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ORIGINAL ARTICLE

European governments' electromobility plans: an assessment with a focus on infrastructure targets and vehicle estimates until 2030

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Abstract Electromobility offers great potentials to the decarbonisation of the transport sector. The purpose of this study is to analyse the development of electromobility in the European Union (EU) and in the United Kingdom (UK) by 2030. The study is based on the objectives provided by the EU Member States and UK in their national implementation reports, as foreseen by the Directive 2014/94/EU on the deployment of alternative fuels infrastructure. As the initial data coverage was not full, in order to produce a complete data set on registered electric vehicles and public recharging points, we estimated missing values with different statistical techniques and critical analysis of the initial data. A set of proposed indicators, namely the share of electric vehicles, the density of publicly accessible recharging points, the electric vehicles and recharging points annual growth rates and the sufficiency index, were averaged at EU27+UK level to depict the envisaged evolution of electromobility in the present decade. The results show that the objectives of the countries' governments are overall less ambitious than the goals defined in the EU Green Deal for 2025 and in the Sustainable and Smart Mobility Strategy for 2030. Most of the indicators vary significantly in the 2016–2030 period, often revealing an increased divergence between the development of electric vehicles and public recharging points. Two policy implications are derived: (i) the use of a combined set of indicators to assess the governments' electromobility plans could be pursued, while the ratio of ten electric vehicles per recharging point may no longer be a useful benchmark; and (ii) measures supporting the uptake of recharging infrastructure are still needed to mitigate the divergence with electric vehicles and to meet the ambitious objectives of the EU Green Deal and Sustainable and Smart Mobility Strategy.

Keywords Alternative fuels · Recharging infrastructure · Electric vehicle · Energy policy · Electromobility

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Abbreviations

AF	alternative fuel
AFID	Directive 2014/94/EU
AGR	annual growth rate
AT	Austria
BE	Belgium
BEV	battery electric vehicle

BG	Bulgaria
CNG	compressed natural gas
CY	Cyprus
CZ	Czechia
DE	Germany
DK	Denmark
EC	European Commission
EE	Estonia
EL	Greece
ES	Spain
EU	European Union
EV	electric vehicles
FCEV	fuel cell electric vehicle
FI	Finland
FR	France
GHG	greenhouse gas
GD	Green Deal
HEV	hybrid electric vehicles
HR	Croatia
HU	Hungary
IE	Ireland
IQR	interquartile range
Is	sufficiency index
IT	Italy
LEV	low-emission vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LT	Lithuania
LU	Luxembourg
LV	Latvia
MS	Member State
MT	Malta
NIR	national implementation report
NL	Netherlands
NPF	national policy framework
PHEV	plug-in hybrid electric vehicle
PL	Poland
PT	Portugal
PWA	population weighted average
RO	Romania
RP	recharging point
RPdens	density of publicly accessible recharging points
RWA	road length weighted average
SE	Sweden
ShEV	share of electric vehicles
SI	Slovenia
SK	Slovakia
SSMS	Sustainable and Smart Mobility Strategy
SWA	total land surface of each country weighted average
TEN-T	Trans-European Network for Transport
TF	total vehicle fleet
TWA	TEN-T road length weighted average
UK	United Kingdom

Introduction

The transport sector is still vastly reliant on fossil fuels (EC, 2021a). In 2019, road transport accounted for 72% of all domestic and international transport greenhouse gas (GHG) emissions (EEA, 2022).

The EU aims to be climate-neutral by 2050, an objective that is at the heart of the European Green Deal (GD) (EC, 2019a). In line with EU's commitment to global climate action under the Paris Agreement (United Nations, 2016), the Green Deal was adopted in December 2019. In particular, in order to accelerate the shift to sustainable and smart mobility, lowering climate emissions, air pollution and noise, it targets 13 million zero- and low-emission vehicles (ZLEVs) on EU roads and about 1 million public recharging and refuelling points by 2025.

In September 2020, the European Commission (EC) issued the 2030 Climate Target Plan (EC, 2020a) to raise the EU's ambition on reducing GHG emissions to at least 55% below 1990 levels by 2030, as an intermediate target to achieve climate neutrality by 2050.

To address specific challenges of the transport sector, in December 2020, the EC published the Sustainable and Smart Mobility Strategy (SSMS), hereinafter called 'Mobility Strategy' (EC, 2020b). Among the milestones set out in it, there is the achievement of 30 million zero-emission vehicles (ZEVs) on EU roads, served by 3 million public recharging points (RPs) by 2030.

The European Climate Law (EU, 2021a), adopted in July 2021, writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. To deliver the targets agreed in the European Climate Law, the EC put forward a set of legislative proposals known as the 'Fit for 55 package' (EC, 2021b), which are currently under discussion. The estimated number of electric vehicles (EVs) in the proposed 'Fit for 55 package' is more ambitious than those of the Green Deal and Mobility Strategy.

The current legislative framework is based on Directive 2014/94/EU on the deployment of alternative fuels infrastructure (EC, 2014), hereinafter referred to as the 'Directive' or 'AFID'. The Directive defined a framework of common measures for the deployment of such infrastructure in the EU. It required Member States (MS) to set up national policy frameworks (NPFs) to establish markets for alternative fuels and ensure that an appropriate number of publicly accessible recharging and refuelling points were put in place, particularly also to enable free cross-border circulation of such vehicles and vessels on the Trans-European Network for Transport (TEN-T).

As a first step, the Directive required Member States to set up by the end of 2016 long-term NPFs (EC, 2019b) for the development of the alternative fuels market and the planning of the deployment of relevant alternative fuels infrastructure, with different milestones for 2020, 2025 and 2030 for different alternative fuels. Electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas and liquefied petroleum gas (LPG) were identified as the principal alternative fuels (AFs) with a potential for long-term oil substitution. Member States had to submit a report on the implementation of their national policy framework to the Commission by 18 November 2019, and every 3 years thereafter. The national implementation report (hereinafter 'NIR') has to cover the information listed in Annex I of the Directive and, where appropriate, to include a relevant justification regarding the level of attainment of the national targets and objectives.

A lack of ambition, consistency and coherence among the Member States' infrastructure planning in their NPFs were identified in EC, (2019b) and Thiel et al., (2019). An analysis of the NPF objectives revealed a 3% reduction in tailpipe CO_2 emissions from cars in 2030 when compared with a scenario that does not take incentives for alternative fuels into account (Gómez Vilchez et al., 2019).

These initial findings have been further scrutinised throughout the assessment of the EU27+UK NIRs, which has also confirmed the increasing inadequacy of the Directive towards the raised ambition of the European Union in terms of electromobility and decarbonisation. In order to overcome these limitations, a more ambitious proposal for a Regulation on the deployment of EU Alternative Fuels Infrastructure (AFIR) (EC, 2021a), repealing the Directive, has been made by the European Commission, as part of the 'Fit for 55 package'. In EU legislation, the Regulation is a more powerful tool to implement a policy. The AFIR is setting mandatory targets and minimum requirement for all MS, which was not the case in the Directive.

The electrification of transport (electromobility) not only significantly reduces energy consumption and GHG emissions, but also enhances Europe's energy security and it has several additional benefits such as less air and noise pollution (Biresselioglu et al., 2018).

While legislative acts indicate a desired way forward for electromobility in the EU, it is relevant for citizens and policymakers to estimate the level of fulfillment of such EU goals, considering possible future trends/scenarios.

Several recent studies evaluated trends for electric vehicles in the 2030–2050 time frame for different European countries. Al-Alawi & Bradley, (2013) presented a synthesis of the results from existing studies on EV penetration rate estimates in different regions of the World, based on consumer choice, diffusion rate and agent-based models. Fluchs, (2020) estimated EV diffusion speed at national level in 18 EU countries in the 2020–2050 period with an epidemic growth model. Dhakal & Min, (2021) forecasted the global battery electric vehicle (BEV) adoption by 2030 using the Bass growth model. A simulation model was used by Pasaoglu et al., (2016) to develop scenarios up to 2050 for the EU light duty vehicle road transport.

Different stakeholders depict scenarios up to 2030 for electric vehicles (Element energy, 2022) and for the corresponding infrastructure (ChargeUp Europe, 2022) at EU level and beyond.

At country level, Chatzikomis et al., (2014) estimated the Greek vehicle fleet until 2030 and the corresponding hybrid electric vehicle (HEV) and EV market penetration. Brand et al., (2017) examined timing, scale and impacts of the uptake of plug-in vehicles in the heterogeneous UK car market from a consumer perspective. An analysis of Polish government EV goals until 2050 is presented in Ščasný et al., (2018). In Logan et al., (2021), three different vehicle mix scenarios for UK fleet were considered for the 2017–2050 period to estimate overall CO_2 emissions. Klein et al., (2020) examined the diffusion of EVs in Germany in five different scenarios for the target group of young Germans. Forecasts of Portuguese EV sales growth for the 2020–2030 decade are presented in Nogueira et al., (2021), based on three different scenarios estimating a BEV passenger car fleet in 2030 ranging from around 60,000 to 115,000 units. A simulation of the potential uptake of electric vehicles in Italy is presented in Scorrano & Danielis, (2021), pointing out that about one sixth of the Italian car fleet will be composed by BEVs in 2030.

Most of the existing studies conclude that recharging infrastructure has a significant positive effect on EV adoption (Dhakal & Min, 2021; Fluchs, 2020; Gota et al., 2019; Klein et al., 2020; Pasaoglu et al., 2016; Sæther, 2022).

Only a few studies focus on projections of both future EV fleet and recharging infrastructure at European Union level. EU EV and RP projections to 2030 are presented in the Global EV Outlook 2022 from IEA (IEA, 2022). This study foresees EV sales share across all modes over 35% by 2030 in the Stated Policy Scenario and a more optimistic share of 50% according to the Announced Pledges Scenario. An outlook of EV fleet and required public charging infrastructure by 2030 was also presented by different stakeholders (ACEA, 2022; ChargeUp Europe, 2021; T&E, 2022, 2020).

Different authors have discussed optimal ratios among electric vehicles and public recharging infrastructure for groups of countries and tracked their past evolution (Falchetta & Noussan, 2021; Feckova Skrabulakova et al., 2021; Funke et al., 2019; Tsakalidis et al., 2019) concluding that the infrastructure deployment should be discussed in a larger context rather than being based on these ratios only. No clear solution for the optimal value of the ratio emerged since many parameters influence these ratios (e.g. housing types that impact the private infrastructure possibility, power level of infrastructure, grid characteristics and limitations, motorisation rates, vehicle usage patterns, BEV/plug-in hybrid electric vehicles (PHEV) ownership rates, population density). Additionally, the geographical aggregation level of the study is also important as the more granular the analysis is performed, the more precise, useful and relevant for local policy makers the results are. However, it is also a fact that at a higher geographical/administrative resolution level, the data availability of some parameters is rather limited. Therefore, most of the studies targeting groups of countries perform an analysis at national level with few presenting the sub-national/regional or city level situation (Falchetta & Noussan, 2021; Hall & Lutsey, 2020).

NPF data were used to analyse electromobility trends in the 2016–2020 period (Gómez Vilchez et al., 2019; Thiel et al., 2019; Tsakalidis et al., 2019). NIR data can also be used to depict an EU-wide overview of electromobility deployment, as envisaged by the countries. NIR data are a unique data set: they include information directly provided by all Member States in approximately the same time period (2018–2019), with a few exceptions, and they represent commitments and objectives set with ample margins of freedom, according to the MS-specific situations in terms of alternative fuels potentiality, technological progress, transport market development and so on.

As not all the Member States had provided all the necessary information in their NIR, the initial NIR data set lacked some numerical values for objectives. In order to produce a complete NIR data set for the 2016–2030 period, in this study, we estimated missing values of 2025 and 2030 with different statistical techniques and critical analysis of the NIRs.

Thus, in our work, we distinguish between the initial and the complete NIR data set. Concerning the future values reported in the government plans, we use ‘target’ and ‘estimate’ when referring to recharging infrastructure and vehicles, respectively. When referring to both infrastructure targets and vehicle estimates, we use the term ‘objectives’.

In this paper, the focus is on EVs for road transport. For a recent analysis of NIR data related to waterborne and road freight transport, see Gómez Vilchez et al., (2022a, 2022b). The term EVs in this work refers to BEVs and plug-in hybrid electric vehicles (PHEVs). According to the European legislation, PHEVs are considered low-emission vehicles (LEVs) if their type approval CO_2 emissions are below 50 g/km (EU, 2019). However, there is a growing evidence that their real-world emissions can be up to 6 times higher than those at type approval (Chatzipanagi et al., 2022; Tansini et al., 2022). For this reason, some Member States are in fact modifying their EV estimates for 2030 towards a higher share of BEVs versus PHEVs (even up to 100%), as for example the Netherlands (EC, 2022a).

L-category vehicles (i.e. 2- and 3-wheel vehicles and quadricycles) and fuel cell electric vehicles (FCEVs) are excluded from the complete NIR data set. The available NIR data on FCEVs are considered only in the comparison with main EU goals for 2025. Concerning recharging infrastructure, the focus is on publicly accessible recharging points, according to the definition in the Directive.

The objective of this study is thus threefold. First, it provides a comparison between existing overall goals at EU level in electromobility for the 2020–2030 period and the targets and estimates provided by the EU Member States in their NIR. The second objective is to analyse the national and EU27+UK electromobility envisaged evolution in the 2016–2030 period, based on the complete NIR data set. The third objective is to contribute to the assessment of the policy impact of the Directive and provide policy recommendations.

Novelty of this paper compared to the state of the art can be summarised as follows: (i) it provides a complete NIR data set, currently not available in the literature; (ii) it compares the complete NIR objectives with main EU goals for 2025 and 2030 (i.e. from Green Deal and Sustainable and Smart Mobility Strategy); (iii) it presents a NIR data-driven EU27+UK outlook of EV and RP deployment with a novel set of indicators, averaged with different weighting factors in order to consider different aspects and influencing parameters.

A set of proposed indicators at country level, namely the share of electric vehicles, the density of publicly accessible RPs, the EV and RP annual growth rates and the sufficiency index (i.e. the ratio between EVs per RPs), are proposed to depict the envisaged evolution of electromobility at EU level.

The paper is divided into four sections. After this introductory section, the 'Methods' section provides the Methods developed in this paper and details about data sources. The results are presented in the 'Results' section. The last section provides conclusions and identifies future developments. Appendix A and the Supplementary Material contain additional information.

Methods

Overall approach

The methodology followed in this study is based on a pre-processing phase of the initial EU27+UK NIR data on electromobility with the aim to assess the data quality and perform a data cleaning (van der Loo & de Jonge, 2018) in order to obtain a complete NIR database, referred to as 'complete NIR' data set. Data cleaning is meant as the process of adding missing data and correcting, repairing or removing incorrect or irrelevant data from a data set.

Reasons for incompleteness of the initial NIR data set can be found in misunderstanding or unavailability of the requested data. We estimated missing values for the years 2025 and 2030 with different statistical techniques and critical analysis of the NIRs in order to produce a complete NIR data set.

The complete NIR data set was used to analyse patterns and trends in EV and RP deployment at EU27+UK level and to identify the impact of relevant countries. The analysis is based on different indicators, to which different weighting criteria are applied and the results are compared.

Initial NIR data set description

The initial NIR data set for each Member State included an incomplete list of alternative fuels vehicles and alternative fuels infrastructure past data and future estimates and targets. The alternative fuel/transport mode pairs covered by the initial NIR data set are the following: electricity/road, compressed natural gas (CNG)/road, liquefied natural gas (LNG)/road, hydrogen (H_2)/road, liquefied petroleum gas (LPG)/road, electricity/inland waterways, electricity/maritime, LNG/inland waterways, LNG/maritime, electricity/air, electricity/rail and H_2/rail.

The electricity/road pair was the most covered by almost all MS in their NIRs and it represents the focus of this study.

The initial NIR data set covers the period 2016–2030, in line with the time frame of the Directive requirements (EC, 2014) and the NPF/NIR reporting period. More specifically, the covered years are 2016, 2017, 2018, 2020, 2025 and 2030. The data were submitted to the EC in the 2019–2020 period: at that time, reporting years up to 2018 were 'past years', and those from 2020 onward were 'future years'. The initial NIR data set used in this study does not include L-category data, provided only by a few Member States. FCEV data were also excluded and they were not mandatory for the reporting in the Directive.

In case of NIRs omitting data for 'future years' that had been previously reported in the NPFs, the NPF data was considered valid also for the initial NIR data set, as NPF data was assumed to be tacitly confirmed. Another source of information for filling in missing 'past years' data was the European Alternative Fuels Observatory (EAFO) (EC, 2021c), a publicly available portal supported by the European Commission. In both cases, we regarded these alternative data as reliable.

The initial NIR data set can be found in the Transport Alternative Fuels Infrastructure Data Collection (JRC, 2022).

Data pre-processing

Data quality assessment and cleaning

The most appropriate trend type (i.e. trendline to estimate the data profile) for electromobility development needed to be defined by using available historical data and future objectives, as specified by the countries. The evaluation of the trend type best describing the EV evolution was carried out at EU27+UK level in the 2008–2030 period. Past data (2008–2020) for the calculation of EV evolution trend type were retrieved from EAFO (EC, 2021c). As a general approach, future years with a sufficiently high NIR data coverage (in terms of 2020 EV fleet) were considered to compute the EV evolution trend type.

For RPs, the same evolution type as the one identified for EVs was considered in the analysis due to the following reasons (EC, 2022a):

- It is assumed that vehicles are the driving force for the uptake of AF transport systems and infrastructure will follow.
- The Directive foresees the EV and recharging infrastructure having a synchronised development, meaning the same evolution type as it recommended a ratio of 10 EVs per publicly accessible recharging point.

The assessment of the quality of the NIR initial data set included the evaluation of the data coverage for both EV and RP, in order to understand the level of data gap filling need.

The type of evolution trend identified at EU27+UK level was used to define the electromobility trends at country level.

After the data quality assessment, a data cleaning process was applied to obtain the complete NIR data set for 2025 and 2030, in which a value was made available for each Member State in all reporting years.

The data imputation approach for the missing EV and RP values in 2025 and 2030 at country level consisted in interpolation and extrapolation techniques that used the evolution trend type of EVs identified at EU27+UK level. In particular, in order to fill the data gaps, the missing values were obtained from the country's EV and RP evolution trends, calculated using available values from 2016 (either taken from NIR, NPF or EAFO (EC, 2021c)), and the initial NIR objectives for 2020, 2025 and 2030 (taken from NIR or NPF). When all objectives for future years were missing for a country, the evolution trend used for imputing the missing values was calculated based on the available data only. A verification was performed that the interpolated/extrapolated imputed values were not corresponding to trend values representing outliers or significantly modifying the main statistical characteristics of the calculated trends dataset (see Appendix A and Supplementary material). Few corrections of the data provided by the countries were also needed to ensure consistency of the category of provided values (see Appendix A).

It has to be noted that in the initial and complete NIR data sets the share of high power RPs (>22kW) is not considered because not all Member States provided this information and private recharging points are not counted, according to the Directive definitions.

Construction and evolution of relevant indicators

Once the complete NIR data set was generated for the 2016–2030 period, a set of relevant indicators was defined to evaluate the temporal evolution of EV and RP deployment at EU27+UK level. The main indicators considered, described hereafter, are share of electric vehicles (ShEV), density of publicly accessible RPs (RPdens), EV and RP annual growth rates (AGRs) and the sufficiency index (Is).

The share of electric vehicles (ShEV) is the ratio between EV fleet and total vehicle fleet (V) values. $ShEV_i$ is calculated as shown in Eq. 1:

$$ShEV_{i,t} = \frac{EV_{i,t}}{V_{i,t}} \quad (1)$$

where the index i refers to the country and the index t refers to the year.

The density of publicly accessible RPs (RPdens) allows to evaluate the RP deployment. RPdens is calculated as number of RPs adjusted by the total land surface (S_i) [km^2] of each country i, as indicated in the following:

$$RPdens_{i,t} = \frac{RP_{i,t}}{S_i} \quad (2)$$

In the Commission Staff Working Document on the Updated detailed assessment of the MS Implementation Reports (EC, 2022a) hereinafter called 'SWD', the density of RPs was also calculated. However, in that study, RPs were adjusted by the total length of roads. In this study, the adjustment on land surface is preferred because it allows eliminating the influence of the uncertainty in how the categories of roads are determined at national level and the possible inconsistencies among countries. On the other hand, the adjustment on total land surface does not allow to exclude inaccessible or scarcely populated areas, where RPs would not actually need to be placed, being a national level indicator.

Two other indicators considered in this analysis are the EV and RP average annual growth rates (AGRs) in the 2016–2030 period. These two indicators were originally proposed in the SWD (EC, 2022a) for the individual Member States. In this study, the values are presented at EU27+UK level. The evolution type previously identified for EVs and RPs was used as basis to evaluate the annual growth rates (see Appendix A).

Finally, the adequacy between EVs and publicly accessible RPs at country level was analysed by calculating the sufficiency index (Is), which is the ratio between EVs and RPs:

$$Is_{i,t} = \frac{EV_{i,t}}{RP_{i,t}} \quad (3)$$

It is worth mentioning here that this simple indicator has been presented in our study according to the requirements of the Directive, which had proposed an indicative target value of 10 for the ratio between all the EVs and RPs in each country. In the 'Results' section, we will show and discuss the limits of this indicator.

The flowchart of the data pre-processing methodology is presented in Fig. 1.

Averaging methods for EU-wide patterns and trends

The selected indicators presented in the 'Data pre-processing' section were averaged to obtain their EU27+UK trends in the 2016–2030 period. Six types of averages were considered: an unweighted average (UWA) and five weighted ones (P, population; V, total vehicle fleet; S, total land surface; R, road length; T, TEN-T road length). All averaged indicators are calculated as in Eq. 4:

$$(XWA)_t = \frac{\left(\sum_{i=1}^{28} w_i \bullet I_i\right)_t}{\left(\sum_{i=1}^{28} w_i\right)_t} \quad (4)$$

where:

X = type of average

t = year (applicable in all indicators except the AGRs)

I = indicator

i = country

w = weighting factor.

A weighting factor equal to 1 was used for the unweighted average (UWA). Clearly, this average might be seen as misleading since it assigns an identical weight to all countries. However, we have considered it interesting for two reasons: firstly, it mirrors the EU institutional architecture, where all Member States have the same dignity; secondly, the unweighted average constitutes a sort of extreme situation that can be compared to all the other averages. The weighting factors used for the five weighted averages are the yearly values of population (for PWA), total vehicle fleet (for VWA), land surface (for SWA), road length (for RWA) and TEN-T road length (for TWA). This entails dynamic weighting.

Concerning the population weighted average (PWA), data on population for the 2016–2020 time frame were retrieved from Eurostat (Eurostat, 2022a),

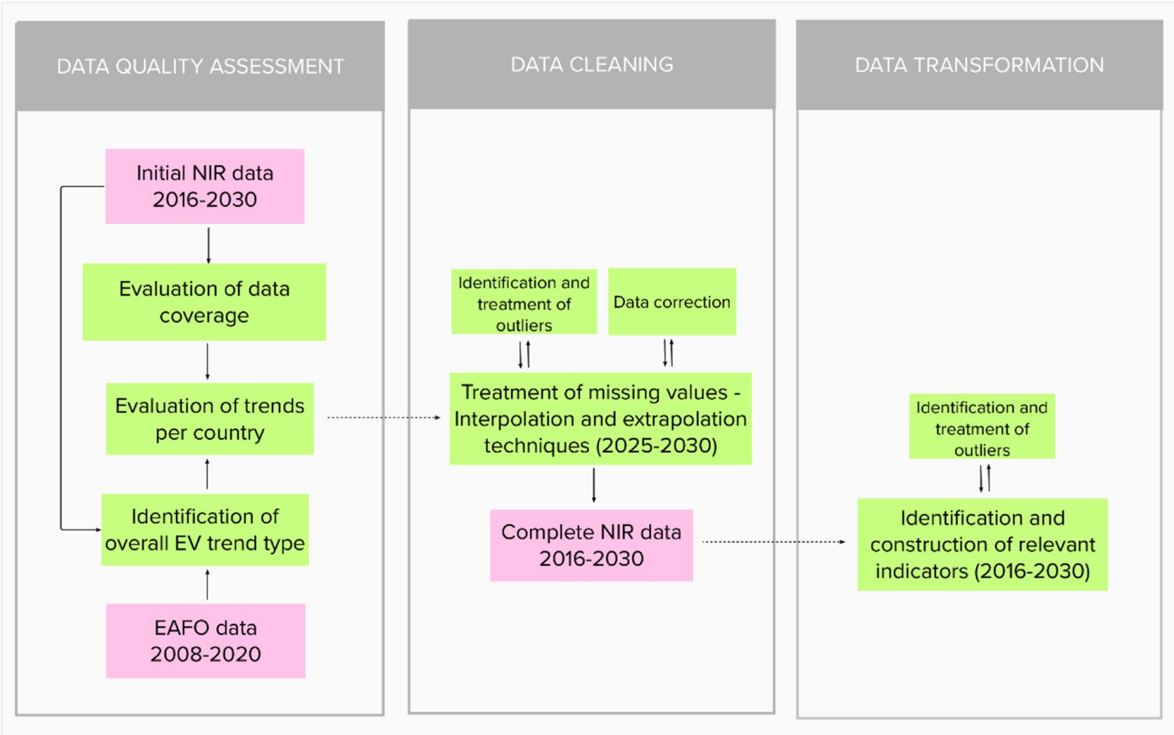

Fig. 1 Flowchart of the data pre-processing methodology. Pink boxes identify sets of data, while green boxes depict actions on the data

while future population values for 2025 and 2030 were taken from the baseline projection by Eurostat (Eurostat, 2022b).

For the vehicle weighted average (VWA), data on total vehicle fleet for the 2016–2018 period were retrieved from Eurostat and EU Statistical Pocketbook (EU, 2021b). Projected total vehicle fleet in 2020, 2025 and 2030 are based on the EU Reference scenario 2016, but excluding the incentives for alternative fuels provided at the Member State level. The scenario was developed with the PRIMES-TREMOVE model (i.e. the same model used for the 2016 EU Reference scenario (EC, 2016)).

The land surface values for the surface weighted average (SWA) were taken from Eurostat Land Cover Overview (Eurostat, 2022c).

Values for total road length used for the road weighted average (RWA) were taken from Eurostat (Eurostat, 2022d) and EU Statistical Pocketbook (EU, 2021b) and the values include motorways, main/national and secondary/regional roads.

The land surface and road length values are assumed constant for the 2016–2030 period.

The lengths of roads of the TEN-T were obtained from the TENtec portal (EC, 2022b). Also these values are not dynamic (i.e. they do not change every year) as they represent the total planned TEN-T Core according to TEN-T Regulation from 2013 (EU, 2013).

The temporal evolution of the weighted indicators was analysed in the 2016–2030 time frame, identifying main trends.

Outliers were detected with extreme value analysis, implemented by using interquartile range (IQR) analysis. Results with extreme outliers substituted with the upper value of the IQR range are also presented.

In addition to the averages, the no-border (NB) case was also investigated for all the selected indicators in the 2016–2030 period. The no-border results are obtained by considering EU27+UK as a single country, with a single population, surface and road

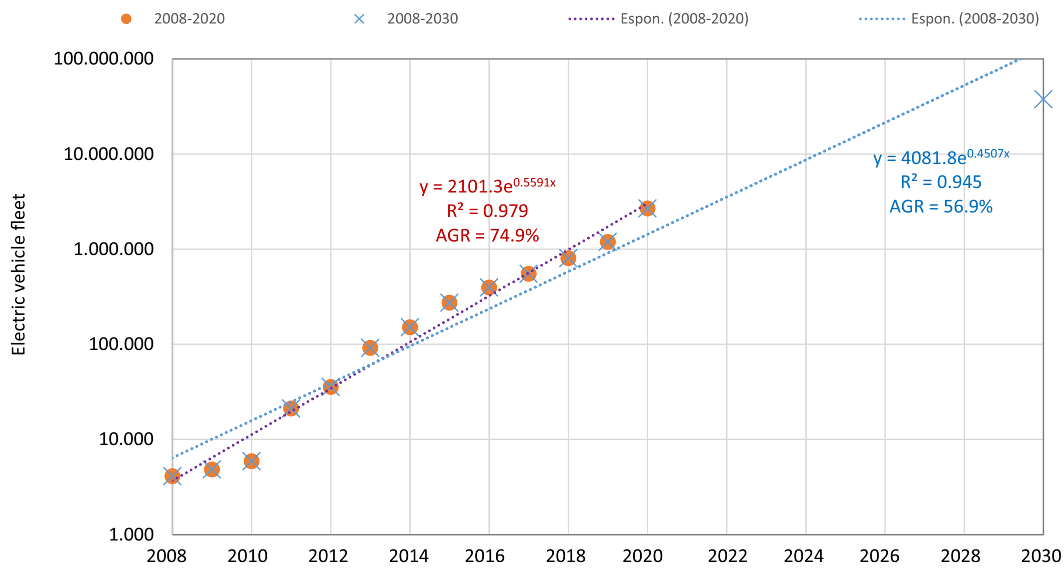

Fig. 2 Evolution of total EV fleet at EU27+UK level. 2008–2020 data from EAFO and 2030 data from initial NIR data set. Log scale

length, thus representing a higher geographical aggregation level.

Results

Total EV fleet and publicly accessible recharging points in the 2008–2030 period

Of the 28 countries assessed, 93% provided an EV estimate for 2030 (see Supplementary Table 1). Estimates for 2030 were only missing for Estonia and Croatia, which were responsible for less than 0.2% of the 2020 EV fleet, according to EAFO (EC, 2021c). On the other hand, 24 over 28 countries assessed (i.e. 86%) provided an estimate for 2025: estimates were missing for Germany, Estonia, Croatia and Italy, which were responsible for about 27% of the 2020 EV fleet (i.e. the 2025 initial NIR data set has a fleet coverage of about 73% in terms of 2020 EV fleet). Due to this limited fleet coverage, the 2025 initial NIR data were excluded from the calculation of the type of evolution of the overall number of EVs. For all the years between 2008 and 2020, the minimum threshold of 80% of coverage was respected.

Using past available data (2008-2020) on EV stock from EAFO (EC, 2021c) and 2030 data from the initial NIR data set, the EV evolution at EU27+UK level was calculated, as depicted in Fig. 2. Since for Estonia and Croatia data were missing for 2030, the most recent available data (i.e. 2020 data from EAFO) was considered to compute the EV number evolution. The coefficient of determination R^2 was used to establish the best fitting curve among exponential, power and linear. The highest R^2 was found for the exponential (R^2 = 0.945) (see Supplementary Figure 1). Even considering the 2008–2020 period only, the type of evolution remains clearly exponential (R^2 = 0.979). We also calculated the annual growth rate (AGR) at European level with the no-border concept, which consists in considering all the EVs in EU27+UK together regardless of their distribution in the specific country. It can be observed that the no-border AGRs for the 2008-2020 period is higher than the corresponding no-border AGR for the 2008–2030 period obtained by adding the NIR estimates. It can thus be inferred that if the growth continues as in the 2008–2020 period, in 2030 higher values that the NIR estimates might be expected.

The exponential function was thus used to estimate EV and RP missing values at countries level with interpolation and extrapolation techniques. Outliers were also detected and treated, as detailed in Appendix A.

Consequent to the data quality assessment and data cleaning, the complete NIR data set for 2025 and 2030 was obtained for both EVs and RPs (see Supplementary Table 1 and Supplementary Table 2).

In Fig. 3, the evolution of the total EV number at EU27 level with the EAFO+complete NIR data set is shown, together with a comparison with the goals of the European Green Deal (EC, 2019a) and the Sustainable and Smart Mobility Strategy (EC, 2020b). Table 1 shows the main exponential trend parameters for the evolution of the total EV number.

As can be seen in Fig. 3, estimates from the complete NIR data set for EVs (i.e. BEV+PHEV) are around 2.5 million lower than the plan set out in the European Green Deal for 2025. Even considering the growing contribution of FCEVs (at least 88,035 vehicles are estimated in 2025 in the EU27 according to the NIRs), the complete NIR estimates are around 20% lower than the European Green Deal goal for 2025.

Concerning 2030, since the Mobility Strategy target refers to zero-emission vehicles (ZEVs), in order to compare the value with the EU27 complete NIR data, a value for BEV only is also shown, having been obtained by applying the population-weighted average BEV/PHEV share in 2030, according to the 2020 EU reference scenario (EC, 2021d). Following this approach, estimates from the complete NIR data set for BEVs are around 3 million lower than the Mobility Strategy goal. Even considering FCEVs (at least 212,016 vehicles in 2030 in the EU27 according to the NIRs), the complete NIR estimates appear to be around 9% lower than the Mobility Strategy goal for 2030. Only considering the seemingly optimistic estimate of 2,903,700 FCEVs in 2030 in Italy from the Italian NPF (not reported in the Italian NIR), the complete NIR estimate for ZEVs in 2030 would be in line with the Mobility Strategy.

The complete NIR estimates of EVs in 2025 and BEV in 2030 appear less ambitious than the respective Green Deal (GD) and Sustainable and Smart Mobility Strategy (SSMS) goals. Also, the no-border annual growth rate (AGR) of ZLEVs considering the GD goal for 2025 is higher than the AGR of BEV+PHEV from the complete NIR estimates. On the other hand, it can be observed that the AGR considering the SSMS goal for ZEVs in 2030 (i.e. 53.1%) is approximately in line with the AGR of BEVs from the complete NIR estimates (i.e. 52.6%).

Figure 4 depicts the comparison between the complete NIR targets for RPs and refuelling points[1] and the goals of the European Green Deal and the Mobility Strategy for the period 2010–2030. 2010–2020 data on RPs were taken from EAFO, where 2010 data are the first available values. Table 2 reports the main exponential trend parameters for the evolution of publicly accessible recharging points and hydrogen refuelling points.

Targets from the complete NIR data set for RPs are 374,607 lower than the Green Deal goal (−37.5%) in 2025. Even considering also hydrogen public refuelling points in the EU27 in 2025 according to the NIR database (i.e. at least 850 points in 2025), NIR figures remain considerably lower than the Green Deal value (−37.4%). 2025 hydrogen estimates from NIR data were provided only by 13 MS, which covered only 43% of the EU27 hydrogen vehicles fleet in 2020. The gap with the EU goals decreases in relative terms when comparing the Mobility Strategy target for 2030 for RPs with the complete NIR. In this case, the complete NIR estimates are 654,298 lower (−21.8%). Accordingly, considering 2010–2030 AGR, the complete NIR data set exhibits a lower value compared to the Mobility Strategy one. Hydrogen points do not have to be considered when comparing NIR estimated with the 2030 Mobility Strategy target, as the latter apparently refers only to BEVs and public recharging points.

As it can be observed in Supplementary Table 2, 25% of the countries assessed (7 out of 28) did not provide RP targets for 2025 and 2030. Thus, the number of RP targets imputed by statistical analysis in the complete NIR is higher than the EV estimates obtained in a similar way. Possible reasons might be the necessity to wait for the adaptation of their national plans to new EU strategies or policies and/or for technological and market developments.

By comparing Fig. 3 b and Fig. 4 b, it is possible to observe that the AGR of EVs are higher than the corresponding values for RPs, signifying that the EVs are expected to develop at a higher pace than the RPs. It is also possible to observe that the R^2 are higher for EVs than for RPs, showing that the exponential trend is more suitable for EVs than for RPs.

[1] The Green Deal refers to recharging and refuelling 'stations' and 'points', while the Mobility Strategy and the complete NIR data set refer to recharging and refuelling 'points'. 'Points' are generically used throughout the document with the definitions provided in the Directive 2014/94/EU Article 2 (3) and (8).

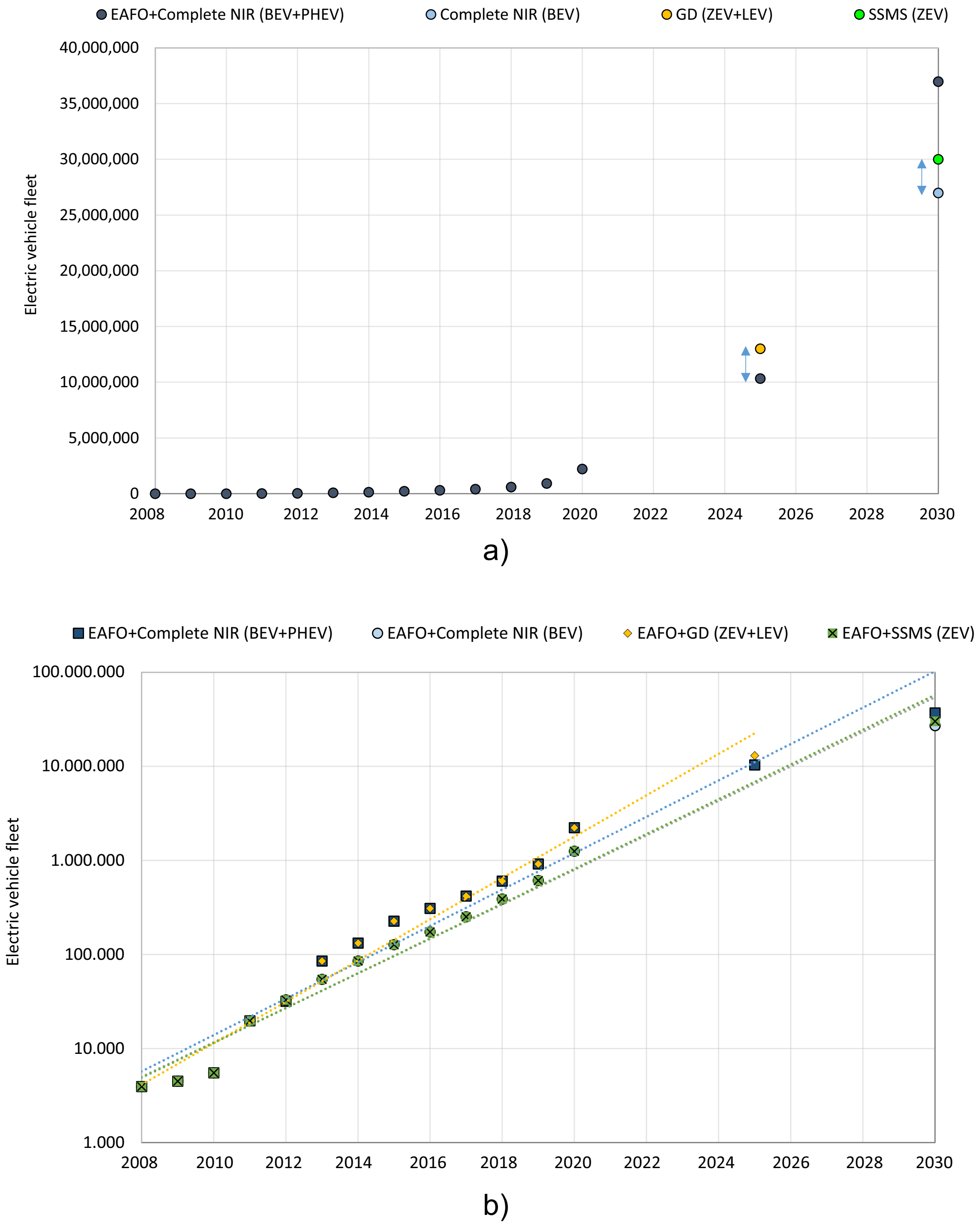

Fig. 3 Evolution of total EV number at EU27 level. EAFO = 2008–2020 data from EAFO; Complete NIR = 2025 and 2030 data from complete NIR data set; GD = 2025 data from European Green Deal (EC, 2019a) and SSMS = 2030 data from Sustainable and Smart Mobility Strategy (EC, 2020b) goals. **a** Linear scale; **b** logarithmic scale

Table 1 Exponential trend parameters for the evolution of the total EV number at EU27 level

	EAFO+GD (ZEV+LEV)	EAFO+Complete NIR (BEV+PHEV)	EAFO+Complete NIR (BEV)	EAFO+SSMS (ZEV)
R^2	0.992	0.971	0.999	0.999
AGR	65.8%	56.1%	52.6%	53.1%
Equation	$y = 2491.9 \bullet e^{0.5058x}$	$y = 3652.9 \bullet e^{0.4452x}$	$y = 3266.9 \bullet e^{0.4223x}$	$y = 3193.1 \bullet e^{0.426x}$

EU-wide patterns and trends in the 2016–2030 period

Share of electric vehicles

The EU27+UK ShEV has a slightly right-skewed distribution in 2025 and 2030. High excess kurtosis in 2025 indicates that the ShEV distribution is a leptokurtic one with heavier tails and with more chances of outliers than the normal distribution. Excess kurtosis is close to zero in 2030, indicating a mesokurtic distribution close to the normal one. The complete set of ShEV values for each country in the 2016–2030 time frame can be found in the Supplementary Table 3.

As it can be seen in Fig. 5, the EU27+UK ShEV values differ considerably in the 2016–2030 period: the share in 2030 more than doubles the 2025 values. The values differ substantially also among countries: from 0.02% for Cyprus to 19.22% for Luxembourg in 2025, and from 0.11% for Cyprus to 34.36% for Luxembourg in 2030.

According to the IQR analysis, one extreme outlier is identified for 2025 (i.e. Luxembourg value of 19.22%). Luxembourg has also the highest car density in the EU in 2019 (681 per 1,000 people (Eurostat, 2022e)). However, the 2025 averages with the outlier substituted with the upper value of the IQR range do not differ significantly from the averages obtained from the original set of data (see Fig. 5), since the contribution of Luxembourg to the weighted averages is quite low (see Supplementary Figure 2).

In this case, the use of different weighting factors does not dramatically vary the result. The highest ShEV values in 2030 are VWA, based on total vehicle fleet, the no-border (NB) case and PWA (i.e. 11.38%, 11.38% and 11.21%, respectively), based on population, followed by RWA, UWA, TWA and SWA (with 10.78%, 10.49%, 10.48% and 10.41%, respectively), based on road length, unweighted, TEN-T road length and surface average respectively. This is due to the fact that countries with more vehicles and population compared to roads and surface (e.g. Germany) have a higher ShEV in 2030 (see Supplementary Figure 2). The ShEV values for the no-border (NB) case do not differ from those of the averaged ShEV.

Density of publicly accessible recharging points

The EU-wide surface RPdens has a right-skewed distribution in 2025 and in 2030. The high values of the excess kurtosis of 12 in 2025 and 23 in 2030 indicate that the RPdens distributions are leptokurtic ones with heavier tails and more chances of outliers than the normal distribution. In this type of distributions, more values are located in the tails of the distribution instead of around the mean. The complete set of RPdens values for each country in the 2016–2030 time frame can be found in the Supplementary Table 4. These results reflect a strongly inhomogeneous RP distribution among countries. In particular, it can be noted that in 2020 around 70% of all RPs were installed in 5 countries, which cover only around 30% of the total land surface and total road length as well as around 40% of the population and the total vehicle fleet.

As can be seen in Fig. 6, the EU 27+UK RPdens values differ significantly in the 2016–2030 time frame: the values in 2030 more than triple the 2025 values. The values differ significantly also among countries: from 0.0012 for Romania to 5.58 for Malta in 2025, and from 0.0015 for Romania to 27.20 for Malta in 2030. The NB values for RPdens are among the highest.

According to the IQR analysis, four extreme outliers are identified for 2025 (i.e. Belgium value of 1.15, Luxembourg value of 1.99, Malta value of 5.58 and Netherlands value of 2.93). In 2030, three extreme outliers are also identified (i.e. values for Luxembourg value of 3.98, Malta value of 27.20 and Netherlands value of 6.42). Among these outliers, it has to be noted that Malta and Netherlands values for 2025 and 2030 were obtained through extrapolation; thus, they have a higher degree of uncertainty.

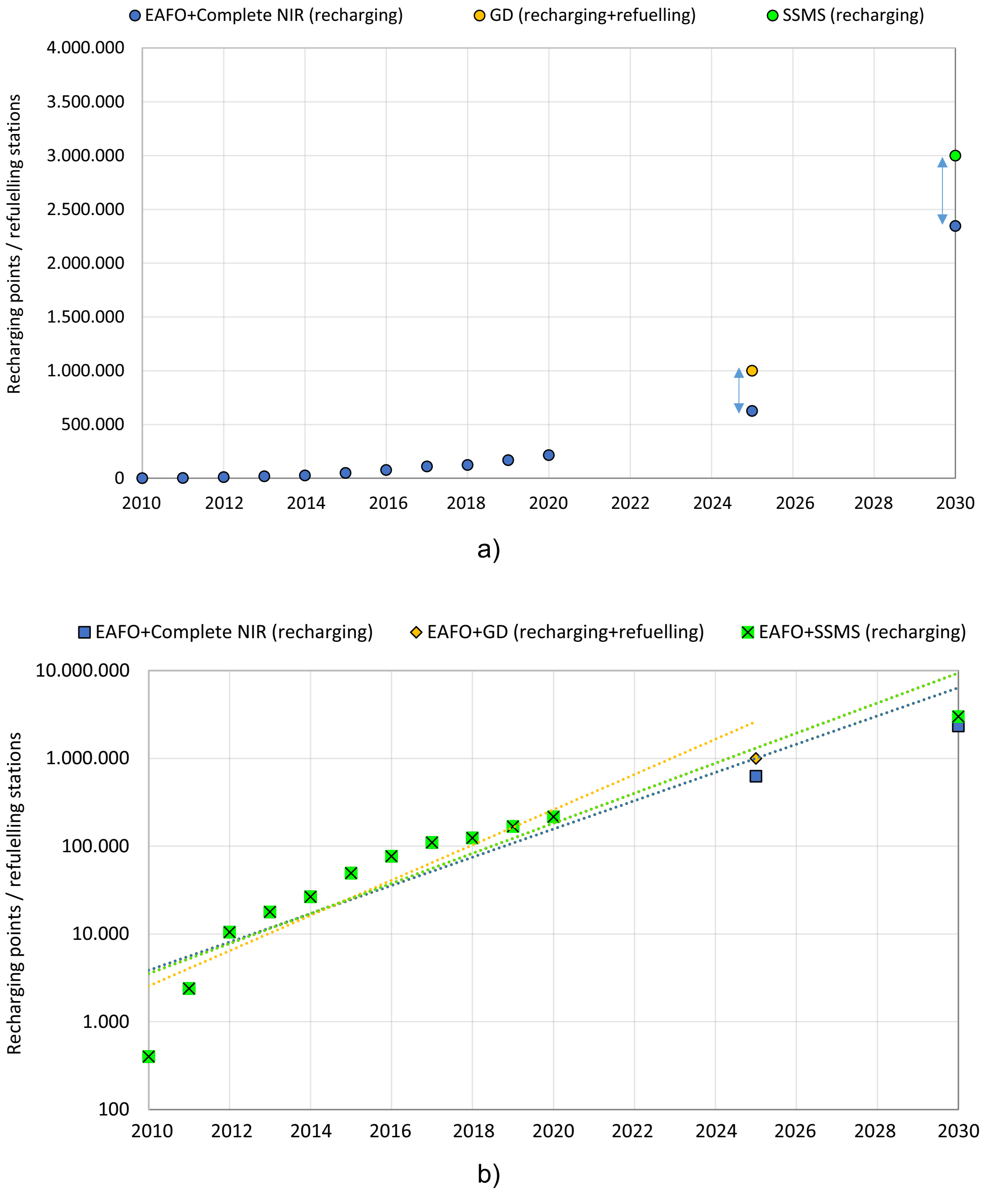

Fig. 4 Evolution of publicly accessible recharging points at EU27 level. EAFO = 2010–2020 data from EAFO; complete NIR = 2025 and 2030 data from complete NIR data set. GD = 2025 data from European Green Deal (EC, 2019a) and SSMS = 2030 data from Sustainable and Smart Mobility Strategy (EC, 2020b) goals. **a** Linear scale; **b** logarithmic scale

Table 2 Exponential trend parameters for the evolution of publicly accessible recharging points at EU27 level

	EAFO+GD	EAFO+Complete NIR	EAFO+SSMS
R^2	0.9761	0.9855	0.9961
AGR	58.8%	44.9%	48.3%
Equation	$y = 1609.4 \bullet e^{0.4625x}$	$y = 2666.3 \bullet e^{0.3706x}$	$y = 2382.7 \bullet e^{0.3944x}$

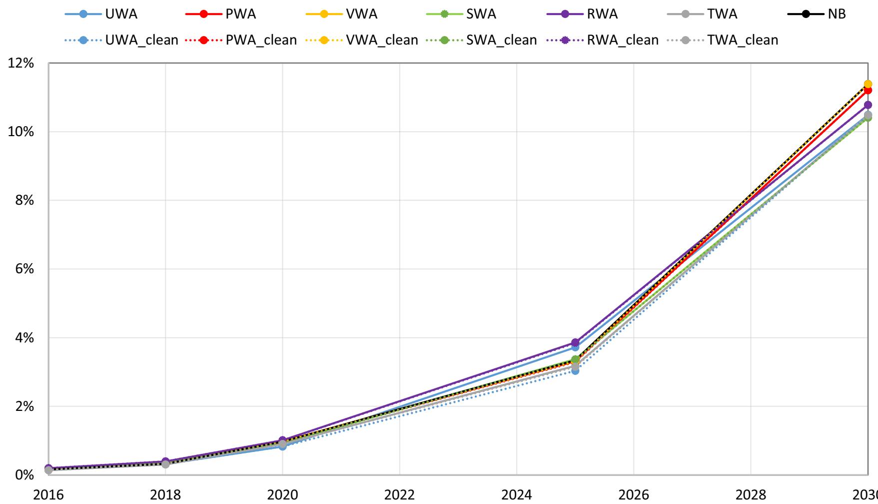

Fig. 5 Temporal evolution of the share of EVs (ShEV) in the fleet at EU27+UK level. Data from complete NIR. Comparison with ShEV values with treated outliers (i.e. xWA_clean, where 'x' stays for U (unweighted), P (population), V (total vehicle fleet), S (total land surface), R (road length), T (TEN-T road length), depending on the type of average)

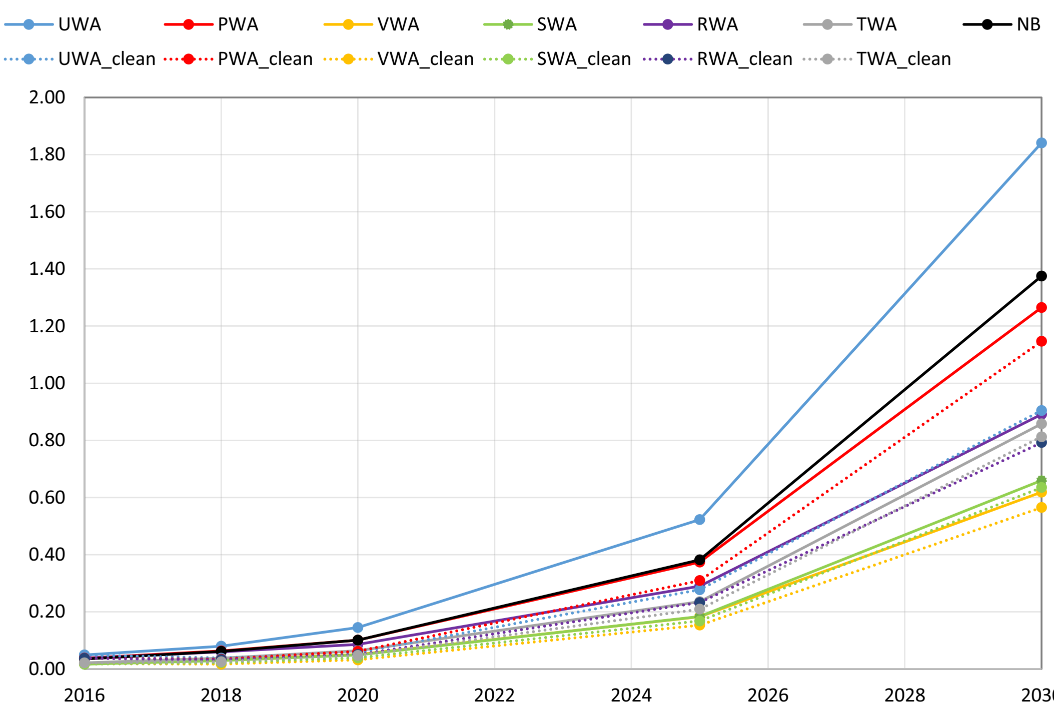

Fig. 6 Temporal evolution of the surface density of publicly accessible RPs (RPdens) at EU27+UK level. Data from complete NIR. Comparison with RPdens values with treated outliers (i.e. xWA_clean)

The 2025 and 2030 averages with outliers substituted with the upper value of the IQR range decrease significantly from the averages obtained from the original set of data (see Fig. 6). The outliers in this case are particularly extreme (e.g. Malta values of 5.58 in 2025 and 27.20 in 2030) and more numerous, and the effect of their treatment is highly visible at EU27+UK level, especially in the unweighted average UWA case.

When comparing the surface RPdens values with the population density in each country, it is possible to observe that in most cases the highest RP densities

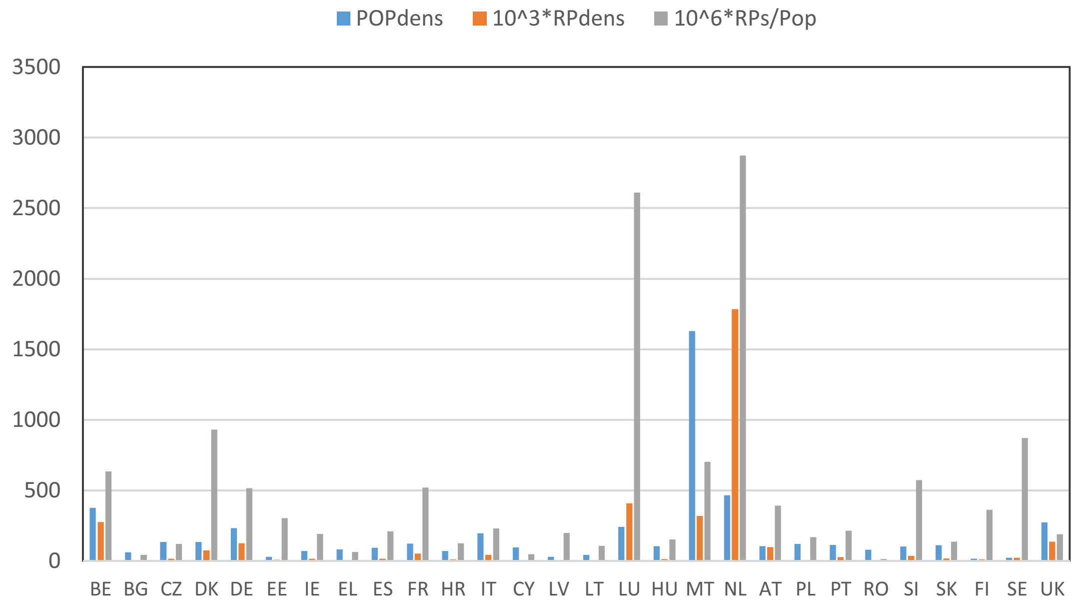

Fig. 7 Population density (POPdens), surface density of publicly accessible RPs (RPdens) and the ratio RPs/Population at EU27+UK level. 2020 data of RPs from EAFO

can be found in the most densely populated countries (e.g. Malta, Netherlands, Belgium and Luxembourg). If 2020 data on RPs are divided by population (see Fig. 7), it can be seen the favourable situation of Netherlands and Luxembourg in comparison with other countries, showing the significant effort made by their government to deploy public recharging network. According to this population adjustment, well positioned in terms of RP availability are also, in decreasing order, Denmark, Sweden, Belgium, Malta and Slovenia.

EV and RP average annual growth rates

Results for the EVs and RPs average AGRs in the 2016–2030 period corresponding to the complete NIR data set are presented in Fig. 8. These values differ from the AGRs presented in Fig. 3 a and b, which refer to another time frame (i.e. 2008–2030) and are based on past data from EAFO. AGR values for EVs and RPs for the period 2016–2030 vary significantly among countries. In the case of EVs, they range from 6.8% of Estonia to 69.5% of Poland (it has to be noted that both Estonia and Poland values were obtained with extrapolation). In the case of RPs, they range from 1.3% of Estonia to 66.0% of Lithuania (it has to be noted that Estonia value was obtained with extrapolation). The complete set of AGR values for each country can be found in the Supplementary Table 5.

Figure 8 depicts that the average EV AGR ranges between 35.5% and 41.3%, depending on the weighting factor considered. The AGR for RPs is definitely lower, ranging between 30.1% and 32.8%. This result shows that future plans of these countries on average foresee a more pronounced development of EVs compared to the corresponding public infrastructure. It is worth mentioning though that this could be also due to the increasing recharging power of the RPs foreseen in the future.

Finally, it is possible to observe that the no-border (NB) case has the lowest values of AGR, both for EVs and RPs, indicating that a lower paced deployment of electromobility is obtained when the overall value of all countries considered together is used and the country-level characteristics and weightings are not taken into account.

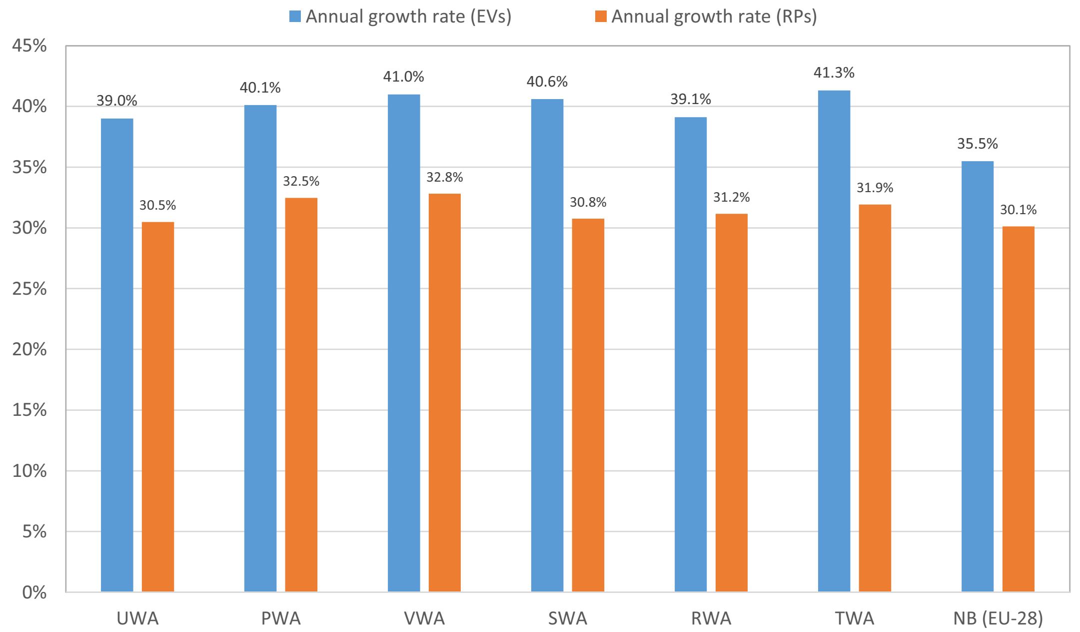

Fig. 8 EV estimates and RP target annual growth rates (AGRs) at EU27+UK level in the 2016–2030 period. Data from complete NIR data set

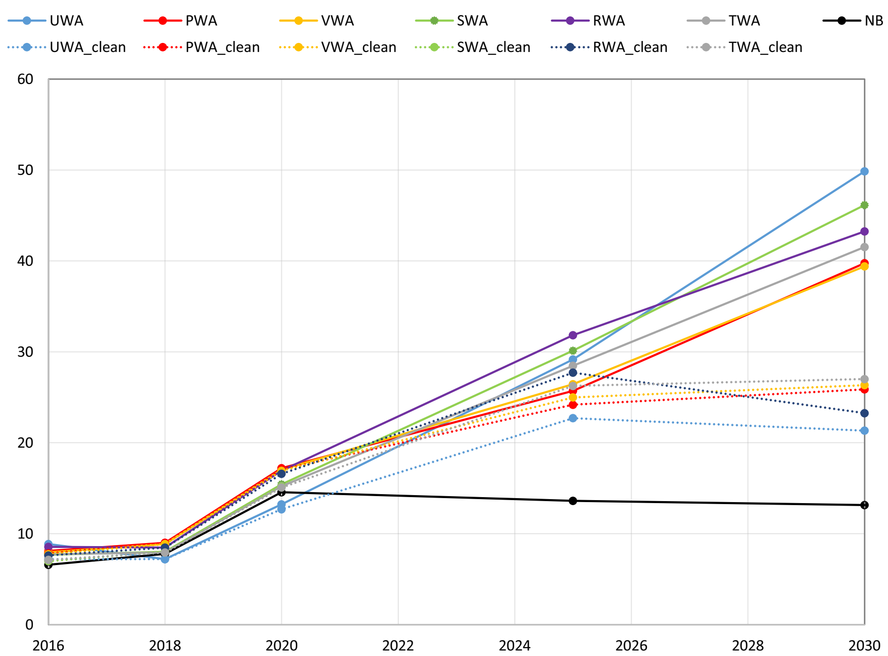

Fig. 9 Temporal evolution of the sufficiency index (Is) at EU27+UK level. Data from complete NIR data set. Comparison with Is with treated outliers (i.e. xWA_clean)

Sufficiency index (Is)

The EU27+UK sufficiency index has a rather right-skewed distribution in 2025 and 2030. High excess kurtosis indicates that the distribution is a leptokurtic one with heavier tails and with more chances of outliers than the normal distribution. Around 20 countries have Is below 20 in 2025 and 2030. These countries cover around 50% of the total land surface and total road length as well as around 60% of the population and total vehicle fleet. The complete set of Is values for each country in the 2016–2030 time frame can be found in the Supplementary Table 6.

Figure 9 shows that the EU27+UK Is values diverge considerably in the 2016–2030 time frame. According to the IQR analysis, three extreme outliers were identified for 2025 (i.e. Ireland value of 164.8, Lithuania value of 166.2 and Poland value of 77.2) and for 2030 (i.e. Ireland value of 780.3, Spain value of 134.2 and Austria value of 102.1). To this respect, it has to be mentioned that, in its NIR, Ireland foresees recharging points being represented mainly by private infrastructure in the future.

The temporal evolution of Is depicted in Fig. 9 shows that countries are expecting a progressive increase of the number of EVs per RP towards 2030. Considering the recommended ratio of 10 EVs per publicly accessible RPs of the Directive, on average EU27+UK countries are moving from an adequate balance between EV and RPs in 2018 (average values ranging between 5 and 10) to a progressively higher ratio in 2030, with average values ranging from 25 to 35 in 2025 and from 40 to 50 in 2030, depending on the averaging method. Only the NB case which represent a higher aggregation level is showing Is values below 15 for 2025 and 2030. As in this case, the national values are not considered independently; the few very high Is values of some countries are not influencing the final results like for the other types of averages studied. This could also be the reason why UWA_clean is showing lower values for 2025 and 2030.

It is worth to note that, if extreme outliers are substituted with the upper value of the IQR range, the average Is values are all below 27.6 in 2025 and below 27.2 in 2030. As in the case of RPdens, the outliers are particularly extreme and the effect of their treatment is highly visible at EU27+UK level.

Following the no-border case (i.e. 13.2), the lowest values in 2030 are UWA_clean and RWA_clean (i.e. 21.3 and 23.3, respectively), followed by PWA_clean, VWA_clean, TWA_clean and SWA_clean (25.9, 26.3, 27 and 27.2, respectively). This can be due to the fact that countries with greater road length (e.g. France and Poland) have a lower sufficiency index than countries with greater TEN-T road length (e.g. Germany and Spain) and land surface (e.g. France and Spain) (see Supplementary Figure 1). The average index values with treatment of extreme outliers are less dispersed both in 2025 and 2030 (they are all in the 20–28 range).

The increasing Is values depicted in Fig. 9 in the 2016–2030 time frame are in line with the results from the AGR analysis.

Given that the share of high power RPs is not considered, that private recharging points are not counted (see the 'Data pre-processing' section) and given the uncertainty related to the number of RPs (stations versus numbers), we gather the evidence that the concept of the simple ratio between number of EVs and number of RPs to assess the adequacy of the recharging infrastructure has several pitfalls. As a confirmation that the ratio of 10 EVs per RP is not a necessary condition for the successful uptake of zero-emission vehicles and low-emission vehicles (Funke et al., 2019), we bring the example of a European EV leading market like Norway, where the Is largely exceeds the value of 10.

These results support the formulation of the revision of the Directive.

Conclusions

This study aimed to investigate the use of a complete NIR data set to estimate future EU trends in electromobility. The NIR data set from EU27+UK includes their past situation until 2018 and their objectives (estimates for EVs and targets for recharging infrastructure) for the 2020–2030 period.

Using statistical tools and critical analysis, a complete NIR data set was obtained from the initial NIR data submitted by each country. The data set was completed after analysing overall EV deployment trends, which showed that an exponential growth trend was the most appropriate assumption.

Results indicate that the NIR objectives of the countries regarding electromobility are not ambitious enough to reach the current EU transport decarbonisation policy goals. More specifically, the NIR estimates for low and zero-emission vehicles result around 20% lower than the Green Deal goal for 2025. In addition, the NIR estimates for zero-emission vehicles appear to be around 9% lower than the Mobility Strategy goal for 2030. They would be in line with the Mobility Strategy goal only if the seemingly optimistic NPF Italian estimate of around 2.9 million FCEVs was considered.

RP targets from the NIR data set are around 37.5% lower than the Green Deal goal in 2025. The gap decreases to 21.8% when comparing the RP target of the NIR data set with the 2030 Mobility Strategy target.

The evolution of the electromobility path was analysed on the basis of five indicators, namely the share of electric vehicles (ShEV), the surface density of publicly accessible RPs (RPdens), EV and RP annual growth rates (AGRs) and the sufficiency index (Is).

Different averaging methods were used to obtain an overview of the evolution at EU27+UK level in the 2016–2030 period. Six types of averages were considered: one unweighted and five weighted, on population, total vehicle fleet, land surface, total road length and TEN-T road length. Additionally, the EU no-border case was also investigated and, since it corresponds to a higher geographical aggregation level, the results obtained contain no influence from the countries. Clearly, compared to unweighted averages, weighted ones allow the final average numbers to reflect the relative importance of the specific value from each country.

For each indicator, the following conclusions are drawn:

- The average share of EVs increases significantly in the 2016–2030 time frame; the values differ substantially also among countries, e.g. from 0.11% for Cyprus to 34.36% for Luxembourg in 2030; the use of different weighting factors does not dramatically vary the results. The highest values in 2030 are the vehicle VWA and population PWA weighted averages.
- Also the EU27+UK surface RPdens values increase significantly in the 2016–2030 time frame: the values in 2030 more than triple the 2025 values. The values differ substantially also among countries. Expectedly, the highest RP surface densities can be found in the most densely populated countries (e.g. Malta, Netherlands, Belgium and Luxembourg). If RPs are adjusted on population, the favourable situation of Netherlands and Luxembourg can be seen in comparison with other countries, showing the significant effort made by their governments in public recharging network. Considering population-adjusted RP densities in 2020, well positioned in terms of RP deployment are also, in decreasing order, Denmark, Sweden, Belgium, Malta and Slovenia.
- The EU27+UK AGR for EVs in the 2016–2030 period ranges between 35.5% and 41.3%, while the AGR for RPs is definitely lower, ranging between 30.1% and 32.8%. This result shows that future plans of these countries on average foresee a more pronounced development of electric vehicles compared to the corresponding public infrastructure. It is worth mentioning though that this could be also due to the increasing recharging power of the RPs foreseen in the future (and the increasing private recharging points). The no-border case has the lowest AGR values, both for EVs and RPs, indicating that a lower paced deployment of electromobility is obtained when considering EU27+UK as a whole.
- In terms of sufficiency index, the overall EU27+UK situation that includes country influences is moving from an ‘adequate’ balance between EVs and RPs in 2018 (average values ranging between 5 and 10) to a progressively higher ratio towards 2030, with average values ranging from 25 to 35 in 2025 and from 40 to 50 in 2030. In the no-border case, when the countries’ individual values of the index do not influence the results, the situation is significantly different with overall index values below 15 for both 2025 and 2030.

In the case of RPdens and Is, the outliers are particularly extreme and the effect of their treatment is highly visible at EU27+UK level; thus, the average values are strongly influenced by the weightings considered.

The no-border results show the drawbacks of setting goals at EU level, since they could easily be reached due to the considerable effort made by a few countries but they might not represent an adequate and balanced electromobility deployment at country level.

This study proposed the use of several indicators to evaluate EV and RP deployment. The analysis of each indicator considered alone does not allow to obtain a complete picture of the situation, but the combination and adjustment of the proposed indicators do provide useful insights into the current EU perspective regarding electromobility by including the influence of different national specificities. While this analysis brings valuable information for national and European wide strategies and policies, to support decisions at regional and city level more studies at a higher geographic resolution level would be needed. In this case, the inclusion of an adjustment by local population density as indicator might bring additional useful insights.

The methodology to evaluate the electromobility trends proposed in this paper can be used when the new set of NIR data will be provided by the Member States in the next reporting period.

The limitations of our study are of two species: first, there are limitations related to some requirements and initial assumptions in the Directive on the evolution of the alternative fuels technologies that have not remained robust with time; the second type of limitations is represented by the missing values in the initial NIR data set and the disharmony among MS for some of the available data, with the unavoidable uncertainty in the creation of the complete data set. This is particularly valid for RPs, where a higher share of missing values was found and the distinction between stations and points was not always clear.

We have attempted to cope with both types of limitations by highlighting the elements of the Directive that needed a policy and technological update, and by analysing the initial and complete NIR data sets in order to help shed a light on the impact of the Directive towards the achievement of the new and more ambitious 2025 Green Deal and 2030 Mobility Strategy goals.

For example, the ratio of 10 EVs per RP given as an indication by the Directive (recall the 'EU-wide patterns and trends in the 2016–2030 period' section) has been put to test in this work with historical data and future values. The results of the Is analysis indicate that the ratio can vary widely by country and year. Moreover, the ratio of 10 is seldom consistently attained by the examined countries. The sufficiency index is a simple parameter based only on the absolute numbers of EVs and RPs and it is unable to capture the technological developments that occurred since it was recommended in 2014. Therefore, the results of this study confirms the policy direction presented in the Alternative Fuels Infrastructure Regulation (EC, 2021a). This paper also supports the need for new policy measures supporting a faster uptake of recharging infrastructure to ensure that it does not greatly lag behind EV fleet growth.

This study has shown that the approach contained in the Directive, which basically provided Member States with a high margin of free initiative in the set up and development of their alternative fuels uptake strategies needs to be revisited as to better reflect and capture the increased ambition of the European Union in terms of electromobility development, and more in general in terms of decarbonisation towards 2050. Our results thus confirm the introduction of a new approach to define the minimum infrastructure needs in the Alternative Fuels Infrastructure Regulation, for example a more refined and complex dependency between EVs and RPs, like a minimum recharging power of the infrastructure per vehicle, a differentiation between BEV and PHEV energy needs, a minimum distance criterion of the RPs distribution on the TEN-T network and a differentiation in terms of recharging need for light duty and heavy duty vehicles.

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Author contributions Alessandro Marotta: validation, writing—review and editing, Chiara Lodi: conceptualisation, methodology, formal analysis, writing—original draft. Andreea Julea: conceptualisation, methodology, validation, writing—review and editing. Jonatan Gómez Vilchez: validation, writing—review and editing.

Data availability The datasets generated and/or analysed during the current study will be available in a publicly accessible repository. The repository will be the Joint Research Centre Data Catalogue-Transport Alternative Fuels Infrastructure Data Collection, available at the following link: https://data.jrc.ec.europa.eu/collection/id-00352.

Declarations

Competing interests The authors declare no competing interests.

Appendix

Identification and treatment of outliers within the data imputation process

During the data imputation process, an extreme value analysis was performed based on the exponential evolution trend dataset (i.e. annual growth rates (AGRs) of the countries defined in the 'Overall approach' section), containing the countries that provided 2025 and 2030 values in their NIRs and thus these values were not obtained by interpolation or extrapolation. Using this analysis and the determination of the permitted interval, it was possible to verify if the AGRs used to obtain extrapolated values represent outliers for the AGR data set computed for the countries were the NIRs values were provided and imputation was not needed.

The selection criterion for outliers was based on AGR interquartile range analysis.

The identified AGR outliers were replaced with values corresponding to AGR calculated with the EAFO 2020 real values instead of NIR 2020 planned values. Only one outlier was identified and treated (i.e. the AGR for Poland's RPs).

Corrections of the data provided by the countries

The NIR information provided by some countries were corrected to ensure consistency within each data category according to the definition of the respective category. In particular, the NIR data corresponding to the EV category were corrected based on other available information for certain years for three countries (i.e. Bulgaria, Netherlands, and Romania). It was considered that the NIR values provided by Bulgaria and Romania for EV category contained also the values for hybrid electric vehicles (HEVs) and consequently a correction was applied by subtracting the HEVs values (according to the definition used in this study the EV category contains only BEVs and PHEVs). In the case of the Netherlands, the EV corrected values concerned only the years 2025 and 2030. Netherlands provided numeric estimates for these years that correspond only to BEVs. The decrease of 2% per year of the number of PHEVs for the 2018–2019 interval that was presented in the NIR was assumed to continue in the following years. This allowed adding the contribution of the PHEVs for the EV estimates corresponding to 2025 and 2030.

Pattern of the exponential evolution type for Annual Growth Rate

When the EV and RP evolution type is exponential, the normal exponential function under its form $f(x) = ae^{kx}$, employed in situations of continuous growth or decay, can be considered. If a quantity grows continuously by a fixed percentage r (i.e. growth rate), the pattern can be depicted by the following:

$$f(x) = ab^x = ae^{kx} = a(1 + r)^x \tag{5}$$

where:

a = initial value
b = base
x = exponent (i.e. year)
k = constant of proportionality
r = growth rate, where $r = e^k - 1$.

Detection and treatment of outliers for indicators

Interquartile range (IQR) analysis was performed to evaluate the spread of the distribution.

$$IQR = 75th\ percentile - 25th\ percentile \tag{6}$$

Extreme outliers were detected as values outside the following boundaries:

$$UB = 75th\ percentile + IQR \times 3 \tag{7}$$

$$LB = 25th\ percentile - IQR \times 3 \tag{8}$$

Where:

UB = Upper boundary
LB = Lower boundary

The detected outliers were replaced by the corresponding UB and LB values.

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