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Economic and environmental sustainability of Dynamic Wireless Power Transfer for Electric Vehicles supporting reduction of local air pollutant emissions

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Abstract

In recent years, Dynamic Wireless Power Transfer (DWPT) technology has gained interest within the market of charging systems for electric vehicles. This technology can potentially boost the diffusion of electric vehicles (EVs) and consequently contribute in reducing the local air pollution and the related externalities.

In this context, an environmental and economic analysis has been performed to estimate the social costs saving derived by the decarbonization of the passenger cars mobility. The benefits evaluated in the analysis are compared to the investment and maintenance costs necessary to install and operate a DWPT infrastructure. This under the basic assumption of the present work that considers the widespread adoption of electric vehicles achievable only in presence of the parallel integration of DWPT systems in the motorway infrastructure. At the same time, the work takes into account the possible variations of the energy mix and the effects related to the increase of the electric energy demand related to the increase of the

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circulating electric vehicles.

The analysis is carried out for the six most populous European countries (i.e. Italy, France, Germany, Poland, Spain and UK) and it indicates as the estimated social costs savings are capable to sustain the investment for a wide integration of DWPT in almost all these countries.

Keywords: Electric Vehicles, Wireless Power Transfer, Externalities, Local Pollutants

Nomenclature and units

A_f	equivalent frontal area of the vehicle $\left(\mathrm{m}^2\right)$
C	specific energy consumption for electric vehicles (kWh/km)
C_r	rolling resistance coefficient
C_x	drag coefficient
CF	cash flow (€)
d_V2V	average vehicle-to-vehicle distance (m)
$d_{y,j}$	average yearly distance travelled by a car passenger in j-th country (km)
$\Delta E_{c,i,j}$	yearly reduction of i-th pollutant emitted by passenger cars in j-th country(t/year)
$\Delta E_{ep,i,j}$	yearly increase of i-th pollutant emitted by power plants in j-th country(t/year)
$E_{c,i,j}$	yearly emission of i-th pollutant emitted by passenger cars in j-th country(t/year)
$E_{ep,i,j}$	yearly emission of i-th pollutant emitted by power plants in j-th country(t/year)

$EF_{c,i,j}$	emission factor of i-th pollutant emitted by passenger cars in j-th country (kg/km)
$EF_{ep,i,j}$	emission factor of i-th pollutant emitted by power plants in j-th country (kg/kWh)
EV	electric vehicle
$EC_{c,j}$	external costs reduction due to decarbonization of mobility in j-th country (€)
$EC_{ep,j}$	external costs increase due to the growth of electricity demand in j-th country (€)
η_{DWPT}	efficiency of the dynamic wireless power transfer system (%)
$\eta_{g,j}$	efficiency of the national electricity grid in j-th country (%)
$\eta_{ep,j}$	average efficiency of the thermal power plants in j-th country (%)
η_{tr}	power train efficiency (%)
g	gravitational acceleration m/s^2
k	fraction of the registered passenger cars replaced by electric vehicles
k_v	fraction of vehicles with internal combustion engine substituted by electric vehicles
I_t	investment costs on DWPT infrastructure in the year (€)
IR	inflation rate (%)
m	mass of the average vehicle (kg)
$N_{v,j}$	number of passenger cars registered in j-th country

NPV	net present value (€)
N_{EV}	number of vehicles per kilometer of DWPT charging lane
$OPEX$	operation and maintenance costs (€)
P_{DWPT}	maximum power absorbed by a single active DC/AC supplying a transmitter coil (kW)
P_{EV}	power requested by the electric vehicle during motion (kW)
$P_{y,j}$	yearly gross electricity production in j-th country (kWh)
r	real discount rate
ρ_{air}	air density $\left(\mathrm{kg/m^3}\right)$
$S_{solid,j}$	share of solid fossil fuels on the energy mix in j-th country (%)
$S_{oil,j}$	share of oil on the energy mix in j-th country (%)
$S_{gas,j}$	share of natural gas on the energy mix in j-th country (%)
$S_{FF,j}$	share of fossil fuels on the energy mix in j-th country (%)
SCS_j	social costs saving in j-th country (€)
SDR	social discount rate (%)
v	vehicle speed (m/s)

1. Introduction

Fossil fuels played a key role for the economic growth in all countries of Europe since the first industrial revolution. Nowadays, despite an increase of the share of renewable sources, the dependence on these non-renewable remains still relevant in the European Union (EU) [1]: fossil fuels share has still accounted for around 72% of the primary energy source demand in 2016, showing a decline from the 78% of 2005. This dependance has remained particularly relevant in the transport sector [2] for which final energy consumption of petroleum products accounts for around 78.8%.

This has led to an evident increase of air pollution [3] that is having a significant impact on environment and human health causing the raising of the average temperature of the Earth's surface, the growth of the acid rain phenomenon, bioaccumulation in organisms, eutrophication of water and the increase in the incidence of diseases and tumors with consequent reduction in life expectancy [4, 5]. The transport sector contributes considerably to air pollution, especially in urban and densely populated areas, in an extent that depends on the considered pollutant [6, 7, 8].

Consequently, a strategy for phasing out from fossil fuels is becoming urgent. In this direction, the electrification of the private transport sector is seen as a possible solution for the mitigation of air pollution effects due to mobility. In this view, electric vehicles (EVs) represent the most interesting solution as, with respect to cars equipped with internal combustion engine (ICE), do not give rise to any emissions while circulating. However, the numbers of EVs still represent a negligible share of the present car's global market. Despite in the period from 2013 to 2017 the number of EVs in the European Union (EU) increased from 0.25 millions to approximately 2 millions, this represents only the 0.8% of the cars registered in the EU Member States [9]. The two main causes of this limited diffusion are represented by the low energy density of the batteries and the lack of charging infrastructures supporting the needs of electric mobility [10, 11]. Indeed, while the present ranges offered by electric cars are suitable for the adoption in an urban environment, they are still not adequate to cover long distances. In fact, one of the main barriers to the social acceptance of EVs is still represented by the needs of long and frequent stops for the recharge and the so-called range anxiety i.e. the feeling to do not have enough energy to reach the destination [11, 12, 13]. Hence, an infrastructures supporting long trips is fundamental.

A novel charging technology to foster a large EV diffusion and overcome the pointed out problems is represented by Dynamic Wireless Power Transfer (DWPT) technology [14, 15, 16]. DWPT is based on the magnetic coupling between coils installed under the ground level, called the transmitters, and a coil mounted under the vehicle floor, called the receiver, connected to the vehicle battery by means of a power electronics converter. Thanks to the absence of electric contacts, DWPT allows powering the EV while driving eliminating the necessity of stops for the recharge. The integration of charging lanes based on DWPT in motorways together with an appropriate diffusion of charging points in urban roads, would definitely support the widespread adoption of electric vehicles.

Nevertheless, a wide adoption of DWPT technology can take place only if its sustainability from the economic and environmental point of view is demonstrated. This paper intends to investigate the sustainability of the integration of a DWPT charging lane in the motorway infrastructure through a social costs saving analysis. The sustainability is based on a cost-benefit analysis, comparing the cost for the implementation of a DWPT infrastructure with the benefits, in terms of external costs, derived by the decarbonization of the private mobility.

The evaluation of external costs is based on an existing methodology developed by the European Commission and called ExternE (External Costs of Energy) [17]. This approach was already used in literature to evaluate the impact of vehicle circulation on the environment and human health. For example, the competitiveness of different powertrain/fuel options, including EVs, were performed in [18] by considering the external costs calculated by the ExternE approach. However, in this latter work, the EU context is analyzed considering average conditions and not differentiating them country by country. Another example of the ExternE approach is shown in [19] where the decrease of external costs due to EVs circulation is evaluated for Germany by considering the share of renewable energy sources (RESs) in the electricity generation.

Differently from these examples, the decrease of external costs is used in this paper to evaluate the sustainability of the DWPT diffusion in some of the most populous EU countries: France, Germany, Italy, Poland, Spain, Sweden and UK. This country-by-country analysis allows to explore the results on different contexts of electricity generation mix, extension of motorway infrastructure and air pollution conditions.

2. Local air pollutants and DWPT sustainability

All combustion processes release pollutants into the atmosphere. The two main processes taken into account in the studied landscape have been the electricity production in power plant and the combustion of the vehicle engines.

The pollutant emissions determine a deterioration of the air quality. Depending on the type, the concentration in the environment and the duration of exposure, the presence of pollutants can cause medium or long term damages to human health [20] and to other living organisms as well as to the overall ecosystem [5, 21]. The main pollutants considered in this study are:

- Carbon monoxide (CO)
- Sulfur oxides (SO_x)
- Nitrogen oxides (NO_x)
- Ammonia (NH_3)
- Atmospheric particulate matter generally known as particulate matter (PM)
- Non-methane volatile organic compounds (NMVOC)

The sustainability of the DWPT technology is based here on a cost-benefit analysis comparing the cost of the implementation of this system with the benefits derived by the electrification of the light-duty private transport sector. The starting assumption moves from the consideration that the acceptance of the consumers towards the purchase of electric vehicles, even in urban areas, cannot prescind from the existence of an infrastructure allowing to use the same vehicles also for long-distance trips. Hence, the analysis stems from considering that, the possible increase of electric vehicles due to the diffusion of DWPT and the corresponding reduction of conventional vehicles with internal combustion engine, can strongly contribute to reduce the local air pollution and, consequently, the related social costs (i.e. negative externalities). This assumption easily applies to urban areas. In fact, even if an increase of electric vehicles would mean an increase in the production of electric energy, the pollutant emissions by electricity generation takes place in less densely populated areas where power plants are usually installed. Besides, energy mix based on high share of non-emitting power plant, like renewable energy sources (RES), can further contribute to reduce externalities. Consequently, the sustainability of EV diffusion through the adoption of DWPT is calculated here as the net difference between the social costs reduction due to the electrification of mobility and the increase of the externalities, due to the growth in the electricity consumption. If this difference is positive, the electrification of transports based on the integration of DPWT can be considered sustainable from a social costs point of view. In other words, this would mean that the reduction of air pollution concerned to mobility justifies the increase of electricity demand due to the growth of the number of circulating electric vehicles.

In this context, the costs for the transition from conventional mobility to electromobility as well as the maintenance costs of electric vehicle battery are supposed to be charged to the cars' owners and not included in the analysis. Similarly, environmental pollution cost of discarded battery are not considered here, since second-life is supposed for the EV battery to be used in stationary application as energy storage [22].

In this light, the evaluation of the emissions due to both transport sector and electricity production is crucial as it allows to quantify the aforementioned social costs for the transport and the electricity production sectors.

2.1. Pollutant emissions of passenger cars

The circulation of around 257 million of private cars was observed in the EU during 2016 [23]. Approximately 53.9% of these vehicles were fed by petrol and 42.0% by diesel. The remaining 4.1% was represented by hybrid, electric and methane or LPG fueled vehicles. This car fleet significantly contributes on air pollution in urban areas, since main pollutants emitted by road transports, i.e. NO_x and CO, represent respectively around 39% and 20% of total emissions of all other sectors (e.g. industry, buildings, etc.)[24]. In this context, the electrification of passenger cars can lead to a reduction of these emissions consequently favoring the decrease of negative externalities.

The evaluation of the social costs reduction is based on the identification of the emission factors defined as the unitary emission of a given i-th pollutant per each kilometer of distance travelled. In this paper, a simplified approach is used where each emission factor EF_c is calculated for passenger cars as the ratio between the total yearly emission of a given i-th pollutant and the overall average distance travelled by all the passenger cars circulating in a certain country, as follows:

$$\overline{EF}^{(0)}_{c,i,j} = \frac{E^{(0)}_{c,i,j}}{N^{(0)}_{v,j} \cdot d_{y,j}} \tag{1}$$

where $E^{(0)}_{c,i,j}$ is the annual emission of a given i-th pollutant, $N_{v,j}$ is the total number of passenger cars registered in the j-th country and $d_{y,j}$ is the average distance travelled by a passenger car in j-th country. Basically, equation (1) assumes that each emission factor represents the pollutant emitted by an average equivalent (i.e. representative) passenger car for each travelled kilometer, in the reference year fixed here at 2016.

Data about the yearly emissions for each main pollutant due to passenger cars at the reference year are reported in the emission inventory of the European Environment Agency (EEA) available at [25] for each j-th EU country. Clearly, each country has a different mix of circulating vehicles differing in fuel type, registration year, etc., as well as different average distances travelled by passenger cars. This mirrors in the emission factor of a given pollutant that can differ, even significantly, country by country as reported in Table 1 for the reference year. Countries with a similar circulating fleet of vehicles $N_{v,j}^{(0)}$, for instance, can potentially have different yearly emission of a given pollutant $E_{c,i,j}^{(0)}$ due to either different average age of vehicles or a different share of diesel-fueled and petrol-fueled cars. Data about the average distances d travelled by an average passenger car in the considered countries and the number of passenger cars $N_v^{(0)}$ registered in each country are reported in Table 2.

Table 1: Calculated emission factors of the main air pollutants at reference year (2016) for an average vehicle by countries.

	CO (mg/km)	**NMVOC (mg/km)**	**NO_x (mg/km)**	**NH_3 (mg/km)**	**$PM_{2.5}$ (mg/km)**	**PM_{10} (mg/km)**	**SO_x (mg/km)**
France	455.46	45.64	547.08	8.09	26.50	26.50	1.15
Germany	823.87	89.34	392.98	18.03	5.94	5.94	0.82
Italy	632.78	59.08	366.04	12.52	12.12	12.12	0.57
Poland	2752.73	290.05	594.16	29.53	24.50	24.50	0.002
Spain	291.52	27.17	519.80	7.95	14.13	14.13	0.86
UK	517.00	28.70	356.67	9.73	7.05	7.05	2.47

Once the emission factors are identified for the time $T = 0$ fixed at 2016 (i.e. the reference year), the reduction of pollutant emissions due to the substitution of the ICE passenger cars with electric cars can be calculated

Table 2: Number of registered passenger cars and average travelled distances by countries [23, 26].

	$N_v^{(0)}$ (Millions)	d (km/year)
France	31.9	13000
Germany	45.1	14100
Italy	37.9	11125
Poland	20.7	6670
Spain	22.3	12500
UK	33.5	13200

by a lineaer equation for each air pollutant in each target year T, as follows:

$$\Delta E_{c,i,j}^{(T)} = \overline{EF}_{c,i,j}^{(0)} \cdot d_{y,j} \cdot k_v^{(T)} \cdot N_{v,j}^{(0)} \tag{2}$$

where $k^{(T)}$ is the fraction of substituted vehicles at the target year T. The multiplication of the last three factors in eq. (1) represents the yearly distance travelled by the circulating fleet that will be covered by electric cars in the target year T, by assuming unchanged the driving patterns (i.e. drivers' habits) of passenger cars. Moreover, the emission factors calculated using eq. (1) have been assumed unchanged at each target year T, since the progressive replacement of ICE vehicles with EVs is supposed to involve only cars having the same average emissive characteristics of those registered at the reference year. Of course, the higher is the fraction of the passenger cars replaced with electric vehicles, the higher is the reduction of pollutant emissions. The emission reduction can be finally used to evaluate the external cost avoided in each target year T thanks to the electrification of passenger cars.

2.2. Pollutant emissions of the electricity production

Conventional power plants for electricity production are still diffusely fed by fossil fuels and they generate almost half of the electric energy (about 48.7%) in the 28 EU countries [27]. The electric energy production is responsible for pollutant emissions which account for more than half of the total SO_x, around 19% of NO_x and around 4% of PM emissions [6]. The impact of these pollutants on environment and human health produces negative externalities that need to be taken into account when electrification of transport sector is analyzed.

Similarly to the approach proposed for the transport sector, the analysis of the social costs related to electric power generation is based on the definition of the emission factor EF_{ep} for each i-th pollutant. In this case, the emission factor represents the unitary emission of a given i-th pollutant per each kWh of electricity generated by fossil fuel power plants, calculated as follows:

$$\overline{EF}^{(0)}_{ep,i,j} = \frac{E^{(0)}_{ep,i,j}}{P^{(0)}_{y,j}} \tag{3}$$

where $P_{v,j}$ is the yearly gross electricity production in the j-th country. Data about the yearly emissions for each main pollutants $E_{ep,i,j}$ due to electricity production are still reported in [25], while data on electricity production by country are presented in [28]. Even in this case, 2016 is considered the reference year ($T = 0$). There is a significant variation in the emission factors calculated country by country, as reported in Table 3, since each country has a different share of electricity generation by fossil fuels and a different share of renewable energy sources (RES). In other words, countries can have different early emission $E_{ep,i,j}$ at fixed yearly gross electricity production $P_{v,j}$

due to how the electricity is produced (i.e according to the primary energy resources used to produce electricity).

Table 3: Emissions factors $\overline{EF}^{(0)}_{ep,i,j}$ of the main air pollutants for electricity production by countries in 2016.

	CO (mg/kWh)	**NMVOC** (mg/kWh)	$\mathbf{NO_x}$ (mg/kWh)	$\mathbf{NH_3}$ (mg/kWh)	$\mathbf{PM_{2.5}}$ (mg/kWh)	$\mathbf{PM_{10}}$ (mg/kWh)	$\mathbf{SO_x}$ (mg/kWh)
France	360.73	12.89	512.17	16.72	28.38	34.46	141.03
Germany	324.08	23.19	646.23	4.44	19.68	21.74	412.64
Italy	104.07	13.11	169.11	0.80	2.28	3.37	61.13
Poland	342.89	27.16	1280.89	0.00	84.79	143.17	1822.79
Spain	202.18	47.20	799.18	0.13	31.63	43.05	736.24
UK	203.33	9.35	589.21	0.85	12.79	15.67	172.50

Once the emission factors are identified for the reference year, the emission increase owing to the substitution of ICE passenger cars with EVs is calculated, for each air pollutant, in a given target year T. Basically, these emissions are evaluated by a simplified approach where the reference emission factors calculated by (3) are opportunely rescaled in order to take into account the yearly variation of the efficiency in electricity production by thermal power plant, the yearly variation of the share of RES and the share of non-RES production with respect to the reference year. Consequently, the evaluation of the emission increase for CO, NMVOC, NO_x, $PM_{2.5}$, PM_{10} and SO_x is calculated, as follows:

$$\Delta E^{(T)}_{ep,i,j} = \frac{C}{\eta_{g,j} \cdot \eta_{DWPT}} \cdot \overline{EF}^{(T)}_{ep,i,j} \cdot d_{y,j} \cdot k^{(T)}_{v} \cdot N^{(0)}_{v,j} \tag{4}$$

with:

$$\overline{EF}^{(T)}_{ep,i,j} = \overline{EF}^{(0)}_{ep,i,j} \cdot \frac{\eta^{(0)}_{ep,j}}{\eta^{(T)}_{ep,j}} \cdot \left(\frac{\omega_{i,solid} S^{(T)}_{solid,j} + \omega_{i,oil} S^{(T)}_{oil,j} + \omega_{i,gas} S^{(T)}_{gas,j}}{\omega_{i,solid} S^{(0)}_{solid,j} + \omega_{i,oil} S^{(0)}_{oil,j} + \omega_{i,gas} S^{(0)}_{gas,j}} \right) \tag{5}$$

$$\omega_{i,oil} + \omega_{i,gas} + \omega_{i,solid} = 1 \qquad \forall i \tag{6}$$

where C is the per unit electricity consumption required by an electric vehicle for traveling, $\eta_{g,j}$ is the efficiency of the national electricity grid, η_{ep} is the efficiency of the thermal power generation, η_{DWPT} is the efficiency of the DWPT system, and S_{solid}, S_{oil} and S_{gas} are the shares of non-RES production by fuel type.

Differently from eq. (2), the simplified approach proposed in (4) assumes a variation of the reference emission factors $\overline{EF}^{(0)}_{ep,i,j}$, in the target year T. In fact, the primary energy resources used to produce electricity in a country can change along the years according to national policies introduced by Governments for the reduction of pollutants emission. Similarly, technology development in the electricity sector can improve the efficiency of the thermal power plants reducing the pollutants emitted at fixed gross production.

The variation of $\overline{EF}^{(0)}_{ep,i,j}$ proposed in eq. (5) is influenced by the variation of all those parameters impacting the pollutants emission by thermal power plants. The variation of the efficiency of the thermal power generation with respect to the reference year is taken into account in eq. (5) by the ratio $\eta^{(0)}_{ep,j}/\eta^{(T)}_{ep,j}$. In fact, the improvement of η_{ep} can reduce emission at fixed primary energy consumption, and vice versa. Instead, the last ratio proposed in (5) allows to rescale the reference emission factor of each pollutant $\overline{EF}^{(0)}_{ep,i,j}$ according to the possible variation in the mix of the non-renewable primary energy resources used to produce electricity in each target year T. For this reason, the weights ω_{solid}, ω_{oil} and ω_{gas} have been introduced in (5) to take into account the influence of each fuel type in the emission of a given i-th pollutant. These weights have been extrapolated by analyzing the emission factors of the main electricity generation systems fed by different primary sources consisting of fossil fuels [29] and are summarized in Table 4.

Table 4: Weights for the products of combustion (pollutants) by fuel type. Source [29].

	CO	**NMVOC**	$\mathbf{NO_x}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$	$\mathbf{SO_x}$
$\omega_{i,solid}$	0.1385	0.1695	0.4750	0.1441	0.2279	0.6235
$\omega_{i,gas}$	0.6210	0.4407	0.2023	0.0377	0.0263	0.0002
$\omega_{i,oil}$	0.2405	0.3898	0.3227	0.8182	0.7458	0.3763

It is worth nothing, in fact, that SO_x emission is mainly related to the combustion of solid fossil fuel, like coal, instead of natural gas which is mainly responsible for carbon monoxide emissions. Each weight is then multiplied in eq. (5) by the share S of the corresponding non-renewable fossil fuel used to produce electricity in order to reflect energy policy in the in the country. If, for example, national energy targets at the year T are basically oriented in shifting electricity generation from coal to natural gas, the corresponding $S^{(T)}_{gas,j}$ is expected to increase while $S^{(T)}_{coal,j}$ decreases. Similarly, if more gross electricity generation is supposed to be based on RES or nuclear, all the parameters $S^{(T)}_{oil,j}$, $S^{(T)}_{gas,j}$ and $S^{(T)}_{coal,j}$ decreases, up to reach zero in case the entirely electricity production was not baed on fossil fuel. So, the consequent emission of the pollutant in the target year T will be zero.

Differently, the emission of NH_3 due to electricity production is not generally associated to combustion of fuel, but it mainly appears as a result of the incomplete reaction in NO_x abatement systems [29]. So, the emission increase for ammonia is calculated as follows:

$$\overline{EF}^{(T)}_{ep,i,j} = \overline{EF}^{(0)}_{ep,i,j} \cdot \frac{S^{(T)}_{FF,j}}{S^{(0)}_{FF,j}} \tag{7}$$

where $S_{FF,j}$ is the fraction of gross electricity production generated by power plants fed by fossil fuel where NO_x abatement systems are typically installed. Consequently, $S_{FF,j}$ can be assumed, as follows:

$$S_{FF,j}^{(T)} = S_{oil,j}^{(T)} + S_{gas,j}^{(T)} + S_{coal,j}^{(T)} \tag{8}$$

It can be noticed from Table 5 that $S_{FF,j}$ differs, even significantly, country by country. In some cases, this difference is due to relevant generation by nuclear power plants or RES that are not fed by fossil fuels and consequently free of pollutant emissions. If, the gross electricity production was entirely based on RES or nuclear, in the target year T, the corresponding ammonia emission factor decreases to zero in eq. (7).

Table 5: Fossil fuels share by country at the reference year T=0 (2016). Source [28].

	France	**Germany**	**Italy**	**Poland**	**Spain**	**UK**
$S_{FF,j}^{(0)}$ (%)	10	64	68	90	41	63

The adopted values for $\eta_{g,j}$ in the different countries are based on data retrieved from [30] and reported in Table 6. According to the data provided in [15, 31] and considering the indications provided by the SAE J2954 and IEC 61980 standards related to static WPT [32, 33], a precautionary value of 80% is assumed for the efficiency of the DWPT system. The per unit consumption of electric vehicle C is considered constant at 0.15kWh/km, as extrapolated from [34].

Table 6: Efficiency of transmission and distribution electric grid by country. Source [30].

	France	**Germany**	**Italy**	**Poland**	**Spain**	**UK**
$\eta_{g,j}$ (%)	93.6	96.2	93.5	93.5	90.3	92.2

The increase of emission calculated by (4) and (5) can be finally used to evaluate the additional social costs due to the electrification of passenger cars.

3. External cost assessment

The externalities due to the polluting substances emitted by the power plants and the private transports, are costs that are typically not incurred by the owners of the power plants or the owners of the ICE vehicles, but they are spread over the entire population. Consequently, the present level of air quality in urban areas is having serious and relevant impact on the public spending. In fact, the pollutant emissions in populated areas has a social impact in terms of increased costs due to respiratory hospital admissions, cases of chronic bronchitis, cancer, etc. However, external costs are not easy to be estimated, since numerous uncertainties connected to the complex ”monetization” of factors, such as damage to the human health and the environment, need to be taken into account.

With a series of projects starting from the 90s, the European Commission has set up the *ExternE* methodology [17] for assessing, in a standardized way, the external costs associated to the production of electricity, heat and the transport sector. The method is based on the Impact Pathway Approach (IPA), where benefits and costs are estimated by identifying the changes in health and environment caused by the emissive sources (see Fig. 1). Finally, all these changes are expressed in a monetary form. By following the IPA, all the quantities of pollutants emitted are evaluated taking into account the geographical location of the sources, weather conditions, type of fuel used, efficiency of the plants and presence of abatement systems. Subsequently, models of dispersion in the atmosphere are used to determine in detail the transport of pollutants and to identify their concentration in the environment. Then, damages to human health and environment are modeled using dose-damage functions and calculated using data on exposure and concentration in the environment. These models determine how the incidence rate of diseases changes following a variation of the concentration of harmful substances in the air. Finally, the physical impacts are evaluated in monetary terms, in order to obtain a total final value of external costs [17, 35].

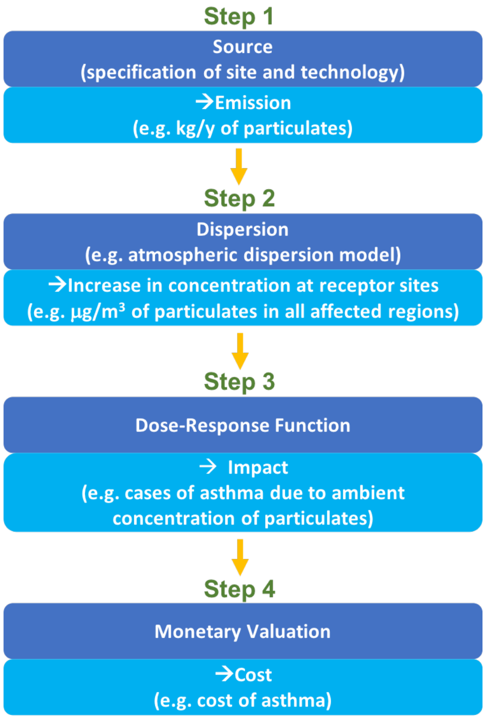


Figure 1: Steps within the IPA analysis. Source: [17, 35]

3.1. EcoSenseLE

The models and data of the ExternE projects have been integrated in the web calculation tool EcoSenseLE (Light Edition). This tool, available online [36] is the instrument adopted in the present work to provide assessments, from an economic point of view, of the impacts on human health and environment related to pollution in the framework of the analyzed scenarios. EcoSenseLE [36] includes the IPA and is consequently capable to monetize the impact of pollutant emissions.

The use of the EcoSenseLE tool is articulated in three steps. The first one defines the main information useful in creating a new scenario by choosing between three different options:

- *additional emissions*, where the level of emissions are increased with respect to a reference scenario to calculate the related damages;
- *reduced emissions*, where the monetary savings due to the reduction of emissions is quantified on a national scale;
- *emissions from point sources*, where the economic impact caused by an emissive point-source is calculated.

According to the context analyzed in this paper, the *reduced emissions* option has been adopted to evaluate the external cost reduction due to the electrification of passenger cars. On the other hand, the *additional emissions* option has been used to evaluate the external cost increase due to the growth of electricity consumption in decarbonizing the considered portion of the private transport sector.

In the second step, the values in annual metric tons of pollutants are entered by distinguishing between emissions at *high altitude*, at *low alti-*

tude. High altitude identifies emission sources located at higher positions like power stations with high stacks, while low altitude refers to emission sources closer to the ground level like cars. In this light, the latter option has been used to represent the pollution due to vehicular traffic, while the former option has been used as representative for electricity generation.

In the last step, the total cost related to externalities is provided in output, divided in damage to human health, impact on crops and materials, effects on the ecosystem. This monetary value corresponds to the total cost for a scenario with additional emissions, while it represents the overall savings in case of a scenario with reduced emissions.

3.2. Evaluation of social costs saving

In a first phase, EcoSenseLE is used to evaluate, in each target year T, the avoided external costs due to the replacement of ICE cars with electric ones. The corresponding emission reduction calculated by (2) is monetized by considering the vehicular traffic spread over the whole country and by assuming at low altitude the sources location. Specifically, EcoSenseLE web tool subdivides emissions at low altitude in two further different categories: emissions in rural areas and emissions in urban areas. This further subdivision allows to specify which parts of the pollutant emissions due to vehicular circulation take place in densely populated areas (i.e. urban areas) or not (i.e. rural areas). According to this subdivision, the distribution of the population by degree of urbanization [37] has been used to define how to share the avoided emission calculated by (2) in urban and in rural area for each country (see Table 7).

In the second phase, the increase of externalities due to the growth in the electricity consumption for suppling electric vehicles is calculated for

Table 7: Distribution of population by degree of urbanization. Source [37].

	Urban (%)	**Rural (%)**
France	65.0	35.0
Germany	76.8	23.2
Italy	84.5	15.5
Poland	57.7	42.3
Spain	73.6	26.4
UK	86.4	13.6

any target year T. In this case, the increase of emissions calculated by (4) and (5) is monetized by considering at high altitude the emission point for the power stations.

The difference between the externalities obtained in the first and the second phase represents the potential costs saving achievable by electrification of the passenger cars in a given target year T, as follows:

$$SCS_j^{(T)} = EC_{c,j}^{(T)} - EC_{ep,j}^{(T)} \tag{9}$$

where $EC_{c,j}$ represents the avoided external costs due to the replacement of ICE cars with electric ones in the given j-th country, while $EC_{c,j}$ represents the additional external cost due to the increase of electricity consumption due to the electrification of passenger cars. If $SCS_j^{(T)}$ is positive, this implies a net final social costs saving. Vice versa, a negative $SCS_j^{(T)}$ indicates an increase on social costs owing to the electrification of passenger cars.

3.3. Economic sustainability of DWPT

The social costs saving calculated as proposed in Section 3.2 for each target year T, represents a potential positive cash flow for each country considered in this paper. This potential positive benefit represents also an additional economic resource for supporting investments in solutions capable to promote the diffusion of EVs. In this paper, this technological solution is represented by the dynamic wireless power transfer.

The economic sustainability of a DWPT system is here analyzed taking into account the investment costs to build the infrastructure as well as the positive cash flows generated by the electrification of passenger cars. According to the Guide to Cost-Benefit Analysis of Investment Projects [38], the Net Present Value (NPV) is considered here as the economic indicator to evaluate the opportunity to invest in DPWT technology, as follows:

$$NPV_j = \sum_{T=0}^{N} \frac{CF_T}{(1+r)^T} \tag{10}$$

where CF_T is the yearly cash flow calculated as the difference between social costs saving SCS, investment cost I_T and operation and maintenance costs $OPEX_T$ at the corresponding target year, as follows:

$$CF_T = SCS_j^{(T)} - I_T - OPEX_T \tag{11}$$

In particular, the cash flow calculated in (11) is actualized in (10) by means of the real discount rate r calculated on the basis of the nominal social discount rate (SDR) including the inflation rate (IR) for a given country, as follows:

$$r = \frac{SDR - IR}{1 + IR} \tag{12}$$

In eq. (12), the SDR has been fixed at 3% for France, Germany, Italy, Spain, Sweden, UK and 5% for Poland according to the suggestion included in the Annex III of the Implementing Regulation on application form and Cost-Benefit Analysis methodology for the programming period 2014-2020 [39]. The inflation rates used for each country have been instead estimated as an average value calculated over the past 10 years [40] and are presented in Table 8. If NPV is negative, the adoption of DWPT infrastructure is not longer justified from the social benefits point of view. Vice versa, if NPV is positive, the investment on DWPT infrastructure is sustainable and the social costs savings self can sustain the diffusion of this technology.

Table 8: Average inflation rate by Country. Source [40].

	France	**Germany**	**Italy**	**Poland**	**Spain**	**UK**
IR (%)	1.35	1.45	1.45	1.93	1.40	2.40

4. DWPT technology and costs

4.1. General description of a DWPT system

In this section the different cost items for the installation of a DWPT system in the motorway infrastructure are analyzed. The provided data stems from previous works oriented to light duty vehicles that took into account the overall cost of the components of a DWPT system as well as the road works and the components for the integration in the motorway infrastructure. The core-components of a DWPT system for EVs are represented in Fig. 2. Each of these systems is developed around the two magnetically coupled inductors, the transmitter placed at the ground level and the receiver mounted under the vehicle floor. The transmitter is powered with a power electronics converter (i.e. a DC/AC converter) providing a high-frequency current that gives rise to a time-varying magnetic field. This magnetic field links with the receiver giving rise to the appearance of an induced voltage at the coil terminals. This induced voltage is managed by one or more power electronics converters, installed on board the vehicle, that allow the flowing of electric current towards the vehicle battery. An AC/DC converter stage has to be adopted in order to rectify the ac signal provided by the electric network and provide the dc signal needed by the on-ground DC/AC converter.

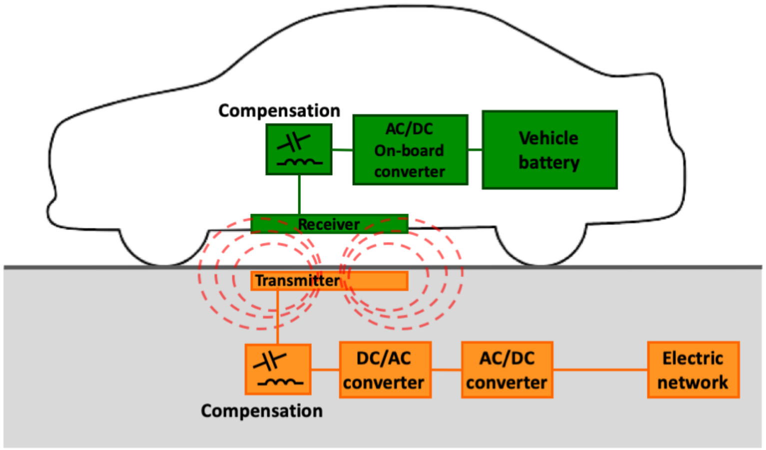


Figure 2: General scheme of the main components of a DWPT system for the charge of electric vehicles.

In order to create a DWPT charging lane, this basic structure has to be repeated several times along the considered path in the motorway infrastructure. In the present work the coils are considered continuously distributed along a dedicated charging lane. It is firm opinion of the authors that this choice is unavoidable if the DWPT infrastructure has to work in support of and in coordination with the urban electric mobility (i.e. the main assumption of the work). A uninterrupted DWPT charging lane guarantees the continuous powering of the EV whose battery state of charge remains unvaried along the motorway path. In this way the stored energy in the EV battery can be used once the vehicle heads out from the motorway and starts to move in the urban area. Once inside the urban area, the driver can reach the final destination eventually using the urban infrastructure for the recharge.

The repetition of the basic elements and the consequent growth of the system length implies the increase of the number of vehicles that can pass above the charging lane asking for the needed power. This calls for the increase of the size of the components that supply the transmitter side. When the overall power level exceeds some decades of kilowatt, the adoption of dedicated power transformers for the connection to the medium voltage (MV) electric grid becomes mandatory for the robust and efficient management of the electric network [41].

Naturally, DWPT technology is still in an early stage and there are not real cases of integration in a motorway infrastructure. This makes hard to find market data related to the cost of the installation. However, there is some prototypal system developed in the view of a real integration in a road infrastructure. Among these, probably the most famous one is the OLEV system developed by the Korea Advanced Institute of Technology (KAIST) [14, 42]. This system is effectively working on an electric bus that operates inside the institute campus. Unfortunately, this system operates at a power level that is not compatible with the levels expected for light duty vehicles. Moreover, the power electronics, as well as the magnetic structure of the OLEV system, are strictly customized and, practically, there is no match between the OLEV structure and components with the ones proposed by the literature and standards on light-duty vehicles. In the present form, these standards refer to static applications (i.e. with the vehicle stopped or parked) but they have been developed in the view of their extension toward dynamic applications. Other systems that investigated the integration of DWPT have been presented in [43, 44]. However, also these systems are oriented to heavy duty vehicles, mainly busses operating in urban areas, and in these cases, there are not still data about costs made available.

The present work takes as a reference, the system developed by the Politecnico di Torino, in Italy, within the European project FABRIC [45]. This system, named PoliTO Charge While Driving (CWD), has been devoted to private transports and oriented to light duty EVs. The PoliTO CWD offers a significant amount of information as it consists in one of the longest DWPT charging lanes (100 meters long) directly integrated in the road pavement in the view of a real integration in the motorway infrastructure. Moreover, this system considers also a dedicated electric network and an ICT infrastructure for the management of the charging process from the booking to the billing [46, 47].

The electrical infrastructure of the PoliTO CWD is sketched in Fig. 3. The connection with the electric grid is made by means of an insulation transformer that supplies a three phase AC/DC converter. This converter provides a stabilized DC voltage distribution line at which all the DC/AC converters supplying the related transmitters are connected. The DC distribution line is made by a buried cable and each DC/AC converter is placed in a dedicated manhole laying aside the equipped carriage way. The real appearance of the integrated system in the road infrastructure is shown in Fig. 4. Together with the electrical infrastructure, the system comprises several actors devoted to the monitoring, the management and the exchange of information. All these components are described in [46, 47] and are not here reported for the sake of brevity.

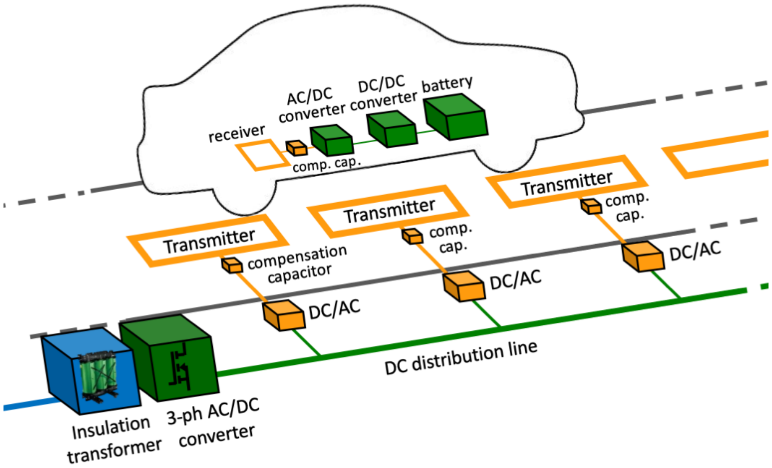


Figure 3: Scheme and components of the electrical infrastructure of the PoliTO CWD system.

In the view of an application in a motorway environment, the structure depicted in Fig. 3 has to be extended. Hence, the length of the charging lane increases together to the number of vehicles that can run above it. This consequently implies a modification in the infrastructure architecture according to the increase of the covered distances, the increase in the power rating demanded to each section of the charging lane and the related increase of the power rate of the converter (i.e. the AC/DC converter) that supplies each section. Naturally, the installation of such an infrastructure requires the complete renovation of the road pavement with milling operations for the construction of the lane in which the transmitter coils and the related cabling are housed, with consequent material handling operations, construction of the new road surface and consequent curing and finishing.

Figure 4: Picture of the PoliTO CWD system. In the picture are visible the shape of the transmitter coils embedded in the road pavement, the boxes containing the DC/AC converters placed outside their manholes, the equipped vehicle.

4.2. Estimation of the cost of the DWPT infrastructure

In order to provide an estimation of the costs of the infrastructure based on DWPT in motorway environment, it is fundamental to investigate which is the power that can be demanded by the system per unit of length of the charging lane.

This quantity is strongly dependent on the power that can be requested by each EV. It is for this reason that the first step of the evaluation starts from the construction of a model for the estimation of the power consumption P_{EV} of an average electric car. The adopted model is represented by the following equation:

$$P_{\mathrm{EV}} = \frac{1}{\eta_{\mathrm{tr}}} \left(m C_{\mathrm{r}} v + \frac{1}{2} \rho_{\mathrm{air}} A_{\mathrm{f}} C_{\mathrm{x}} v^2 \right) \tag{13}$$

It describes a steady-state model of the vehicle that, therefore, considers a constant speed of the vehicle when moving along the charging lane in absence of slope. The model instead considers the two main terms related to the

Table 9: Parameters for the evaluation of the EV's dynamic referred to equation (13).

Symbol	**Description**	**Value**
m	Mass of the average vehicle	2000 kg
g	Gravitational acceleration	9.81 m/s^2
C_r	rolling resistance coefficient	0.008
ρ_air	air density	1.225 kg/m^3
A_f	Equivalent frontal area of the vehicle	2.23 m^2
C_x	Drag coefficient	0.4
η_tr	Power train efficiency	0.8

vehicle inertia and rolling friction of the wheels (first term in brackets) and aerodynamic friction (second term in brakets). For the sake of simplicity, the efficiency η_tr is considered independent of the vehicle speed and takes implicitly into account the power absorbed by the ancillary services that can be usually neglected with respect to the power for traction. The adopted model and the related equation's parameters have been inferred from [15, 48] and are described in Table 9.

According to the European legislation on the driving codes related to the motorway [49], the considered speeds range from 90 km/h to 130 km/h. The resulting power absorbed by the vehicle versus the speed is reported in the graph of Fig. 5. The results provide a maximum power of 42 kW absorbed in correspondence of the maximum speed. By continuing to assume an overall efficiency of the DWPT system equal to 80% (see Section 2.2), this value mirrors in an input power for each active DC/AC converter along the charging lane equal to 52.5 kW. This value is compatible with the ones found in previous works [48, 50].

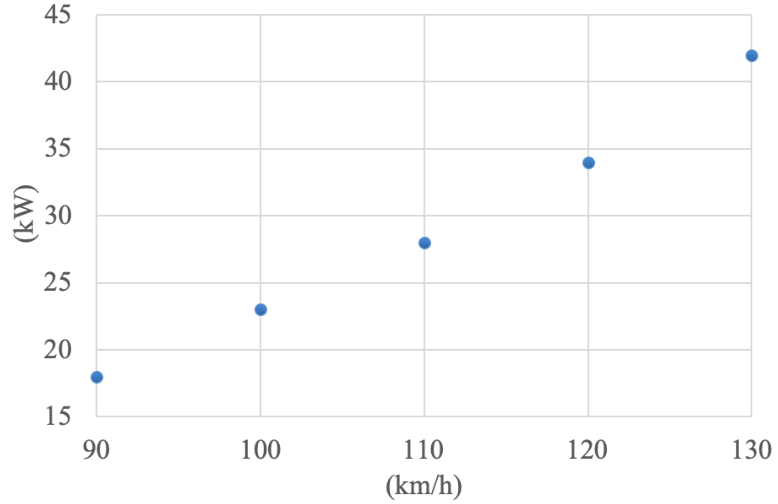


Figure 5: Power required by the EV versus vehicle speed.

The obtained values of power are used as reference to estimate the average power absorbed by the DWPT system in relation to the number of vehicles that can run over a section of the charging lane at a certain speed. This step is carried out by considering that, as suggested by the abovementioned standards on WPT [32, 33] and as actually done in the PoliTO CWD system, the power electronics on board the vehicle controls the system in the way to ask only for power instantaneously needed [51]. The evaluation of the power absorbed by the DWPT system per kilometer is performed by taking into account that, with increasing average speed of the vehicles, there is an increase of the distance that has to be maintained between the vehicles, mainly for safety reasons. The calculation of this distance is mainly based on the vehicle speed but it takes into account different parameters like the typology of the vehicle, the conditions of the tires and the braking system, etc. Moreover the rules among Europe are still not harmonized on this topic. Hence, in this case, a simplified model based on the Italian Driving Code [52, 53] is used in which the vehicle-to-vehicle distance d_{V2V} is evaluated as:

$$d_{\mathrm{V2V}} = \left(\frac{v}{10}\right)^2 \cdot 1\ \frac{\mathrm{s}^2}{\mathrm{m}} \tag{14}$$

The distance d_{V2V} is used to evaluate the number of vehicles N_{EV} per kilometer in function of the average speed of the vehicle as:

$$N_{\mathrm{EV}} = ceil\left(\frac{1000}{d_{\mathrm{V2V}}}\right) \tag{15}$$

The ceiling function is used to map N_{EV} to the least integer greater than or equal to the ration $1000/d_{\mathrm{V2V}}$. This operation matches the physical reality of the problem for which, a transmitter remains active (i.e. powered) until even a portion of the EV is above it. The total electric power P_{DWPT} that has to be provided for each kilometer of charging lane is then obtained as:

$$\text{total } P_{\mathrm{DWPT}} = \frac{P_{\mathrm{EV}} N_{\mathrm{EV}}}{\eta_{\mathrm{DWPT}}} \tag{16}$$

The results of the evaluation are summarized in Table 10. They show that the trend of the required power per kilometer of charging lane versus the vehicle speed is not monotone. As example, the case with vehicles running at 110 km/h is less power demanding than the case with an average vehicle speed of 100 km/h. The worst case remains the one that considers an average vehicle speed of 130 km/h for which a power of 315 kW/km is demanded on the DC side on ground.

On the base of the obtained values of demanded power, the evaluation of the infrastructure cost has been carried out considering the architecture sketched in Fig. 6 in which it is considered the presence of a medium-voltage/low-voltage (MV/LV) transformer and a three-phase AC/DC con-

Table 10: Absorbed powers for different vehicle speeds.

vehicle speed (km/h)	$\boldsymbol{P_{\mathrm{EV}}}$ **(kW)**	$\boldsymbol{d_{\mathrm{V2V}}}$ **(m)**	$\boldsymbol{N_{\mathrm{EV}}}$	**total** $\boldsymbol{P_{\mathrm{EV}}}$ **per km (kW/km)**	**total** $\boldsymbol{P_{\mathrm{DWPT}}}$ **per km (kW/km)**
90	18	81	12	216	270.0
100	23	100	10	230	287.5
110	28	121	8	224	280.0
120	34	144	7	238	297.5
130	42	169	6	252	315.0

verter, having rated power 300 kVA, per each kilometer of charging lane. It is assumed that the transmitters have length equal to 2 m and are installed subsequently along the motorway lane. The length of 2 m is one of several possibilities but it is considered a good compromise in relation to the typical length of the vehicles considered in the application [54, 15]. Finally, this assumption means to consider 500 coils per kilometer.

The costs of the electrical components of the DWPT charging lane have been inferred from the data reported in [15, 46] which include the ICT components and the road works. In particular, a cost of 15 €/kW for the power electronics (i.e. main AC/DC converter and DC/AC converters), a cost of 40 €/kW for the MV/LV transformer, and a cost of 340 € for each transmitter coil plus its compensation capacitor have been assumed. Missing data about other elements necessary for the installation like material hauling, surface grader, surface treatments, etc., have been retrieved from [50].

The resulting costs are reported in Table 11 divided by each category. They indicate as the electrical components constitute practically half the cost of the overall infrastructure.

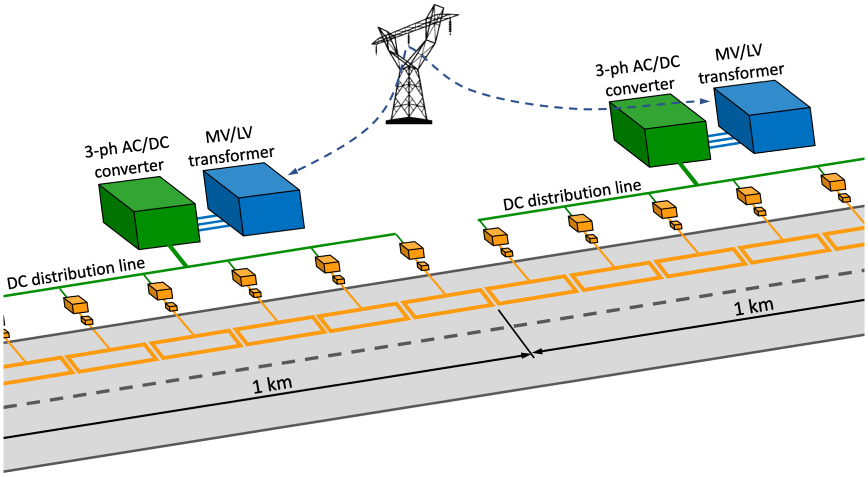


Figure 6: Adopted architecture for the evaluation of the cost of a DWPT charging lane in motorway environment.

4.3. Estimation of the maintenance costs

The accounting of maintenance costs is certainly complex since, as there are no practical long-term implementations, there is not enough data for a reliable forecast. Despite the due differences in terms of architecture and power, some data in this regard has been reported in [14] with reference to the implementation of the OLEV system of KAIST. In this work, a cost related to the maintenance of the inverters, which are the components of the electrical infrastructure more prone to faults, is indicated equal to 2.23% of the total cost of the DWPT infrastructure. Another possibility is to refer to existing infrastructures that offer similarities with the DWPT one. Probably, the infrastructure that best serves this comparison is the railway infrastructure. With regard to this latter, [55] indicates that the cost of maintenance of electrical components alone is between 1 and 3 percent of the yearly percentage of the investments. This data is in strong similarity

Table 11: DWPT infrastructure category costs.

Category	**Item**	**Item cost (€/km)**	**Category cost (€/km)**
Traffic control			34 795
Road works	Milling	38 204	561 154
	Placing concrete	220 878	
	Curing and finishing	302 072	
DWPT electrical and ICT components	MV/LV transformer	12 600	601 551
	AC/DC converter	4 725	
	DC cables	3 571	
	ICT and ancillary powering cables and pipes	1 905	
	Power and data connectors	10 000	
	Manholes	5 000	
	DC/AC converters	393 750	
	Transmitter coils and compensation capacitors	170 000	
TOTAL			**1 197 500**

with that provided by KAIST. Following these assessments it has been decided to assume, as maintenance cost, a precautionary value equal to 5% of the total cost of the electrical infrastructure of the DWPT system. The standard maintenance costs of the road infrastructure are not taken into account as these costs would still be present regardless of the DWPT system installation.

5. Simulations and Results

The considered time horizon for the evaluation of the externalities related to electrification of private mobility and the assessment of the economic sustainability of DWPT is evaluated within a time horizon of 20 years, from 2020 to 2040. In this period all parameters affecting the pollutants' emission calculated in (2), (4) and (5) are taken into account. In particular, the yearly rate of passenger cars substitution $k^{(T)}$ (i.e. the rate of the number of ICE cars that are substituted by electric cars) adopted in the analysis is shown in Fig. 7. This estimated trend was proposed in [56] forecasts a share of electric cars of approximatively 58% of the whole circulating fleet in 2040. The trends for the variations of thermal power plants efficiency η_{ep}, share of electricity generation by the different fossil fuel typologies $S^{(T)}_{solid}$, $S^{(T)}_{gas}$, $S^{(T)}_{oil}$ and share of RES adopted in the analysis are shown in Fig. 8 and Fig. 9. These variations have been extracted from [57] where the perspective for RES and non-RES generation are discretized every 5 years. A linear

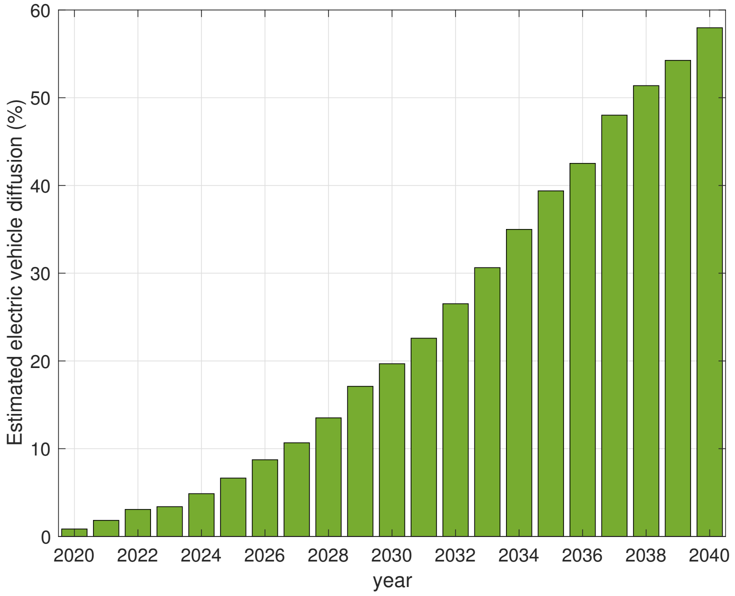


Figure 7: Expected electric cars share within the circulating fleet in EU.

approximation has been adopted to obtain the annual variations within each five-years interval. In other words, the yearly value at each target year T has been calculated assuming a linear trend within each five-years interval.

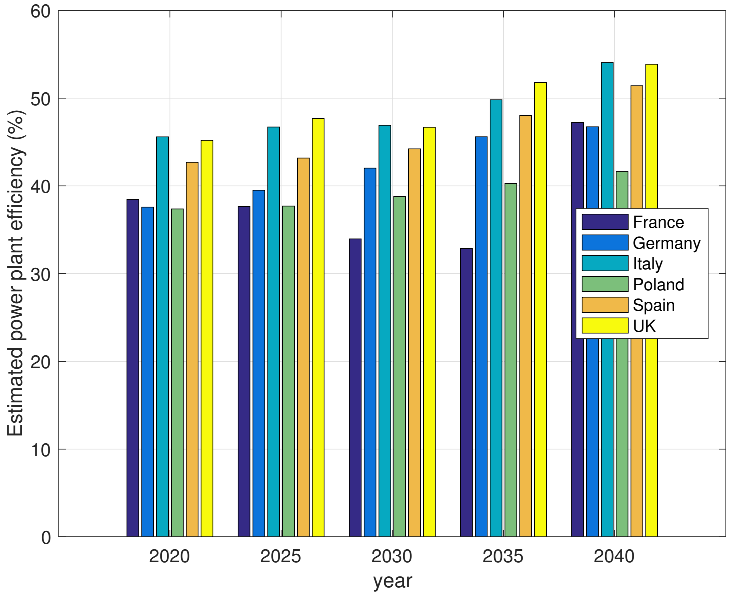
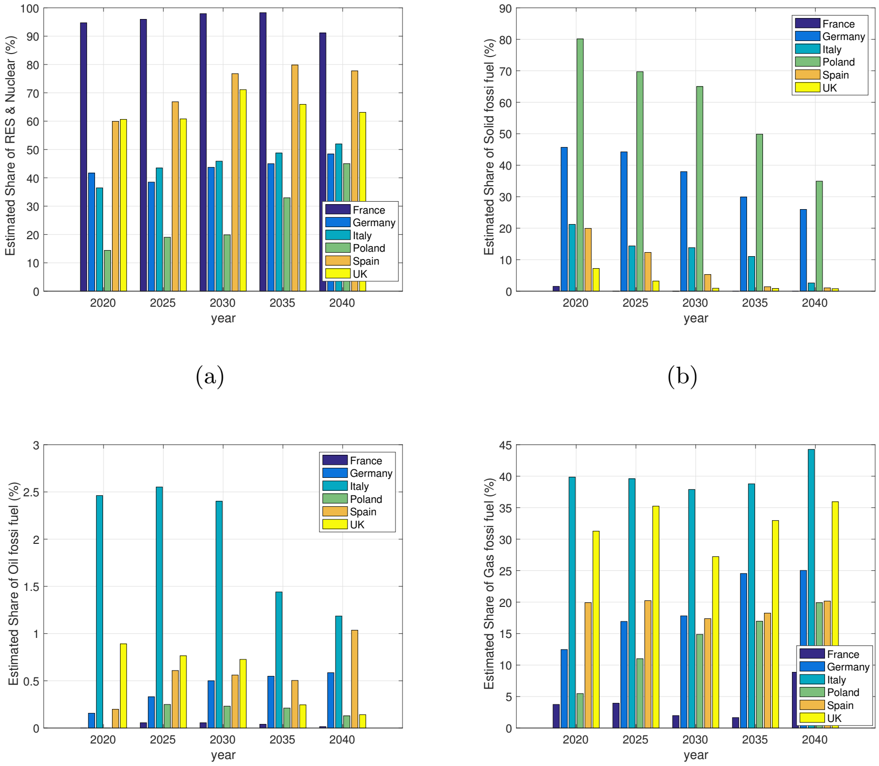


Figure 8: Expected trend of efficiency for power plants fueled by fossil fuel.

Generally, the expected future evolution of the energy system is oriented toward a progressive increase of the efficiency of the thermal power plants of the EU countries considered in this study (see Fig. 8). Furthermore, a general increase of RES and nuclear generation is expected in the period 2020-2040 as reported in Fig. 9a. In particular, [57] considers both the possible phase out from nuclear of some EU countries, such as Germany, and the possible phase in for others, as in the case of Poland. Moreover, Fig. 9b, Fig. 9c and Fig. 9d highlights how the mix of fossil-fuel power generation is expected to change in the future. For example, a progressive



(a) (b)

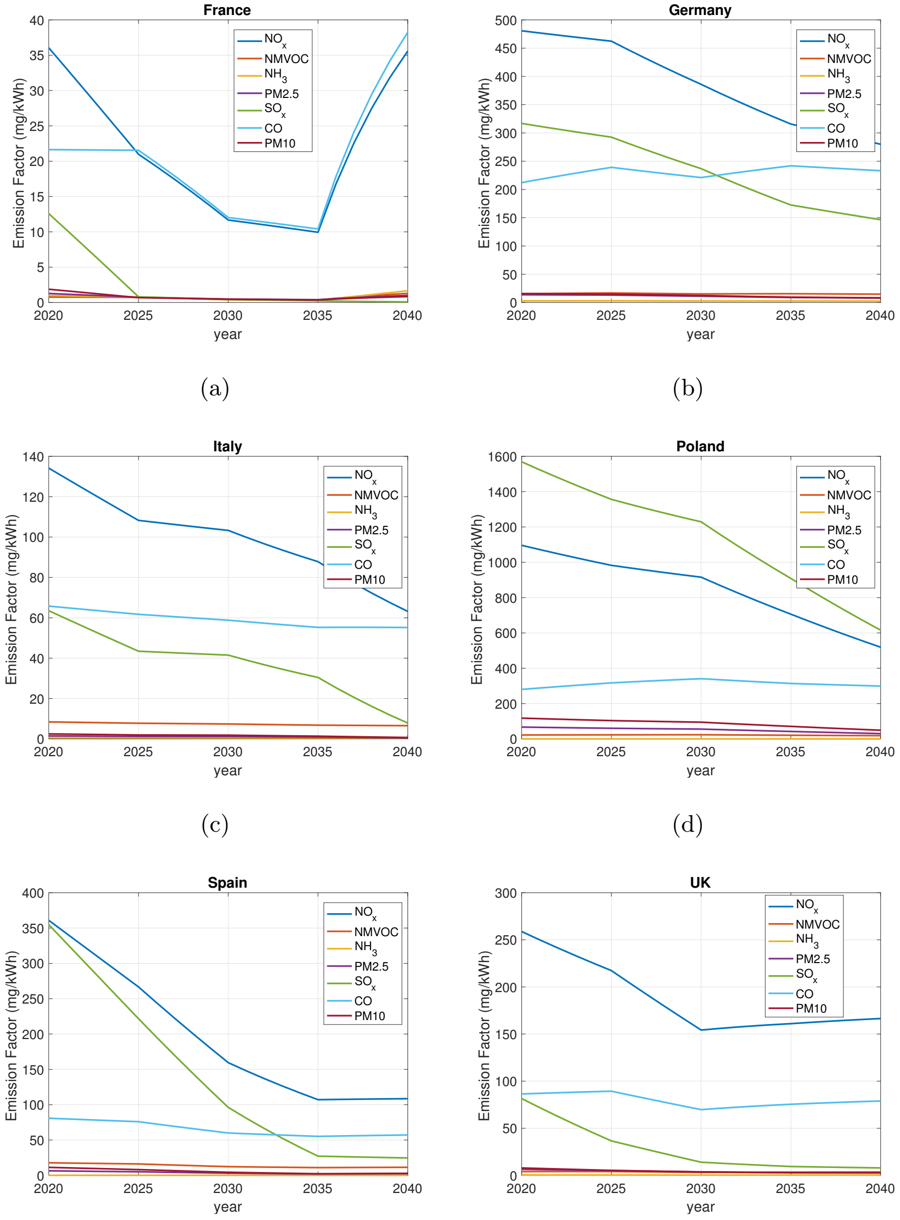
(c) (d)

Figure 9: Estimated trends of the share for electricity generation: a) RES&Nuclear, b)Solid fossil fuel, c) Oil fossil fuel, d) Gas fossil fuel. [57]

reduction of solid fuel use is generally expected with a progressive increase of the use of natural gas in all those countries where coal is widely used in power generation like Germany and Poland.

Figure 10 shows the results of the elaboration for the emission factors of power generation by country. A reduction of the emission factors is expected in almost all countries involved in this study. This result is due to the combination of different factors: increase of RES and, in some cases, increase in production from nuclear, improvement in the efficiency of power plants and change in the mix of fossil fuels used in thermal power plants. For example, $\mathrm{SO_x}$ and $\mathrm{NO_x}$ emission factors strongly decrease for Poland (see Fig. 9) because of an increase of electricity production from non-emitting sources (i.e. RES and nuclear) up to 45% of the whole national generation plants and a phase out from solid fossil fuel (i.e. coal) in favor of natural gas in thermal power generation plants. This last factor influences the emission factors, as already mentioned in Section 2.2, according to the weights presented in Table 4. Similar results can be observed for Italy, Germany and Spain where a strong reduction of electricity production by solid fossil fuel is expected in favor of natural gas and non-emitting primary sources.

Some differences with respect to this general trend can be observed in other EU countries. For example, the share of thermal power plants is supposed to increase in France passing from 2% in 2035 to almost 10% in 2040, as shown in Fig. 9a. Contemporarily, the mix of fossil fuels in power generation is supposed to be oriented toward natural gas within the same period, leading to a substantial growth of the emission factors for $\mathrm{NO_x}$ and CO in France. Nevertheless, the emission factors for France show low values if compared to other EU countries thanks to the electricity production widely based on nuclear.



(a) (b) (c) (d) (e) (f)

Figure 10: Estimated trends of the Emission Factors by Country.

Figure 11 shows the results about the evaluation of the social costs saving potentially achievable calculated by means of the EcoSenseLE tool and eq. (9). In this case, the non-actualized social costs saving differs country by country at each target year T according to the number of ICE vehicles replaced by EVs and the amount of pollutants emitted in the same target year by power plants. For example, a minimum in the social costs saving can be observed in 2023 for all countries: this is due to a change in the rate of ICE cars replacement with EVs, that is supposed to be affected by a contraction, as reported in [56] and shown in Fig. 7. Nevertheless, a progressive increase of the social costs saving in the period 2020-2040 can be observed for all countries, thanks to the gradual increase of RES generation.

Table 12: Cumulative social costs saving within the period 2020-2040.

	France	**Germany**	**Italy**	**Poland**	**Spain**	**UK**
(M€)	2599.3	2501.6	2049.9	521.2	881.9	1078.4

Table 12 shows the sum of the non-actualized social costs saving potentially achievable by each country in the period 2020-2040. The most favored country is France with around 2.6 b€ of cumulated social costs saving. This becuase at least 90% of France national electricity generation is always based on non-emitting sources plants within 2020-2040 (see Fig. 9a and Table 5) and the number of ICE cars potentially replaceable is quite high (see Table 2). On the other hand, Poland is the country with lower benefits, since generation by non-emitting power plants is expected to grow up to no more than 20% of the national electricity production in the period 2020-2040. The overall non-actualized social costs savings are in fact around

520 M€ for Poland.

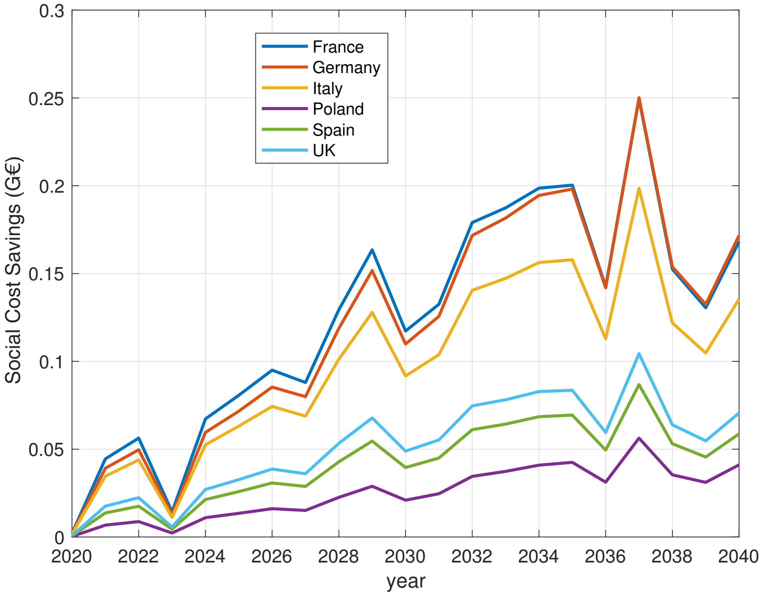
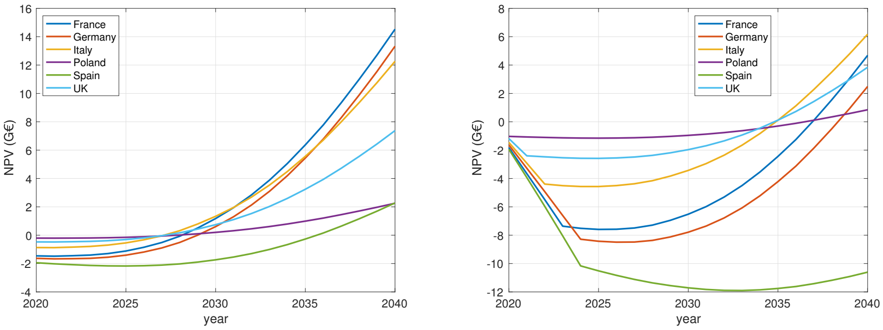


Figure 11: Expected yearly social costs saving by country.

Once the annual social costs saving has been defined for each country, NPV is also estimated considering the investment for the implementation of the DWPT system in motorways. The per-length costs of installation are those presented in Section 4.2, while the timescale for the installation has been supposed to be different country by country according to the extension of the national motorway network. Spain, that has the longer motorway network (see Table 13), has been supposed to be capable to integrate the DWPT system in the overall motorway network within 10 years. Consequently, the timespan for DWPT installation has been calculated proportionally for the other countries. Clearly, a lower timescale has been considered if only a fraction of the total national motorway network length has been supposed to be subject to DWPT integration.

Table 13: Length of motorway network by country. Source: [58].

	France	**Germany**	**Italy**	**Poland**	**Spain**	**UK**
(km)	11610	13000	6950	1640	15450	3770



(a) (b)

Figure 12: NPV profiles considering different portion of motorways subjected to DWPT installation: a) 10% and b) 50%.

Figure 12 shows two examples of NPV profiles obtained for different countries considering the actualization of the social costs saving, the installation costs and the operational and maintenance costs. It can be observed that the sustainability of the investment is strictly influenced by the supposed diffusion of the DWPT system. This result is due to the fact that the obtained social costs saving, used to calculate the yearly cash flows in NPV, are assumed independent from the diffusion of the DWPT system. In fact, the social costs saving presented in Fig. 11 depend only on the trend of the replacement rate of conventional passenger cars with electric vehicles and on the evolution of how the electricity is generated in each country. So, social costs saving in Fig. 11 are always the same independently by the diffusion of DWPT. Consequently, sustainability depends on the length of the motorway section concerned by the integration of the DWPT system, because of increasing investment costs (i.e. increasing diffusion of DWPT) are associated to the same benefits in terms of externalities. In fact, Fig. 12a and Fig. 12b show the NPV profiles when 10% and 50% of the length of each national motorway network sees the integration of DWPT, respectively. From these examples, it is clear that the smaller the motorway portion involved in the integration, the higher the sustainability of the investment on DWPT infrastructure. When just a small portion of the motorway network is upgraded by DWPT (e.g. 10%), all countries highlight the sustainability of the installation. When a more consistent portion (e.g. 50%) of the motorway network is upgraded, the time interval to reach the condition $NPV = 0$ becomes longer.

Finally, the analysis allows to identify, in each country, the maximum portion of motorway network upgraded with DWPT, economically sustained by the only social costs saving. This is done by calculating the portion of motorways such that NPV is zero at the end of the period considered in the economic analysis (i.e. 20 years). The results are summarized in Fig. 13. This figure highlights that social costs saving is capable to significantly sustain the diffusion of DWPT in almost all the considered EU countries. In particular, Italy and UK are potentially capable to cover a portion of around 90% of their respective motorway networks. This encouraging result is due to the extension of UK's motorway network, that is around half of the Italian one, despite social costs saving for Italy is around twice with respect to UK. Similarly, Poland can potentially cover around 75% of its national motorway network, even if the country has the lower benefits in terms of social costs

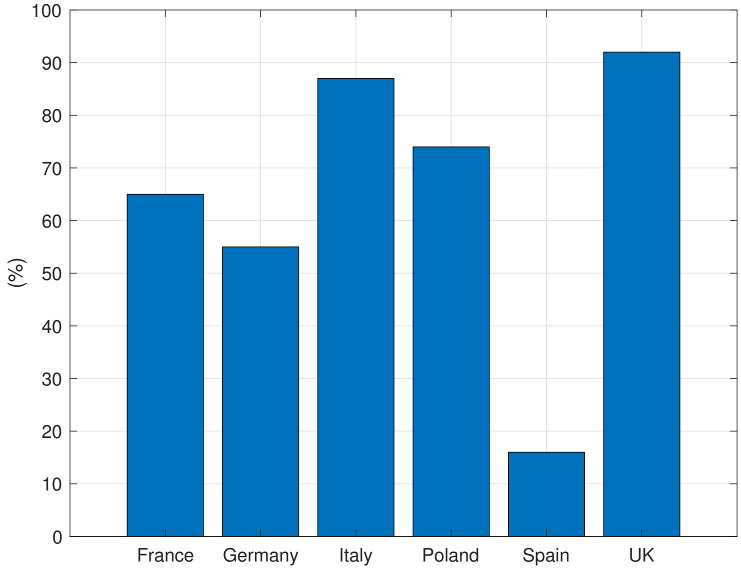


Figure 13: Maximum DWPT diffusion in motorway ensuring sustainability.

saving. This thanks to the fact that the extension of Polish motorways is the lowest one. Germany and France can instead theoretically cover 65% and 55% of their motorway networks, respectively. Spain is the most disadvantaged because the country has the longest motorway network (i.e. more than four times the UK's motorway network) and one of the lowest social costs saving (that is similar to the one of Poland).

These results remark the economic opportunity offered by the decarbonization of passenger cars mobility. In the event that this push to the decarbonization would be offered by the adoption of the DWPT infrastructure on long-distance roads, these results show how the significant cost for the installation of this infrastructure would be directly recovered by simply reducing the costs associated with the effects of the emissions on environment and people's health.

6. Conclusion

The work has assumed the possible scenario in which, the adoption of DWPT in the motorway infrastructure, would support the social acceptance of the electric cars for private mobility.

At urban level, this would lead to a reduction of air pollution. On the other hand, the increase of EVs would lead to the increase on electricity consumption and a consequent increase of pollutants emission by power plants. Thus, the diffusion of DWPT could lead to two conflicting results: a reduction of external costs related to air pollution, but also an increase due to additional emission from power plants. This paper has tried to provide an answer to this issue by analyzing the potential social costs saving achievable by the decarbonization of passenger cars mobility supported by the widespread adoption of DWPT in motorways in the period 2020-2040.

The external costs computation has been based on the ExternE methodology and estimated through the EcoSenseLE web application. Firstly, the emission factors of the main air pollutants have been estimated, for both passenger cars and power plants. The yearly variation of the emission factors has been evaluated by taking into account the expected change on the mix of electricity generation as well as the improvement in efficiency of thermal power plants. Hence, the reduction of pollutants emission due to the diffusion of EVs has been evaluated together with the related increase of emissions due to the growth of electricity demand. Finally, the estimated variation of pollutant emissions has been used to evaluate the potential social costs saving obtained by the expected diffusion of EVs.

This first part of the analysis alone has shown that the progressive replacement of ICE vehicles with EVs can generate positive externalities in the order of a billion euros in the six most populous EU countries: France, Germany, Italy, Poland, Spain and UK.

The benefits evaluated in the first part of the analysis have been compared to the investment and maintenance costs necessary to install and operate the DWPT infrastructure. The economic analysis revealed that the estimated social costs saving are capable to sustain the investment for a wide diffusion of the DWPT in almost all the countries considered in this study. Roughly, this means that the integration of DWPT would be practically self-sustainable from the point of view of the public spending.

Naturally, the presented results have to be read in the light of the adopted assumption and hypothesis. Mainly, these results are influenced by the considered evolution of the energy mix composing the gross electricity production. Generally, a progressive growth in RES or non-emissive generation plants favors the sustainability of DWPT while a stop towards this direction would unavoidably penalize either the adoption of DWPT as well as the electric mobility diffusion. Another source of incertitude can be found in the estimation of the DPWT costs. In this case data have been mainly inferred from previous prototypal implementations and it can be expected some difference with respect to a large scale installation for which the costs could be even lower than the ones considered in the work.

Finally, it is appropriate to specify that external costs due to accidents have been not taken into account in this study, since EcoSenceLE web application estimates only impacts related to air pollution. As reported in [59], the impact of accidents is relevant, but the habits of drivers have been here supposed to be unchanged by the adoption of EVs. In reality, it is easily predictable that the adoption of EVs will meet future technologies for autonomous driving. This integration will contribute to significantly reduce accidents and the corresponding social impacts. At the same time, autonomous driving would provide an effective solution to improve the performances of DWPT by maintaining a good alignment with the charging lane [60].

Future works are encouraged to improve the analysis by better detailing some aspects. For instance, the inclusion of more realistic average distances between vehicles and speed profiles based on field measurements can surely further improve the cost analysis of the DWPT infrastructure. Externalities due to traffic congestion can be also considered in future work as further factor that moves towards the sustainability of the DWPT diffusion and the process of mobility decarbonization. Finally, a future extent of the work could also include all the EU countries not considered here to present and discuss the DWPT opportunity as a whole.

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