Feasibility study on applicability of dynamic IPT (Induction Power Transfer) for a sustainable and environment low impact electric mobility

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Abstract

The study investigated the state of the art of IPT technology and its application to electric mobility in the motorway sector. On the basis of the vast bibliography analyzed, a feasibility project was developed based on the following pillars: 1) The reasons that lead to the development of IPT technology in the motorway field, 2) the choice and study of a motorway route, 3) related implementation aspects to the choice of materials and methods of inclusion of power transmission technology in the motorway surface, analysis of charging efficiency based on the number of on-board receivers (case studies with 1 or 2 receivers), 4) analysis of sustainability issues energy based on the motorway speeds of the vehicles considered (TESLA 3, TESLA S, TESLA). Ultimately, we verified the positive correlation between the results of our study and the ongoing results of the "Arena del Futuro" project, the first example of technological transfer and joint experimentation between authoritative universities, highways, and primary international industrial groups in the automotive, components sector. and electrical equipment, telecommunications.

Keywords*: Electric mobility, Dynamic Inductive Power Transfer (DIPT), Electric Vehicles (EV – Electric Vehicle), Economic sustainability, Energy sustainability, Environmental sustainability*

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Introduction

The scarcity of fossil fuels expected in the coming years and the damage to the environment and health caused by combustion engines have pushed the development of technologies for electric mobility in recent years. Technological innovations in this field have mainly concerned the use of batteries and charging infrastructure.

However, the intense scientific activity has led to the development of prototype solutions that are not always compatible with each other. Even from a regulatory point of view, there is little tendency in the various countries of the world to converge towards the adoption of infrastructures for the diffusion of electric propulsion in times that are coherent and compatible with technological developments.

At present, the technological solution that has taken hold is based on the spread of charging stations (Quick stations with power up to 22kW: 100% charging in 2 hours, Fast stations (installed on state roads and motorways) with power up to 50kW : 100% recharge in less than an hour, Ultra-Fast Stations with power up to 350kW: 100% recharge in less than 25 minutes). Charging times are reduced by recharging by 70/80%. Obviously the charging times do not only depend on the power used to charge (power in kW of the socket available in the charging stations), but also on the maximum power accepted by the battery charger inside the vehicle, on the type of cable used and obviously also on the capacity of the on-board storage system and state of charge. This choice aims to guarantee a standardization of the charging process of electric propulsion vehicles with competitive times compared to traditional refueling stations for combustion vehicles. However, the fear of a possible difficulty in charging either due to the lack of columns, or the unavailability of the same which would lengthen the waiting time for a recharge, together with the high prices of electric vehicles which also include the costs of disposing of the batteries, have limited a decision-making transition of users towards electric mobility. It is necessary, especially for long-distance motorway journeys, that the continuous growth of electric mobility is accompanied in parallel by the development of infrastructures that guarantee the charging of electric vehicles everywhere and in a short time, with acceptable costs and without creating any inconvenience. or fear to travellers.

An interesting and alternative solution is provided by Wireless Power Transfer Systems, which appear capable of overcoming some obstacles of current electric mobility and above all of promoting the real decision-making transition that accompanies the abandonment of traditional propulsion (combustion so to speak) for the electric one.

In the field of WPT technology, our interest has moved in the direction of the specific variants known as IPT (Induction Power Transfer) and in particular for the Dynamic IPT which allows a battery to be recharged while the vehicle is running. It should be noted that this technology, even with some limitations that are the subject of research, is first and foremost a safe, weatherinsensitive and long-lasting form of energy transmission, which offers the possibility of getting rid of annoying wired connections. It also creates a charging method standard for all vehicles that adopt this system, avoiding the complex homologation of the various systems present today.

The system transfers energy during the vehicle's motion to power the traction motor and recharge the battery at the same time. In this way, a single continuous charging infrastructure is created capable of guaranteeing vehicles, in the near future, to have unlimited autonomy and a consequent reduction in the size of the electrochemical accumulators on board, with induced advantages in terms of environmental and economic impact. Currently, this technology has yet to fully mature in terms of power transfer efficiency and rated power.

The main advantages of wireless charging technology, when compared to standard charging for electric cars, are:

- absence of cables necessary for charging the vehicle;
- reduction in the weight and size of the battery pack;
- lower electricity consumption due to the reduced weight of the battery pack;
- autonomy of movement without the need for stops during the journey;
- lower vulnerability of the system to adverse climatic conditions;
- less damage and risks related to vandalism;
- greater reliability of the devices thanks to the removal of connectors or batteries indicated as the most vulnerable components;
- the possible reduction of batteries reduces costs and increases compatibility with the environment;
- elimination of electrocution risks linked to the presence of connectors exposed or immersed in water.

On the contrary, the main disadvantages are the following:

- high installation costs;
- lower efficiencies on average;
- greater technological complexities;
- difficulties related to the construction and implementation of infrastructures;
- greater high frequency electromagnetic fields, potentially harmful to humans;

lack of sector-specific rules and regulations.

A. Objective of this feasibility study

The feasibility study, based on current scientific knowledge, aims to analyze the implementation aspects of the Dynamic IPT (Dynamic Induction Power Transfer) technology, in the motorway stretch from Milan to Reggio Calabria (or vice versa) passing through the A2, A30, A1. The choice of this long route which develops over an area with variable altitude allows us to highlight the limits and stress conditions of current electric mobility, such as:

- greater consumption due to greater speed,
- greater number of refuelings necessary as a consequence of higher energy consumption (estimated four stops with the leading market models TESLA 3, TESLA S, TESLA
- poor availability of charging stations in proportion to the growing number of electric vehicles.

Starting from the state of the art of technology at an international level, the main technical problems of applicability of an IPT infrastructure and the impact of this choice in terms of economic, energy and environmental sustainability are analysed. Finally, two case studies are analyzed in which the vehicle is equipped with a) a receiver in the first case and b) two receivers in the second case. Through the study it was possible to identify solutions for the main problems underlying the application of IPT technology, as well as obviously the factors that could limit the application of this technology on the motorway section considered. The report is based on a bibliographic collection and on the results of completed or ongoing experimental projects, both at an international and national level.

B. Compliance of dynamic IPT (DIPT) with Industry 5.0

The choice of the title of the study is motivated by the fact that the solution fits into the Industry 5.0 scenario that will characterize the coming years. This scenario was presented in February 2022 and described by the European Commission in the dedicated document "Industry 5.0 - Towards a resilient and sustainable post pandemic recovery" [1], commissioned by the European Commission to the CEPS (Center for European Policy Studies) Task Force. The consistency of DIPT technology with Industry 5.0 is given by the following characteristics:

1. **Sustainable** – the solution is sustainable in terms of:

   a. Environmental protection; in general the IPT is based on electric engines and therefore compared to thermal engines the savings in terms of CO2 emissions are significant. Obviously, for environmental sustainability it is important that the environmental impact is also assessed in terms of the type of materials used and their production.

   b. Economic sustainability; the cost of the IPT infrastructure is significant but in any case sustainable, especially if we consider this particular motorway technological adaptation as a major engineering work that brings numerous advantages. According to some evaluations (reported below), if we consider the cost of 1 million per km for just two charging lanes with IPT technology, 1000 km would cost 1 billion, 1/6 of the MOSE, ¼ of the estimated cost of the bridge over the Strait of Messina. Consider that for the construction of the Salerno-Reggio Calabria the cost was on average 22 million 700 euros per km. It must also be said that works of this type must be carried out without creating excessive inconveniences on mobility and therefore it is presumable that the cost will be spread over 10 years, making it certainly sustainable for the state budget.

c. Energy sustainability, IPT makes sense if it is possible to support its operation with adequate energy production, i.e. if compared to our electricity production capacity, we are able to introduce a quantity into the IPT infrastructure that does not jeopardize others services intended for industrial production and domestic use and for public utility use (trains, public lighting, etc.). We will see that this assumption is respected considering the current daily mobility throughout the year.
d. Operational sustainability, an IPT infrastructure could require significant levels of maintenance both due to adverse weather conditions and wear. However, these are operating costs to which all motorways are normally already subject, but we will certainly see that with the IPT these costs increase.
e. Push for the use of electric cars on a large scale; the IPT promotes greater sustainability in the diffusion of the electric car, as all the critical issues currently recognized for the electric car are overcome on the user side (number of stops and variability of charging times which lead to less use of the car electric on long routes, presence of few electricity supply points compared to a hypothetical growing number of electric cars in circulation, variability of charging costs depending on the power of the charging stations)

1. **Humancentric** – IPT introduces a concept of mobility created for man and his needs, in which it is not necessary to make stops to recharge the electric car, consumption is calculated automatically, and together with consumption it is possible also estimate the km traveled and then with the same pricing principle, pay the toll. We can therefore fully say that the solution responds to people's need to experience electric mobility in a carefree manner, becoming themselves the primary objective of the service. The car at the service of man and his comfort in a more extensive way than what has happened so far first with thermal engines and then with current electric mobility.
2. **Resilient –** any interruptions in the operation of some transmitters or energy supply problems of part of the dynamic IPT infrastructure on motorway sections are compensated by the battery charge which still allows you to continue the journey. It can be hypothesized that the use of dynamic IPT technology on the main motorway communication arteries allows you to exit them with a charged battery and be able to travel several hundred kilometers in the surrounding areas. To integrate dynamic IPT on the motorway, it would be appropriate to provide static IPT solutions in parallel in car parks. Another interesting aspect of resilience is given by the possibility of reducing the size of the batteries and consequently the use of the increasingly rare and expensive so-called "raw materials" resources (lithium, cobalt and nickel) used for their manufacture (waiting for them to mature the technological evolution towards other forms of batteries: for example salt batteries [68] [69]).

Methods

For the feasibility study, data on the geomorphology of the territory, distances and experimental results of appropriately referenced and linked research projects were considered

Motorway section considered

For the feasibility study we considered the motorway stretch from Reggio Calabria to Milan (or vice versa) involving the use of 3 motorways (A1+A30+A2). Knowledge of the characteristics of the motorway stretch in terms of length, morphology and traffic is important for an estimate of the average power required from the electric car with consequent induced effects on energy consumption.

Highway A1

With its 759.8 km of length, the A1 Milan-Naples motorway, also called Autostrada del Sole or more briefly Autosole, is the longest Italian motorway in operation. It connects Milan to Naples internally crossing the Italian peninsula and passing through Bologna, Florence and Rome. From an altimetric point of view, the motorway starts at a height of approximately 100 meters near Milan and drops below 60 meters in the Fiorenzuola-Bologna section. In the Bologna-Florence stretch, that is, straddling the Tuscan-Emilian Apennines, it reaches an altitude that exceeds 700 meters in some sections and then drops and remains below 350 meters between Florence and Naples.

For our traffic needs, only the Milan-Caserta South section, 745 km long, should be considered.

The A1 is generally characterized by very intense traffic during daytime hours with constant slowdowns in the Florence area in both directions, despite the introduction of the 3-lane variant in the same area.

Even at night the motorway has traffic linked to the movement of goods and therefore mainly made up of heavy vehicles. The motorway is mainly developed on 3 lanes which are reduced to 2 only in some sections between Rome North and Florence South. Below is a map taken from the Michelin guide in which the Milan Caserta South section is highlighted in blue.

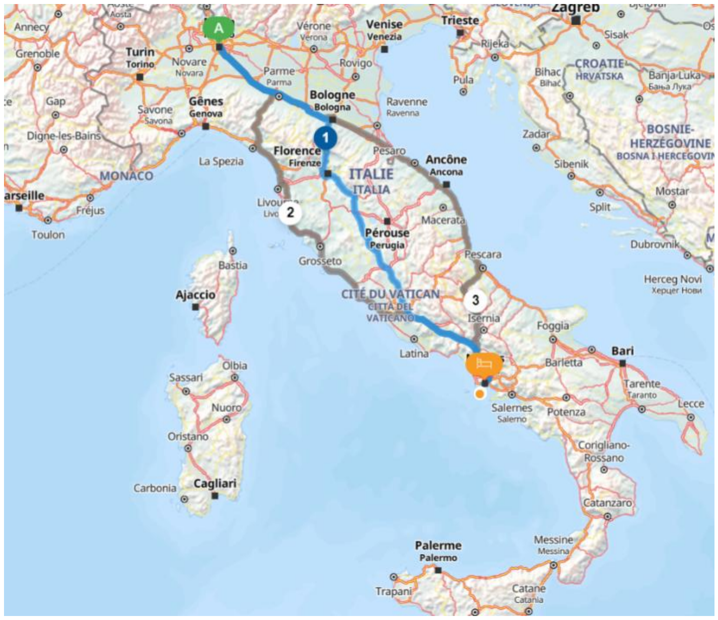

Figure 1 – Milan - Caserta South motorway section (source Michelin Guide [73])

Highway A30

The A30 is a motorway that connects Caserta-South to Salerno. The motorway route is entirely in a flat area and is 56.3 km long, and is spread over three lanes. This motorway artery is characterized by smooth traffic with rare queues also thanks to an adequate number of exit gates in relation to the traffic which we could define as medium-low, except in short periods of the year coinciding with Christmas, Easter and holiday travel in the which, right near the Mercato San Severino motorway toll booths, can cause significant queues. The A30 motorway has an altitude of less than 50 m along its entire route and represents the link between the A1 (Mi-Na) and the A2 (Sa-Rc).

Below is a map taken from the Michelin Guide in which the flat stretch between Caserta Sud – Salerno is highlighted in blue, through which you enter the Mediterranean motorway (A2).

Figure 2 – Caserta Sud-Salerno motorway section passing through Fisciano (source Michelin Guide [73])

Highway A2

The A2 motorway, also called the Mediterranean motorway or Salerno-Reggio Calabria, connects Fisciano (Sa) to Reggio Calabria passing through Cosenza and Vibo Valentia. 432.3 km long, it is entirely managed by Anas and is free. It is characterized by a medium-low traffic density which increases significantly on some days of the summer period, i.e. close to the movements of holidaymakers.

The motorway crosses the Lucanian and Calabrian Apennines for over 50% of the entire route. For long stretches (over 200 km), the route has the typical characteristics of "mountain" motorways and there is a junction at one of the highest motorway altitudes in Europe, that of Campotenese - in Calabria - at 1,050 meters above sea level. sea. The altimetric plan of the route is very demanding and with a frequent succession of tunnels and viaducts.

The Mediterranean Motorway is preparing to become one of the first Smart Roads in Italy prepared for the next autonomous driving. On 27 July 2018, the 20 million euro contract was signed for the supply and installation of systems and stations for the implementation of the advanced Smart Road technological infrastructure for the connectivity of Anas users and operators on the A2 motorway, an intervention financed under the Operational Program PON Infrastructure and Networks 2014-2020 of the Ministry of Infrastructure and Transport (www.ponir.mit.gov.it). Below is a map extracted from the Michelin guide in which the stretch between Salerno and Reggio Calabria is highlighted once again in blue.

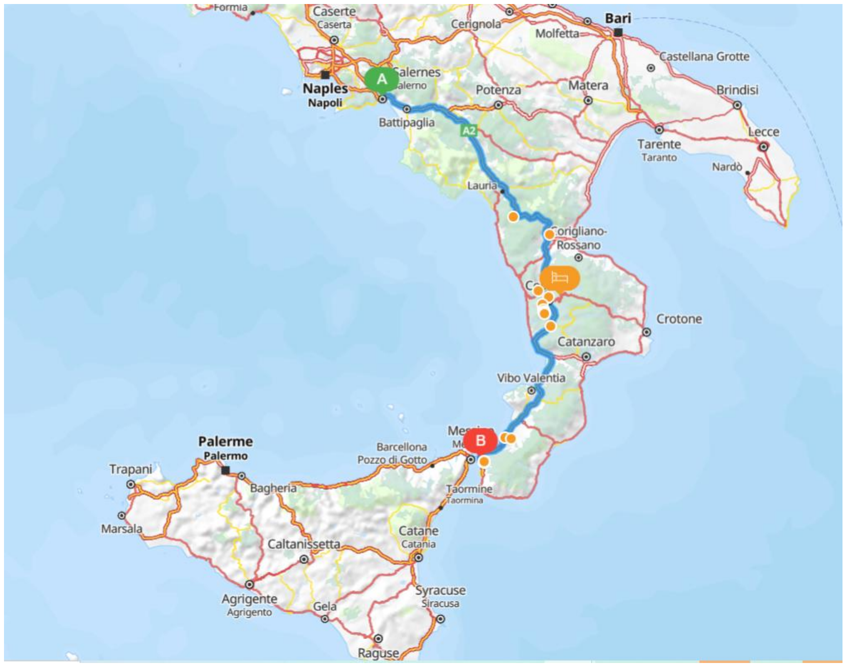

Figure 3 – Tratto autostradale Salerno- Reggio Calabria (source Michelin Guide [73])

Complete route

The complete route consisting of the A1+A30+A2 for a total of 1233.6 km is displayed in the following map:

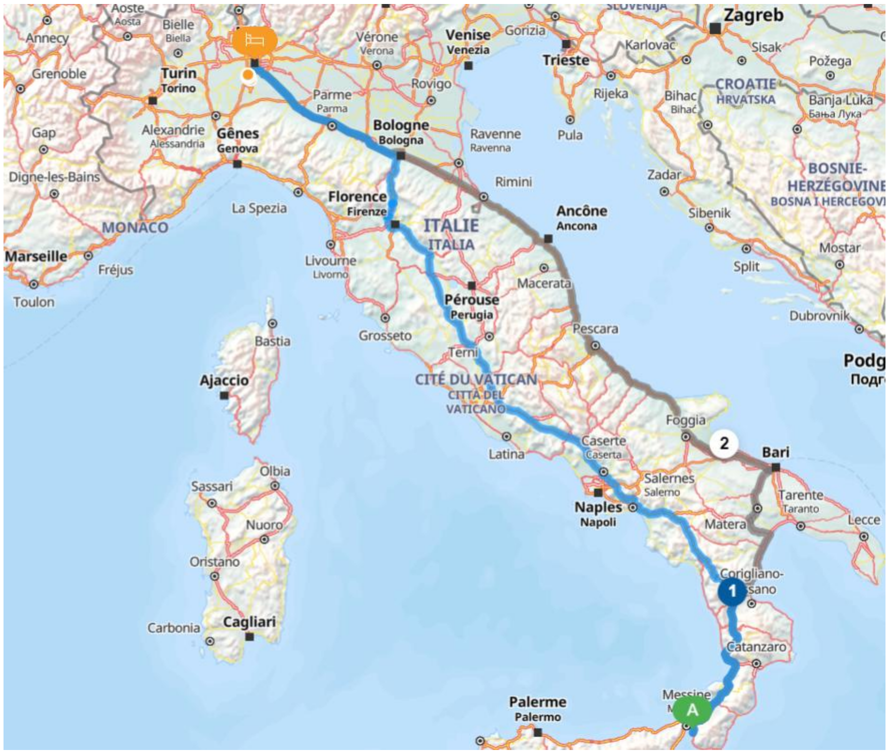

Figure 4 – Motorway section considered complete from Milan to Reggio Calabria (source Michelin Guide [73])

As we have illustrated, the MI-RC section has variable altitude. Over 95% of the pavement was adapted with draining asphalt. Along the entire route, a surface of at least 1 meter is available outside the side lanes in both directions, in which it is possible to house the technological energy transport networks and the electronic components necessary for the creation of the Dynamic IPT infrastructure.

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Results

The following sections illustrate the conclusions of our feasibility analysis, based on several key aspects such as economic sustainability, energy sustainability, and environmental sustainability. Furthermore, specific case studies have been analyzed

A. Economic sustainability: costs for installing an IPT infrastructure

Cost of building the infrastructure

It is difficult to accurately determine this cost, both because we are faced with a new technology which in some ways is still in the testing phase, and because there is not yet a standardization of systems often based on a different technological approach.

Dynamic wireless charging is certainly the most expensive charging option as it involves not only the cost of the system but also high installation costs.

In [35], the set of two consecutive transmitters of the implementation solution illustrated in the previous paragraph, and the related components, are used as a unit of measurement for an economic evaluation of the IPT system. Figure 5 graphically shows what is considered a unit of measurement:

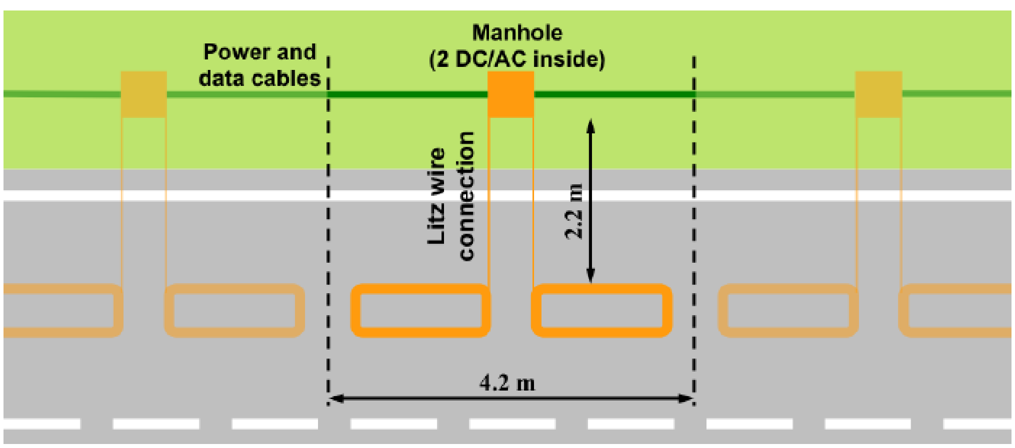


Figure 5 –Diagram of an economic unit of measurement considered for estimating the cost per meter [35]

The chosen unit of measurement is used as a basic element for estimating the costs of creating a charging lane. Table 1 summarizes how the cost in euros was determined for the measurement unit considered.

Description	Quantity	Cost
DC cables	4.2 m	15.00 €
Data and auxiliary supply cables and pipes	4.2 m	8.00 €
Manhole	1	20.00 €
Power and data connectors	1	40.00 €
Transmitter and comp. capacitors	2	500.00 €
DC/AC converter	2	600.00 €
Materials for transmitter embedding	Lump sum	300.00 €
Manpower for DC line and manholes placing and manholes placing	Lump sum	320.00 €
Manpower for transmitters embedding	Lump sum	540.00 €
	Total cost	**2343.00 €**

Table 1 – Charging unit components and costs [35]

From the cost per unit of measurement, the cost of the IPT infrastructure for each meter is obtained, dividing the cost per unit of measurement (2343) by the length of the unit of measurement (4.2 m). equal to approximately 558 e/m. We thus obtain the value of approximately 558 e/m (cost in euros for each meter) to be precise: 557,8571 e/m.

This is equivalent to saying that the cost per km is 557,8571 x 1000= 557,857.1429 e/km
Whereas

- he motorway stretch between Milan and Reggio Calabria is 1233.6 km long
- an adaptation of the motorway network considered with a Dynamic IPT infrastructure may concern:
  - or two lanes in the opposite direction of travel
  - or four lanes, two in one direction and two in the opposite direction

we can deduce a first rough economic evaluation:

Two lanes in the opposite direction for 1,233.6 km (Milan-Reggio Calabria)		
Cost of one lane from Milan to Reggio Calabria	557,857.1429 x 1,233.6 km	688,172,571.43 euros
Cost of one lane from Reggio Calabria to Milano	557,857.1429 x 1,233.6 km	688,172,571.43 euros
	Total	1,376,345,142.86 euros

Table 2 – rough economic evaluation for two lanes in the opposite direction of traffic from Milan to Reggio Calabria using the cost per meter obtained from the costs in table 6

We would also have arrived at this evaluation by directly multiplying the cost per unit of measurement of 4.2 meters (2343), the number of units of measurement contained in 1 km (238.10) and the total number of km of the route (1233.6).

Therefore, thinking about an adaptation of only two lanes, in the opposite direction, of the Milan - Reggio Calabria motorway section in the opposite direction, we know that the cost for each km would be 1,115,714.29 euros.

If the adjustment concerned 2 lanes the cost would be **2,231,438.57** euros/km

We mentioned at the beginning the difficulty of making an accurate determination of the cost of creating the system in the absence of a reference technological standard. Therefore, we also evaluated another case in the bibliography [13] [37] [38]. To evaluate the reliability of this first evaluation. As in the previous case, here too for the evaluation of the costs of the IPT infrastructure, account was taken not only of the electronic components necessary for the functioning of the charging system, but also of the expenditure relating to labor for the milling work, positioning of the asphalt and road surface treatment. As regards the electrical part, the most significant cost items are the inverters, which have the function of converting the input current from direct to alternating, and the transmitters with the relevant capacitors, capable of generating a magnetic field to induce an electromotive force in the secondary or receiver circuit. To calculate the final costs, it was assumed that an inverter would be installed for each coil, approximately 500 per kilometre; a cost of €15/kW was also assumed for the inverters. Regarding the transmitters, components capable of transferring a nominal power of 50 kW were chosen at a cost of €250 per single element. Finally, there is a medium to low voltage transformer every 1000 m of infrastructure, with a cost of €12,000 [13] [37] [38]. Table 2 shows the costs divided by categories:

Category	Task	Cost (€/km)	Category Cost (€/km)	%
Traffic Control	Median (Barrier)	33.823	34.795	3,1
	Signs	849		
	Cones	123		
Milling	Mill	3.191	38.204	3,4
	Haul milled material	34.623		
	Surface Grader	390		
Placing Concrete	PCC Material cost	213.020	220.878	19,6
	Portable Batch Plant	535		
	Pour/Transport Concrete	6.371		
	Paver	952		
Curing/Finishing	Surface Treatment	267.234	302.072	26,8
	Broom Finish	34.838		
Electronics and Grid Connection	DC cables	3.571	532.476	47,2
	Data and auxiliary supply cables and pipes	1.905		
	Manhole	5.000		
	Power and data connectors	10.000		
	Transmitter and comp. Capacitors	125.000		
	DC/AC converters	375.000		
	MV/LV transformer	12.000		
TOTAL		1.128.425	1.128.425	100

Table 3 – IPT infrastructure costs per 1000 meters [13] [37] [38]

As can be seen in table 2, the highest costs are attributable to the "Electronics and Grid Connection" category (approximately 47%), in particular with regard to the two subcategories previously mentioned and described, i.e. inverters and transmitters. The “Curing/Finishing” group follows, with approximately 27% of the total costs, mainly due to the final treatment of the road surface. The “Placing Concrete” category is also not irrelevant; in fact it affects 20% of the overall cost of the infrastructure. However, the two classes "Milling" and "Traffic Control" are potentially negligible, both accounting for approximately 3%. In this case we obtain a cost of: 1,128,425 euro km for the creation of the Dynamic IPT infrastructure.

Comparison of the results from the two calculation methods used

By comparing the cost of the first solution analyzed with that of the second, we note that they are of the same order of magnitude, as shown in Table 4

Km	Costo METODO 1 (singolo km)	Costo METODO 2 (singolo km)
Costo Infrastruttura IPT x 1 km	1.115.714	1.128.425
K totali percorso	**Costo Totale METODO 1 (intero percorso)**	**Costo Totale METODO 1 (intero percorso)**
1233,6	1.376.345.148	1.392.025.080

Table 4 – Comparison of costs per 1,000 m and for the entire route

Over the entire route, the difference would be less than €16 million. Obviously, these estimates have been calculated based on costs related to specific project trials. Considering the Milan – Reggio Calabria route, we are dealing with large-scale figures; therefore, it is foreseeable that the cost could be improved by at least 10%. Consequently, we can hypothesize a realistic construction cost for the Dynamic IPT infrastructure of €1,000,000/km

B. Energy sustainability

Sizing Model

The costs of providing the service depend on the power required by the vehicles which in turn depends on the speed of the car.
We consider the 90 km/h and 130 km/h intervals as a representative interval of average motorway speeds to calculate the power required by each vehicle for dynamic charging. Therefore, to meet this request it was necessary to assume a constant installed power of the system equal to 50 kW.
The minimum safety distance was also evaluated for each speed which allows the number of vehicles circulating per kilometer to be evaluated with the aim of simulating the most unfavorable scenario in terms of use of the infrastructure, having to obtain total coverage on the motorway sections in where we plan to install the DIPT system, i.e. the Milan-Reggio Calabria section, it has been estimated that the number of coils per kilometer should be equal to 500, each having a length of 2 metres.

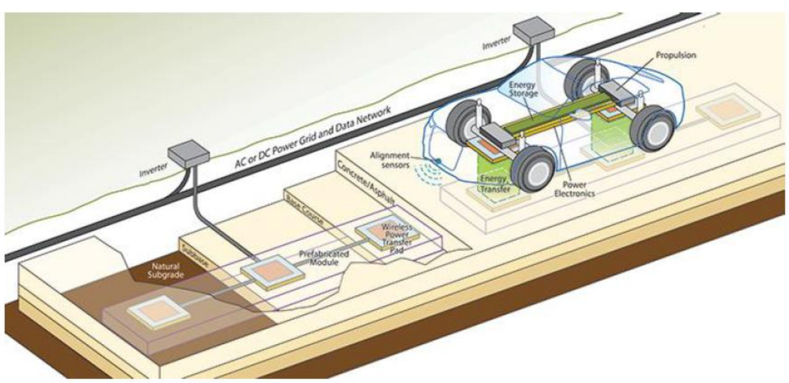


Figure 6 –Representation of the main components of the IPT system [39]

The calculation model used for the power required by the vehicle is based on the following formula

$$P_{vehicle} = \frac{1}{\eta_{tr}}\left(mgC_r v + \frac{1}{2}\rho A_f C_x v^3\right)$$

Where:

- η_{tr} is the vehicle's transmission efficiency, considered constant and equal to 0.8;
- m is the mass of the electric vehicle, with an average value of 2,000 kg;
- g is the gravitational acceleration (9.81 m/s²)
- C_r is the rolling resistance coefficient, assumed to be 0.008;
- v is the vehicle speed, the only variable in the function;
- ρ is the air density (1.225 kg/m³);
- A_f is the frontal area of the car, considered to be 2.23 m²;
- C_x is the aerodynamic drag coefficient (0.4).

Using this model it is possible to note that the power necessary to power the electric vehicle has a non-linearly increasing trend with the increase in the average speed of the vehicle, as shown in figure 7 [13] [40].

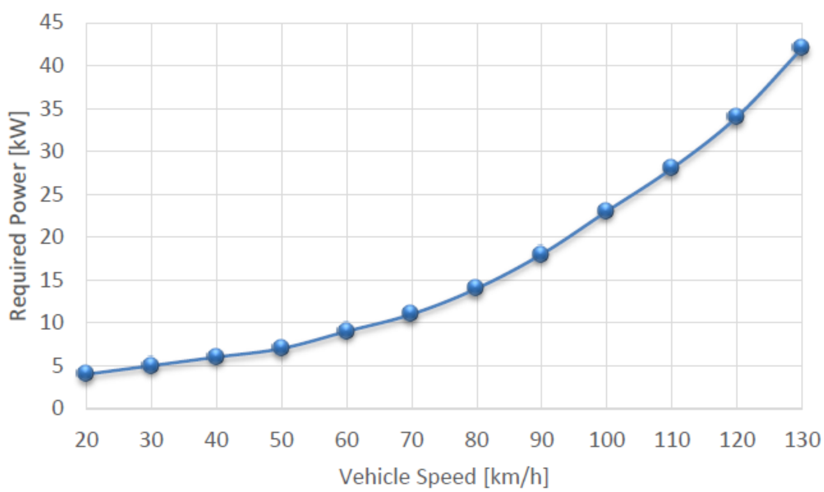


Figure 7– Power required depending on vehicle speed [13] [40]

Following the calculation of the power required by each vehicle, the simultaneity coefficient k was determined for each value in the speed range between 90 and 130 km/h. It represents the dimensionless ratio between the actual power absorbed by all the vehicles present in a kilometer and the total installed power. This allows you to estimate the percentage of use of the system, with the aim of determining the most unfavorable condition and maximum load. The contemporaneity coefficient is given by:

$$k = \frac{P_{vehicle} \cdot N_{vehicles}}{P_{coil} \cdot N_{coils}}$$

P_{coil} è la potenza di ciascuna bobina (50 kW), $Nvehicles$ è il numero di veicoli elettrici e N_{coils} è la quantità di bobine posizionate al di sotto del manto stradale, questi ultimi due riferiti al singolo chilometro. Nella tabella 4 sono riportati i valori numerici di ciascuna variabile utile per il calcolo del coefficiente k.

Vehicle Speed (km/h)	Requested Power (kW/EV)	Safe Distance (m)	Number of Vehicles (EVs/km)	Total Requested Power (kW/km)	Contemporaneity Factor k
90	18	81	12	222	0,0089
100	23	100	10	230	0,0092
110	28	121	8	231	0,0093
120	34	144	7	236	0,0094
130	42	169	6	249	0,0099

Table 5 – Estimation of the simultaneity factor for different speeds of the vehicle and power required [13] [40]

From the different simultaneity coefficients obtained for each speed, it can be seen that, from the point of view of electricity consumption, the worst case occurs when the vehicle speed is maximum and equal to 130 km/h. In this condition there is a higher absorption of electricity, despite the number of cars in circulation being lower than in the other scenarios listed.

Analysis and stress model of energy sustainability

We then carried out an energy sustainability assessment of the hypothetical Dynamic IPT infrastructure to be built on the Milan-Reggio Calabria motorway section, in terms of the number of vehicles present on the section considered.

We hypothesized traveling on the motorway with cars that had a declared autonomy between 400 and 600 km and were appropriately adapted (revamped) to be recharged by a Dynamic IPT infrastructure. We considered the models tested in consumption by Nextmove [71]:

Tesla 3	Tesla S	Tesla X

		
1. Battery capacity: 79 kWh, 2, Autonomy: with 100% SOC: up to 602 km, 3, Recharge up to 275 km in 15 minutes at Supercharger stations.	1. Battery capacity 95 kWh, 2. Autonomy with 100% SOC: up to 634 km, 3. Recharge up to 322 km in 15 minutes at Supercharger stations	1. Battery capacity 95 kWh, 2. Autonomy with 100% SOC: up to 543 km, 3. Recharge up to 282 km in 15 minutes thanks to the latest Supercharger technology

Figure 8: Technical characteristics of the tested models [72]

Table 5 shows the models considered and the consumption tested by Nextmove (www.nextmove.de), traveling at an average speed of 130 km/h:

Car Models	Verified Consuptions
Speed 130 km/h	KWh /100km
Tesla Model 3	18,5
Testa Model S	20,4
Tesla Model X	24,1

Table 6 – Market electric car consumption [71]

For our general assessments we can consider a vehicle with a consumption of 22.1 kWh, i.e. equal to the average consumption of the market vehicles considered.

We tried to hypothesize a method for calculating the energy requirement on the Milan - Reggio Calabria motorway section.

N° cars on the route MI-RC	GWh requested fron network	TWh requested fron network
1	0,000243	0,000000243
1000	0,243	0,000243
10.000	2,431	0,002431
50.000	12.155	0,012155
100.000	24.310	0,02431
1.000.000	24.3100	0,2431
10.000.000	2.431.000	2,431

Table 7 – Data for calculating the energy requirement on the stretch MI-RC

Tutti i valori si riferiscono ad un viaggio giornaliero completo

Using the values from table 6 (which can be extended), if we consider a number of Ncar cars traveling on the MI-RC motorway section for the number of days in the year N days, we can calculate the network requirement as:

Fabbisogno rete = (TWh da immettere in rete per Ncar) x N°giorni

If we hypothesize:

- Ngiorni=365
- Nauto=10.000.000

It menas that 10.000.000 of vehicles they make the MI-RC trip every day and request 2,431 x 365 = 887,32,63 TWh. Clearly it is an extreme case that would not be sustainable considering that national energy production is 280,5 TWh.

If we consider an average daily presence of cars on the Milan – Reggio Calabria stretch equivalent to 10,000 cars making the entire route,

- Ngiorni=365
- Nauto=10.000

We obtain an energy requirement for the DIPT solution between Milan and Reggio Calabria equal to: 0.887315 TWh, therefore the solution appears sustainable by varying the Nauto parameter with a realistic number of vehicles in transit on the MI-RC motorway section. Unfortunately it was not possible to obtain official data on the number of cars in transit on the route considered daily.
Obviously with this method we can calculate the energy requirement of the DIPT solution for any number of cars regardless of whether they have completed the complete or partial journey on the motorway stretch from Milan to Reggio Calabria. In fact, it is enough to add all the kilometers traveled and divide by the distance between Mi and RC which we have seen is 1,233.6 km, thus obtaining the simulated value of the total number of cars that have theoretically traveled the entire motorway section considered.

With regards to the problems of calculating network requirements for billing purposes, the calculation of the km travelled, the average travel speed (and therefore energy consumption) could be automatically deduced from a system for recognizing the license plates of cars entering and leaving the toll booths located within the MI-RC motorway section. This system currently already exists and is functional although it is only intended to detect the license plates of those who do not make the payment correctly in the lanes with telepass, manual payment and automatic payment (cash and electronic cards).
From the license plates we could quickly trace, through the revenue agency database in which all the vehicles and their owners are registered, the model of the electric car (EV), the technical characteristics which together with the average speed give us an indication of the possible consumption, and to the name of the owner of the vehicle to whom the energy consumption for the km traveled will be invoiced. The management of foreign license plates for Dynamic IPT compliant electric vehicles requires the sharing at a European or non-European level of databases similar to that of the agency of revenue or alternatively the maintenance of the forms of payment already in use.

In summary, the number of km calculated for each model allows us to evaluate the network needs and at the same time allows us to calculate the automatic pricing to be applied for energy consumption.
In fact, if we assume:

- Energy price in KWh = 0.501 euros (cost as of 8 December 2022)
- Power required by the vehicle for the average speed calculated between entry and exit which for simplicity we set constant at 130 km/h = 21 KWh
- Travel time in hours = 11

The tariff for energy consumption alone would be calculable as the product of the three variables which for the hypothesized values is: 115.731 euros

Obviously, the toll rate corresponding to the motorway section between entry and exit could be added to this figure.
In the energy impact analysis model we have provided the tools to understand the sustainability of the system in proportion to the number of vehicles on the motorway stretch and we have shown a theoretical situation in which the system is not sustainable based on the current energy production capacity electricity in our country.

This method can be useful for determining energy needs even by assuming an exponential trend in the growth rate of electric vehicles, based on estimates from the IEA and Bloomberg NEF (New Energy Finance) which predict a percentage of 34% for 2040 [41] and on the European Union proposal contained within "Fit for 55" [43] which provides for a stop in the use of petrol or electric cars by 2050. The expected evolution of the number of electric cars is reported in following graph:

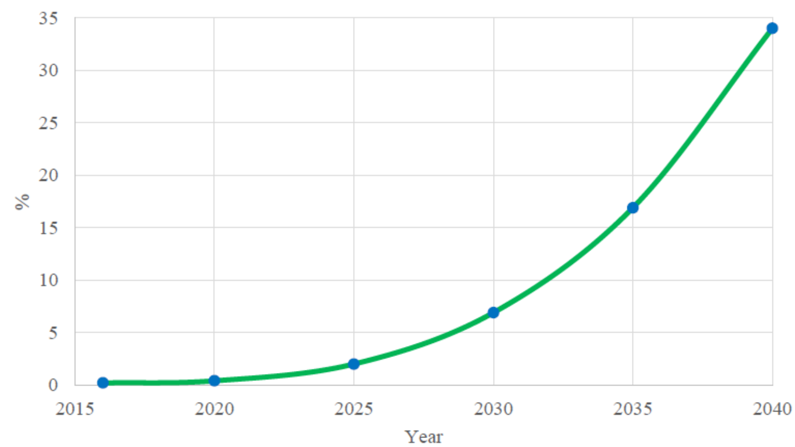


Figure 9– Future trend of electric vehicles in Europe [41]

It is desirable that the energy sustainability of the Dynamic IPT infrastructure accompanied using clean energy from renewable sources, with a progressive abandonment of the use of fossil fuels for the production of the energy necessary for operation. In this sense it must be said that on the motorway stretch from Salerno to Reggio Calabria there are numerous areas with high winds and therefore predisposed to the installation of wind turbines, some of which are already present.
Even on some stretches between Salerno and Rome there are stretches characterized by strong winds. The entire remaining stretch could be energetically supported with the installation of photovoltaic fields.

This hope is in line with the data from the "EU Reference Scenario" document, drawn up by the European Commission in 2016; we note that, in addition to analyzing data relating to energy generation in the various European states, it also takes into consideration the transport sector and greenhouse gas emissions [44].

As the following graph highlights, and as is widely predictable, in a time scale ranging from 2016 to 2040 there is a point in which electricity production from RES (Renewable Energy Sources) exceeds that from conventional energy sources.

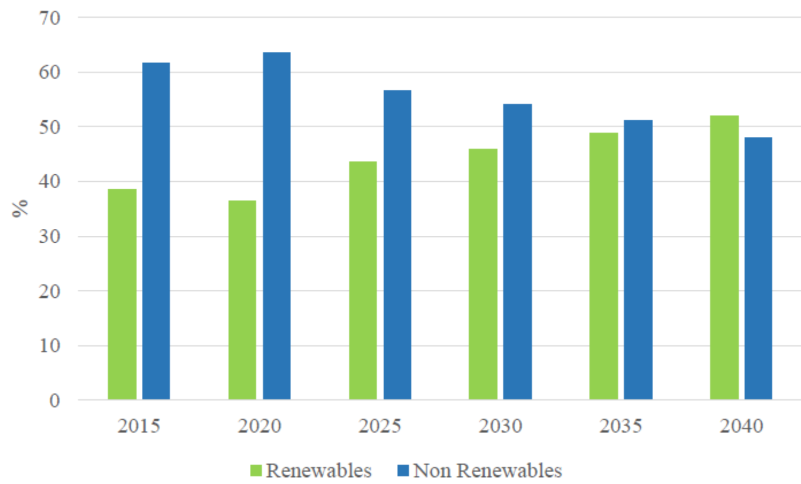


Figure 10: Percentage of gross electricity production in Italy [44]

C. Environmental sustainability

As existing literature has shown (see [49], for a summary in Italian), the CO2 emissions of BEVs (Battery Electric vehicles) and ICEVs (Internal combustion engine vehicles) depend on numerous factors. An analysis that aims to be as complete as possible must consider the entire life cycle of the car and the fuel, carrying out what in international literature is called life-cycle analysis. This is a procedure that is far from simple to implement, requiring in-depth knowledge of the materials and technologies used in the production processes and the availability of data that is not easy to find as it is confidential or covered by industrial secrecy. Furthermore, some of the parameters to be used are not stable, they change over time in relation to technological progress, industrial choices, market trends and the public regulatory framework.
The study does not operate on specific units of measurement (for example the km) but on overall results of CO2 emissions linked to the life cycle of a motorway infrastructure with and without the integration of Dynamic IPT technology. This means that the application of these results to the adaptation of the Milan-Reggio Calabria motorway section allows us to be aware of the difference in CO2 emissions between traditional mobility and one adequate with DIPT technology.
There is sufficient general consensus on the fact that to carry out a serious analysis of the entire life cycle of the car, the quantity of CO2 emitted must be considered:

- in the extraction, refining and distribution phases of the fuels necessary to power the ICEVs or to produce electricity;
- for the production and transmission of electricity;
- for the production of vehicle components, including the battery, their assembly and disposal or reuse;
- to move the vehicle.

Graphically, the phases of the car life cycle analysis can be represented as in figure 11:

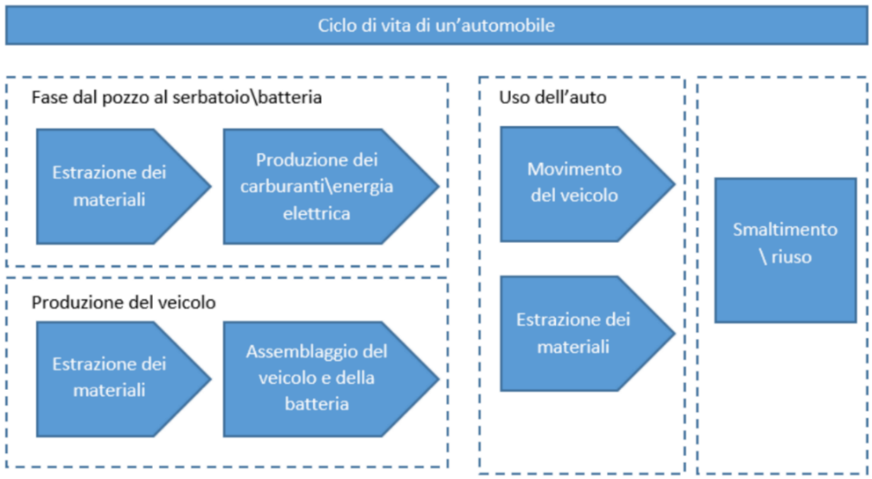


Figure 11 – LCA model used to estimate CO2 emissions from BEVs and CEVs [49]

The estimation model used by Daniels [50] provides:

- the selection of the sample of cars to be compared;
- the calculation of average CO2 emissions per km traveled for ICEVs (petrol, diesel, hybrid) for the most sold cars in Italy;
- the calculation of the average energy consumption in kWh per km traveled for BEVs on sale in Italy;
- the identification of average emissions to produce and distribute energy in Italy;
- the calculation of CO2 emissions to manufacture and dispose of the vehicle;
- the calculation of CO2 emissions to manufacture and dispose of batteries;
- the calculation of CO2 emissions to extract and refine the raw materials necessary to produce fuels, energy, cars and batteries.

Using this model and the data on CO2 emissions detectable from two important databases:

- the one managed by the US Environmental Protection Agency (EPA, 2016), which also reports data on fuel consumption and CO2 emissions.
- maintained on behalf of the English government by the Vehicle Certification Agency (VCA), an agency of the UK Department of Transport [70].

Daniels et al. [50] demonstrate, with specific reference to car models circulating in Italy, that electric cars emit less CO2 overall than cars with internal combustion engines: 19% less than petrol cars, 18% less than diesel cars and 9% less than hybrids.

This result is certainly interesting and supports the political choice, shared at a European level, to promote electric mobility in the future over thermal mobility. However, this result is not sufficient for our analysis. In fact, by using an IPT infrastructure, one cannot limit oneself only to the environmental impact assessment induced by the construction of the vehicle and its use, but it is also necessary to evaluate the environmental impact caused by the construction and maintenance of the IPT infrastructure for electric vehicles.

To analyze these further aspects Balieu at al. [51] apply an LCA model based on the ISO 14040 standard (Environmental Management–Life Cycle Assessment: principles and framework) to evaluate the environmental impact for a certain duration of an IPT infrastructure. In fact, the study also makes a comparison with two other electric mobility solutions based on the use of the pantograph and the use of electrified tracks, which allow us to better evaluate the advantages and disadvantages of the choice of IPT technology; for the study we will limit ourselves to considerations that concern only the comparison between a traditional motorway mobility solution, for example the current MI-RC motorway section) and the same motorway section adapted with DIPT technology. Since there is no clear "end of life" in pavement [52], this paper therefore presents a Cradle-to-Gate model that includes:

- raw material production of both asphalt and loading system,
- the asphalt mixing process,
- the construction of the eRoad (intended as a road with Dynamic IPT technology),
- winter maintenance operations and road rehabilitation.

A complete approach to the environmental impact of a system requires that it is also assessed with reference to broad-spectrum factors such as climate change, ozone depletion, terrestrial acidification, human toxicity, natural transformation of the soil or the depletion of fossils. For the analysis we considered only some results of the works carried out by Daniels et al [50] and Balieu et al [51], i.e. those relating to the adaptation and integration of a traditional transport infrastructure (in our case the Milan-Milan motorway section Reggio Calabria) with an IPT infrastructure, leaving aside sustainability aspects linked to the pre-existing motorway infrastructure, as it is not the subject of the study. For simplicity, electrical components such as connectors and embedded capacitors (IPT solutions) are not included in the proposed LCA model, but have been considered in the economic impact analysis. Furthermore, since the purpose of this study is to evaluate the impact of the road infrastructure in terms of environmental impact, the power supply, shelter distribution lines and power electronics (DC/HF) were not considered in the study.

Results of the LCA analysis

In this section, the CO2 impacts associated with the construction, operation (winter maintenance) and rehabilitation phases of the Dynamic IPT solution on the Milan-Reggio Calabria motorway section will be analysed, compared to the traditional one. After the winter maintenance and rehabilitation operations which are variable in the proposed model, a sensitivity analysis is presented to investigate the effect of these parameters on the total life cycle of the infrastructure considered.

Construction phase

The results in terms of CO2 emissions resulting from the analysis of the relevant inventory:

a. the production of raw materials necessary for the construction of the eRoad solution based on Dynamic IPT e
b. the construction of a traditional motorway,

are displayed in the following graph:

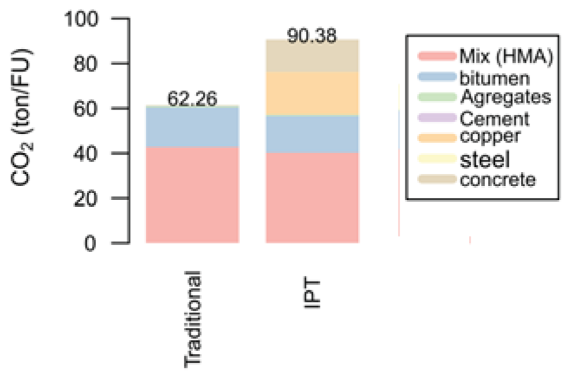


Figure 12 – CO2 impacts related to the production of raw materials necessary for the construction of various roads [51]

It is obvious that all suitable eRoad solutions with Dynamic IPT technology have a higher CO2 impact than a traditional road as there are more raw materials involved in their constructions. It is interesting to note the significant amount of CO2 resulting from the use of concrete for the manufacturing of the IPT technology charging system integrated into the road surface. This technology is still in the development phase, an optimization of the dimensions of the charging system could significantly reduce the environmental impact induced by the production of concrete. The CO2 impact of the entire construction process [51], including paving operations and transportation of construction material, are summarized in Figure 13:

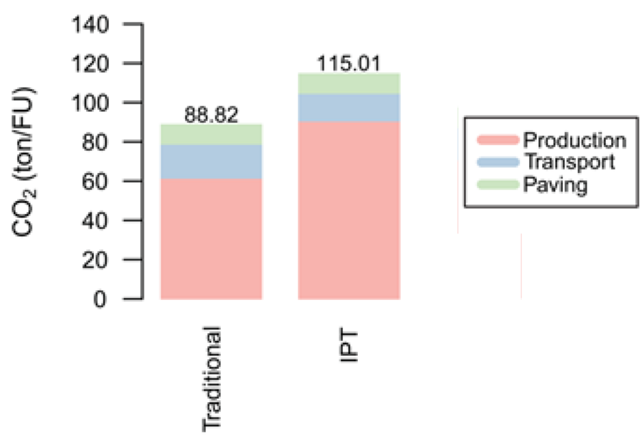


Figure 13 – I CO2 impacts related to the entire construction process of the various roads [51].

It is clear from the graph that the production factor of raw materials has a significant impact on the adaptation of the motorway with DIPT technology. Let's now evaluate the entire life cycle.

Entire life cycle including winter maintenance and rehabilitation operations

The first study was carried out with the same frequency of winter maintenance and road rehabilitation for both the traditional solution and the one with Dynamic IPT to compare their impacts with the construction process and compare the two solutions with each other. In this analysis, the restorations on the considered lifetime of the roads are the replacement of the upper layer (3 times) and the replacement of the entire pavement (1 time). The frequency of sand and salt spreading is 2 and 4 times per year, respectively, and the frequency of snow clearing is assumed to be 10 times per year.
Figure 14 presents the CO2 impacts of the entire life cycle considered (20 years), including construction, winter maintenance and rehabilitation operations of a traditional motorway and the motorway with the Dynamic IPT solution.

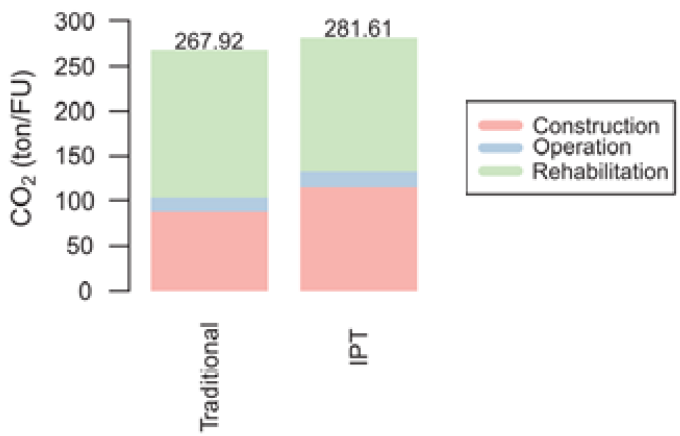


Figure 14 – CO2 impacts related to the entire life cycle of different roads [51].

For all solutions, the maintenance operation is the phase with the greatest CO2 impacts on the entire life of both an eRoad with IPT and a traditional road. Maintenance operations represent 61.43% and 53.08% of the total CO2 impacts of traditional and IPT solutions respectively.

Sensitivity analysis

Road rehabilitation operations require a significant quantity of raw materials and have a large impact on the final environmental impact assessment. The frequency of maintenance interventions is therefore a key parameter in the sustainability of a road infrastructure and, unfortunately, making accurate predictions of the maintenance frequency of a particular solution is not possible due to the huge number of parameters that influence long-term behavior of a road, electrified or not, e.g. load, temperature, humidity, mixing process, construction process. “Finite element” (FEA) simulations carried out by Chen, Balieu, Cordoba, et al. (2019) [53] and Chen, Balieu, et al. (2018) [54] showed greater damage in pavement where IPT charging systems are embedded in the asphalt. In terms of final evaluation, it must be considered that using a Dynamic IPT solution the frequency of all rehabilitations of the motorway surface should be multiplied by 3. [54].

Furthermore, the simulation shows that the eRoad solution based on Dynamic IPT presents greater damage after 1,000,000 passages of heavy vehicles. Therefore, to guarantee good efficiency of power transfer, the frequency of winter maintenance interventions only in the presence of a Dynamic IPT solution should be multiplied by 2.

The CO2 impacts of the entire life cycle considered (20 years) including construction operations, winter maintenance and rehabilitation of a traditional motorway infrastructure and one integrated with Dynamic IPT technology are shown in figure 15.

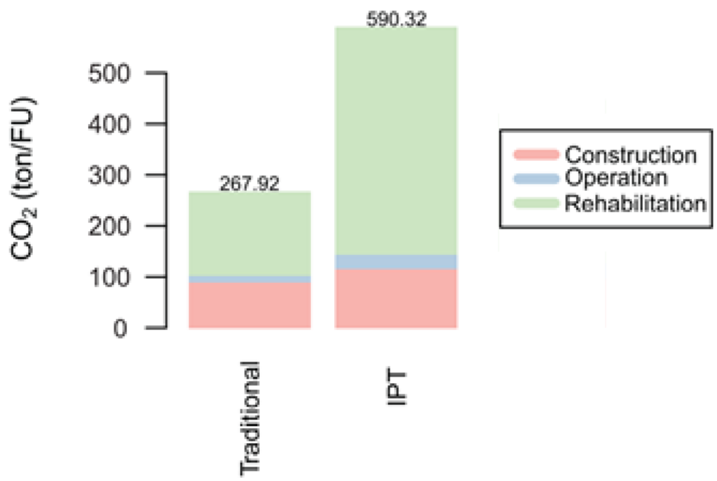


Figure 15 – CO2 impacts with increased maintenance and rehabilitation operations for the IPT solution [51].

We see that the solution with inductive power transfer has a greater CO2 impact than a traditional solution. The increase in the frequency of winter interventions only moderately affects the overall impact of the solutions. But considering the rehabilitation operations in the case of the eRoad with IPT Technology, which are multiplied by 3 compared to a traditional motorway infrastructure, an increase of over 200% is observed in CO2 emissions for the entire life cycle considered.
Without taking into account the gain resulting from the reduction of vehicle emissions, the total CO2 emissions of transport infrastructures such as eRoads built with DIPT technology are therefore 220% higher than a traditional road.
It is therefore of primary importance to ensure that the gain obtained from the reduction of CO2 emissions from vehicles is not nullified by further rehabilitation operations.
These results highlight the importance of pavement rehabilitation in the life cycle of the road. It is essential to propose electrified roads with good structural performance to limit the maintenance necessary to guarantee the correct functioning of the system.
If applied to the MI-RC motorway section, the results of these studies lead us to believe that the technological adaptation of this artery with a Dynamic IPT solution could entail a significantly higher cost in terms of CO2, unless new materials are identified raw materials that require less

environmental impact for their production and that present greater resistance to the stresses of heavy vehicles, such as graphene for example. The first results in this sense have already demonstrated that compared to traditional asphalt or concrete, graphene mixtures allow for an improvement in fatigue resistance with a result greater than 250%, resistance to deformation for the same amount of applied effort, the stiffness modulus , in fact, it was measured at different temperatures showing an improvement of 46% at 40°C, resistance to the passage of vehicles of 35% more and finally, in terms of permanent plastic deformation: the rutting values (traces left by the tyres) they were 35% lower at 60°C. [55][56]
The combination of new technologies (such as Gipave) and the regeneration of old road pavements allow the reuse of materials already present on the road, an increase in their lifespan and the consequent reduction in maintenance. So much so that, they estimate, roads built with Gipave can be 100% recycled, thus reducing the extraction of new materials and the use of first-use bitumen.
This will obviously have a decisive impact on reducing the environmental impact of construction and maintenance in the adoption of eRoad solutions based on Dynamic IPT technology.

D. Case studies

In this paragraph we investigate a further aspect to improve the applicability of DIPT technology on the motorway stretch from Milan to Reggio Calabria, that relating to the optimization of charging efficiency. To analyze this aspect we consider two case studies in this regard which differ in the number of receivers on board. The first case involves the use of a receiver in the centre, the second case involves two: one in the front part and one in the rear part of the vehicle. Let's analyze whether the choice of one or two receivers affects charging efficiency.

Case study 1: Using a center receiver
There are two main types of transmitter coils: (i) long-track pads which are quite similar to exciter rails; and (ii) multiple short-range pads that are quite similar to a series of relatively small primary coils fixed to the road. The two solutions are schematically shown in figure 16. The first architecture is better for electric vehicles as they have quite uniform excitation during their motion, but it is not very energy efficient, and electromagnetic pollution of the surrounding environment it's significant. The second architecture is more complex and the vehicle has different excitations during the movement, but it is more efficient and the electromagnetic pollution is limited since the shoes of the short track are energized one at a time only when an electric vehicle is just above a pitch. The maximization of efficiency and the reduction of the safety problem of the electromagnetic field (EMF) make this solution the most promising but also the most complex today. However, there are some important points that need to be considered when adopting this setup. First, the size of the GA coil is a critical parameter, as a shorter GA coil allows for high levels of efficiency, but the vehicle can only be powered for a short distance comparable to the length of the coil.
In contrast, a longer coil allows for high transmission coverage but with reduced efficiency due to high magnetic flux dispersion. In addition to the size of the individual GA coil, another critical aspect is the separation between adjacent GA coils along the way (x-axis). To make the system operate in optimal conditions, the GA coil turns on only when the VA coil is sufficiently aligned with the GA coil itself. Thus, in the space between two adjacent GA coils, the VA coil is not

energized. To avoid this problem, the GA coils should be very close together or even overlapped, with a significant increase in the number of transmitting coils along the way. Therefore, typically, a compromise is calculated between the maximum number of GA coils and the space where the VA coils are not excited.

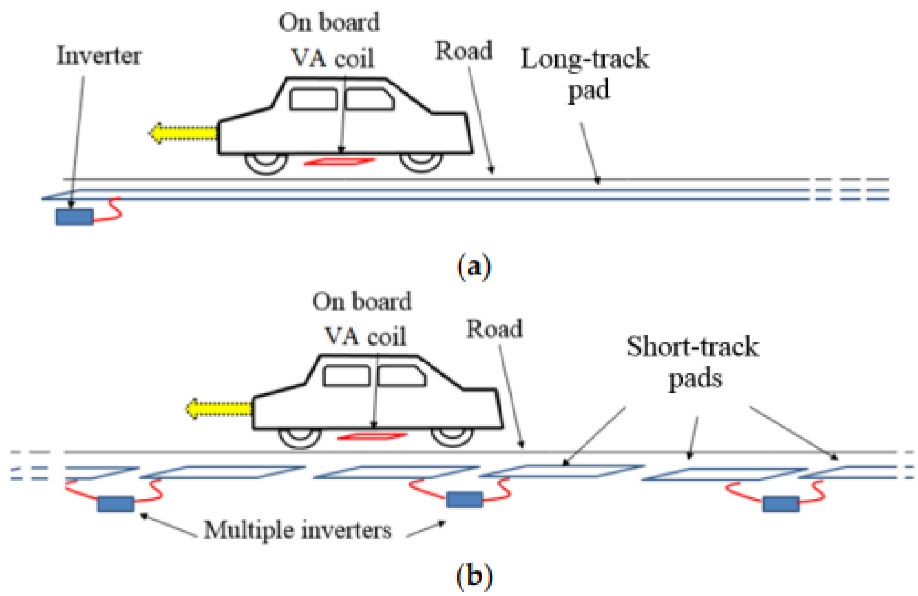


Figure 16 –. DIPT coil architecture: long-track pads (a) and multiple short-track pads (b) [57]

However, the discontinuity of the power supply for the EV leads to several problems: the overall charging time is increased, the battery life is reduced as the charge is not constant but with many peaks due to the transition of the coils and, finally, the Rapid transition between coils gives rise to current transients that can produce electromagnetic interference (EMI) in the vehicle, harmonics in the mains and magnetic fields in the environment.

It should also be considered that the solution based on long track pads is less resilient in the event of failure and may require rapid maintenance times compared to possible isolated failures of the GA coils of the short track pad solution.

Case study 2: use of two receivers, one front and one rear

In this case, an innovative conFiguretion for the DWPT system based on a new receiver architecture based on two independent VA coils mounted in the underbody of the electric vehicle is considered. The two coils work one at a time depending on the position of the electric vehicle along the electrified road. Selecting the best VA coil to activate is based on maximizing the inductive coupling to the transmitter coils.

Figure 17 describes a typical short track conFiguretion. On the GA side, each transmitter coil is powered at high frequency by an independent inverter and compensated by an impedance matching network (IMN) connected to the main network by a bus (often DC but can also be AC at power frequency) by means of some power electronic devices.

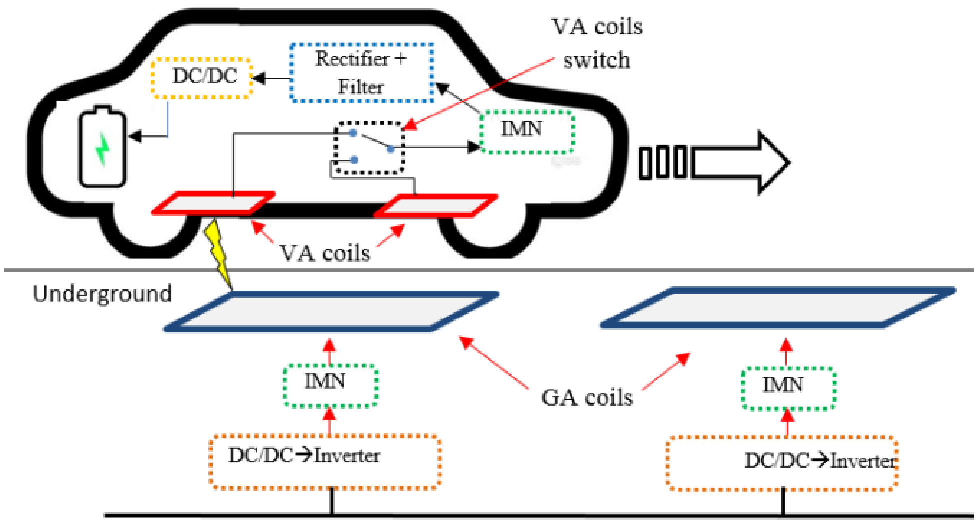


Figure 17 –. Operational flow of the proposed architecture [57]

An electric vehicle equipped with the proposed two-coil system moves on an electrified road with multiple short-range pads (GA1, GA2, . . . , coils) embedded in the road pavement. The proposed architecture and the operational approach adopted for the design of the system are described below.

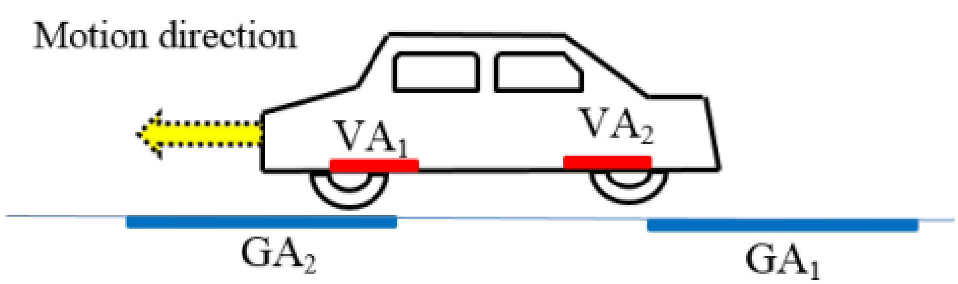


Figure 18 – Vehicles with two receivers for an IPT infrastructure [57]

Figure 19 shows a diagram of three different positions for the vehicle moving along the road.
In sequence 1 (corresponding to time t1), GA1 is activated to transfer energy to VA1. When the coupling between GA1 and VA1 becomes too low due to EV motion and the efficiency drops below a predetermined level, VA1 is disconnected and VA2 is activated as a receiver, as shown in Sequence 2 at time t2 > t1. This condition is maintained until the coupling between GA1 and VA2 drops below the preset level. At this point GA1 is deactivated and the next coil GA2 is activated.

At the same time, VA2 is disconnected and VA1 is activated as a receiver again, as shown in Sequence 3 at time t3 > t2. Then, the procedure is repeated, as in the sequence just described.

Ideally neglecting the activation time, with this solution, the power supply to the EV is almost continuous, since one of the two VA coils is always powered by the GA coils with a short-range architecture.

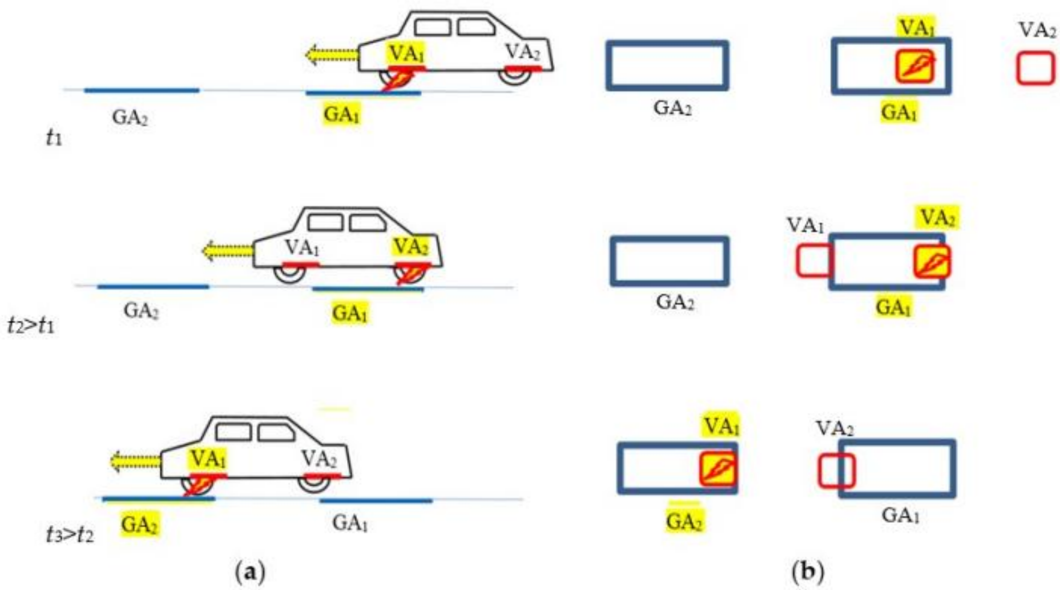


Figure 19 – Diagram of three different sequences at different times of the proposed charging solution during the movement of the EV. (a) Side view. (b) Top view (GA coil depicted in blue and VA coil in red, red lightning indicates coil activation) [57].

The two VA coils are installed on the underbody of the vehicle and connected to a single IMN via a switch to select the most suitable VA coil to activate. When one VA coil is used for energy transfer, the other is in open condition; therefore, no current flows inside it. The switch will operate at a lower frequency than the resonant frequency of the WPT system.
The two VA coils have square shapes with external side lengths of lVA = 50 cm. A square layer of ferrite with side wfe = 50 cm and thickness tfe = 8 mm [19] is placed between the copper VA coil and the metal one of the electric vehicle body to mitigate eddy currents in the conductive frame. The GA coils have rectangular shapes with an appropriate width of wGA to ensure adequate tolerance with respect to possible lateral misalignments of the coupled coils. Assuming that lGA is the length of the GA coil, SGA is the separation between adjacent GA coils, and SVA is the separation between the two VAs, it is assumed that the coils are the design variables that need to be optimized. To keep costs low, no conductive shields or magnetic materials are used in GA coils.

Efficiency difference using 1 or 2 receivers

Mohamed et al. [58], carried out a study on the efficiency obtained by using two receivers instead of just one. In particular, the magnetic fields induced by the transmitting coil were analyzed using one or two receivers respectively.

The mutual inductance, the coupling coefficient and the shape of the distributed field were analyzed based on the translation of the transmitter towards the receiver parts. The Maxwell platform was used to obtain the survey results. The results demonstrated how much energy is acquired by the receiver(s) in all possible positions and were validated with the creation of an experimental prototype.

It was thus possible to evaluate the efficiency aspects of the IPT infrastructure for the autonomy of electric vehicles. Let's see some of the results obtained:

Power transfer factor for the case of one or two receivers coils.

	Distance (mm)	Power Transfer	Efficiency	Max_{eff}	Max_{pow}	Av_{pow}
Simple receiver coil	−200	0.3 kw	10%	92%	4.9 kw	2.34 kw
	−100	1.9 kw	54%			
	−50	3.6 kw	78%			
	0	4.9 kw	92%			
	50	3.5 kw	77%			
	100	1.9 kw	54%			
	200	0.3 kw	10%			
Multiple receiver coils	−300	0.5 kw	12%	96%	5.1 kw	3.95 kw
	−250	3.7	79%			
	−200	4.8	87%			
	−100	4.9	88%			
	−50	5.1 kw	96%			
	0	5.2 kw	96%			
	50	5.2 kw	95%			
	100	5 kw	90%			
	200	4.9 kw	88%			
	250	3.7 kw	79%			
	300	0.5 kw	12%			

Av_{pow}: Average outputted power; Max_{eff}: Maximum achievable coil system efficiency; Max_{pow} : Maximum achievable output power.

Table 7 – Power transfer efficiency with 1 and 2 receivers [58]

Table 7 shows how in the case of using two receiving coils, using Dynamic IPT technology, a power transfer efficiency of up to 96% can be achieved versus a maximum efficiency of 92% achievable with a single coil.
The tests were carried out assuming the following characteristics [58]:

Coil diameter	50 cm
Distance between coil	150 cm
Width of winding "w"	21 cm
Average winding radius "r"	14.5 cm
Number of turns "N"	15 Turns

Table 8 – Characteristics of the test environment [58]

And the following conFiguretion on the Maxwell platform [58]:

Designation	Used Choice
Coil material	Copper
Polygon Segments	4
Polygon Radius	1 mm
Start Helix Radius	20 mm
Radius Change	2.05 mm
Pitch	0
Turns	10
Segments Per Tum	36
Right-Handed	1

Table 9– ConFiguretion of the Maxwell platform adopted for testing [58]

If the coupling coefficient and mutual inductance are considered, the suitability of the wireless charging system can be evaluated.
Figure 20 shows the results of Mutual inductance with one and two receivers as a function of the distance between the transmitter and the receiver(s).

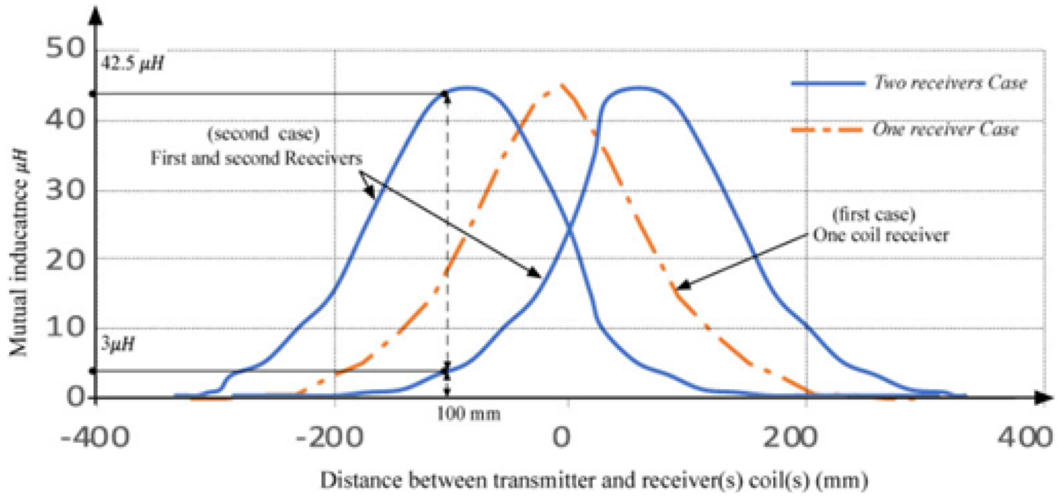


Figure 20 – Variations of mutual inductance as a function of distance between transmitter and receiver(s) [58]

The best mutual inductance value remains constant at approximately 45 µH, up to a distance of 180 mm. Then its value begins to decrease until it disappears beyond 200 mm, a distance beyond which there will be no more energy transfer.

From the analysis of the case studies it emerges that there are technical problems relating to power transfer, to which ongoing research activities are trying to provide effective answers.
In general, Dynamic IPT systems are much more complicated systems than the traditional plug-and-socket cable-based solution, as Dynamic IPT suffers from lower efficiency, higher costs, limited flexibility and possible safety issues due to magnetic fields.

There are also other issues that require further scientific investigation, such as [59]:

- **Foreign and living objects (FO/LO)**
  The possibility of the electromagnetic field being absorbed by nearby foreign (metallic) bodies or living elements exists when considering the idea of transporting energy via air using magnetic fluxes. Not only does this result in losses by first requiring higher power levels to be transmitted, but the risk also arises from the fact that these scenarios can introduce significant heating of the intrusive bodies [60]. Even power transmission systems up to 5W can heat objects to levels not accepted by standard safety levels [61].
- **Misalignment**
  The receive coils must not only be close to the transmitter coils, but they must also be correctly aligned with them for proper power transfer to occur. Misalignment is a major problem of IPT as widely illustrated [62], [63], [64] and introduces considerable losses into the system. Misalignment problems can be both horizontal and vertical.
- **Interoperability**

IPT systems are the subject of continuous research to identify approaches capable of improving their performance. For this optimization, the geometries of the coils are studied in particular, which can offer better tolerance to misalignment [65] [66].

E. Industrial repercussions underway

The arguments and problems addressed in this report are the compendium of numerous international research projects aimed at the application of IPT technology in the field of electric mobility. It is desirable, in consideration of the technological complexity of the solution and the high implementation costs, that a technological transfer be carried out towards large industrial companies in the automotive, electrical and motorway sectors to start a preliminary joint experiment in real operational mobility contexts electric highway. This will allow for greater confidence in the application of DIPT technology on a large scale. This which might appear to be a hope for the future is already a pioneering model being implemented in Italy itself, which involves important industrial partners with prestigious universities. In fact, the “Arena del Futuro” project represents an important initiative to experiment and improve knowledge on the application of IPT technology. The following are participating in the project: the A35 Brebemi-Aleatica Motorway, ABB, Electreon, FIAMM Energy Technology, IVECO, IVECO Bus, Mapei, Pizzarotti, Polytechnic of Milan, Prysmian, Stellantis, TIM, Roma Tre University and the University of Parma. The collaboration is aimed at creating the conditions for the development of an innovative zero-emission mobility system for people and goods along motorway transport corridors. The project aims to demonstrate the effectiveness and efficiency of technologies relating to the powering of electric cars, buses and commercial vehicles through non-contact dynamic inductive charging.
The uniqueness of this innovative project is precisely that of seeing a pool of important international industrial companies joined together, for the first time in the world, supported by prestigious universities and public institutions, with the aim of analyzing all the data that will emerge during the testing of this futuristic technology, before it is used on a large scale.
The project includes, in particular:

- the construction of a 1,050 meter asphalt ring powered with an electrical power of 1MW, called the "Arena of the Future", located in a private area of the A35 motorway near the Chiari Ovest exit
- the application of “Dynamic Wireless Power Transfer” technology to different ranges of electric vehicles in static and dynamic environments
- advanced connectivity through 5G and IoT (Internet of Things) technologies to guarantee maximum road safety and optimize the productivity of commercial vehicles
- the optimization of the road pavement in order to make it more durable and not alter the efficiency of the inductive charge.

Figure 21 – The test track created with the "Arena del Futuro" project

The "Arena del Futuro" project traces some themes and addresses technical problems that were the subject of study for the creation of this report. Therefore, the experimental results of the "Arena del Futuro" project represent a test bed for the validation of the design and technology transfer elements promoted with this study.
The "Arena del Futuro" circuit is powered by direct current (DC). This choice offers a series of advantages:

- Reduction of power losses in the electricity distribution process;
- Ensure direct integration with renewable energy sources without the need for DC to AC conversion;
- Possibility of using thinner cables than those for alternating current distribution with evident advantages in terms of packaging, weight and harmonic pollution;
- Use of aluminum power distribution cables, a material that is easier to find, at half the cost of copper, lighter and easier to recycle in a circular economy model.

To date, the technical choices adopted with the "Arena del Futuro" project go in the direction envisaged by the feasibility analysis reported in our report. In particular:

- <u>Technological choice</u>. The choice of wireless induction technology compared to those of concatenated collection and collection with track in the asphalt, being a more promising technology and capable of ensuring greater safety.
- <u>Economic sustainability:</u> the evaluation of costs per km (from 1,500,000 to 1,200,000 million euros per km provided by the technical and operational director of the Brebemi motorway, Giuseppe Mastroviti [75]), is in line with the economic evaluations of our report [35] [13] [37] [38].
- <u>Choice of materials.</u> The choice of materials and inclusion methods used in the "Arena of the Future" project appears in line with those suggested in our report [35]

Other assessments of coherence between the "Arena del Futuro" industrial project and our feasibility analysis may be carried out as the industrial project makes public the results achieved with the ongoing experimentation (phase III of testing is currently underway) .
It should be underlined and reiterated that our study covered multiple aspects of the design of an IPT solution in the motorway field, being the compendium of various experimental projects carried out at an international and national level.
Therefore, we hope that the data collected and processed with our study can offer food for thought for researchers involved in the "Arena of the Future" project.
Certainly the "Arena of the Future" project represents a unique opportunity to pool academic and industrial knowledge to improve and make IPT technology more efficient in real operational contexts.

Discussion

State of the art

In wireless transfer, the energy taken from the network is transferred to an electrical load without there being electrical contact between source and receiver; Air is used as a propagation medium.
The term WPT indicates a set of technological systems capable of transferring electrical energy wirelessly. We can divide this set into different subsets based on the type of coupling used:

- magnetic (inductive),
- electrical (capacitive) o
- electromagnetic, also called “far-field connection” or far-field.

The different WPT technologies as reported in [13] can be classified as in the following block diagram:

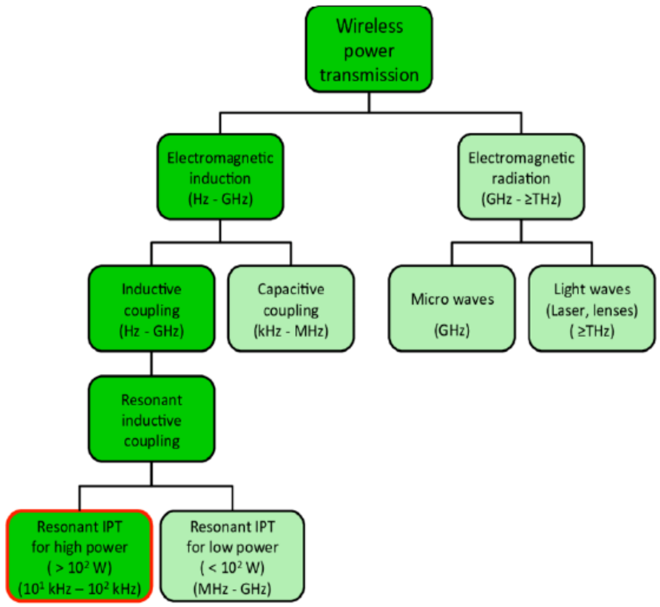


Figure 22 – Different technologies for wireless power transfer [13]

With the more intense color we highlighted the technological path explored with the study. There are four criteria to consider in the design phase to determine the overall efficiency of this technology:

- transmitted power;
- geometry of the turns;
- coupling parameters;
- frequency.

Below we report some of the most important research projects regarding IPT technology (static and dynamic):

- **OLEV** (On-line Electric Vehicle) project has been developed since 2009 in phases and successive versions by KAIST (Korea Advanced Institute of Science and Technology). This is a working and well-proven dynamic IPT system based on Shaped MagneticField In Resonance (SMFIR) technology. The SMFIR concept is based on the use of a massive amount of ferrite to force the flow to meet a defined path [2].
- **Halo WEVC** (Wireless Electric Vehicle Charging) project. Created by the Qualcomm company, following the acquisition of the HaloIPT company in 2011, in collaboration with Renault. The project was aimed at developing high-efficiency wireless charging technology [3].
- **European FABRIC project** (Feasibility analysis and development of on-road charging solutions for future electric vehicles), developed in the period January 2014 - December 2017 by 25 different organizations from 9 European countries. The project's main objective was a detailed feasibility analysis of dynamic wireless charging for electric vehicles. It was partly

funded by the European Union, and focused on the technological and economic feasibility, as well as the socio-environmental sustainability of the technology in question. [4]

- **eCo-FEV project**, acronym for "efficient Cooperative infrastructure for Fully Electric Vehicles", which had as its primary aim the creation of a platform for cooperative electric mobility. This platform would have made it possible to encourage the spread of electric vehicles thanks to real-time communication between different infrastructures, such as roads, car parks and stops, public transport, vehicles and charging systems [5].
- **VICTORIA project** (Vehicle Initiative Consortium for Transport Operation and Road Inductive Applications) was started in 2013, in Spain, by the electricity company Endesa, together with a consortium made up of 4 companies and 3 academic research organisations. The project started the development of a cable-free charging system to double the autonomy of electric buses in the city of Malaga, without changing their charging operation times, while combining static and dynamic IPT technologies [6].
- **UNPLUGGED project** was created by 17 partners and included some of the main companies in the energy (Enel, Endesa), automotive (Volvo, Continental) and transport (Transport for London) sectors, as well as various companies and research centers . The project was born with the aim of creating a fast and flexible infrastructure, capable of recharging the batteries of electric vehicles using a high-power static IPT system: specifically, a rapid wireless charging system of up to 50 kW, which allowed 80% of the charge to be completed in less than 30 minutes. UNPLUGGED also investigated in detail the actual socio-economic impact, technological feasibility, customer acceptance, interoperability and safety of different solutions for charging electric vehicles [7].
- The **PRIMOVE project** carried out by the Bombardier company concerns not only buses and trams, but also light commercial vehicles, trucks and private cars. The project was aimed at testing IPT technology to offer commercial solutions for different types of means of transport [8].
- **MICEV** [2017-2022] is a European project financed by EMPIR – EURAMET and aimed at studying: a) the efficiency of an IPT infrastructure to support electric traffic, b) the impact of electromagnetic exposures on passengers [9]
- **Plugless Power project**, led to the availability of a product with a similar name consisting of a 3.3 kW IPT charging station, developed by EVATRAN and marketed in collaboration with Bosch. It consists of a system adaptable to any EV model with a transmitter side composed of a control panel containing power electronics directly connected to the BT electrical network and a transmitter pad that can be positioned on the floor of a car park or garage. Plug-free power has been successfully tested with the Chevrolet VOLT and Nissan Leaf electric vehicles [10].
- **WAVE** startup born within Utah State University, markets with its brand a starting IPT technology and with the IPT Technology brand a more cutting-edge technology for charging electric buses by induction. The first demonstration prototype was implemented on a campus shuttle equipped with a receiver having the same dimensions as the transmitter embedded in the pavement of the bus stations. This system allows the transfer of 25 kW at 20 kHz to each bus stop. The transfer occurs over an air gap of 15-25 cm achieving efficiency
- A spin-off of the Massachusetts Institute of Technology (MIT), **WiTricity**, which develops wireless power transfer systems for various industries and applications, also offers a solution

for static IPT. A 3.3 kW system has been demonstrated to work but is not yet commercially available. However, Toyota has licensed the WiTricity wireless system and has initiated trials and verification tests for its electric and hybrid models [12].

Table 10 summarizes the methods of application of the illustrated solutions and the parameters that characterize them.

Technology provider	Application	Power (kW)	Frequency (kHz)	Air-gap (mm)	Maximum efficiency (%)
IPT technology	Buses (static)	60	20	40	90[a]
WAVE	Buses (static)	25-50	20	150-250	90[b]
Bombardier (PRIMOVE)	Buses (static and dynamic)	200	N/A	N/A	N/A
KAIST (OLEV 3G)	Buses (dynamic)	200	20	100-200	74[b]
Halo IPT	Cars (static and dynamic)	3.3-6.6-22	85	125-175	95[d]
WiTricity	Cars (static)	3.6-7.7-11	N/A	100-150	94[a]
Evatran (PLUGLESS)	Cars (static)	3.3	19.5	100	88.8[b]
CIRCE/Endesa (UNPLUGGED)	Buses (static)	50	25	250	N/A
ORNL	Cars (dynamic)	2.2	23	100	75[c]
Politecnico di Torino (POLITO CWD)	Light commercial vehicles and cars (dynamic)	20	85	100-250	91[c]

a: info about measurement points n.a. b: AC grid to battery input c: AC/DC output to AC/DC on board output d: coil to coil

Table 10 - Summary of system parameters of main IPT projects [13]

Open issues

Although several aspects related to static IPT are still only approximately resolved, it seems that the standardization process can be concluded in a short period of time. Differently, in dynamic IPT, research activities have just begun and a large number of technical problems still represent open questions. As with the different static IPT solutions, there is no clear agreement on the shape of the magnetic structure of the transmitter and receiver as well as on the position of the receiver under the vehicle.

For example, KAIST is continuing towards a long-track transmitter on the order of a hundred meters [14]; the Auckland team is proposing the adoption of small pads composed of multiple coils superimposed with practically the same ones
size for both the transmitter and the receiver [15]; ORNL is investigating the use of small circular pads [16] on both sides; Bombardier proposes a trace that forms a three-phase magnetic field distribution [17]. The same also happens for the choice of power levels and frequency. These two

parameters influence the technology of electronic switches, the relationships between coil size, transmittable power and air gap [18]. In particular, the frequency value should pass the scrutiny of the electromagnetic compatibility (EMC) analysis with reference to on-board electrical devices and the electrical power supply network. This analysis still seems not specifically investigated.
Another relevant problem for dynamic IPT is the identification of the vehicle when it approaches a transmitter and the management of the transition between subsequent transmitters. Here too, various techniques are being studied such as the use of auxiliary coils for vehicle detection [19], optical sensors, radio communications [20] or cable data links between power electronics converters.

Directly related to all the previous issues is the aspect of protection against exposure to magnetic fields generated in IPT applications. Few substantial studies have been conducted in this domain [21-23] and, in dynamic IPT, standard measurement conditions, reference cases and adopted technical standards are still lacking. A first study attempt is provided in [24].
Finally, there is the enormous amount of challenges represented by all aspects linked to the construction of the road infrastructure, the insertion of the transmitter into the road surface, the choice of paving material, the management of rainwater, the need for communication with the related management infrastructure.
In order to design and apply a dynamic IPT charging system, i.e. inductive charging of moving vehicles, on the Milan – Reggio Calabria motorway section, several preliminary investigations are still needed which concern the following aspects:

- applicability to the motorway infrastructure on the section considered;
- financial impact;
- energy impact; injection of a large amount of electricity into the infrastructure;
- environmental impact;
- management of system efficiency in terms of charging;
- payment system to calculate the energy consumed by individual vehicles and issue the invoice to the vehicle owner.

This work, starting from the technological and scientific state of the art, seeks to respond to the previous problems by providing useful elements for the creation of a sufficiently reliable solution in the MI-RC motorway section.
Other issues related to system design are not covered in the report, such as:

- influence of electromagnetic fields on the health of people and animals; for example, the charging system must not interfere in any way with the functioning of devices such as pacemakers.

Specifically, in this report, we intend to focus attention on the applicability of IPT (Inductive Power Transfer) technology in the motorway sector, i.e. having an inductive type coupling which, in the case of use for charging electric vehicles, is resonant for high powers [25].
The operation of this technology is similar to that of a transformer, for this reason the analysis of an inductive IPT system is based on the modeling of the transformer itself [26].
The operating principle of an inductive coupling is based on the use of a magnetic field that varies over time, generated by an alternating current that passes through a winding and, linking with a second coil, induces an electromotive force in it, in turn originating a alternating current in the secondary circuit.
The primary circuit refers to the transmitter, while the secondary circuit refers to the receiver.
For efficient power transfer, a strong magnetic coupling between the coils is required. Since the axial and angular misalignment between the coils drastically weakens the coupling, IPT is mainly used in high power transmission over short distances [27].
Figure 23 shows the reference model. Inductive power transfer (IPT) occurs when a primary coil of an energy transmitter generates a predominantly variable magnetic field across the secondary coil of the energy receiver within the field, typically less than one wavelength. The power of the magnetic field then induces voltage/current through the secondary coil of the energy receiver within the field.
The operating frequency of inductive coupling is typically in the kilo Hertz range [28]. Adjusting the frequency of the secondary coil, equal to the operating frequency, improves the efficiency of the system [29].

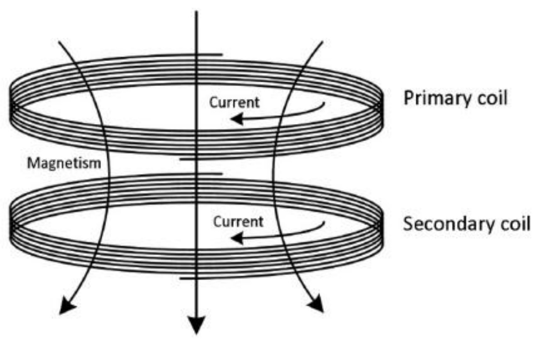


Figure 23 – Inductive coupling [28]

A magnetic IPT system for the wireless charging of electric vehicles is generally composed of three components which in turn are regulated by an appropriate control system in order to guarantee optimal performance of the overall apparatus:

1. 1. mains power supply unit;
2. 2. transmission unit (primary circuit);
3. 3. receiving unit (secondary circuit).

In figure 24 the three systems are represented as used in practice, using a block diagram.

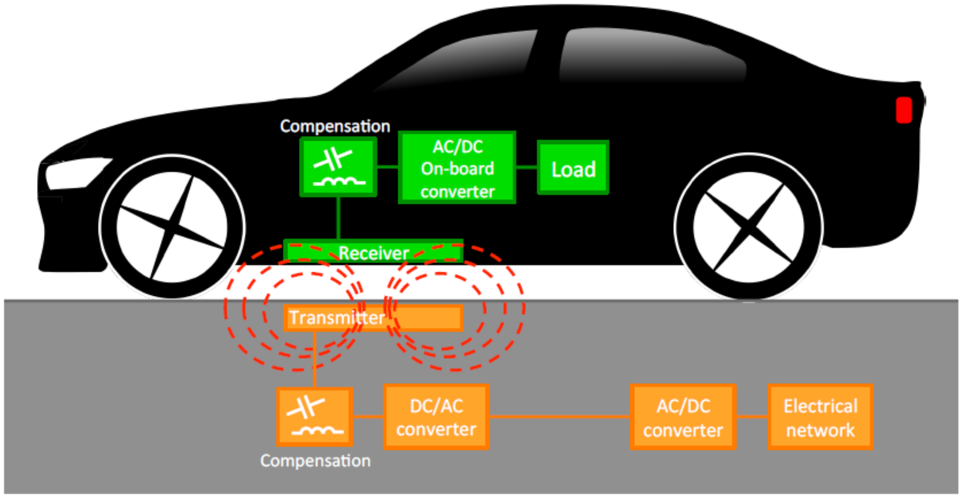


Figure 24 –.Block diagram of an inductive power transfer system for electric vehicles [13]

- The first unit consists of a power converter and an inverter which allow optimal values of frequency, voltage and power of the electric current to be obtained, so as to be able to transfer the latter to the primary circuit with the lowest possible losses. The frequency range is between 10 kHz and 100 kHz; typically 20 kHz is assumed as the standard reference value.

- The second unit is basically composed of two pads magnetically coupled and characterized by their own inductance and resistance. In other words, the transmission unit is nothing more than a transformer characterized by a very low magnetic permeability of the core, since the core itself is composed of air. Depending on their function, it is possible to distinguish the two coils into transmitter and receiver; the latter is placed underneath the vehicle itself, while the transmitter is typically placed inside the road surface. Regarding the transmission of energy, it is certainly important to consider how the various physical factors, first of all the mutual position between the two pads, influence the power delivered. Specifically, the main parameters to evaluate are:
    - or horizontal misalignment
    - o the air-gap (distance in air) between transmitter and receiver; the latter typically between 10 and 20 cm.

- The third unit, located inside the electric vehicle, includes a power rectifier and the battery pack. It is important to note that one of the main disadvantages is represented by the high cost of the battery, as well as its high weight, even if the latter is significantly reduced compared to the case of a traditional electric vehicle with a standard charging system [30].

Dynamic IPT (DIPT) charging methods for electric vehicles

IPT charging for electric vehicles presents numerous advantages when compared to the classic charging method which, showing various problems connected to public or private charging stations, times and wiring, struggles to spread adequately on the market. Thanks to growth in the development of IPT technology, it has been possible to increase power transfer distances from a few millimeters to several centimeters; Despite this, however, there are still numerous problems connected to the marketing of this charging system. The main difficulties concern: the achievement of acceptable power transfer efficiencies, the obtaining of wider tolerances relating to the misalignment between transmitter and receiver, the resolution of problems related to the safety and health of people, the lowering of the high costs of installation.
The two main types of charging are: static (static IPT) and dynamic (dynamic IPT); the latter which can be studied as a sequence of static conFiguretions.

Charging efficiency

Static Inductive Power Transfer (IPT) charging represents a viable alternative to standard electric charging; however, in this case as well, the vehicle must remain parked throughout the charging process. Laboratory-calculated efficiency for this technology is sufficiently high, at approximately **90%** (see Table 2). In recent years, several companies have invested in this field, developing and commercializing projects such as:

- “PLUGLESS” by Evatran.
- “Qualcomm HaloIPT” by Qualcomm Co.
- “Leaf” by Nissan Motor Co.
- “2014 Volt” by Chevrolet [31].

Institute	Power (kW)	Switching frequency (kHz)	Air-gap (mm)	Efficiency (%)	Year
University of Auckland	2	20	200	-	2011
	2-7	20	100-250	-	2013
	1	85	100	91.3[c]	2015
UM-Dearborn	3.3	1000	150	95[b]	2015
	6	95	150	95.3[b]	2015
	7.7	79	200	96[b]	2014
KAIST	5-15	20	150	-	2014
Utah State University	5	20	175-265	90[a]	2012
Saitama University	3	50	200	90[b]	2012
ETH Zurich	5	100	52	96.5[b]	2015

a: AC grid to battery pack efficiency b: DC input to battery pack efficiency c: coil efficiency

Table 11 - Summary of the system parameters of the selected stationary charging systems [32]

Dynamic IPT charging, unlike static charging, allows the vehicle to recharge on the move, thus eliminating the need to stop for several hours in the designated charging areas; consequently this leads to a reduction in the capacity of the battery pack, and therefore its volume and weight. An adequate infrastructure present in the area would theoretically allow electric vehicles capable of taking advantage of this technology to circulate on the road without autonomy limits thanks to more frequent recharging carried out in less time. On the other hand, when compared to static charging, the dynamic type has yields that are a few percentage points lower, as shown in table 12:

Institute	Power (kW)	Switching frequency (kHz)	Air-gap (mm)	Efficiency (%)	Year
KAIST	3-25	20	10-200	72-83[a]	2009
ORNL	1.5	23	100	75[b]	2013
NCSU	0.3	100	170	77.82[b]	2014

a: AC grid to battery pack efficiency   b: DC input to battery pack efficiency

Table 12 - Summary of system parameters of selected dynamic charging systems [32]

A third possible use of the IPT system is the stationary one and represents an intermediate solution between the two described above. This type of charging occurs when the car, with the engine running, stops for short stops (for example in the case of a red light) or, as regards buses, during the various stops made along the established route. The efficiencies are sufficiently high, as in the case of the static system, except for some losses connected to the misalignment between receiver and transmitter which appear when the vehicle is stopped.

Dynamic IPT

In the case of a Dynamic IPT infrastructure, since the time constant of the electrical problem is much smaller than that relating to the speed of the EV, the coupling between the fixed transmitting coil and the mobile receiving coil can be analyzed as a sequence of static configurations, each characterized by a variable reciprocal position of the coils, without considering the movement.
Suppose that the transmitter coils are activated, one at a time, only when the receiver is above the transmitter or in close proximity. With this hypothesis, the analysis of the coupling between the transmitting and receiving coils can be extended to all coils along the electrified road. The configuration in question is, therefore, composed of a single transmitting coil and a single receiving coil with variable reciprocal position. The couplings between the coils can be modeled as two coupled inductors in an equivalent circuit representation. To improve electrical performance in terms of efficiency and transferred power, the system resonates by introducing compensation networks on both the transmitter and receiver sides to compensate for the inductive reactance of the inductors using capacitive loads.

The simplest compensation network is a capacitor connected in series with the inductor running both sides of the circuit (transmitter and receiver). This typology, known as series-series (SS), was chosen for its simplicity and excellent performance [67].
An automotive IPT system is composed of electrical and electronic components of the ground transmitter called GA and the electrical and electronic components of the on-board EV receiver called VA. The entire system is, therefore, composed of many electrical and electronic components, but to simplify the study, the system can be modeled in resonance with an equivalent circuit with all analog components, as shown in figure 8 where VS is the source of voltage, RS is its internal resistance, RL is the equivalent resistive load, RGA and LGA are the resistance and self-inductance of the GA coil, while RVA and LVA are the VA coil resistance and self-inductance respectively. The mutual inductance between GA and VA coils is modeled by the following relationship:

$$M = k\sqrt{L_{GA}L_{VA}},$$

where k is the coupling factor. The equivalent series resistors (ESR) and the self-inductances of the coils do not significantly depend on the movement of the EV, which mainly affects the coupling factor k and consequently on the mutual inductance M. The latter varies during the movement of the vehicle and the its value is maximum when the transmitter and receiver coils are aligned. SS compensation has been adopted here as it guarantees high efficiency for the considered conFiguretion, and the values of the compensation capacitors are not affected by the M variation unlike other compensation topologies. This implies that the system does not have to be retuned for any mutual position of the GA and VA coils as it maintains the resonance for any value of M.
This is a very important feature for DIPT systems.

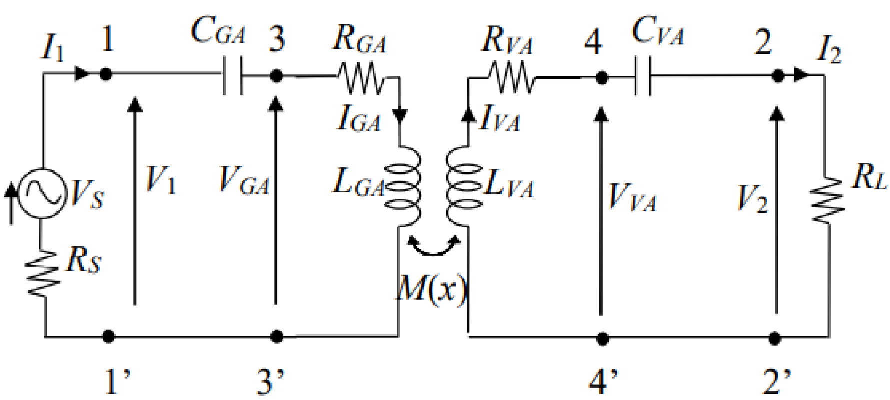


Figure 25 –Equivalent simplified circuit of an IPT system with SS compensation [67]

Assuming f0 is the resonant frequency, the compensation capacitors SS CGA and CVA are given by the following [33]:

$$C_{GA} = \frac{1}{(2\pi f_0)^2 L_{GA}} \quad (1)$$

$$C_{VA} = \frac{1}{(2\pi f_0)^2 L_{VA}} \quad (2)$$

Where it can be noted that CGA and CVA depend only on the self-inductances and the resonant frequency.
The circuit analysis in Figure 8 allows you to predict the electrical performance of the IPT system, mainly provided by the real power P2 at port 2-2' delivered to the load RL and the power transfer efficiency n given by the following formula:

$$\eta = \frac{P_2}{P_1} \quad (3)$$

where P_1 is the real power input to port 1-1'. In the case of the variable M with the mutual position of the coils (e.g. M=M(x) when x is assumed to be the separation between the centers of the GA and VA coils along the road (x-axis) and the zero lateral offset in the y direction, efficiency and power transferred depend on x and (3) becomes the following [34]

$$\eta(x) = \frac{P_2(x)}{P_1(x)} = \frac{(2\pi f_0)^2 M(x)^2}{\left(1+\frac{R_{VA}}{R_L}\right)\left(R_{GA}(R_{VA}+R_L)+(2\pi f_0)^2 M(x)^2\right)} \quad (4)$$

From (4) it can easily be observed that the efficiency η=η(x) is a function of the coil misalignment x; therefore, to obtain an almost constant value, it is necessary to ensure that the variation of M with x is extremely limited

Implementation aspects

Let's now see how it is conceivable to apply IPT technology to the motorway stretch between Milan and Reggio Calabria, considering the characteristics of its pavement, generally in draining asphalt. We also know that throughout the entire stretch of motorway there is at least 1 meter of usable surface on both sides of the lane outside the emergency lane for the placement of manholes and the installation of a duct for a technological infrastructure parallel to the intended road to the transport of electricity.

A first experimental objective was to evaluate the characteristics of the transmitting coil. In [35] six different coils labeled as L1, L6 were built to be tested directly at the test site. Each coil was buried following a different procedure or using different materials. The characteristics of each coil (transmitter) tested are shown in Table 13:

Coil name	Inner dimensions	Num. of turns	Wire diameter
L_1	0.5×1.5 m	9	4 mm
L_2	0.5×1.5 m	9	4 mm
L_3	0.5×1.5 m	10	5.5 mm
L_4	0.5×1.5 m	9	4 mm
L_5	0.5×1.5 m	10	5.5 mm
L_6	0.5×1.5 m	9	4 mm

Table 13 –Tested coil characteristics [35]

The second objective of the experimentation of [35] was the identification of a method of integrating transmitters into the road pavement based on technological and road pavement construction skills.
Table 14 summarizes the results of the tests carried out on a short experimental section with respect to the materials analyzed and the inclusion methods.

Material	Use	Test result
Concrete	Intermediate layer	✓
Cold asphalt	Pavement	✓
Bituminous coating	Separation coil-ground	✓
Epoxy resin	Separation coil-ground	✓
Elastomeric bitumen	Separation coil-ground	×
MAPEI Mapegrount	Pavement	×
MAPEI Plastimul	Separation coil-ground	×

Table 14 –Results of experiments based on materials used and inclusion methods [35]

Based on these experimental results, the first section of a charging test lane (Susa) was created by adopting the technique of digging a rectangular track in the asphalt to house the coil and using concrete for the covering layer. Concrete was the only material that satisfied the main requirements of low impact on the behavior of the coil (in the presence of an adequate dielectric layer), simplicity of installation and mechanical robustness. It is worth remembering that the characteristics of concrete in terms of adhesion are not advisable for any type of road pavement. In this experiment, the concrete was treated to increase its roughness, improving its characteristics in terms of grip, guaranteeing safety conditions for the pilots during the tests. The result obtained for the integration of the transmitter on the road pavement is illustrated in figure 26:

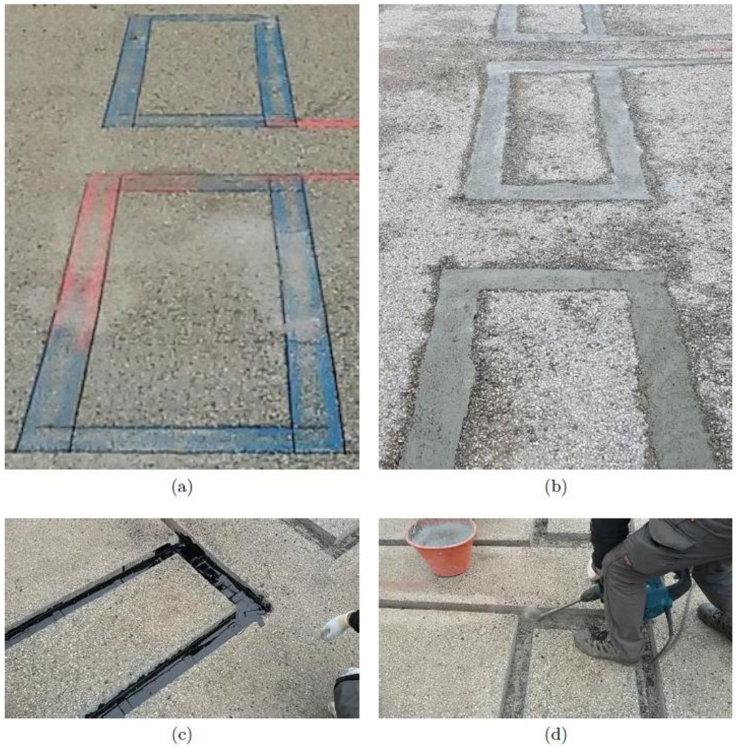
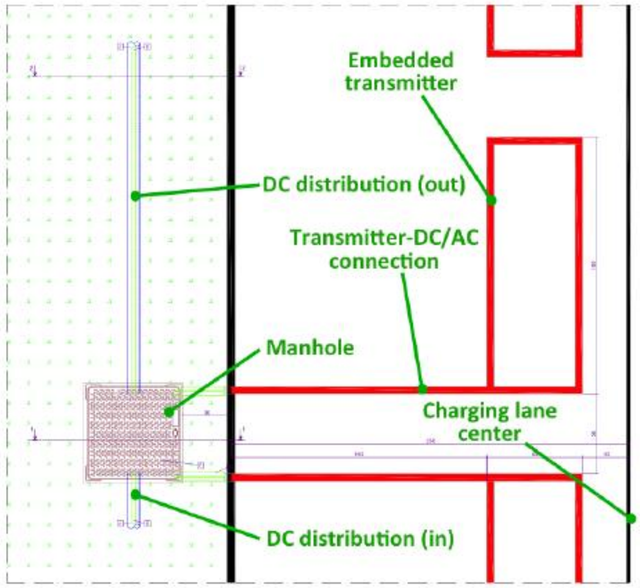


Figure 26 –Cutting the edges of the template hole (a). Digging a hole in the road asphalt (d). Filling the separation material between the coil and the ground (c). Last layer of concrete (b) [35].

The first step is cutting the edges of the hole in the asphalt using an angle grinder and then digging out the interior asphalt using a pneumatic drill. The bottom of the hole is flattened with a hand press, then the transmitter is placed at a depth of 5 cm below the flooring level. The hole is filled with bituminous lining until the transmitter is completely covered. When the bitumen is completely dry, a layer of approximately 3 cm of concrete is used to cover the hole until it reaches the level of the pavement.

The distance between the transmitters was chosen using the models developed in chapter 6. When a transmitter is active and powered with the nominal current, the distance of 50 cm guarantees a coupling with the non-active transmitters in proximity which gives rise to a voltage at vacuum lower than 30 V. This voltage does not create problems for the DC/AC converter and is perfectly manageable during the starting phase.

The connection between the transmitter, the DC/AC converter and the DC distribution is made as illustrated in figure 27. The coil terminals reach a manhole located 2.2 m from the transmitter. The two terminals are twisted together to limit the additional self-inductance introduced by the long connection.



(a)

(b)

Figure 27 – Installation plan of the coils, manhole and connection with the DC distribution line (a) and construction (b) [35].

The terminals of two consecutive transmitters are placed about a man's pace apart, then two DC/AC converters are housed mounted on two sides of the same heatsink (figure 28).

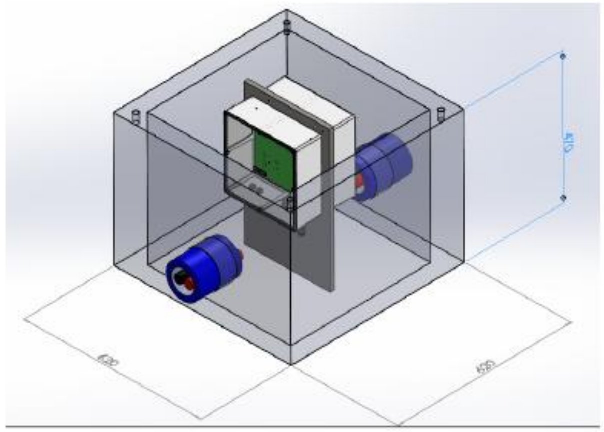


Figure 28 – 3D model of the heatsink in the well with the mounting of the two DC/AC converters. In blue the connectors for connection to the DC distribution and to the transmitter [35].

The pit is also the connection point between the DC distribution line and the converters through a parallel connection (in-out scheme [36]). The final appearance of the charging lane is shown in Figure 29.

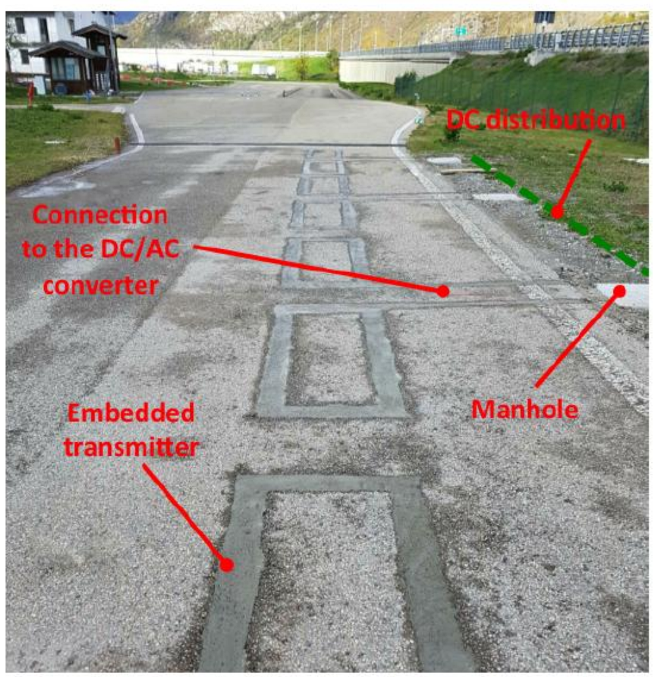


Figure 29 –Final appearance of the charging lane installed in the road infrastructure [35]

This technique, in addition to allowing a reliable application result, appears to be quick to apply. This aspect is not irrelevant if we consider the length and high traffic intensity of 60% of the motorway section considered between Milan and Reggio-Calabria.

Conclusion

The study investigated the state of the art of IPT technology with particular reference to dynamic applications. Starting with a study of the main research projects developed in this field at an international level and from an analysis of the international bibliography, we tried to understand how these applications could find applicability on a motorway stretch from Milan to Reggio-Calabria (or vice versa). The choice of such a long motorway stretch is motivated by the fact that this distance is able to highlight the limits and stress conditions of current electric mobility, such as: a) greater consumption due to greater speed, b) greater number of refueling necessary as consequence of high energy consumption (estimate at least four stops with the leading market models TESLA 3, TESLA S, TESLA Let's analyze the results of the investigations schematically.

Investigation aspect 1: path analysis. All motorway sections have been described in terms of length, road conditions and altitude.

Investigation aspect 2: the state of the art of technology. In this context, the main projects carried out at a national and international level were analyzed and for each of them the objectives pursued with the research activity.

Investigation aspect 3: operating principle of the technology. In this context, the operating characteristics of inductive charging systems in general were analyzed, but orienting the analysis towards those that can be used for dynamic charging. The efficiency losses obtained with dynamic charging compared to static charging were analyzed.

Investigation aspect 4: method of integrating DIPT technology into the motorway surface. An application feasibility case currently being tested was analyzed, to integrate the transmitting coils within the road surface.

Investigation aspect 5: economic impact of applying DIPT technology in the MI-RC section. To support the idea of applicability of the technology on the motorway section considered, assessments were made, confirmed by the scientific production cited, on the economic sustainability of the initiative which involves the adaptation of the motorway section examined to allow the charging of cars in movement for at least two lanes in opposite directions. The results obtained confirmed that it is reasonable to consider the cost of 1 million euros per 1 km for the adaptation of two lanes in the opposite direction as reliable.

Investigation aspect 6: energy sustainability. An energy sustainability analysis was carried out to understand the feasibility of the initiative in relation to the national electricity production capacity. In this context, the consumption data of some electric vehicles on the market were analyzed and a method of correlation between the number and type of vehicles with expected consumption was developed.

Investigation aspect 7: environmental sustainability. With regards to environmental sustainability both during the construction phase and in the subsequent maintenance and rehabilitation phases of a Dynamic IPT motorway infrastructure, CO2 emissions are significantly greater than those produced for the similar phases of a traditional motorway.Investigation aspect 8: two case studies to understand how to increase charging efficiency with a Dynamic IPT infrastructure in the MI-RC section. Two case studies were analyzed regarding Dynamic IPT solutions which include one or two receiving coils on board the vehicle; it has been seen that in the second case the charging efficiency improves.

Final deduction

On the basis of the study carried out, we believe that the Dynamic IPT technology can represent, despite the significant costs of technological adaptation that we have detected for a hypothetical application in the Milan-Reggio Calabria stretch, the driving force for the diffusion of electric mobility on a large scale, guaranteeing resilience and availability of solutions in line with the key points of the Industry 5.0 program presented in February 2022 by the European Commission.

For its effective use, the aspects of economic, energy, environmental and operational sustainability must be kept under control, which may represent an obstacle to the use of Dynamic IPT technology.

Of particular interest is certainly the positive correlation between the results of the report and the ongoing results of the first Dynamic IPT technology testing project in the motorway sector, called "Arena of the Future".

All the information and figures reported in this report are the result of bibliographical research in scientific journals, conference proceedings and results of national and international research projects. In this sense, the sources have been indicated for all the information reported and images present in the report

References

[1] European Commission. (2022). "Industry 5.0 - Industry 5.0 - Towards a sustainable, human-centric and resilient European industry, https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-towards-sustainable-human-centric-and-resilient-european-industry_en

[2] I. Suh. (2011). "Application of shaped magnetic field in resonance (SMFIR) technology to future urban transportation," in CIRP design conference.

[3] A. Frizzarin. (2016). “Dimensionamento di un sistema WPT per veicoli elettrici commerciali”, Università degli Studi di Padova.

[4] “FABRIC project website.” http://www.fabric-project.eu/.

[5] “eCo-FEV project website.” https://www.eco-fev.eu/.

[6]“ENDESA develops wireless en-route charging for electric buses in malaga.” http://www.endesa.com/en/saladeprensa/noticias/wireless-en-routecharging-electric-buses.

[7] “UNPLUGGED project website.” http://unplugged-project.eu/wordpress/.

[8] “PRIMOVE Bombardier website.” http://primove.bombardier.com/applications/ebus.html.

[9[INRiM Istituto nazionale di ricera e metrologica, MICEIV- “Metrology for inductive charging of electric vehicles” https://micev.eu/

[10] R. W. Carlson and B. Normann.(2014).“Test results of the plugless inductive charging system from evatran group, inc,” SAE Int. J. Altern. Powertrains, vol. 3, pp. 64–71.

[11] “WAVE website.” http://www.waveipt.com/.

[12] Toyota licenses WiTricity patent portfolio for wireless power. http://witricity.com/news/toyota-licenses-witricity-patent-portfolio-forwireless-power/.

[13] V. Cirimele, M. Diana, F. Freschi, M. Mitolo. (2018). “Inductive power transfer for automotive applications: state-of-the-art and future trends”, IEEE Transactions on Industry Application,

[14] S. Choi, J. Huh, W. Lee, S. Lee, and C. Rim. (2013). “New cross-segmented power supply rails for roadway-powered electric vehicles,” Power Electronics, IEEE Transactions on, vol. 28, pp. 5832–5841.

[15] G. Covic and J. Boys. (2013). “Modern trends in inductive power transfer for transportation applications,” Emerging and Selected Topics in Power Electronics, IEEE Journal of, vol. 1, pp. 28–41, March 2013.

[16] O. C. Onar, J. M. Miller, S. L. Campbell, C. Coomer, C. White, L. E. Seiber, et al., “A novel wireless power transfer for in-motion EV/PHEV charging,” in Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty- Eighth Annual IEEE, pp. 3073–3080, IEEE.

[17] J. Meins and K. Vollenwyder. (2013) “System and method for transferring electric energy to a vehicle,”. US Patent 8,360,216.

[18] G. A. Covic and J. T. Boys, “Inductive power transfer,” Proceedings of the IEEE, vol. 101, no. 6, pp. 1276–1289, 2013.

[19] G. Nagendra, L. Chen, G. Covic, and J. Boys. (2014).“Detection of EVs on IPT Highways,” Emerging and Selected Topics in Power Electronics, IEEE Journal of, vol. 2, pp. 584–597.

[20] J. Boys and A. Green. (2015) “Inductive power pick-up coils,”WO Patent App. PCT/NZ1994/000,115.

[21] I. Laakso, A. Hirata, and O. Fujiwara. (2014). “Computational dosimetry for wireless charging of an electrical vehicle,” in Electromagnetic Compatibility, Tokyo (EMC’14/Tokyo), 2014 International Symposium on, pp. 202–205, IEEE

[22] P.-P. Ding, L. Bernard, L. Pichon, and A. Razek. (2014). “Evaluation of electromagnetic fields in human body exposed to wireless inductive charging system,” Magnetics, IEEE Transactions on, vol. 50, pp. 1037–1040.

[23] L. Lu, J. Nadakuduti, and P. Guckian. (2014). “Compliance assessment of human exposurefrom wireless electric vehicle charging system,”. US Patent App. 14/574,095.

[24] Aydin, E.; Aydemir, M.T.; Aksoz, A.; El Baghdadi, M.; Hegazy, O. (2022). Inductive Power Transfer for Electric Vehicle Charging Applications: A Comprehensive Review. Energies 2022, 15, 4962. https://doi.org/10.3390/en15144962

[25] E. Gazzola. (2018). “Analisi della risonanza in due diverse topologie di compensazione per un caricabatterie wireless”, Università degli Studi di Padova.

[26] C. Rondena. (2016) “Tecnologie per il Wireless Power Transfer: stato dell’arte e prospettive future”, Politecnico di Milano.

[27] S. D. Barman, A. W. Reza, N. Kumar, Md. E. Karim, and A. B. Munir. (2015). ‘Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications’, Renewable and Sustainable Energy Reviews, vol. 51, pp. 1525–1552, Nov. 2015, doi: 10.1016/j.rser.2015.07.031.

[28] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han. (2016). ‘Wireless Charging Technologies: Fundamentals, Standards, and Network Applications’, IEEE Communications Surveys & Tutorials, vol. 18, no. 2, pp. 1413–1452, doi: 10.1109/COMST.2015.2499783

[29] S. Y. R. Hui, W. Zhong, and C. K. Lee. (2014). ‘A Critical Review of Recent Progress in Mid-Range Wireless Power Transfer’, IEEE Transactions on Power Electronics, vol. 29, no. 9, pp. 4500–4511, Sep. 2014, doi: 10.1109/TPEL.2013.2249670.

[30] M. Pedretti, I. Simonini. (2017). “Design and Analysis of an IPT Wireless System for Electric Vehicles”, Politecnico di Milano

[31] D.M. Vilathgamuwa, J.P.K. Sampath. (2015). “Plug-In Electric Vehicles in Smart Grids”, cap. 2 “Wireless Power Transfer (WPT) for Electric Vehicles (EVs) - Present and Future Trends”.

[32] Z. Bi et al., (2016). "A rewiew of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility", Applied Energy-

[33]. Wang, C.-S.; Covic, G.A.; Stielau, O.H. (2014). Power Transfer Capability and Bifurcation Phenomena of Loosely Coupled Inductive Power Transfer Systems. Trans. Ind. Electron. 51, 148–157. [CrossRef]

[34]. Campi, T.; Cruciani, S.; Maradei, F.; Feliziani, M. Near-Field Reduction in a Wireless Power Transfer System Using LCC Compensation. IEEE Trans. Electromagn. Compat. 2016, 59, 686–694. [CrossRef]

[35] Cirimele Vincenzo. (2017). "Design and integration of a dynamic IPT system for automotive applications", PhD Thesis, Politecnico di Torino, DOI:10.6092/polito/porto/2666564

[36] Technical guide. (2015) The MV/LV transformer substations (passive users)

[37] B. Limb et al., (2018) "Economic Viability and Environmental Impact of In-Motion Wireless Power Transfer", IEEE Transactions on Transportation Electrification

[38] R. De Doncker. (2014). "Power electronic technologies for flexible DC distribution grids", International Power Electronics Conference (IPEC-Hiroshima 2014 – ECCE ASIA).

[39] C. Fleming (2014). "Wireless electric car charging tested for in-motion vehicles", Sustainable Electrified Transportation Center (SELECT).

[40] D. De Lillas. (2018). "Valutazione dell'impatto ambientale della ricarica wireless per autoveicoli", Politecnico di Torino

[41] Bloomberg NEF, "Electric Vehicle Outlook 2018", Https://about.bnef.com/electricvehicle-outlook/.

[43] Commissione europea, https://ec.europa.eu/info/sites/default/files/chapeau_communication.pdf

[44] Commissione europea. (2016). "EU Reference Scenario 2016 - Energy, transport and GHG emissions: trends to 2050".

[45]. Choi, S.Y.; Gu, B.W.; Jeong, S.Y.; Rim, C.T. (2015). Advances in wireless power transfer systems for roadway-powered electric vehicles. IEEE J. Emerg. Sel. Top. Power Electron, 3, 18–36

[46]. Quinn, J.C.; Limb, B.J.; Pantic, Z.; Barr, P.; Zane, R. (2015). Techno-economic feasibly and environmental impact of wireless power transfer roadway electrification. In Proceedings of the 2015 IEEE Wireless Power Transfer Conference (WPTC), Boulder, CO, USA, 13–15 May 2015.

[47]. Lukic, S.; Pantic, Z. (2013). Cutting the Cord: Static and Dynamic InductiveWireless Charging of Electric Vehicles. IEEE Electrif., 1, 57–64.

[48]. Plugless Power, Why Get Wireless EV Charging?| Plugless. Available online: https://www.pluglesspower.com/learn-about-plugless-2/.

[49]. Romeo Danielis. (2015). Inquinano maggiormente le auto elettriche o le auto convenzionali? Stime recenti, variabili determinanti e suggerimenti di politica dei trasporti, Rivista di Economia e Politica dei Trasporti, n. 3, art. 1.

[50] Romeo Danielis. (2017). Le emissioni di CO_2 delle auto elettriche e delle auto con motore a combustione interna. Un confronto per l'Italia tramite l'analisi del ciclo di vita, No 17_1, Working Papers from SIET Società Italiana di Economia dei Trasporti e della Logistica

[51] R. Balieu, F. Chen & N. Kringos. (2019). Life cycle sustainability assessment of electrified road systems, Road Materials and Pavement Design, 20:sup1, S19-S33, DOI: 10.1080/14680629.2019.1588771

[52] Butt, A. A. (2014). Life cycle assessment of asphalt roads (Doctoral dissertation). KTH Royal Institute of Technology, Stockholm.

[53] Chen, F., Balieu, R., Córdoba, E., & Kringos, N. (2019). Towards an understanding of the structural performance of future electrified roads: A finite element simulation study. International Journal of Pavement Engineering, 20(2), 204–215

[54] Chen, F., Balieu, R., & Kringos, N. (2018). Comparative assessment of long-term structural performance of different electrified road systems. Journal Construction and Building Materials (under review).

[55] Ange-Therese Akono, (2021). "Fracture toughness of one- and two-dimensional .nanoreinforced cement via scratch testing", The Royal Society Publishing, https://doi.org/10.1098/rsta.2020.0288

[56] "PROGETTO ECOPAVE", finanziato da un bando dell'Unione Europea & Regione Lombardia (POR-FESR 2014- 2020/Innovazione e Competitività), Open Innovation - Progetto ECOPAVE (regione.lombardia.it)

[57] Campi, T.; Cruciani, S.; Maradei, F.; Feliziani, M. (2021). Two-Coil Receiver for Electrical Vehicles in Dynamic Wireless Power Transfer. Energies 2021, 14, 7790. https:// doi.org/10.3390/en142277

[58] Mohamed N, Aymen F, Issam Z, Bajaj M, Ghoneim SSM, Ahmed M. (2021). The Impact of Coil Position and Number on Wireless System Performance for Electric Vehicle Recharging. Sensors

(Basel). 2021 Jun 25;21(13):4343. doi: 10.3390/s21134343. PMID: 34201995; PMCID: PMC8271799.

[59] M. E. Baghdadi, Y. Benomar, O. Hegazy, Y. Yang, and J. Van Mierlo, (2016). 'Design approach and interoperability analysis of wireless power transfer systems for vehicular applications', in 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Sep. 2016, pp. 1– 11. doi: 10.1109/EPE.2016.7695695.

[60] N. Kuyvenhoven, C. Dean, J. Melton, J. Schwannecke, and A. E. Umenei, (2011). 'Development of a foreign object detection and analysis method for wireless power systems', in 2011 IEEE Symposium on Product Compliance Engineering Proceedings, Oct. 2011, pp. 1–6. doi: 10.1109/PSES.2011.6088250.

[61] ISO. Ergonomics of the thermal environment. Methods for the assessment of human responses to contact with surfaces Part 1: Hot surfaces.'. Available: https://www.iso.org/standard/43558.html

[62] S. Y. R. Hui, W. Zhong, and C. K. Lee. (2014). 'A Critical Review of Recent Progress in Mid-Range Wireless Power Transfer', IEEE Transactions on Power Electronics, vol. 29, no. 9, pp. 4500–4511, Sep. 2014, doi: 10.1109/TPEL.2013.2249670.

[63] S. D. Barman, A. W. Reza, N. Kumar, Md. E. Karim, and A. B. Munir. (2015). 'Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications', Page | 84 Renewable and Sustainable Energy Reviews, vol. 51, pp. 1525–1552, Nov. 2015, doi: 10.1016/j.rser.2015.07.031.

[64] P. Venugopal, S. Bandyopadhyay, P. Bauer, and J. Ferreira. (2017) 'A Generic Matrix Method to Model the Magnetics of Multi-Coil Air-Cored Inductive Power Transfer Systems', Energies, vol. 10, p. 774, Jun. 2017, doi: 10.3390/en10060774.

[65] R. Bosshard, U. Iruretagoyena, and J. W. Kolar. (2016). Comprehensive evaluation of rectangular and double-d coil geometry for 50 kW/85 kHz IPT system, IEEE J. Emerg. Sel. Topics Power Electron, vol. 4, no. 4, pp. 14061415, Dec. 2016 (cit. on pp. 20, 25).

[66] Hwang, K.; Cho, J.; Kim, D.; Park, J.; Kwon, J.H.; Kwak, S.I.; Park, H.H.; Ahn, S. (2017). An Autonomous Coil Alignment System for the Dynamic Wireless Charging of Electric Vehicles to Minimize Lateral Misalignment. *Energies* 2017, *10*, 315. https://doi.org/10.3390/en1003031

[67] Campi, T.; Cruciani, S.; Maradei, F.; Feliziani, M. (2021). Two-Coil Receiver for Electrical Vehicles in DynamicWireless Power Transfer.Energies 2021, 14, 7790. https://doi.org/10.3390/en14227790

[68] C Iclodean, B Varga, N Burnete, D Cimerdean, B Jurchiș. (2017). Comparison of Different Battery Types for Electric Vehicles , IOP Conf. Series: Materials Science and Engineering 252 012058 doi:10.1088/1757-899X/252/1/012058

[69] Minyuan M.Li, Xiaowen Zhan, Evgueni Polikarpov, et al. (2022). A freeze-thaw molten salt battery for seasonal storage, Cell Reports Physical Science, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2022.100821

[70] http://www.dft.gov.uk/vca/

[71] http://www.nextmove.de

[72] http://www.tesla.com

[73] Guida Michelin *https://www.viamichelin.it/*

[74] https://www.vaielettrico.it/la-ricarica-wireless-viaggia-veloce-ma-dove-arrivera/

[75] https://www.autobusweb.com/arena-del-futuro-brebemi-presentazione

[76] La Russa G, Farina D., (2018). “Valutazione dell’impatto ambientale della ricarica wireless per autoveicoli”. Politecnico di Torino, Tesi di Laurea Magistrale, Relatore Prof Aldo Canova, Correlatori Ph.D Vincenzo Cirimele, Ph.D Paolo Lazzeroni.