27 + UK, NO, IS PEV market (right y-axis).

3 Results

The following section presents the results of our research. First, we outline the results regarding the share of charging location. 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 the combination of the newly collected survey results with existing data and the cluster analysis. Hence, we arrive at the aimed data structure (see Table 1).

3.1 Share of charging locations

Based on the survey data of PEV users, we were able to fill the gap on charging locations for Germany and Spain. Results are presented in Table 3. In Germany (n = 867), 53% answered the question of the charging location (n = 460). We computed a mean of the share of charging location across all participants. Results show that 59% of all charging processes are done at home, 14% of the charging occassions are performed at work as well as 14% at public slow charging stations and 12% at public fast charging stations. It is noteworthy that the percentages represent the charging frequences (not the charging amount).

In Spain (n = 609), 61% of participants answered the question regarding charging location (n = 370). Results show only slight differences from the German data: The majority (58%) of charging processes are completed at home. However, public slow charging stations are used more frequently than in Germany: 21% of the charging processes are done here. The remaining 21% are equal split for working charging and public fast charging stations.

Table 3: Share frequency of charging processes at the different charging locations in Germany and Spain based on survey data including 95% confidence intervals (missing to 100% from rounding).

	Germany (n = 460 responses)	Spain (n = 370 responses)
Home	59 ± 4.5 %	58 ± 5.0 %
Work	14 ± 3.2 %	10 ± 3.1 %
Public slow	14 ± 3.2 %	21 ± 4.2 %
Public fast	12 ± 3.0 %	10 ± 3.1 %

Due to the limited data available from the studies analyzed as well as the authors' own surveys and the presented cluster analysis, the data 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 addressed in Section 2.4. The evolving country-specific data set is shown in Table 8 in the Supplementary Material. Based on this data set, the cluster-specific shares for the different PEV charging locations were calculated by weighting the country-specific values with the country-specific EU PEV share within each cluster. The result of this calculation is shown in Table 4. The survey data from our Spanish sample is also considered representative for all other countries in Cluster 2 (i.e., Portugal, Italy, Greece, and Czech Republic).

The shares of charging location in Cluster 3 are derived from the combination of our survey results for Germany and the available study data for the UK (Dodson/Slater 2019) and France (Avere France/Ipsos 2020).

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	7%	58%	27%	10%	5%
2	9%	58%	10%	21%	10%
3	48%	63%	14%	15%	8%
4	21%	76%	20%	3%	1%
Not clustered	14%	58%	27%	10%	5%
Total (EU27 + UK, NO, IS)	**100%**	**64%**	**18%**	**12%**	**6%**

Similarly, for Cluster 4, the available data for Norway (Figenbaum/Nordbakke 2019) are also adopted for Sweden. Here, the results indicate that home charging is the dominant charging location of PEV representing three quarters of all charging processes. In contrast to Spain, public charging plays only a minor role in Cluster 4.

For Cluster 1 without country-specific data and no country covered by the cluster analysis, the data from NewMotion 2020 are applied. For the Netherlands, which is not assigned to a country cluster, country-specific study data are available in Gardien et al. (2020) and Duurkoop et al. (2021) and Helmus et al. (2020), but these data are not used here. The reason for this is that the Netherlands is already very strongly represented in the results of NewMotion 2020 (approx. 50% of the responses). The dominance of the Netherlands in these data is acceptable, as just under half of the 21% PEV shares as sum of Cluster 1 and all non-clustered countries are accounted for by the Netherlands.

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: In Germany, 697 participants answered whether they have a renewable eletricity tariff for charging their PEV (or not). Other participants skipped this item or did not know their electricity tariff. Of these 697 participants 84% reported to have a 100% renewable electricity tariff to charge their PEV. In Spain, 461 participants completed the item and 56% reported having a 100% renewable electricity tariff to charge their PEV.

For work charging, we analysed the survey data completed by fleet managers. Due to the small response rate, only the data for Germany can be analysed. In Germany, 94 fleet managers (being in charge of 6252 PEV) knew the electricity tariff they are providing for charging PEV at work. Of these, 81% reported to have a 100% RE tariff. Resembling the procedure regarding the survey results of PEV users and the share of RE in public charging (determined in section 2.4), this result will be used of other countries in this cluster (i.e., France and the UK).

For all other clusters, the share of renewable electricity in the country-specific balanced electricity mix is used as the share of RE in the charging electricity (see section 2.4). An exception is the share of RE contracts for home charging in Cluster 1, for which the value for Spain from the survey is used. Combining this value with the country-specific share of RE in the balanced electricity mix for the other charging locations is valid, since the share of charging electricity in relation to the total electricity consumption is still very low. The country-specific data set resulting from this calculation is presented in Table 9 in the Supplementary Material. Based on this data set, the cluster-specific shares of charging locations listed in Table 5 are calculated for the charging locations 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 in EU27 + UK, NO, IS	Home	Work	Public slow	Public fast
1	7%	48%	48%	48%	48%
2	9%	56%	27%	27%	27%
3	48%	82%	81%	49%*	52%*
4	21%	38%	38%	38%	38%
Not clustered	14%	47%	47%	47%	47%
Total (EU27 + UK, NO, IS)	**100%**	**63%**	**60%**	**44%***	**46%***

* An earlier version of the paper reported different numbers; the modification was necessary due to a revision of the database for public charging in Cluster 3.

The values shown in Table 4 and Table 5 allow the calculation of a **total contracted RE share of at least 58%* for the total PEV charging in 2020 in the EU27, the UK, Norway and Iceland**. For this purpose, all shares of charging locations in Table 4 are multiplied with the related RE share and the PEV share of the corresponding cluster in Table 5. The RE share of 58%* for the total PEV charging results from the sum of those muliplications. For comparison, calculating and weighting the national electricity grid mixes in the same manner leads to a RE share of 46% – 12%* lower than the more elaborated RE share developed in this study with the help of existing data and survey results.

4 Discussion

The aim of the present paper was to develop an elaborated 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 also determined the shares of charging location as a first step. Following our step-wise methodology to close as many data gaps with available and the 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.

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. Our analysis indicates that the share of RE in charging electricity lies above the grid mix with at least 58%* of European PEV users charging their PEV with RE – across all charging locations. From a psychological point of view, this is not overly surprising given the fact that PEV users are more likely to have high pro-environmental beliefs (compared to ICEV users) and, in turn, high pro-environmental beliefs are associated with a higher likelihood to have a RE tariff. Moreover, following cognitive dissonance theory, people tend to behave in a consistent manner being led by their beliefs and attitudes, including their pro-environmental beliefs (but see literature on rebound effects, spillover and compensatory green beliefs, e.g. Dütschke et al. 2021; Capstick et al. 2019).

---

* An earlier version of the paper reported different numbers (e.g., total contracted RE share of 62% in Europe); the modification was necessary due to a revision of the database for public charging.

4.1 Methodological discussion

Regarding the representativness of the study, we would like to highlight that survey samples are not representative. For instance, this becomes obvious, when looking at the offical PHEV share in Germany and Spain which is higher than in the present samples of PEV users.The lack of representative samples is caused by the fact that information about the entire population of PEV users in Europe and the different European countries are missing. Consequently, we used a snowballing technique to receive as many European PEV users as possible. In addition, we only analysed survey data if more than 150 people from one European country have completed the survey. This procedure was applied to avoid results that are not reliable. Thus, we believe our survey results are reliable and valid, also given the fact that more than 500 PEV users in Germany and Spain and 168 German fleet managers (accounting for more than 8500 PEV) completed the questionnaire. Generally, the success of recruiting participants varied largely across countries. It depended mostly on the willingness of very large, often national-wide newsletters and related associatiosn to share our survey link. We would like to mention that especially surveying CPO appeared more challenging than expected. Consequently, the most suitable way for the present study was to use existing data and an adequate methodology to process registered data of German CPO to close the data gap.

On a different note, we would like to highlight that the data were collected during the COVID-19 pandemic in fall 2021, thus, the answers might be affected by phenomenons like an increased number of working from home (which could have led to an increased share of home charging compared to work charging). Nonetheless, we do not assume a large effect of the pandemic conditions and our results on the share of charging location do not differ largely from pre-COVID-19 results (but extend them further).

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. It is noteworthy that the Netherlands present a special case: Although it has a high share of the EU PEV market, it was categorized in the last cluster. This is due to the fact that data on the cluster variables were not available for the Netherlands, leading to an exclusion of the Netherlands from the cluster analysis (as all other European countries without available data on the cluster variables). Additionally, one might wonder whether the results from Germany (with very little to no nuclear power) can be transfered 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. In general, we made sure that the applied procedures were strict and careful to arrive at conservative values for a lower bound of the share of RE and of charging location in the European PEV charging.

4.2 Further discussion of RE and related aspects

The present studies provides a lower bound for the share of RE in PEV charging in Europe. We only analyse the contracted RE share as well as the RE share in the country-specific grid 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 electricity cannot be physically labelled and that most European distribution grids are highly connected. Nonetheless, we would like to discuss the RE share and its analysis in the present study more deeply.

Firstly, since we were not able to fill all identified data gaps with existing or new survey data, we applied a common approach and used the average electricity grid mix as baseline for RE shares in PEV charging. Some studies argue that the usage of new PEV results in an increased electricity demand and that the electricity consumed by PEV would only be covered by the electricity from additional capacities of fossil power plants, the marginal electricity mix. However, PEV are not the only "new" electricity demand but new demand also stems from heat pumps, information and communication technology, or an increasing demand of electricity in the industry. At the same time, the energy demand for certain applications, such as lights and household applications decreases. In this dynamic system, it is arbitrary to assign the marginal electricity mix to PEV while assuming that other applications are powered by the average mix. In contrast, future research should focus on how to increase the share of RE in PEV charging to further decrease GHG emissions and comply with the Paris agreement. One example from Germany is the fact that governmental subsides for charging stations are bound to the premise that the charging stations need to have a 100% RE tariff. Since the usage of PEV reduces GHG emissions and varies depending on the charged electricity, this measure in Germany leads to further savings in GHG emissions.

To illustrate the savings in GHG emissions when assuming the national grid mix or a high RE share, we refer to the study by Wietschel et al. (2019). When purchasing a BEV in Germany, one can save significant GHG emissions over the BEV's average time of use of 13 years. These GHG emissions savings range from 28% – when compared to a high-class diesel car – to 42% savings, when compared to a small gasoline car. These savings are based on charging with the national grid mix in Germany; thus the GHG emissions of BEV can decrease further when assuming a 100% supply of RE; with this assumption, GHG emissions of a BEV are 65-75% lower than those of a ICEV. The role of RE is also highlighted in a report of the European commission which compared the carbon footprint of a BEV to the footprint of an ICEV (EU, 2020): The report shows that in countries with a high share of RE in the grid mix (such as Austria), the carbon footprint is significantly better compared to countries with a high share of coal-fired power plant (such as Poland). Consequently, it makes a relevant difference whether the GHG emission benefits from PEV are calculated assuming the national electricity mix vs. the actual charging electricity. Our results show that people having a PEV are also likely to have a RE tariff for PEV charging.

Secondly, in the present paper, we analyzed the share of renewable electricity purchased through contracts. However, there are different forms of RE tariffs; the relevant two cases are presented below.

Case 1: A RE supply contract: RE is not a protected legal term in Germany and other EU countries. However, providers of RE contracts have their offers certified by various institutions. The certification criteria used vary widely. RE contracts can, for example, be based on Guarantees of Origin (GO). These are certificates without any kind of physical link to an electricity supply. They are based on the implementation of Directive 2009/28/EC of the European Parliament and of the Council. GO can be purchased. The requirements for GO do not include double counting of RE generation and external verification. However, in general, the environmental benefits are often weak. For example, the GO used in Germany are mainly from Norwegian hydropower – the share of GO from new RE plants is low. Thus, there is a rather low climate benefit because no additional RE plants are built. Therefore, the additional costs for electricity purchase incurred by GO are also low (UBA 2019). However, if more and more RE is sold in this form in the future, existing plants will no longer be sufficient and additional renewable plants will have to be built – leading to the intended effect.

There are also offers that make higher demands on environmental additionality. For example, only new RE plants that are not subsidized otherwise or that have a geographical connection to the place of purchase count towards RE production. The resulting additional costs of these offers are usually significantly higher than those of offers based on GO.

Case 2: A physical renewable power purchase agreement (PPA). This type of green power supply contract is characterized by certain additional requirements. In this case, the RE are connected to the power grid. Furthermore, the electricity must generally be supplied from a specific RE plant or a RE plant park. A temporal and geographical correlation between electricity supply and generation is also provided. Additionality arises from the fact that new RE plants are required outside public funding regimies. However, since the electricity purchased under these contracts is usually not sufficient to meet the entire electricity demand of a customer (or since there may be a temporal mismatch between parts of the supply and demand side), the missing amount of electricity must be supplemented by complementary electricity purchases. Complementary power purchases are purchases of electricity from the regular power grid. To conclude, we would like to highlight that the value of a RE production varies depending on the RE contract and that a higher share of RE in PEV charging can significantly lower the GHG emissions of PEV.

5 Summary and further research

This article presents new survey data as well as an evaluation of existing data from published studies on the share of contracted renewable electricity (RE) as well as on the share of charging locations for plug-in electric vehicle (PEV) charging in Europe (EU27, UK, Norway, Iceland). These data are essential to calucate the GHG emissions of PEV because charging presents a large part of the carbon footprint of PEV. Drawing on the outlined data, we were not able to fill all data gaps leading to a step-by-step methodology applying scientific standards to further close existing data gaps. Focusing on countries with high shares in the PEV market as well as developing clusters with relevant cluster variables can help to transfer data from one country to other countries within the same cluster and thus, to fill data gaps. Supporting previous studies, our results indicate that PEV are mostly charged at home, 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. We found that a high percentage of PEV users charge their PEV on the basis of RE contracts across all charging location; this share is above the often assumed European electricity grid mix for the calculation of GHG. With the introduced methodology, we retrieved a total share of 58%* contracted RE charging for Europe across all charging locations (compared to 46% using the same calculations with the electricity grid mix). The country- and cluster-specific data might present a valuable data base for further research and related analyses. Data collection for public charging points (i.e., with charging point operators) appeared more challenging than expected. Moreover, the survey results on home and work charging are mainly driven by answers from German and Spanish PEV users and German fleet managers, with Germany presenting one of the main PEV markets in Europe. For countries without accessible data on RE share, we applied the common approach of integrating the electricity grid mix. Further research should focus on extending the survey data to receive a valid data base for more European countries. In addition, due to the rapid PEV developments, we suggest to update the data on a regular basis and to collect new survey data in all European countries in the near future. It is noteworthy that the survey data on the share of RE in charging electricity present contracted RE without ensuring the actual additionality from the RE production. Future research could analyze the underlying share of RE more deeply by distinguishing contracted RE and RE that were built additionally to meet the electricity demand of PEV. To conclude, this paper presents recent data that start closing the identified gaps regarding shares of charging locations and respective shares of RE for PEV charging in Europe. Our approach presents a scientific methodology to combine existing and newly collected survey data to ultimately arrive at the currently best available data base for an European-wide calculation of the GHG emissions for PEV charging.

* An earlier version of the paper reported a different numbers (i.e., RE share of 62% in Europe); the modification was necessary due to a revision of the database for public charging.

6 Acknowledgements

The authors acknowledge funding from the Volkswagen AG as well as great support in data collection by Marc Keller.

7 References

AIB – Association of Issuing Bodies (2021): European Residual Mixes. Results of the calculation of Residual Mixes for the calendar year 2020. Online: file:///C:/Users/KURO/AppData/Local/Temp/AIB_2020_Residual_Mix_Results.pdf.

Avere France/Ipsos (2020): Consultation auprès de conducteurs de véhicules électriques et hybrids rechargeables. Online: https://www.ipsos.com/sites/default/files/ct/news/documents/2020-12/enquete_ipsos-avere_utilisateurs_ve.pdf.

Baresch, M., Moser, S. (2019): Allocation of e-car charging: Assessing the utilization of charging infrastructures by location. *Transportation Research Part A: Policy and Practice 124*, 388–395, DOI: 10.1016/j.tra.2019.04.009.

BNetzA – Bundesnetzagentur (2023a): Ladesäuleninfrastruktur in Zahlen, Stand: Juli 2023). Online: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/Ladesaeulenkarte/start.html.*

BNetzA – Bundesnetzagentur (2023b). Liste der Ladesäulen (Stand Juli 2023). Online: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/Ladesaeulenkarte/start.html.*

BP (2020): Statistical Review of World Energy [Data file]. Online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Capstick, S., Whitmarsh, L., Nash, N., Haggar, P., Lord, J. (2019): Compensatory and Catalyzing Beliefs: Their Relationship to Pro-environmental Behavior and Behavioral Spillover in Seven Countries. *Front. Psychol. 10:963*. DOI: 10.3389/fpsyg.2019.00963.

Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A. & van Vuuren, D. P. (2018): Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environmental science & technology 52*, 4989–4995, DOI: 10.1021/acs.est.8b00261.

Dodson, T., Slater, S. (2019). Electric Vehicle Charging Behaviour. Final report of a study for National Grid ESO. Element Energy Limited, Cambridge. Online: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2019/04/20190329-NG-EV-CHARGING-BEHAVIOUR-STUDY-FINAL-REPORT-V1-EXTERNAL.pdf.

Dütschke, E., Galvin, R., Brunzema, I. (2021): Rebound and Spillovers: Prosumers in Transition. *Front. Psychol. 12:636109*. DOI: 10.3389/fpsyg.2021.636109.

Duurkoop, T., Gardien, L., Hiep, E., van Biezen, M., Markotic, P., van der Werff, E. (2021): Laden van EV's in Nederland. Ervaringen en meningen van EV-rijders. Nationaal Laadonderzoek 2021. Online: https://www.evrijders.nl/wp-content/uploads/2021/07/Nationaal-Laadonderzoek.pdf.

EAFO – European Alternative Fuels Observatory (2021): AF Fleet M1 Electricity (2021). Online: https://eafo.eu/vehicles-and-fleet/m1.

EHI Retail Institute e. V. (2021): Elektromobilität im Handel 2021. Ladestationen auf Kundenparkplätzen. EHI-Whitepaper. Online: https://www.ehi-elektromobilitaet.de/whitepaper.

Enedis (2021): Utilisation et recharge: Enquête comportementale auprès des possesseurs de véhicules électriques. Online: https://www.enedis.fr/media/2509/download.

EU (2020): Determining the environmental impacts of conventional and alternatively fueled vehicles through LCA. Final Report for the European Commission, DG Climate Action. Ricardo, ifeu, E4Tech.

Eurostat (2018). Distribution of population by degree of urbanisation, dwelling type and income group. Last update: 19-11-2021 [Data file]. Online: http://appsso.eurostat.ec.europa.eu/nui/show.do?query=BOOKMARK_DS-057122_QID_-2221D032_UID_-3F171EB0&layout=TIME,C,X,0;GEO,L,Y,0;INCGRP,L,Z,0;BUILDING,L,Z,1;DEG_URB,L,Z,2;INDICATORS,C,Z,3;&zSelection=DS-057122BUILDING,TOTAL;DS-057122INDICATORS,OBS_FLAG;DS-057122INCGRP,TOTAL;DS-057122DEG_URB,DEG1;&rankName1=BUILDING_1_2_-1_2&rankName2=INDICATORS_1_2_-1_2&rankName3=INCGRP_1_2_-1_2&rankName4=DEG-URB_1_2_-1_2&rankName5=TIME_1_0_0_0&rankName6=GEO_1_2_0_1&sortC=ASC_-1_FIRST&rStp=&cStp=&rDCh=&cDCh=&rDM=true&cDM=true&footnes=false&empty=false&wai=false&time_mode=ROLLING&time_most_recent=true&lang=EN&cfo=%23%23%23%2C%23%23%23.%23%23%23.

Eurostat (2019): Electricity production capacities for renewables and wastes – NRG_INF_EPCRW. Last update: 11-11-2021 [Data file]. Online: https://ec.europa.eu/eurostat/databrowser/product/view/NRG_INF_EPCRW?lang=en

Eurostat (2020): Distribution of population by tenure status, type of household and income group – EU-SILC survey. Last update: 19-11-2021 [Data file]. Online: https://ec.europa.eu/eurostat/databrowser/view/ILC_LVHO02__custom_137548/default/table.

Figenbaum, E., Kolbenstvedt, M. (2016): Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle users. Results from a survey of vehicle owners. TØI Report 1492/2016. Online: https://www.toi.no/getfile.php?mmfileid=43161.

Figenbaum, E., Nordbakke, S. (2019): Battery electric vehicle user experiences in Norway's maturing market. TØI report 1719/2019. Online: https://www.toi.no/getfile.php?mmfileid=50956.

Frenzel, I., Jarass, J., Trommer, S., Lenz, B. (2015): Erstnutzer von Elektrofahrzeugen in Deutschland. Nutzerprofile, Anschaffung, Fahrzeugnutzung. Berlin, Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR). Online: https://www.dlr.de/vf/Portaldata/12/Resources/dokumente/projekte/pakt2/Ergebnisbericht_E-Nutzer_2015.pdf

Gardien, L., Hiep, E., van Biezen, M., van Bokhoven, P., van der Werff, E., Krol, R. (2021): Laden van EV's in Nederland. Ervaringen & meningen van gebruikers. Nationaal Laadonderzoek 2020. Online: https://www.elaad.nl/uploads/files/Rapport_Nationaal_Laadonderzoek_2020.pdf.

Helmus, J. R., Vogel, I. S. P., van den Hoed, R. (2020): Exploring social charging behavior between EV users in sharing charging points. Conference Paper, 33rd Electric Vehicle Symposium (EVS33) Portland, Oregon, June 14 – 17, 2020. Online: https://www.researchgate.net/publication/341203941_Exploring_social_charging_behavior_between_EV_users_in_sharing_charging_points_Science_lab_institute_for_informatics.

Höfling, H., Römer, D. (2019): KfW-Energiewendebarometer 2019, KfW Research,. Online: https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-KfW-Energiewendebarometer/KfW-Energiewendebarometer-2019.pdf.

IEA – International Energy Agency (2021). World Energy Outlook 2021.

Kim, H. C. et al. (2016): Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. *Environmental science & technology 50*, 7715–7722. DOI: 10.1021/acs.est.6b00830.

Marmiroli, B., Maarten Messagie, M., Dotelli, G., van Mierlo, J. (2018): Electricity Generation in LCA of Electric Vehicles: A Review. *Appl. Sci., 8*, 1384. DOI:10.3390/app8081384.

Märtz, A., Plötz, P., & Jochem, P. (2021): Global perspective on CO2 emissions of electric vehicles. *Environmental Research Letters, 16(5)*, 054043.

McKinsey & Company (2018): Charging Ahead: Electricvehicle Infrastructure Demand. McKinsey Center for Future Mobility. Online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/charging-ahead-electric-vehicle-infrastructure-demand.

Leitstelle – National Centre for Charging Infrastructure (2023): Reported number and charging volume of publicly funded charging points in Germany in 2020 (as of December 2023). Requested from and provided by Leitstelle.*

NewMotion (2020): EV Driver Survey Report 2020. Online: https://newmotion.com/nl-nl/kenniscentrum/rapporten-en-case-studies/ev-driver-survey-report-2020-nl.

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M. & van Mierlo, J. (2014): Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *Int J Life Cycle Assess 19*, 1866–1890; DOI: 10.1007/s11367-014-0788-0.

Plötz, P., Schneider, U., Globisch, J., & Dütschke, E. (2014): Who will buy electric vehicles? Identifying early adopters in Germany. *Transportation Research Part A: Policy and Practice, 67*, 96-109. DOI: 10.1016/j.tra.2014.06.006.

Plötz, P., Moll, C., Bieker, G., Mock, P., Li, Y. (2020): Real-World Usage of Plug-in Hybrid Electric Vehicles. Fuel Consumption, Electric Driving, and CO2 Emissions. White Paper, Fraunhofer ISI.

Römer, D., Steinbrecher, J. (2020): Private Ladeinfrastruktur ist eine wichtige Säule für den Ausbau der Elektromobilität, KfW Research, Fokus Volkswirtschaft Nr. 304. Online: https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-Fokus-Volkswirtschaft/Fokus-2020/Fokus-Nr.-304-November-2020-Ladeinfrastruktur.pdf.

Römer, D., Steinbrecher, J. (2021): Die Elektromobilität nimmt Fahrt auf – doch wer setzt sich eigentlich ans Steuer?, KfW Research, Fokus Volkswirtschaft Nr. 331. Online: https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-Fokus-Volkswirtschaft/Fokus-2021/Fokus-Nr.-331-Mai-2021-EMobilitaet.pdf.

Scherrer, A., Burghard, U., Wietschel, M., & Dütschke, E. (2019): Early Adopter von E-Fahrzeugen: Ladeleistungen, Eigenerzeugung und Einstellungen zum Lademanagement. *Energiewirtschaftliche Tagesfragen, 69(11)*, 23-26.

Special Eurobarometer (2020): Special Eurobarometer 501: Attitudes of European citizens towards the Environment (v1.00). (2020). [Data set]. Directorate-General for Communication. Online: http://data.europa.eu/88u/dataset/S2257_92_4_501_ENG.

T&E – Transport & Environment (2020): Recharge EU: how many charge points will Europe and its Member States need in the 2020s. Online: https://www.transportenvironment.org/wp-content/uploads/2021/07/01%202020%20Draft%20TE%20Infrastructure%20Report%20Final.pdf.

Tamayao, M.-A. M., Michalek, J. J., Hendrickson, C., Azevedo, I. M. L. (2015): Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO_2 Emissions across the United States. *Environmental science & technology 49*, 8844–8855. DOI: 10.1021/acs.est.5b00815.

UBA (2019): Marktanalyse Ökostrom II. Marktanalyse Ökostrom und HKN, Weiterentwicklung des Herkunftsnachweissystems und der Stromkennzeichnung. Abschlussbericht. Dessau-Roßlau

Wietschel, M., Kühnbach, M., Rüdiger, D. (2019): Die aktuelle Treibhausgasemissionsbilanz von Elektrofahrzeugen in Deutschland. Working Paper Sustainability and Innovation, No. S 02/2019. Fraunhofer ISI, Karlsruhe.

Wolff, S., Madlener, R. (2019): Charged up? Preferences for Electric Vehicle Charging and Implications for Charging Infrastructure Planning. Institute for Future Energy Consumer Needs and Behavior (FCN), Working Paper No. 3/2019. Online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3491629.

Xu, L., Yilmaz, H. Ü., Wang, Z., Poganietz, W.-R., Jochem, P. (2020): Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies. *Transportation Research Part D: Transport and Environment 87*, 102534. DOI: 10.1016/j.trd.2020.102534.

Yuksel, T., Tamayao, M.-A. M., Hendrickson, C., Azevedo, I. M. L., Michalek, J. J. (2016): Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States. *Environ. Res. Lett*. *11*, 44007. DOI: 10.1088/1748-9326/11/4/044007.

References marked with an * were modified compared to an earlier version of the paper; the modifications were necessary due to a revision of the database for public charging.

8 Supplementary Material

Table 6: Applied criteria with related characteristics for the quality assessment of available studies.

Criteria	higher	medium	lower
Type of source	**official statistics** (authorities, associations, etc.)	**journal article** (peer-reviewed) or **independent study/research reports** (research institutes, agencies, etc.).	**other** (conference and working paper, websites presentations, interest studies, etc.)
Methodology	**empirical** (survey)	**modelling** or **expert survey**	
Representativity	**representative** (sample size sufficient and sample selection unbiased, or essential data only from official statistics).	**partially representative** (sample size somewhat too small and/or sample selection partially biased or essential data from official statistics and independent studies).	**unclear/not representative** (sample size significantly too small and/or sample selection biased or essential data based on assumptions)
Values collected	(shares of) **charging quantities** at locations and/or of renewable electricity	(shares of) **charging frequency** at locations and/or of renewable electricity	(shares of) **charging preferences** at locations and/or of renewable electricity
Recency (survey date)	< 3 years, 2018 and younger	4 - 6 years, 2015 - 2018	> 6 years, 2014 and older
Type of PEV considered	BEV and PHEV separately	PEV only (as sum of BEV and PHEV) or BEV only	PHEV only

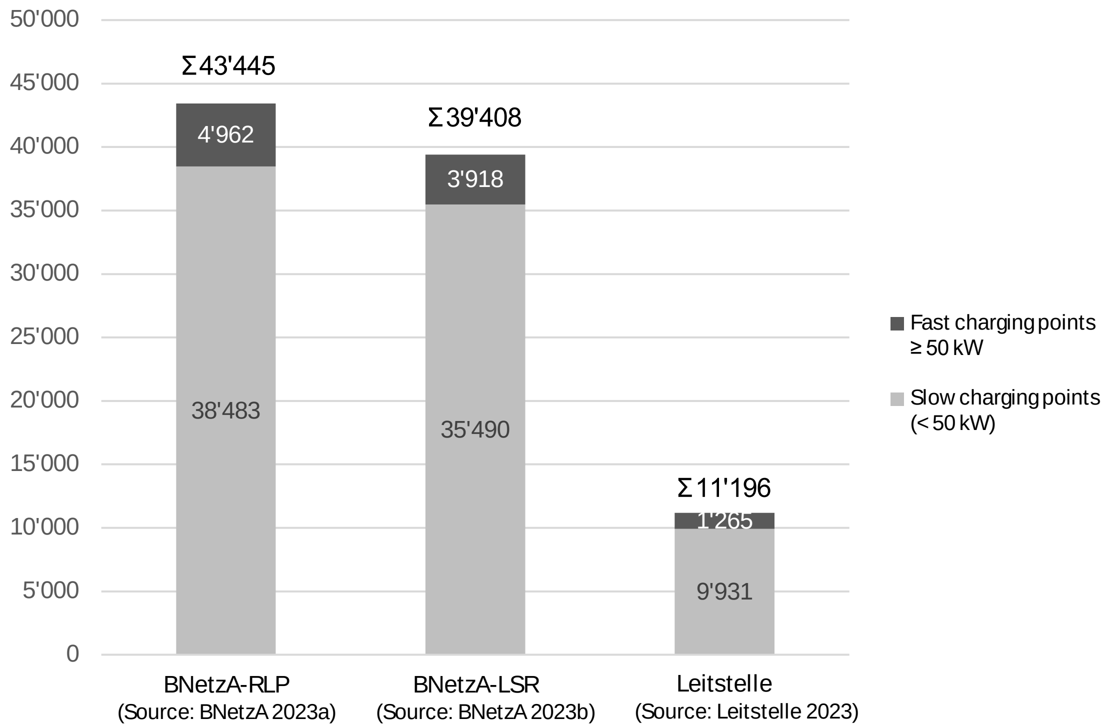

Figure 4: Amount of registered public charching points for the year 2020 in Germany in different registers.*

BNetzA-RLP: Public charging points registered with the Bundesnetzagentur in Germany with commissioning by 31.12.2020 (available aggregated per NUTS 1 region).

BNetzA-LSR: Public charging points listed in the BNetzA's charging point register with the consent of the CPOs, with commissioning by 31.12.2020 (available per CPO and NUTS 1 region). The difference of approx. 4,000 charging points between the LSR and BNetzA 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% renewable electricity requirement in operation in 2020 , which have reported charging volumes to the National Centre for Charging Infrastructure for 2020 (charging point number and charging volumes available aggregated per NUTS 1 region).

---

* An earlier version of the paper reported different numbers; the modification was necessary due to a revision of the database.

Table 7: Reported numbers and charging volumes for 2020 of subsidized public charging points in Germany and average charging volumes calculated from these for NUTS1 regions.*

Region (NUTS 1)	Public slow Number of charging points (CP)	Public slow Reported charging volumes (kWh)	Public slow Average volumes (kWh per CP and day)	Public fast Number of charging points (CP)	Public fast Reported charging volumes (kWh)	Public fast Average volumes (kWh per CP and day)
Baden-Württemberg	2'209	2'763'967	4.5	267	1'746'621	25.4
Bavaria	1'418	2'300'050	5.3	163	982'899	20.8
Berlin**	21	61'021	8.0	8	253'057	(97.6)*
Brandenburg	232	216'746	3.2	21	139'992	27.3
Bremen	77	355'877	13.5	17	201'895	37.4
Hamburg	446	1'696'505	10.5	49	394'177	22.2
Hessen	364	559'110	5.2	70	318'669	22.1
Mecklenburg-Vorpommern	69	110'751	5.0	3	6'368	15.3
Lower Saxony	1'184	1'387'697	4.0	123	413'101	13.4
North Rhine-Westphalia	1'646	2'406'954	5.0	196	1'617'365	29.7
Rhineland-Palatinate	677	853'416	4.4	164	431'491	12.1
Saarland	145	190'694	5.1	17	67'455	13.2
Saxony	466	400'632	2.8	68	334'217	18.9
Saxony-Anhalt	184	153'307	3.1	17	49'265	11.5
Schleswig-Holstein	538	845'396	5.4	26	215'446	29.3
Thuringia	255	268'010	3.1	56	191'977	11.1
Germany (NUTS 0)	**9'931**	**14'570'133**	**4.9**	**1'265**	**7'363'994**	**21.7**

Source: Leitstelle 2023. * An earlier version of the paper reported different numbers; the modification was necessary due to a revision of the database.

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

Table 8: Data used for the share of charging volumes by location.

Country	Cluster	Number of PEV	Home	Work	Public slow	Public fast
BE	1	108'691	*58%*	*27%*	*10%*	*5%*
DK	1	57'265	*58%*	*27%*	*10%*	*5%*
AT	1	56'191	*58%*	*27%*	*10%*	*5%*
EL	2	3'135	*58%*	*10%*	*21%*	*10%*
IT	2	99'519	*58%*	*10%*	*21%*	*10%*
PT	2	64'592	*58%*	*10%*	*21%*	*10%*
ES	2	88'538	**58%**	**10%**	**21%**	**10%**
CZ	2	9'835	*58%*	*10%*	*21%*	*10%*
DE	3	595'176	**59%**	**14%**	**14%**	**12%**
FR	3	409'310	**55%**	**12%**	**29%**	**4%**
UK	3	447'359	**75%**	**15%**	**5%**	**6%**
NO	4	453'960	**76%**	**20%**	**3%**	**1%**
SE	4	190'680	*76%*	*20%*	*3%*	*1%*
BG	-	2'357	*58%*	*27%*	*10%*	*5%*
EE	-	2'025	*58%*	*27%*	*10%*	*5%*
FI	-	55'317	*58%*	*27%*	*10%*	*5%*
IE	-	20'937	*58%*	*27%*	*10%*	*5%*
IS	-	15'197	*58%*	*27%*	*10%*	*5%*
HR	-	1'906	*58%*	*27%*	*10%*	*5%*
LV	-	1'042	*58%*	*27%*	*10%*	*5%*
LT	-	3'504	*58%*	*27%*	*10%*	*5%*
LU	-	8'548	*58%*	*27%*	*10%*	*5%*
MT	-	2'571	*58%*	*27%*	*10%*	*5%*
NL	-	272'895	*58%*	*27%*	*10%*	*5%*
PL	-	12'475	*58%*	*27%*	*10%*	*5%*
RO	-	7'410	*58%*	*27%*	*10%*	*5%*
SK	-	3'506	*58%*	*27%*	*10%*	*5%*
SI	-	4'457	*58%*	*27%*	*10%*	*5%*
HU	-	10'753	*58%*	*27%*	*10%*	*5%*
CY	-	571	*58%*	*27%*	*10%*	*5%*

Data used from available studies (Avere France/Ipsos 2020 for FR, Dodson/Slater 2019 for UK and Figenbaum/Nordbakke 2019 for NO) and own surveys (for DE and ES) are written in bold. Available country-specific data within a cluster are carried forward as substitute data (in italics) to fill data gaps for share of charging locations. Since no country-specific data were available in literature for cluster 1 and the countries in cluster 1 were not sufficiently covered by our own survey, the data from NewMotion (2020) were applied. The data of NewMotion (2020) is also used for all non-clustered countries. For the Netherlands, which is not assigned to a country cluster, country-specific study data are available in Gardien et al. (2020), Duurkoop et al. (2021) and Helmus et al. (2020), but these data were not used. The reason for this is that the Netherlands is already very strongly represented in the results of NewMotion (2020; approx. 50% of the responses). The dominance of the Netherlands in this data is acceptable, because the PEV share of the Netherlands presents almost half of the 21% PEV shares of cluster 1 and all non-clustered countries.

Table 9: Data used for the renewable electricity shares in the total charging volumes (by charging location)*

Country	Cluster	Number of PEV	Home	Work	Public slow	Public fast
BE	1	108'691	*36%*	*36%*	*36%*	*36%*
DK	1	57'265	*36%*	*36%*	*36%*	*36%*
AT	1	56'191	*84%*	*84%*	*84%*	*84%*
EL	2	3'135	*56%*	*30%*	*30%*	*30%*
IT	2	99'519	*56%*	*16%*	*16%*	*16%*
PT	2	64'592	*56%*	*25%*	*25%*	*25%*
ES	2	88'538	**56%**	*41%*	*41%*	*41%*
CZ	2	9'835	*56%*	*10%*	*10%*	*10%*
DE	3	595'176	**82%**	**81%**	**49%**	**52%**
FR	3	409'310	*82%*	*81%*	*49%*	*52%*
UK	3	447'359	*82%*	*81%*	*49%*	*52%*
NO	4	453'960	*27%*	*27%*	*27%*	*27%*
SE	4	190'680	*66%*	*66%*	*66%*	*66%*
BG	-	2'357	*19%*	*19%*	*19%*	*19%*
EE	-	2'025	*16%*	*16%*	*16%*	*16%*
FI	-	55'317	*36%*	*36%*	*36%*	*36%*
IE	-	20'937	*71%*	*71%*	*71%*	*71%*
IS	-	15'197	*28%*	*28%*	*28%*	*28%*
HR	-	1'906	*20%*	*20%*	*20%*	*20%*
LV	-	1'042	*21%*	*21%*	*21%*	*21%*
LT	-	3'504	*75%*	*75%*	*75%*	*75%*
LU	-	8'548	*96%*	*96%*	*96%*	*96%*
MT	-	2'571	*24%*	*24%*	*24%*	*24%*
NL	-	272'895	*51%*	*51%*	*51%*	*51%*
PL	-	12'475	*13%*	*13%*	*13%*	*13%*
RO	-	7'410	*46%*	*46%*	*46%*	*46%*
SK	-	3'506	*23%*	*23%*	*23%*	*23%*
SI	-	4'457	*13%*	*13%*	*13%*	*13%*
HU	-	10'753	*21%*	*21%*	*21%*	*21%*
CY	-	571	*13%*	*13%*	*13%*	*13%*

* An earlier version of the paper reported different numbers; the modification was necessary due to a revision of the database for public charging in Cluster 3.

Data from own analysis and surveys are written in bold (based on BNetzA 2023a, BNetzA 2023b, Leitstelle 2023). The country-specific balance-sheet RE shares (AIB 2021) are used as substitute data (in italics) for the RE shares in charging volumes. The combination of the survey value for home charging and the balance RE share for the other charging locations in Cluster 2 can be justified because PEV charging volumes have accounted for a only very small share of the total national electricity demand so far.

Table 10: Associations and companies contacted for recruiting (upper part for PEV user survey, lower part for fleet manager survey).

	PEV users		
Country	Newsletters, Online Forums	Social Media (LinkedIn, Xing, Twitter, Facebook)	Magazines
DE	7	9	---
ES	8	7	4
FR	4	4	7
IT	1	8	8
UK	---	8	8
SE	1	3	---
NO	1	3	---
NL	4	---	---
Total	**26**	**42**	**27**
	Fleet managers		
	PEV and automobility associations	Selected companies (contracted through personal contact)	Selected companies (contacted through the contact sheet on their website)
Europe	**18**	**150**	**52**

Following Table 10, we shared the survey link with 315 associations and companies that had the potential to further spread the information with interested participants.

We applied the following selection criteria for inclusion or exclusion of PEV users and fleet managers, respectively, in both surveys. We excluded participants who reported to not use a PEV or to have no PEV in their fleet. Also participant who did not fully complete the questionnaire were excluded from data analysis. It is noteworthy that participants were able to skip almost all questions (except filter questions) which still counted as an answer. Moreover, we excluded participants if they did not report a country or the country was not part of our geographical scope (EU27 and UK, NO, IS).

Authors' affiliations:

Dr. Sabine Preuß, PD Dr. Patrick Plötz, Prof. Dr. Martin Wietschel

Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI)
Competence Center Energy Technologies and Energy Systems

Dr. Robert Kunze, Jakob Zwirnmann, Jonas Meier

ESA² GmbH, Bernhardstr. 92, 01187 Dresden, Germany

Contact:

Dr. Sabine Preuß

Fraunhofer Institute for Systems
and Innovation Research (Fraunhofer ISI)
Breslauer Strasse 48
76139 Karlsruhe
Germany
Phone: +49 721 6809-535
E-Mail: sabine.preuss@isi.fraunhofer.de
www.isi.fraunhofer.de

Karlsruhe 2021, updated version from 2024.