D4.6: Grid, urban and road infrastructure upgrading for meeting user expectations

December 2020 (M12)

D4.6:

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Technical References

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Project Coordinator	RENAULT sas xavier.serrier@renault.com
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[1] PU = Public

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Acronym table

Acronym	Definition
AC/DC	Alternating current / Direct current
BEV	Battery electric vehicle (EV that runs only on rechargeable EV batteries)
CCS	Combined charging system
CHAdeMO	DC charging standard for electric vehicles, enabling communication between the car and the charger
CP	Charging point
CS	Charging station (can have several CP)
DCFCS	Direct current fast charging station
DER	Distributed energy resources
DM	Demand management
DSO / TSO	Distribution system Operator / Transmission System Operator
DSS	Decision support system
DWPT	Dynamic wireless power transfer
EMC	Electromagnetic Compatibility
EV	Electric vehicle
ESS	Energy storage system
GO	Grid Operator
HV / MV / LV	High voltage / medium voltage / low voltage
IoT	Internet of things
PHEV	Plug-in Hybrid Electric Vehicle
PQ	Power Quality (PQ)

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PWM	Pulse width modulation
RES	Renewable energy source
SFC	Super-fast charger
SoC	State of charge
UC	Use case (of the INCIT-EV project)
V2B	Vehicle to building
V2G	Vehicle to grid
V2H	Vehicle to home
V2L	Vehicle to load
V2V	Vehicle to vehicle
V2X	Generic word for energy transfer from vehicle to other systems (building, home, other vehicle)

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0 EXECUTIVE SUMMARY

This report presents a summary of the activities of WP4 “Grid, urban and road infrastructure upgrading for meeting user expectations” of the INCIT-EV project, performed during the first year of the project (2020). The objectives of this work package are to define the key aspects of the electricity grid and civil infrastructure for the smooth demonstration of the INCIT-EV use cases and to address the updates needed for the future replication of the solutions.

WP4 is divided into five tasks:

- **Task 4.1 “Grid requirements for charging system deployment”**. The main objective of this task is to define the electric grid requirements to face a wide deployment of electric vehicles, with a focus on the project use cases.
- **Task 4.2 “grid services enabled by charging infrastructure and ESS deployment”**. The main purpose of this task is to establish synergies with the grid network by means of characterizing the grid services triggered by the penetration of the electric vehicle in the grid thanks to services such as V2X. Furthermore, to propose complementary services to be demonstrated during the project, based on these principles.
- **Task 4.3 “Connection with DC networks and integration with tram / metro energy lines**”. The objective of this task is to analyse and establish synergies with both the DC electric and transport networks, especially with the tram and train lines thus exploiting new services triggered by these synergies. This will be possible thanks to the modelling and design of the general solutions which will be demonstrated on the demo-sites.
- **Task 4.4 “Infrastructure upgrading for dynamic wireless charging”**. This task has for purpose to adapt the road infrastructure in order to integrate underground wireless charging modules and to start setting the bases for the later design and deployment of INCIT-EV solutions, for urban and inter-urban applications.
- **Task 4.5 “Theft-proof parking systems for two-wheelers”**. The objective of this task is to define and model a theft-proof parking and charging system for electric two-wheelers (bikes and e-scooters), in order to obtain a reference solution to be later adapted to the particular specifications of the demo-sites.

This report summarises the main results obtained, during the first year of the project, in these different tasks. A more detailed presentation of the results of each task of WP4 can be found in the deliverables of INCIT-EV corresponding to each task: D 4.1, D 4.2, D 4.3, D 4.4 and D 4.5.

The delivery of this deliverable is done in accordance to the description in the Grant Agreement Annex 1 Part A with no time deviation and no content deviation from the original planning.

This deliverable will be updated in M24 according to plan.

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1 INTRODUCTION

1.1 Objectives of the report

This report presents a summary of the activities of WP4 " Grid, urban and road infrastructure upgrading for meeting user expectations" of the INCIT-EV project, performed during the first year of the project (2020). The objectives of this work package are to define the key aspects of the electricity grid and civil infrastructure for the smooth demonstration of the INCIT-EV use cases and to address the updates needed for the future replication of the solutions.

WP4 is divided into five tasks:

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This report presents successively the main results obtained, during the first year of the project, in these different tasks.

1.2 Relation with other work packages and tasks of the project

WP4 has strong links with WP3 "User-centric EV charging solutions", which is in charge of the development of the different electric charging systems that will be demonstrated in INCIT-EV, namely static conductive charging systems, and static and dynamic wireless charging systems.

WP4 has also strong connections with WP7 and WP8, which are in charge of the development of the different charging demonstrators. WP4 is in charge of defining and modelling solutions, which will be implemented in the demonstrators built in WP7 and WP8.

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2 GRID REQUIREMENTS FOR INTEGRATION OF CHARGING SYSTEMS FOR ELECTRIC VEHICLES

2.1 Introduction

This section concerns task 4.1, which partners are CIRCE, Univ Eiffel, ENEDIS, Polito, EESTI, UL and ATOS. The main objective of task 4.1, in the first year of INCIT-EV Project has been analysing the most important grid requirements to face a wide deployment of electric vehicles with special focus on the project use cases. To achieve this objective, the work included two main parts:

1. A theoretical analysis of the technological and practical requirements that a large spread of EVs implies for the electric grid
2. An analysis of the impact that chargers to be developed and tested throughout the project could have on the electrical grid.

In the first part, the negative effect that a wide spread of electric vehicles charging facilities could have on the electric grid and the most common techniques to reduce this impact have been analysed. The negative effect has been treated in terms of load and voltage and power quality issues. The main standards that regulate these negative effects of the electric vehicle have been analysed.

The theoretical analysis of the most common and recommended methods to reduce the impact on the grid that electric vehicle recharge may have has focused on: use of "grid friendly" power topologies in chargers, demand management and distributed generation and storage systems.

To complement the minimum requirements for a wide spread of electric vehicles without threatening the current electrical system, other aspects such as electrical safety, cybersecurity, communications interfaces and safety for dynamic inductive charging have been analysed.

For the grid impact analysis of the chargers, the different project UCs have been considered. They have been grouped in four frameworks, covering different applications:

- Urban framework: where UC2 (France, Dynamic wireless charging lane in urban area), UC6 (Spain, Low power DC bidirectional charging infrastructure for EV, including two-wheelers) andUC7 (Spain, Opportunity wireless charging for taxi queue lanes in airports/central stations) have been analysed.
- Peri-Urban framework: UC5 (Estonia, Tallinn peri-urban area-Estonia).
- Inter-Urban framework: UC3 (France, Dynamic Wireless Charging for long distance -prototype e-road).
- Parking framework: UC4 (Turin, Charging hub in a park-&-ride facility).

The effect that the charging devices to be developed in the project could have on the grid has been analysed using computer simulation tools. This work has been done in five steps:

1. Choice of representative electrical networks for the analysed use cases (since there were no real data on these).
2. Estimation of the use of EV charging stations.
3. Selection of the scenarios to be evaluated.
4. Simulations development and analysis of the effect of the charger on the grid.

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5. Evaluation of main techniques to reduce the EV charge impact on the grid.

The work performed in task 4.1 follows an iterative approach: The work of the task has started from the initial specifications of the charging systems, use cases and demonstrators to analyse the impact on the grid. Generic grid characteristics have also been considered. In the second year, as the definition of the chargers and use cases progresses, more realistic and more precise data will be taken into account in the analysis of the impacts on the grid and simulations.

2.2 Electric vehicle charging impacts on the grid

Different possible effects of EV charging on the electric grid have been identified : EV charging stations act as additional stochastic loads in the distribution grid, which can be characterized by the following impacts:

- Active power demand and - for V2G and battery buffered installations - active power injection into the grid. With unallocated charging time slots, the grid nodes and paths can be easily overloaded, which can result in:
    - tripping of protection apparatus.
    - voltage drop in cables.
    - accelerated aging of power transformers.
    - frequency fluctuations in small isolated frequency clusters.
- Reactive power demand – the EV charging devices are designed to draw near zero reactive power from the grid. In some cases, if enabled by the EV charger internal topology, an EV charger can act as a static reactive compensator to mitigate upstream voltage problems.
- Electromagnetic compatibility – the power electronic devices convert electricity by pulse width modulation (PWM) control. With poorly designed filters, the modulation frequency may radiate back into the grid and into surrounding environment, causing malfunction of sensitive apparatus.

Different solutions for mitigating these impacts have also been identified :

- grid friendly power electronics topologies, which consists in designing the power electronics to assist the grid in reducing frequency harmonics, voltage and frequency balances.
- distributed generation and distributed generation + storage : this means to add to the grid additional energy sources, based on renewable energy systems (RES) and storage units to manage peak power demand constraints, smoothing the load charge, or even increasing the use of "idle" generation capacity during low demand hours.
- Demand management (DM), which refers to a set of actions designed to efficiently manage a grid's energy consumption with the aim of cutting the costs incurred for the supply of electrical energy. It should be noted that, using the Internet of Things (IoT), every grid device could potentially be connected to internet. This will help develop "smart" grids, and enhance demand management by allowing coordination between systems distributed across many consumers. Electric vehicles show both DM and IoT potential: when these vehicles are parked and connected to their chargers, their batteries can serve as aggregated energy storage capacity, which can be coordinated through an Internet connection.
- DM can also achieve great synergy with distributed generation, especially solar photovoltaic systems: when there are both generation and storage resources at the point of consumption, it is possible to optimize operation and reduce the total load on the power grid

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2.3 Definition of charging scenarios

In order to simulate the effect of electric vehicle charging on the electric grid, different simulation scenarios have been defined, corresponding to the different use cases of the project :

- Urban framework: where UC2 (France, Dynamic wireless charging lane in urban area), UC6 (Spain, Low power DC bidirectional charging infrastructure for EV, including two-wheelers), UC7 (Spain, Opportunity wireless charging for taxi queue lanes in airports/central stations) are going to be analysed.
- Peri-Urban framework: UC5 (Estonia, Tallinn peri-urban area-Estonia).
- Inter-Urban framework: UC3 (France, Dynamic Wireless Charging for long distance -prototype e-road).
- Parking framework: UC4 (Turin, Charging hub in a park-&-ride facility).

For each of these scenarios, a typical electric grid, corresponding to the context, has been defined. Typical electric vehicle power demand profiles have also been defined for each scenario.

2.4 Electric vehicle grid impact simulations

Using the scenarios described previously, simulations have been carried out with the objective of evaluating the impact of the charging points that are being developed in the project on the previously defined electric grids. Specifically, the impact on the network in terms of congestion of lines and / or transformers has been evaluated, as well as its effect on the distribution of voltages, over and under voltages. In addition to evaluating its possible negative effect, the influence of the most suitable EV load impact reduction techniques for each simulation scenario has also been evaluated.

2.4.1 Urban framework

Due to their similarities, use cases 2, 6 and 7 were evaluated on the same network and with the same objectives but with different daily use profiles. Due to the lack of information about the network in which the charging stations will be located, it has been decided to use the IEEE benchmark low-voltage grid for Europe

This section presents results of a series of simulations to evaluate the EV charging impact on the grid in terms of losses, congestions and voltage problems of use cases 2, 6 and 7 and of the chargers that will be installed in each use case. These results are presented on figures 1,2 and 3.

As it can be seen, by including the charging stations of these use cases, the losses related to electric energy distribution are slightly increased compared to the base case (without any charger) taken as a reference (figure1). The different losses observed in each use case are related to the energy provided by the charging stations to the electric vehicles rather than to the power of the chargers, two 60 kW in UC 2 and 50 kW in UC6 and UC7.

The connection of these chargers in the benchmark network, directly to the LV output of the transformer, without sharing connection with other loads, causes a low impact on the voltage profiles observed in the grid (Figure).

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The installation of the charging stations near the secondary MV/LV substation and a correct sizing of the electric wiring does not generate any new congested sections, compared to the base scenario (Figure 1).

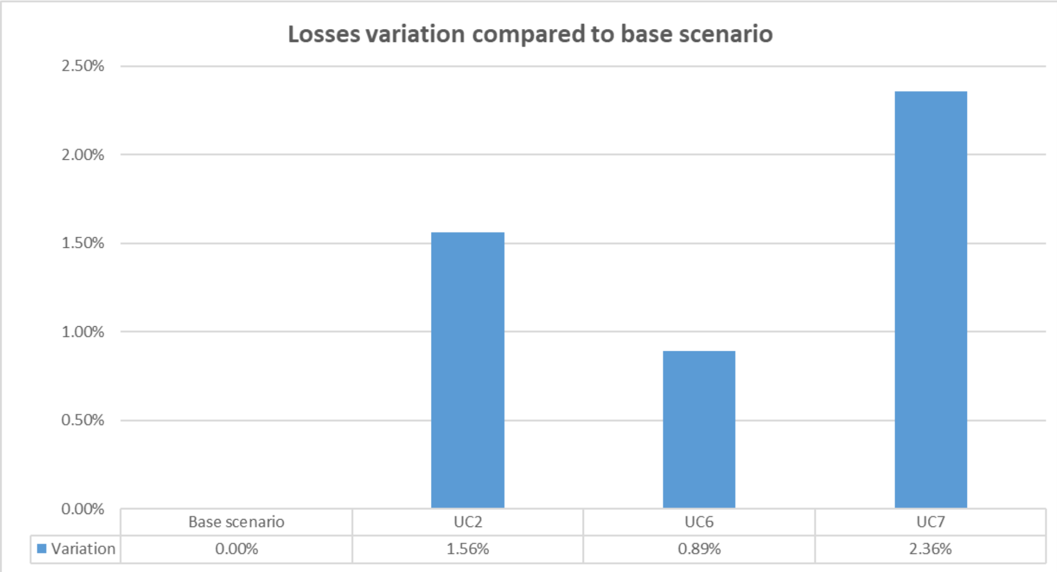

Figure 1. UC2, UC6 and UC7 grid impact in urban area (I), energy losses analysis.

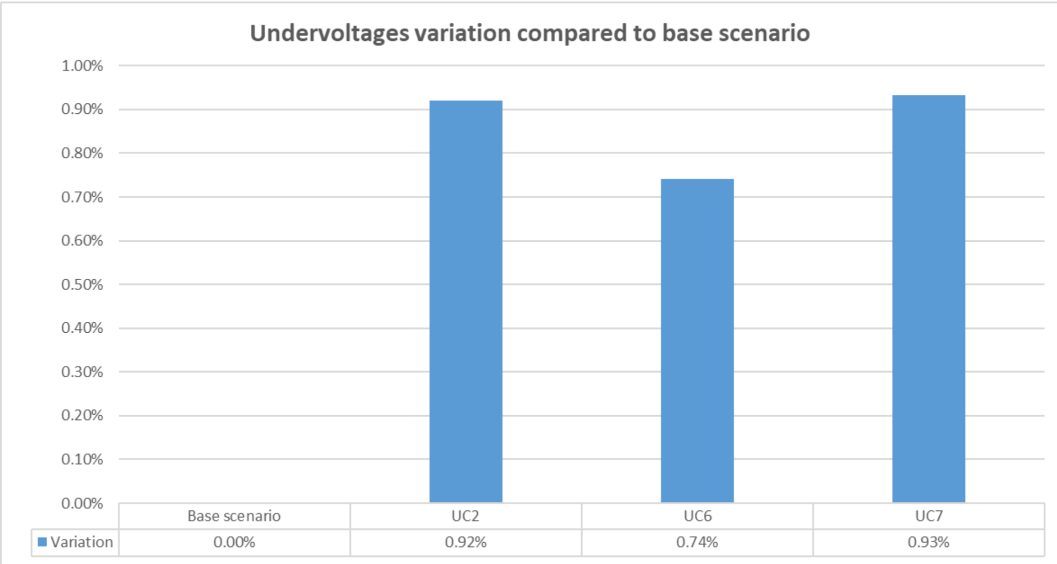

Figure 2. UC2, UC6 and UC7 grid impact in urban area (II), under voltages analysis.

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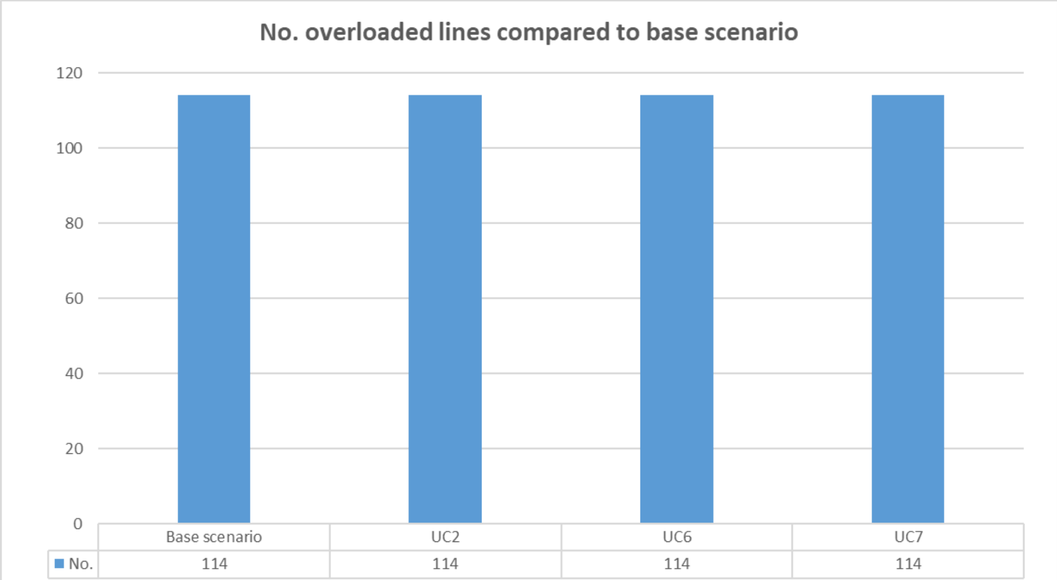

Figure 1. UC2, UC6 and UC7 grid impact in urban area (II), congestion/overloaded wire sections analysis.

As these three use cases will be located in urban areas, it was assumed that there will be no possibility of installing distributed generation or storage, so the only technique to reduce the EV grid impact is demand management. To evaluate the effect of this technique, a moment of day with high energy demand has been chosen and several simulations have been made. For each use case, two scenarios analysing demand management of the electric vehicle charger have been analysed: (i) one in which the charger power is totally reduced (P = 0%) and the other (ii) in which it is reduced to half of the initial demand (P = 50%).

The simulations of demand management have shown that:

- The management of the demand for fast charging stations leads to a high reduction of the power supplied by the MV / LV secondary substation.
- Demand management has no influence on the voltage profiles, at least in the number of under voltages, in the area and at the time studied.
- Demand management reduces energy distribution losses.
- Finally, demand management also has no influence on the number of congested wire sections, since they are located in other areas of the studied network.

As has been observed, connecting the charging stations directly to the LV output of the secondary MV/LV substation makes any problem very local and does not affect other consumers. The negative impact related to losses can be solved with demand management, but this will limit EV charging capabilities. Due to the location of the charging stations, demand management has a limited effect. The impact in terms of congestion and / or undervoltage is avoided with a correct sizing of the connection and with the choice of a secondary MV/LV substation with sufficient hosting capacity for the charging station.

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2.4.2 Peri-urban framework

For use case 5, the impact of an electric vehicle charging station equipped with a super-fast charger (SFC) in an industrial / commercial area, such as those that can be found around any European city, has been evaluated. For these simulations, three possible locations of the charging station were taken into account, based on their geographical proximity to the substation that feeds the industrial area and five scenarios were tested:

- Base scenario. No charging station. This scenario is used as a reference for the other ones.
- Short distance scenario. The charging facilities are located near the HV/MV substation in an empty MV/LV secondary substation.
- Medium distance scenario. The charging facilities are located at a medium distance from the HV/MV substation in an empty MV/LV secondary substation.
- Large distance scenario. The charging facilities are located at a greater distance, in an empty MV/LV secondary substation.
- All charging stations scenario. 3 Charging stations are connected to the grid, in the 3 previous locations.

For the different scenarios, the grid impact was evaluated in terms of losses, congestions and undervoltage for a day. Besides the grid impact, two EV grid impact reduction techniques were evaluated for the medium distance scenario: distributed power generation and demand management. The results obtained are presented on figures 4, 5 and 6.

The installation of charging stations equipped with SFCs in the industrial zone increases the losses of energy distribution (see Figure). As expected, these losses increase with the distance between the point of consumption and the HV/MV substation. A substantial increase in losses is observed when including the three charging stations in the network.

It is also observed (see Figure) that the installation of SFC in the network increases the occurrence of under voltages. This phenomenon is especially important when 3 EV charging stations are installed in the area.

The simulations results also show that the installation of the new electric vehicle chargers increases the amount of congested or overloaded lines. When individual chargers are installed, up to 24 cable sections appear congested at least once a day (and sometimes more) at the charging facility itself or in the surroundings. When all 3 chargers are installed, up to 143 sections are overloaded (see figure 6).

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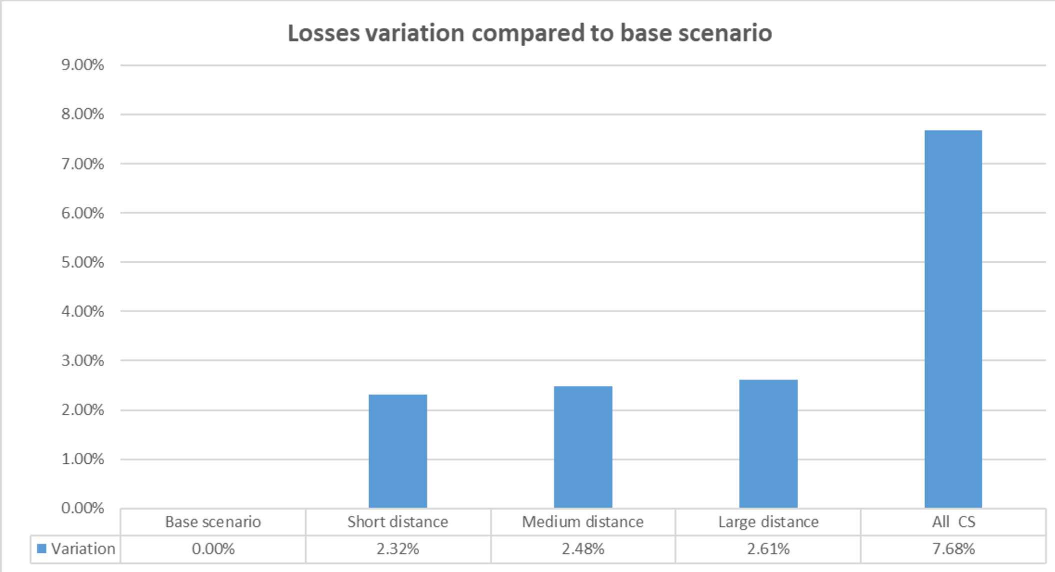

Figure 4. UC5 Charging station impact on the grid in peri-urban area (I), energy losses analysis

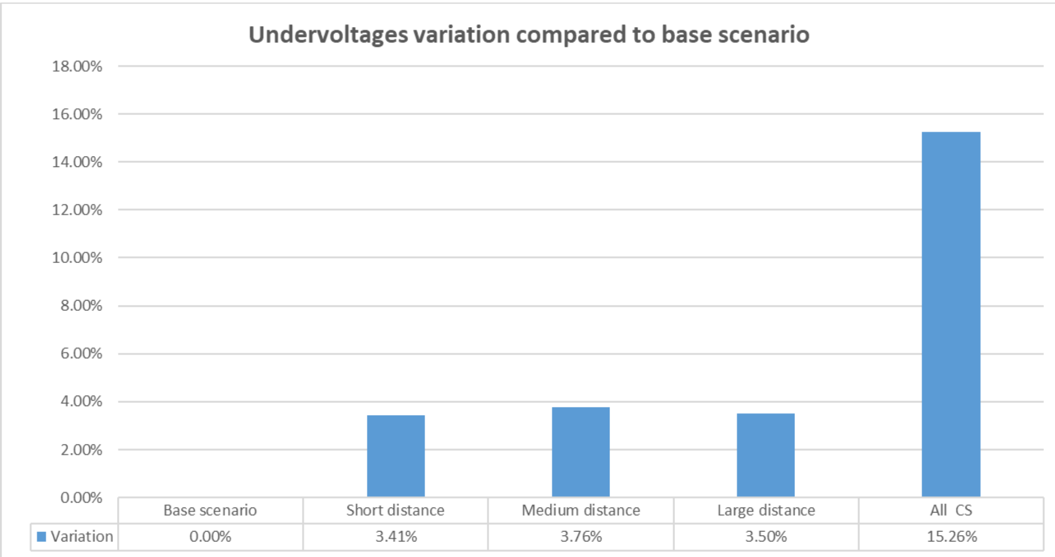

Figure 5. UC5 Charging station impact on the grid in peri-urban area (II), under voltages analysis.

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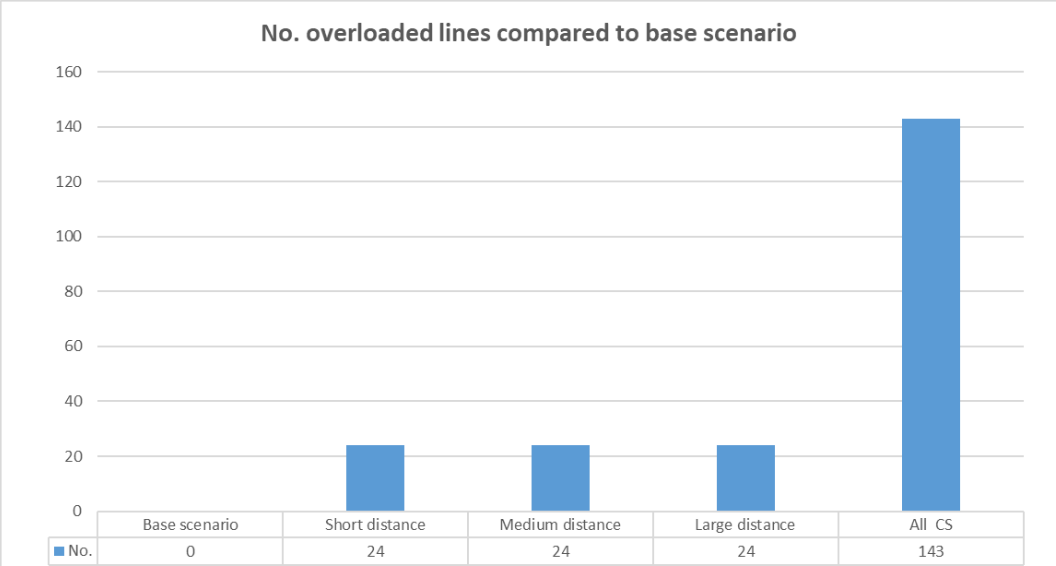

Figure 6. UC5 Charging station impact on the grid in peri-urban area (III), congestion/overloaded wire sections analysis

The simulations show that negative effects will be generated on the grid by the inclusion of SFC points. These negative effects are of course amplified when installing 3 charging stations, but the probability of installing several stations is low, due to the small size of the industrial/commercial area. Due to these negative aspects, the effect of using distributed generation and demand management to facilitate the integration of these chargers has been evaluated.

The first technique evaluated to reduce the impact on the grid of electric vehicle charging is distributed power generation. In this case, the installation of photovoltaic facilities of 100, 200, 300, 400, 500 and up to 600kW has been evaluated in the charger located at a medium distance from the substation of the area. The results of the simulations indicate that :

- The installation of a photovoltaic facility of up to 500 kW next to the charging station reduces losses with respect to the reference case. Above 500 kW, all the power produced is not consumed locally, which can generate losses associated with the transport of this energy. For this reason, the photovoltaic installation should be carefully sized.
- Adding photovoltaic generation also reduces the under voltages, whatever the power installed. However, an excessive power generation could cause the opposite effect and generate over voltages in the area.
- Finally distributed generation allows to reduce the number of congested wire sections along the grid.

Another solution to reduce the impact of SFC on the grid is demand management, which consists in stopping the charging if the grid is too congested. However, this would reduce the advantage of using super fast charging, because the charging time would be increased. Therefore, demand management should be used for SFC only as an emergency option, in case of risk for the electrical grid to which it is connected.

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2.4.3 Inter-urban framework

The inter-urban framework represents an extrapolation of the use case 3 to a 25 km long DWPT track with a maximal consumption of 33 MVA. As a consequence of its higher loading, direct supply from HV network was assumed. Only some preliminary simulations were performed for this use case, since the actual data from the UC is not yet available.

It was assumed that the network supplies two charging stations, with maximal consumption of 33MVA each. Charging stations are supplied through dedicated transformers, installed into an existing HV/MV substation. Additionally, there is a residual load in each HV/MV substation, which represents a general substation demand. Charging station consumption daily profile was defined based on assumptions on traffic on the road, and its daily distribution

Simulations considered two scenarios:

- Base case: existing situation, prior to installation of DWPT charging systems.
- Two UC3 charging stations installed in the network .

Results of these first simulations focussed on voltage and power flow deviations in the network, caused by the newly installed charging stations. The simulations indicated an increase of power demand, associated with the DWPT charging, with peaks around 8.00 AM and 5.00 P.M., which correspond to peak traffic hours. This resulted in some voltage drops, but they remained limited.

It was concluded that the implementation of such charging systems , with a high electric consumption, can affect the operating conditions of the supply network. However, the impact depends on the available capacity of the network…This impact was rather limited in the chosen scenarios, but could be more important with a higher number of installed charging stations.

2.4.4 Parking framework

The last simulations concerned the impact of the EV charging on the UC4 grid in Turin. In this use case, the charging stations are supplied by a tramway power substation. To define the power available for the vehicle charging, the difference between the nominal power of the substation (2.2 MW), and the energy used by the tramway service was calculated.

The available power for vehicle charging is defined by the graph on figure 7. This available power is represented by the blue line on the figure (which corresponds to measurements on the substation), and is compared with the red dotted line, which represents the sum of the power of all the charging points (increased by a factor of safety). When the blue line is above the red line, it means that sufficient power is available for the charging stations. On the contrary, when the blue line is below the red line, it indicates a possible overload of the network. This analysis indicated that the potential overload time is very small, representing only about 0.0072 % of the measurement period. These results validated the possibility to use the sub-station as power source for the UC4 demonstrator.

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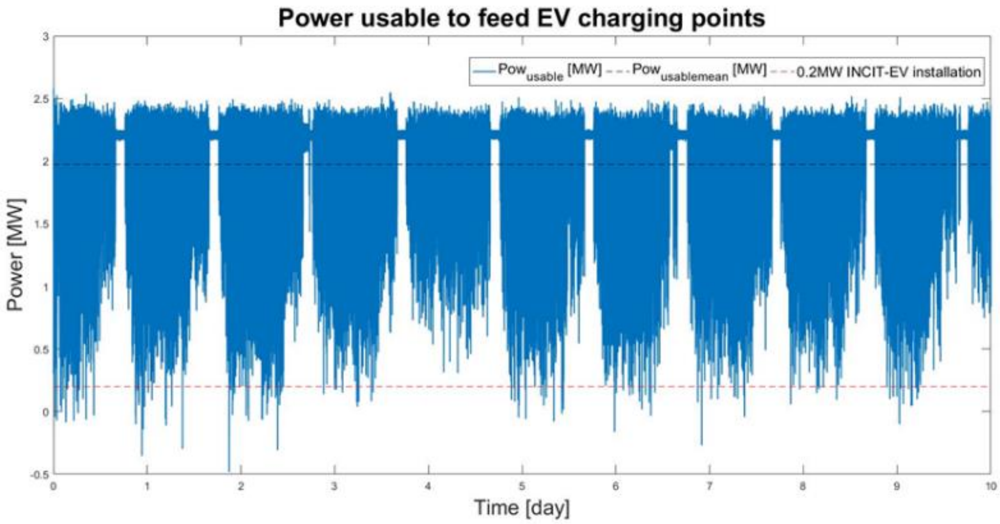

Figure 7. Power available to feed the EV charging points in UC 4 (measurements over a period of 10 days).

2.5 Conclusion on task 4.1 and perspectives

In task 4.1, the work done during the first year consisted in investigating possible impacts of charging systems on electric grids, first theoretically, and then trough simulations of the different use cases of INCIT EV.

The theoretical investigations led to identify different possible impacts of charging systems, linked with increased power demand (voltage drops, grid congestion..), and also with electromagnetic compatibility (generation of unwanted frequency harmonics).

The simulation work confirmed the interest of such simulations for identifying and anticipating possible impacts of the charging systems on grids, and possible solutions for mitigating these effects. Solutions could be :

- Selection of optimum locations for the charging stations.
- Introduction of distributed energy generation (from renewable sources) and storage, to avoid congestion and power limitations.
- Demand management, to reduce power demand during peak periods.

The work has also shown the important role of the Distribution System Operators (DSO), in the development of electro-mobility, to ensure that the EV penetration does not have an impact on the stability of the grid and that reinforcements aimed to increase the EV hosting capacity are implemented in the most cost-effective manner.

At the same time by the involvement of DSO, the size of the energy market will extend further for the benefit of all electricity market stakeholders. Some of the strong roles include:

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- Involvement in public charging infrastructures deployment - The DSO's main role is to be prepared for a rollout of public charging infrastructure and to be supportive, through partnership, both on technical as well as on regulatory field.
- Locating public charging stations - The procedure to determine the location of public recharging points should involve the DSO in the planning in order to maximize the use of available hosting capacity through the minimization of the investment costs for the network reinforcements. DSOs should develop a strategy and methodology to support the installation of public charging points in optimal locations based on grid operational and development conditions.

The work of task 4.1 presented in this section will be completed throughout the next year, as part of the iterative approach of the project, in two directions : new simulations to evaluate the effect on the network of the use cases and EV chargers of the project and development of simulations to obtain general results that will feed the DSS library in task 6.3

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3 GRID SERVICES ENABLED BY CHARGING INFRASTRUCTURE

3.1 Introduction

This section concerns task 4.2, which partners are Univ Eiffel, ENEDIS, CIRCE, REE, POLITO, MRA-E, PITP, EESTI, UL (IRI UL), and ATOS. The main objectives of task 4.2, which concerns grid services enabled by charging infrastructure, in the first year of INCIT-EV Project have been :

- To perform a state of the art review related with potential grid services enabled by the charging infrastructure and electric vehicles.
- To define scenarios of use of the different grid services, related with the different types of use cases that will developed in the project (urban, peri-urban, interurban, parking).
- To start simulations to evaluate the impacts of the different services on grid performance, for each use case.

3.2 State of the art about grid services

The review has been divided in two parts : Services related with grid management and correction of grid problems, and V2X services, which concern the use of energy stored in vehicle batteries for other systems.

3.2.1 Services of assistance to the grid

Grid operators manage electricity supply and demand in the electric system by providing a range of grid services. Grid services are activities that grid operators (GO) perform to maintain system-wide balance and appropriately manage electricity transmission. Such services can include:

- Operating services: Scheduling and dispatch techniques. Because in most electrical systems energy storage is nearly zero, it is necessary to maintain a balance between power production (by generators) and power consumption (demand from consumers). For that, careful scheduling and dispatch are necessary. Scheduling refers to before-the-fact actions (for example scheduling a generator to produce a certain amount of power the next week), while dispatch refers to the real-time allocation of the available resources.
- Reactive power and voltage control: Reactive power is used to synchronize voltage and current. Modern inverters can both provide and absorb reactive power to help grids balance this important resource. Reactive power can be used to compensate the voltage drops, but it must be generally provided closer to the loads than real power needs (this is because reactive power tends to flow badly through the grid). It should be noticed that voltage can also be controlled by using transformer coils and voltage regulators.
- Frequency control: this refers to the need of ensuring the grid frequency within a specific range around the nominal frequency. Mismatch between electricity generation and demand causes variations in frequency, so control services are required to bring the frequency back to its nominal value and ensure it does not vary out of range.

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- Asset Lifecycle Management Services: designed to help transmission and distribution operators to optimize their asset management strategy using digital technology to improve the monitoring, recording and analysis of grid operations and predict asset behaviour.
- Renewable generation: The grid integration of renewable generation simultaneously requires additional ancillary (*auxiliaries*) services and has the potential to provide ancillary services to the grid. The power converters (inverters, rectifiers, ...) that are installed with distributed generation systems and solar systems have the potential to provide many of the ancillary services that are traditionally provided by spinning (as a power reserve) generators and voltage regulators. These services include reactive power compensation, voltage regulation, and flicker control, active power filtering and harmonic cancellation.
- Electric vehicles: Plug-in electric vehicles have the potential to be utilized to provide auxiliary services to the grid, specifically load regulation and spinning (power) reserves. Plug-in electric vehicles can behave like distributed energy storage and have the potential to discharge power back to the grid through bidirectional flow, referred to as vehicle-to-grid (V2G). Plug-in electric vehicles can supply power at a fast rate which enables them to be used like spinning reserves and provide grid stability with the increased use of intermittent generation such as wind and solar. The technologies to utilize electric vehicles to provide ancillary services are not widely implemented today, but have a lot of potential [1].
- Automation and system protection (and: EMC immunity)
- Solutions for energy imbalances.

3.2.2 V2X services

The term V2X is used as a generic word that can describe several types of situations in which the energy, that is stored in the battery of a vehicle, is transferred *from* the vehicle to another system. The distinction between the different kinds of V2X use cases mainly resides in the characteristics of the targeted system.

When the vehicle is used to provide a service to the distribution or transportation network of electricity, we are in presence of “vehicle to grid” (V2G) technology. When it is used to provide a service to a large subsystem that is located downstream of the electricity public network (e.g. a building, a small factory, a micro-grid …), we are in presence of “vehicle to building” (V2B) technology. When the vehicle is used to provide a service to a residence, we are in presence of “vehicle to home” (V2H) technology. Lastly, when the vehicle is directly connected to a small electric equipment that is off the grid (e.g. a water pump, a mobile refrigerator …) we are in presence of “vehicle to load” (V2L) technology.

Vehicle to grid (V2G)

The V2G technology is the most known and discussed practice of bidirectional usage of the battery of electric vehicles. This term is sometimes even used as a generic way of talking about a vehicle discharging its battery into any system. Here, it concerns only the vehicle discharge into the distribution or transmission electricity network.

Different services can be provided to the network :

- Local active or reactive power flexibility, to relieve some topological local constraints on the low or medium voltage distribution networks.
- Frequency regulation. Network operators have interest in those services.
- Power flexibility on a larger scale, with interactions with electricity market actors.

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This technology requires advanced systems in the car, the charging point or/and in the network. It also requires telecommunication infrastructures (locally and on a large scale) where the signals and control data will transit.

Vehicle to building (V2B)

V2B is encountered when a vehicle or, most of the time, a group of vehicles is used to manage, optimize or support the energy consumption of a building or of a site (commercial, tertiary, industrial). The vehicles are located on the site on which the energy is needed. Contrary to V2G, the specificity of this technology is that it is transparent for the rest of the world (public network and electricity market actors). V2B can be achieved by installing smart energy management systems on the sites.

Vehicle to home (V2H)

Vehicle to Home is the second most known technology when talking about bidirectional charging. It is a smaller scale of the V2B already described, on a residential level. The energy management is simpler. The use cases associated to this technology can go from emergency supply of the house in case of a public network blackout to optimisation of the energy consumption of the house in situations with a local storage and production capacity.

Vehicle to Load (V2L)

V2L consists of a single electric vehicle providing energy to a load that is not connected to any larger network. This technology has not really been developed yet but has a strong economic potential. It can be used for emergency purposes (to supply a vital or useful device in the field, when electricity network is down) or for casual use when the use of an electric battery is seen as more convenient than another power source (fuel generator). The main advantage of this technology is that the vehicle can *travel* to the load that needs its energy. It can thus be really useful in remote places where the public electricity network is not dense (rural or poor areas).

Vehicle to vehicle (V2L)

This specific case of V2L is useful to help an electric vehicle that is too far away from a charging point or with an empty battery. Because of the inevitable losses, this situation probably does not have a real economic potential, besides the mentioned help scenario.

3.3 Definition of grid services scenarios

This work has only started, and will consist in defining scenarios of charging infrastructure towards the grid services and consumers (V2X), and storage deployment (batteries). Furthermore, IFSTTAR will investigate the energy storage systems (ESS) as a buffer energy storage.

For each scenario, the main characteristics of the charging in infrastructure will be defined :

- Charger characteristics: I or III phase, max and minimum power, etc…
- Demand profile: P/SoC and use along the day.
- Active power / reactive power (P/Q) curve of the charging point
- Data from WP3.

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Energy storage deployment (ESS) will be investigated. Grid energy storage is a set of methods used for energy storage on a large scale within an electrical power grid. Electrical energy is commonly stored during times when its generation has a tendency to overtake the demand, resulting in reduction of its prices (especially from intermittent power plants such as renewable electricity sources (RES) such as wind power, solar power, etc.), or when the demand is low, and later returned to the grid when the demand is high, and electricity prices tend to be higher.

Any electrical power grid must match electricity production to consumption, both of which vary drastically over time. Energy storage systems (ESS) are a valuable asset for the electrical grid. They can provide benefits and services such as load management, power quality, and uninterruptable power supply to increase the efficiency and supply security.

3.3.1 Scenarios definition on the vehicle side

Different scenarios where the EV could provide services to the grid will also be investigated, but the analysis is made from the EV side, having in mind the limitations and characteristics of the vehicle and the charger.

V2V Charging

V2V stands for "vehicle to vehicle" and refers to the exchange of energy between electric vehicles. This energy exchange process can be due to two reasons:

- Exchange of energy between vehicles in the event of an emergency due to lack of energy in a vehicle and lack of recharging infrastructure in the vicinity. This is still a developing technology.
- Exchange of energy between vehicles for proper management of vehicle fleets, or in moments of difficult or limited access to the electricity grid.

The energy exchange among vehicles for a proper management of fleets can be made in in two ways, depending on the type of energy exchange:

- V2V in AC using the distribution grid as a reference. This design uses common V2G chargers connected through the AC distribution network one vehicle provides energy to the system while the other charges its batteries.
- V2V in DC in the same EV charger. This configuration requires specific chargers with connectors and other infrastructure for at least two vehicles. The main advantages of this configuration are that (i) it is much more efficient as it avoids exchanging energy to alternating current and from alternating current and (ii) the distribution network is not necessary, so it could be done in isolated locations. This solution is going to be tested in UC6.

3.3.2 Grid support services – use of CIRCE Energy box

As has already been indicated throughout this document, the electric vehicle and the associated charging facilities can be providers of support services to the electricity grid in different ways:

- Through active or reactive power generation.
- Individually or coordinated with other charging facilities.
- Locally or in aggregation with other facilities for larger sets of the electrical system.
- Only to the electrical network (V2G) or as part of other installations or microgrids (V2B, V2H or V2L).

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In any case, to provide these types of services, both the charger and the network to which it is going to provide the services must be properly monitored and managed.

Most of today's EV chargers have equipment to be monitored and controlled remotely by control centres, from operators of charging facilities or the DSO/TSO, in order to provide support services to the grid. This monitoring and control allows: commercial management of the charger (use, customer management, payments, etc ...), verification of its status, demand management (limitation of maximum power or duration of the charge for example) and provide services of grid (power limitation, reactive power management or, in some cases, discharge of energy to the network). These possibilities are limited when the charger is a part of a larger infrastructure (chargers of different types and manufacturers, distributed generation and / or storage facilities, etc ...) and it is necessary to manage all the systems in a coordinated way (within an electric station, a building, a house ...). The most common situation is that each provider has its own monitoring and management platform making the integration complicated. Therefore, CIRCE will test the Energy Box (EB) in the chargers it is developing for the use cases 6 and 7. EB is meant as a monitoring element, information concentrator, for communication with external agents, and for the operation of EV chargers in these UCs.

The CIRCE Energy Box is a multi-purpose concentrator for the operation of advanced electrical networks and Smart Grids. In addition to its versatile communication capabilities, it contains an embedded computer that provides computing and processing capacity to implement distributed computing: capture and storage information, execution of algorithms and control of the installation, among others.

As it can be can seen, the EB is the cornerstone of CIRCE developments to provide services to the electric grid:

- Locally, in response to the information coming from the elements of the installation: demand management based on the overall consumption, compensation of the total installation reactive, reactive management to provide voltage support services, asset management to provide frequency services and management of all system elements (EV charger, distributed storage and generation, and other manageable consumption).
- Remotely, following instructions from a remote control centre, either from the management company of the chargers or from the DSO / TSO.

3.3.3 GRID SERVICES IMPACT SIMULATIONS

Simulations have also started to evaluate the impact of the different grid services listed previously on the grid. These simulations are based on the same electric grid description and charging station usage patterns as In task 4.1 (see section 2).

3.3.3.1 Urban framework :

The reference electric grid already used in task 4.1 for the Urban framework has also been used for simulating the impact of grid services. Several simulation have been made, to evaluate impacts of :

- Unbalanced charge of an EV
- Discharging the vehicle batteries to provide energy to the grid, (V2G)
- Charger reactive power control

As most of the consumers and equipment connected to low voltage grids are single-phase, these networks tend to operate unbalanced. It is for this reason that a charger that could operate unbalanced, could support

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the operation of LV networks. This effect has been evaluated and compared by moving this charger upstream, next to the MV / LV transformer, and downstream of the network, next to the most congested points with undervoltage problems.

V2G technologies could be a source of grid supporting services, as discussed in the state of the art. This possible service has been evaluated and compared by placing the charging upstream, next to the MV/LV transformer, and downstream, next to the most congested points with undervoltage problems.

Some electric vehicle chargers can regulate the reactive power that they exchange with the grid, which can be a very interesting grid service. The effect on the network of this possible service is evaluated by simulating the installation of an EV charger upstream in the grid and another downstream. The charger has been programmed in such a way that it regulates reactive power in order to keep the voltage of the furthest point of the grid within limits.

Details of the simulations can be found in deliverable D4.2 of INCIT-EV. To summarise the results, it has been shown that EV charging stations can provide grid services to LV grids but to have an important effect, the charging stations should be placed near the area with voltage or congestion issues ("downstream" simulations). On the other hand, locating high power chargers far away from the transformer can cause additional problems when charging vehicles at full power: additional congestions and under voltages. These problems would be higher if installing high power chargers downstream in LV grids or if the grids are long and/or weak.

3.3.3.2 Peri-Urban framework

To evaluate the local effect of the grid services that a Super Fast Charger (SFC) can provide, two operating options have been simulated: discharge of the electric vehicle batteries (V2G) and reactive power injection with no active power exchange. These two services have been compared to a "base scenario" in which the EV charger operates at nominal power in a minute in which the grid consumption is one of the highest of the day. The following results can be highlighted :

- Battery discharge and reactive power injection (without active power exchange) reduce losses and the energy provided by the HV/MV substation. In the V2G case, the phenomenon almost doubles since it not only stops consuming energy but also discharges energy to the grid.
- Both services have similar and good results avoiding under voltages.
- Both services avoid all the congestions.

3.3.3.3 Other simulations

Simulations will be performed in the second year for the other use cases (inter-urban framework and parking framework).

3.4 Conclusions and perspectives of task 4.2

3.4.1 Benefits of Grid services

For France, The recent reports published in 2019, by both French DSO Enedis, and TSO RTE, show smooth and seemless integration of e-mobility at a minimum cost on both distribution grid and bulk system. This is due to well designed networks (to cope with electric heat use in winter) and to the tariffs (peak off peak)

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which have been used for decades in France. However, more advanced smart charging and V2X might play a further role in reducing integration costs and extracting best value from the future EV usage through its storage capacity.

Energy bill reduction

Currently, the simple charge shifting at off-peak times can enable electric vehicle owners to make significant savings, compared to a "natural", unmanaged charge. Depending on user profile and type of EV consumption, additional savings could be made through avoided power capacity increase cost, and self consumption charging optimisation.

Smart charging (V1G) levers

Smart charging can be driven by three means of optimisation:

- adjusting the charging power (power management) to reduce the vehicle's power demand, thus avoiding to increase subscribed power of the premises;
- time-shifting the charging process (time of use management) incentivised by price offers from suppliers;
- maximising self-consumption, with solar production surplus during the day rather than charging in the evening ...

Future Bi-directional Smart charging (V2X)

Bi-directional smart charging allows power flow to circulate in both directions: from the grid to the car but also from the car back to the grid, when power injection is needed. The principle of Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Grid (V2G) consists of reinjecting the electricity contained in the battery into the household or building's private grid or the public electricity distribution network, respectively. These technologies could offer further flexibility to the grid (for bulk system at national level or distribution grid at local level) and might be called through specific B2C – B2B contracts.

The highest value of V2G has been assessed for frequency system participation and the amount for the French system (Analysis by RTE) ranges between 100 € - 900 € per car, depending on competition environment with other vehicles or storage devices.

3.4.2 Perspectives

The main objectives of task 4.2 in the second year of the project will be to detail the different scenarios of grid services that will be tested in the project, in the different use cases, and to continue and improve the simulations of the effects of these services on performance of the electric grids. In addition, a techno-economic analysis of the grid services will be performed.

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4 CONNECTION WITH DC ELECTRICAL NETWORKS AND WITH TRAM AND METRO NETWORKS

This section concerns task 4.3, which partners are Univ Eiffel, ENEDIS, POLITO, IREN. The main objectives of task 4.3 are to analyse and establish synergies with DC electric and transport networks, especially those of tram and train lines, thus exploiting services triggered by these synergies. in the first year of the INCIT-EV Project , the following tasks were performed :

- A state of the art review about interfacing of power electric chargers with DC networks.
- Case studies of possible solutions for DC power distribution for e-mobility, to evaluate in particular their techno-economic benefits.
- A study of possible synergies with tram DC networks.
- Simulations of chargers interconnected with DC grids, in order to identify and mitigate their impact on electrical networks.

4.1 State of the art related with electric chargers interfacing with DC networks

Although electricity transmission and distribution networks are mainly designed for alternating current, there is a growing interest for direct current solutions:

- The energy transition is leading to a strong development of native uses of direct current: photovoltaic installations, electricity storage and electric vehicles.
- The proportion of energy consumed by direct current in the home is very high (50% in 2018), and growing strongly (80% in 2030). The consumption vectors are LED lighting and electronics, computers, home automation and variable speed drives for motors.
- The ability of direct current to improve the energy efficiency of a network by reducing the number of connection losses.

4.1.1 DC fast charging stations

DC Fast Charging Stations (DCFCS) are essential for widespread use of Electric Vehicle (EVs). They present the advantage of recharging EVs more rapidly than AC charging stations.

DC charging stations require high-power converters which are capable of charging to 80% in less than 30 minutes . These fast-charging applications require modular power converters which can be paralleled to provide different power levels, thereby enabling fast charging. Such converters generally include 2 stages :

- The AC/DC stage (also know as the PFC stage) is the first level of power conversion in an EV charging station. It converts the incoming AC power from the grid (380–415 VAC) into a stable DC link voltage of around 800 V.
- The DC/DC stage is the second level of power conversion in an EV charging station. It converts the incoming DC link voltage of 800 V (in case of three-phase systems) to a lower DC voltage to charge the battery of the electric vehicle. The electric vehicle charging standards are governed by standards

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such as Combined Charging System (CCS) and CHAdeMO. The DC/DC converter must be capable of delivering rated power to the battery over a wide range, for example 50V-500V to accommodate batteries from 48V (e-bikes) all the way up to 400V with the capability of charging the battery at constant current and at constant voltage mode, depending on the State Of Charge (SOC) of the battery.

DC charging stations have special grid hook-ups so they can get and convert far more power. DC stations are large, expensive and require cooling. CHAdeMO chargers vary from 25 to 60kW, and superchargers are 90 to 120kW. They deliver far more power than standard AC chargers. Typically, the fast AC chargers have a power range from 7 kW to 22 kW, and can charge an electric vehicle in 3 to 4 hours. Slow AC chargers for overnight, household use have a nominal output of about 3 kW and usually require six to 12 hours charge an electric vehicle. In the case of AC connected electric vehicles, power conversion (AC/DC) is on-board the vehicle.

4.1.2 Connection with DC grids

Medium voltage direct current (MVDC) applications in distribution grids are nowadays becoming reality with first demonstration projects [2]. In addition to MVDC applications related to distribution or sub-transmission networks, discussions are ongoing about the use of MVDC for the integration to the electrical grid of distributed energy resources (DER) or loads, which utilize DC voltage rather than AC voltages.

The integration of DC loads (fast charging stations for electric vehicles, data centers), DC generation plants (wind and mainly solar) and battery energy systems by means of DC/DC converters is expected to be a major driver for the introduction of MVDC. The main reason is that it can reduce significantly conversion costs.

Converting existing lines from AC to DC can significantly increase the power capacity of an existing grid (by 20 to 80 %). For long, congested feeders in meshed distribution grids, line conversion can be a cost-efficient solution for increasing the power rating. In addition to this greater power transfer, it is possible to improve grid stability.

In some cases, DC networks could increase the overall efficiency of the installation by providing direct supply to “native” DC users, suppressing, therefore, AC/DC conversion stages at the power delivery point. Thus, instead of multiple conversion units, a central AC/DC conversion is probably more energy efficient. Yet, each application requires a dedicated study before deciding which power type, AC or DC, is more efficient. This could lead to a hybrid AC/DC distribution network as shown in figure 8 below.

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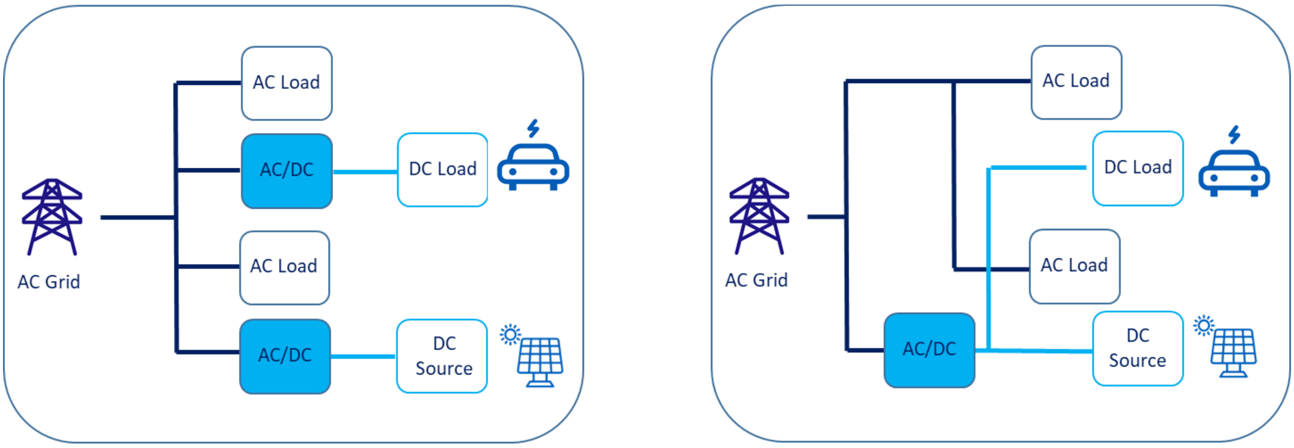

Figure 8. Conventional AC vs hybrid AC/DC distribution networks

DC main advantages over AC would be:

- DC is able to use full peak voltage capability of AC circuits compared to the AC RMS rating
- DC does not suffer from skin effect so there is potential for increased current due to low power losses
- DC will only use 2 conductors instead of 3
- DC will increase the energy efficiency of "native" DC devices

In the task, several case studies of electric vehicle charging infrastructure have been studied, to compare solutions with AC or DC distribution networks, and evaluate the technico-economic benefits of a DC connection for e-mobility. The case studies have concerned :

- Electric vehicle charging infrastructure for parkings in urban areas
- Network for supplying an electric road, which has distributed charging points.

From the analysis of these case studies, it was concluded that DC electrification has sveral advantages depending on its application. Yet, in some cases, energy efficiency may not be sufficient to justify its usage as shown in the electric vehicle charging infrastructure case study. In fact, in short distance distribution networks, DC will bring benefits regarding flexibility and controllability of local system using power electronics. In addition, in case of high penetration of intermittent power sources or loads, DC can improve local power balance and its impact on the AC grid could be thus minimized.

For long distance applications, such as e-roads, DC reduces lines/cables energy losses, which allows increasing the line's capacity or transmission distance.

Finally, to answer the "DC or AC" question, it was concluded that each case requires a dedicated study to evaluate techno-economic benefits of each solution.

4.1.3 Services associated with a DC electrification

In the future, electric vehicles will probably not be limited to a mean of transport. Due to their energy storage capacity, they are able to consume or inject power into the grid, following request. With vehicle-to-grid (V2G) technology, a car battery can be charged and discharged based on different signals, such as energy production or consumption nearby. In its charging mode, similar to smart charging (V1G), the EV will adjust its power consumption based on instructions received from a control unit (DSO or other). EV, like any

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electricity storage system, will be then an active part of the network that could improve local flexibility and in some cases help reduce grid constraints.

Some services are particular to AC electrification like services related to reactive power or frequency regulation. In DC mode, there is no frequency constraint. Yet, demand-response balance remains a major issue affecting DC voltage stability. EV could then play the same role as in AC mode: reduce its consumption or inject power to the grid in case it is overloaded, store energy in case of an excess of local energy production (ex: high PV production). However, at the same time, using V2G should ensure that EV drivers will have enough energy when they need to use their vehicle.

Services that could be enabled by a DC electrification are more related to the power electronics interfacing each load/source with the network. These DC/DC, AC/DC and DC/AC converters allow to control power flow through a smart master unit usually called Energy Management System (EMS). The latter will allow implementing advanced control functions and interface the DC local network with the existing AC grid. It enables local services between different components (EV, smart homes/buildings, PV…) and service-to-grid such as:

- Disconnecting from the main grid to improve local resilience: when a fault is detected on the AC side, local energy sources coupled with EV as an ESS could provide a minimum service to the loads.
- Injecting reactive power to boost the voltage on AC side.
- Consuming reactive power in case of over-voltage detection on AC side.
- Support frequency regulation by active power consumption/production.
- Load shedding if the AC grid is overloaded.

4.2 Synergies with DC tram networks

Tramways and light railway systems form one of the most common applications of DC networks worldwide, as they are found on all continents as efficient and reliable means of transport. Overall, there are defined standards for tramways and light railway systems, and there are only minimal differences from one system to another.

The two different voltage standards with which these systems operate are 600VDC and 750VDC. The 600VDC standard is more prominent, but systems that are more modern tend to adopt the higher voltage. The DC networks that supply power to the trams are often powered by dedicated electric substations with a capacity between about 2,2 MW and 5 MW. These figures enable the network to function without distress, as the relatively infrequent power consumption caused by accelerations does not require such a high energy.

These networks are therefore prudently oversized and there is a lot of potential energy left to be exploited for other purposes, such as EV recharging. The biggest benefit concerning the potential synergies between a DC tram network and EV recharging lies in the fact that tram networks are generally well distributed in the cities. This is especially true for city centres and their immediate surroundings, where charging points, especially fast chargers, are less likely to be found for various reasons.

A study carried out by POLITO in Turin for the UC4, has shown that even an electrical substation that serves two of the most heavily serviced tramway lines in a relatively large city like Turin and which nominal power output is 2.2MW still has plenty of available power to spare. A 500kW charging hub would pose no real threat to the public transportation service.

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4.3 simulations of chargers interconnected with DC grids

in task 4.3, simulations have been started, to evaluate scenarios of different chargers connected to DC grids, in relation with the INCIT EV use cases 2 (Paris), 3(Versailles) and 4 (Turin). Only simulations for the Turin Use case (4) are well advanced, and some results are presented below :

4.3.1 Simulations for Use case 4 (Turin).

For the Turin case study, measurements were carried out, in order to quantify the available energy in the rather unknown Turin DC tramway network. This grid is a fully meshed network which energy supply comes from 22 electric conversion substations located throughout the city that transform the current from AC medium voltage to DC low voltage. The network in itself is divided into 49 energetically independent areas, and each substation supplies energy to at least 2 of these areas . Voltage and current measurements were made at the Caio Mario substation, which will be used in the use case, which has the following characteristics:

- Nominal continuative power 2.2MW
- Power with a 150% overload for 2h = 3.3MW
- Power with a 200% overload for 60s = 4.4MW

Two different types of measurements were obtained: one with a small time lapse (10ms) and one with a bigger time lapse (0.1s).

The measurements lasted for ten days, and the gathered data was then processed and put into graphs in order to compare them with the pre-existing expectations. There were two main targets: 1) find out the overall energy consumption of the Caio Mario substation; 2) assess peak and low voltage and current figures.

The graph on figure 9 shows the recorded electric consumption. The values are cyclic during the week. There is a pronounced power consumption drop during the night, when no trams are in service. The red line represents the nominal power output of the SSE (2.2MW). 73 cases of overload were measured, always for very brief durations.
After assessing the absorbed power needed to supply the tramway service, the power still available, based on the technical specifications of the station (2.2MW) was estimated. Two different constant loads were added to the total figure in order to simulate the charging hub. The first simulation was made a 200 kW load (as planned in the INCIT-EV use case), the other with a greater, 500kW load.

The results obtained are shown on figure 10. The two dotted lines show the output increase caused by a 200kW or 500kW EV charging hub, and compare it with the available power. All the blue peaks below the dotted lines indicate an overload of the network. This occurs only during fractions of seconds. With 200kW installed for EV charging, 629 overloads are detected in 10 days, representing only about 1min combined (0.0072% of all measurements). With 500kW installed, there are 5.358 overloads, representing about 9 min (0.062%).

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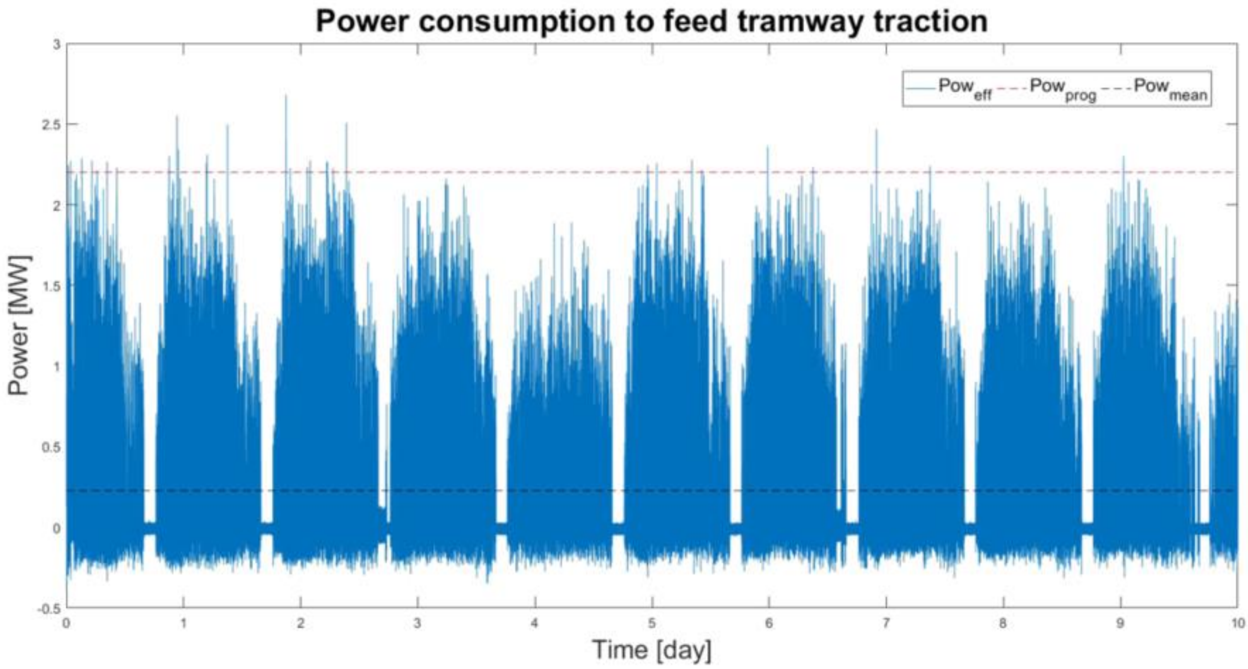

Figure 9. power used to feed the tramway lines

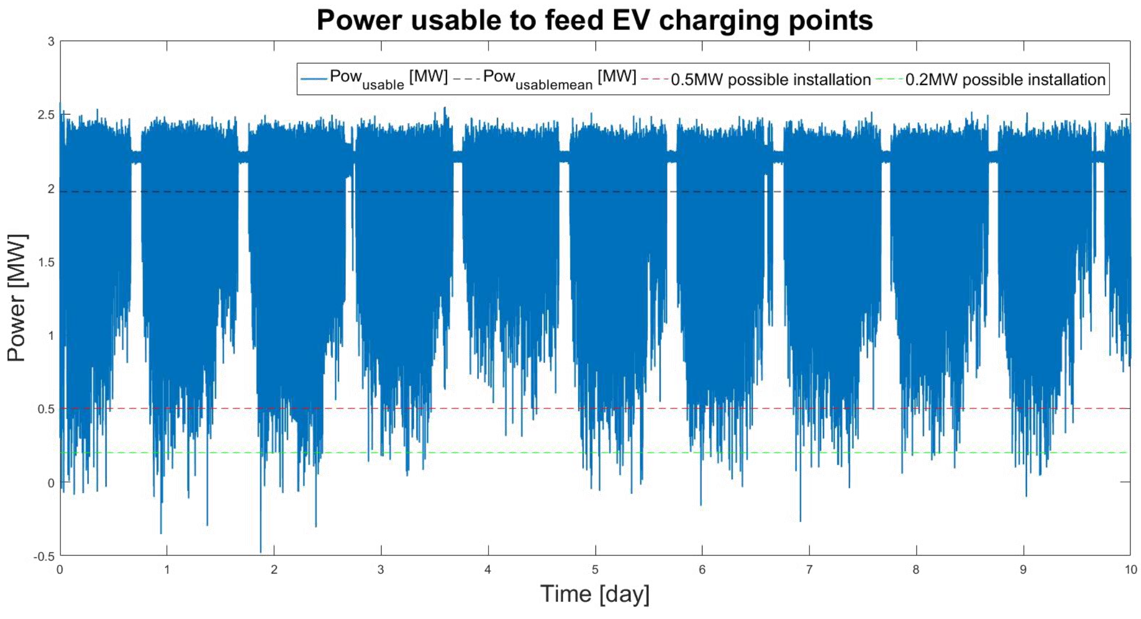

Figure 10. Power usable to feed EV Charging points.

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This analysis shows that there are very few occurrences in which the substation's capacity is overloaded. Even with the a 500kW load added, an overload would happen only in 0.062% of the total time. This means that there will be no problem of synergy between public transportation and the planned recharging hub. A means to reduce the overloads would be to add a storage system.

In conclusion, the analysis of this use case showed that:

- There is a significant amount of energy to be exploited in the SSE Caio Mario. There are indeed moments with high energy loads, but they are of very short duration. A storage system would erase all the potential concerns.
- From a voltage standpoint, there were no dangerously high spikes that could put the EV charging hub in jeopardy.

4.4 Conclusions and perspectives of task 4.3

This task has highlighted the benefits of developing DC electricity networks, in particular for applications linked with the energy transition, which often use direct current, like : photovoltaic installations, electricity storage and electric vehicles. It has also reviewed different possible solutions for DC network architectures, for supplying electric vehicle charging stations. In particular, possibilities of using tram networks to power charging stations have been analysed.

Simulations of different scenarios of charging stations connected to DC networks, corresponding to several INCIT-EV use cases have started. These simulations will be continued during the second year of the project, to identify the impacts of these charging stations on network performance, to be able to optimize the design of the future demonstrators.

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5 TASK 4.4 - INTEGRATION OF DYNAMIC WIRELESS CHARGING SYSTEMS IN ROAD INFRASTRUCTURES

5.1 Introduction

This section concerns task 4.4, which partners are Univ Eiffel, Vedecom, Eurovia, Colas, Polito and MRA-E. The objectives of task 4.4 are to define and develop solutions for integrating the wireless dynamic charging systems developed in INCIT-EV in roads. These solutions will then be implemented in the demonstrators developed in work packages 7 and 8 of INCIT-EV. The work of task 4.4 concerns two wireless charging systems developed in INCIT-EV.

- The system developed by VEDECOM, for urban applications, which will be installed in the Paris demonstrator, built in WP 7.
- The system developed by CIRCE, for inter-urban applications, which will be installed in the Satory demonstrator, built in WP 8.

From the road infrastructure's perspective, the integration of wireless charging technology in roads raises several important issues:

- The development of appropriate construction methods, to ensure satisfactory mechanical properties and protection of the charging system components, and reasonable cost.
- the effect of the surrounding materials on the charging efficiency of the Wireless Power Transfer (WPT) system, i.e. the power loss caused within the road structure when alternating magnetic fields pass through it;
- the influence of the embedded charging components on the structural performance of the road under operational conditions;
- the consideration of the maintenance needs of the charging system (access to some components) and of the road itself (renewal of the surface layer for example).

The work performed in task 4.4 of INCIT-EV, to prepare the road integration, has consisted in :

- Making a review of existing dynamic wireless power transfer (DWPT) systems, with a focus on integration of these solutions in road structures.
- Reviewing the characteristics of the Vedecom and CIRCE charging systems, and proposing possible solutions for their integration in roads.
- Starting a test program, for developing and testing solutions for the integration of the charging modules in pavements, to ensure satisfactory charging performance, safety, durability and resistance to traffic loads.

A summary of these different tasks is presented in this section. A more complete presentation is available in deliverable D4.4 "Road infrastructure upgrading for dynamic wireless charging".

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5.2 Review of existing wireless power transfer systems, and of solutions for their integration in pavements

5.2.1 Main elements of dynamic charging systems

Inductive charging is a new way of charging of electric vehicles in opposition to conventional chargers, where charging is made by means of plugs and cables. Inductive charging uses the principle of magnetic induction, to transfer an electric current. The chargers are composed by coils and charging is achieved without contact, when the two coils are close to each other.

Another advantage of inductive charging is the possibility to perform dynamic charging when the vehicle moves. It requires the installation of coils inside the road infrastructure and adaptations in the power grid. The main challenge today is to develop interoperable systems, to ensure the compatibility between solutions developed by different manufacturers

Each use case of the technology imposes different constraints that need to be taken into account to adapt the system to maintain efficiency and cost. In the INCIT-EV project, the objective is to develop dynamic wireless charging systems **for light and half-duty vehicles, for urban and extra-urban use cases**.

An inductive charging system includes the following main components (see figure 11) :

Power grid: the system is grid connected and depending on the power, it needs to have a triphasic or monophasic connection.

PFC: The power factor corrector device is not only responsible for improving the quality of the grid connection but also to adapt the AC voltage to a DC voltage to power the inverters. The PFC will generate a DC bus and its localisation is important to reduce the voltage drop in the track and also to reduce the losses.

Inverters: These are the most complex devices because they are responsible of communication, control and regulation of the power transfer to the vehicle. In best conditions, they require easy access for maintenance, possibilities of cooling, to dissipate the power losses.

Resonant circuit and coils: The resonant circuit and the coils are composed by passive elements that will be powered by the inverter. The resonant circuit allows to compensate the inductance of the coil and provide the resonance condition. In most systems, high voltages are generated on the terminals of both elements. Because of that, these elements need to be near each other. Normally they are constructed together to avoid electrical isolation problems. In terms of power dissipation, these elements do not have a high efficiency and depending on the environmental conditions, a power dissipation structure may be needed. The coil is the key element responsible for the magnetic field generation, and therefore its size, precise geometry and localisation are primordial to ensure safety and good power transfer rate.

AC/DC converter: This converter is inside the vehicle and is used to adapt the power received by the on-board resonant circuit and coil to recharge the battery of the vehicle.

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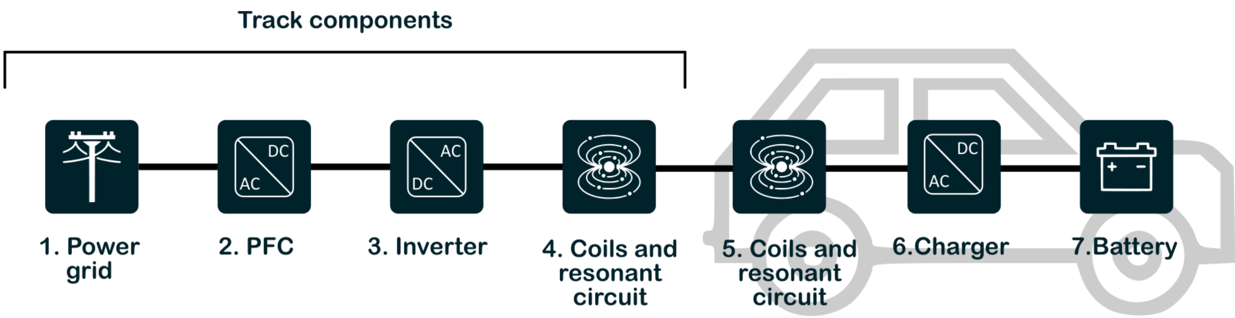

Figure 11. Main elements of a dynamic wireless charging system

Road Integration issues

From the point of view of road integration, this architecture imposes several constraints:

- The primary coils and resonant circuits must be embedded in the pavement, in the middle of the road lane, and at low depth (maximum 10 cm, and if possible less), to minimize the distance between the primary and secondary coils, to ensure maximum power transfer. When operating, the primary coils generate heat, which must be compatible with the materials used in the pavement structure.
- The inverters (generally one per coil), must be placed close to the coils, and remain accessible for maintenance. They must be connected to the coils, and also interconnected, for communication. Finally, these elements heat-up and the generated heat must be dissipated.
- Because a road is never completely impervious, all the components integrated in the road (coils, resonant circuits, inverters, and associated cables and connectors must be fully waterproof, and resist to immersion in water.
- The PFC (power factor corrector) which is a larger equipment, can be located above ground, to remain accessible, and should be placed in a central position, to minimize cable lengths.

5.2.2 Pavement structures and pavement materials

A pavement structure can be defined as the superposition of layers of different materials, designed to distribute traffic loads on the subgrade. The different layers forming the pavement structure are shown in Figure 12. They are designed to allow the movement of traffic, and to ensure the safety and comfort of road users [3].

The pavement layers consist mainly of 3 main elements

The Surface course: It is the uppermost layer of the pavement structure. It may consist of two layers: the wearing course and the binder course. The wearing course is designed to resist to the effects of climate and traffic, and to ensure a good riding quality of the road (evenness, skid resistance).

The Road base: The road base generally consists of two layers, the base course and the subbase. These layers provide the mechanical resistance to the vertical loads induced by traffic and distribute the stresses on the subgrade.

The Subgrade: It is the lowest layer in the pavement structure. It is the compacted natural soil immediately below the pavement layers and acts as a foundation for the highway. The subgrade may be surmounted by

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a capping layer, which is used to improve the homogeneity and bearing capacity of the subgrade, and also to protect it, and offer a good foundation for the construction of the pavement layers.

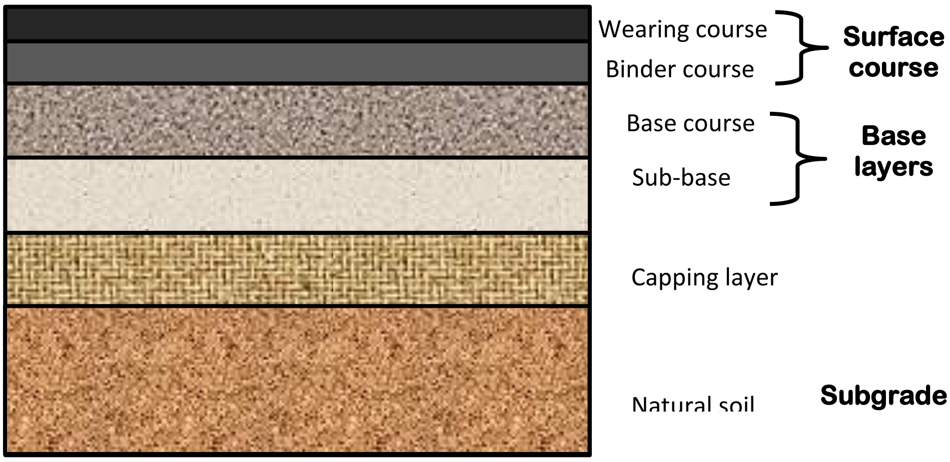

Figure 12. Composition of a pavement structure

Pavement structures are mainly built with two types of materials : bituminous materials, and cement treated materials or concretes, which have somewhat different engineering properties.

Bituminous materials :

Bituminous mixes are composed of aggregates in a variety of fractions, hydrocarbon binder, and, if necessary, additives to improve the workability and the performance of the mix. A typical bituminous mixture is composed of around 5% of binder and 95% of aggregates by mass (80-85% in volume). The hydrocarbon binder, commonly bitumen, is responsible for the cohesion of the mixture and its impermeability. Bitumen presents a viscoelastic behaviour (thermo-susceptible and time-dependent), and affects significantly the properties of the bituminous mixture.

Bituminous materials behave (at small strains) like visco-elastic materials, and their behaviour is very sensitive to temperature and loading frequency. In pavements, their main modes of deterioration are permanent deformations (rutting), occuring at high temperatures, and cracking which can be due to different phenomena (fatigue, thermal cracking, top down cracking..)

Materials treated with hydraulic binders and concretes :

Materials treated with hydraulic binders are a mix of aggregates, cement or other hydraulic binders and water, and if necessary some additives. They can be divided into road concretes, which typically contain between 5 % and 12 % of cement, and granular materials treated with hydraulic binders, which contain lower percentages of cement, or hydraulic binders (between 3 % and 5 %). Road concretes have higher mechanical properties, with elasic moduli of about 30 to 40 GPa, and tensile strenghts around 3 MPa. Granluar materials treated with hydraulic binders have somewhat lower elastic moduli (typically between 20 GPa and 30 GPa), and tensile strengths around 1 MPa. These materials are manufactured in a mixing plant, and put in place cold, contrary to bituminous materials.

Materials treated with hydraulic binders have the property of hardening with time, after mixing, and generally need 28 days to reach their final mechanical properties (or even more with some binders). They

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present a merely elastic behaviour at low strains, and contrary to bituminous materials, their behaviour is not sensitive to temperature. These materials present a high mechanical resistance, and are used mainly for base layers of heavy traffic pavements. Due to their high stiffness, the main mode of deterioration of materials treated with hydraulc binders is cracking, which can be due to shrinkage (during the hardening of the material), fatigue, and thermal cracking.

Electromagnetic properties of pavement materials

The WPT systems use a magnetic field to transfer power to the vehice. Therefore, the performance of these systems will be influenced by the electromagnetic properties of the surrounding pavement materials, and the values of these electromagnetic properties are needed for the modelling of these charging systems.

The properties to consider are :

- electric resistivity ρ,
- relative electric permittivity ε_r,
- relative magnetic permeability μ_r

A review of electromagnetic properties of pavement materials has been performed and can be found in deliverable D4.4. Typical orders of magnitude of these properties are summarised in table1.

Table 1. Orders of magnitude of electromagnetic parameters of bituminous materials

Characteristic	Values	Comments
Electric resistivity ρ,	10^{7} to 10^{13} Ω.m (for dry materials) 10^{3} to 10^{6} Ω.m (in water)	Parameter sensitive to mix design and moisture content
Relative electric permittivity ε_r,	4.5 to 6.5 for dry bituminous mixes 2.5 to 3 for bitumen	Sensitive to aggregate nature and water. Moisture strongly increases permittivity, especially at low frequencies
Relative magnetic permeability μ_r	Very close to 1	Pavement materials are generally non-ferro-magnetic, and their magnetic permeability is close to that of vacuum

5.2.3 Solutions for pavement integration

Because the primary coils of WPT systems need to be embedded in the road, conventional road structures need to be modified, to integrate these systems. Such structures will be called E-roads in this report. Though there is no defined construction methodology, three main types of designs can be found in existing WPT systems [4] :

1. Trench-based construction (built in situ, or with prefabricated elements);
2. Micro-trench based construction;

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3. Full lane-width construction, (built in situ or made of prefabricated elements)

5.2.3.1 Trench-based construction

Trench-based construction consists in placing the WPT coils in a trench made in the asphalt layer, which is then generally filled with concrete. This structure is then generally covered with a bituminous wearing course. Figure 13 shows a cross section of a road for a trench-based electric road implementation. The trench-based construction is quick to complete, has a moderate cost, and can be used to install the WPT systems in an existing pavement. However, it results in a mixed structure, combining concrete and asphalt, which presents risks of thermal cracking and can have high maintenance costs. The precast solution, for the installation of the coils, offers several advantages: the position of the different components of the charging system can be precisely controlled, and the installation is easier.

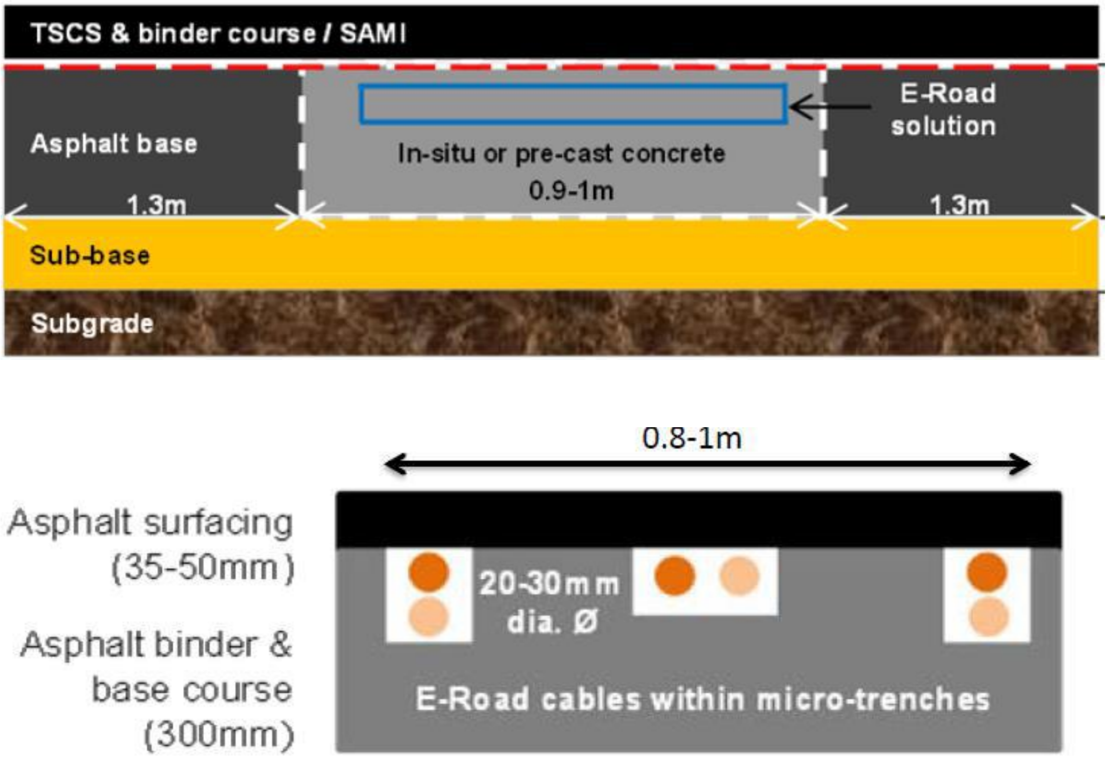

Figure 13. Trench-based construction (top) and micro-trench–based construction (bottom) for integration of WPT

This type of integration solution is used in several recently developed inductive charging systems (Bombardier, KAIST-OLEV)

5.2.3.2 Micro-trench based construction

Compared with trench-based construction, the micro-trench architecture uses narrow, shallow slots in the existing structure, thereby causing less damage to the existing road structure. Figure 13 shows a cross section of road integrating a micro-trench based solution. Similar to the trench-based construction, it is cheap to construct, and can be used on existing pavements; however, the cutting of the trenches can be more

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complex, because they must follow the shape of the coils. In addition, depending on the material used for filling the trenches, the protection of the cables may be less efficient than with the wide concrete trench.

5.2.3.3 Full lane-width construction

Trench-based constructions create grooves and trenches in the existing road structure, which can be a source of cracking and deterioration. In contrast, full lane-width constructions incorporate the coils in a concrete structure covering the full width of the road (see Figure 14). Full lane-width construction can be built in situ or prefabricated. In situ build provides good quality and good protection of the WPT coils. However, full lane-width construction takes more time and is more expensive than trench based construction, and it is mainly adapted to new construction. The advantages of precast full lane-width construction is reduced installation time and more precise positioning of the charging elements. However, the precast concrete slabs are prone to movement under traffic loading. All concrete pavements also require to create longitudinal joints, to avoid uncontrolled cracking of the concrete structure. These joints need maintenance, and can be a source of water infiltration and deterioration.

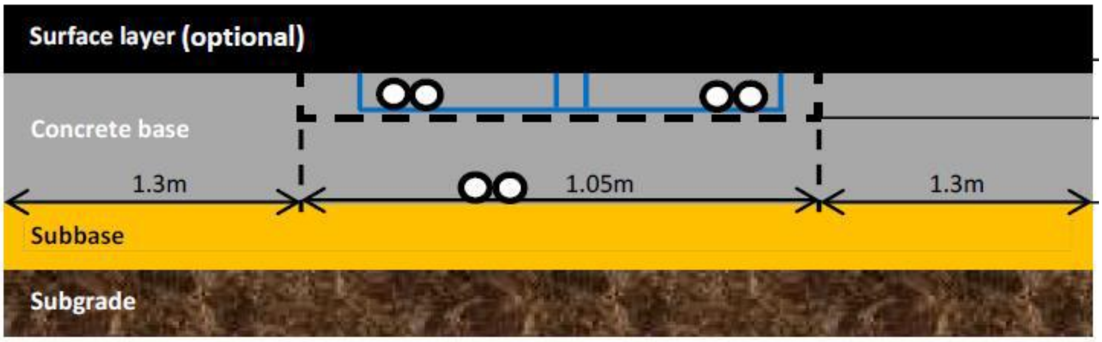

Figure 14. Full lane-width construction for integration of WPT system.

In summary, classical road materials can be used for E-roads, and different types of construction can be used, depending on the projects (new construction or installation in an existing pavement), complexity of the charging elements and tolerances for their positioning.

However, several aspects require special attention:

- The integration of the charging system in the pavement creates discontinuities and joints between materials with different mechanical and thermal properties, and can lead to cracking and deterioration. Good bonding between the inclusions and the pavement materials is essential to achieve good performance.
- The WPT systems must be installed at low depth below the pavement surface (ideally about 5 to 6 cm), to limit the gap between the primary and secondary coils. This means that they will only be covered by a thin wearing course. This can create a risk of fatigue and cracking of this upper layer, especially if the inclusions present a lower stiffness, or if sufficient bonding with this wearing course is not ensured. The use of an appropriate joint material at the interface can reduce this risk.
- Due to their electromagnetic properties, pavement materials can affect the performance of the charging system, especially if they contain water. Therefore, it seems necessary to use nonconductive materials as dielectric between the WPT coils and the surrounding road materials.

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5.2.3.4 Resistance to traffic loads and climatic conditions

Because the E-road structure is different from classical road structures, and integrates rigid inclusions, and discontinuous interfaces or joints, this creates more complex stress states in the structure, and risks of premature damage due in particular to cracking, caused by traffic loads and climatic variations. Phenomena which can be expected are for example:

- reflective cracking, due to the presence of joints, which is frequently observed in composite pavements, with a hot mix asphalt surface layer over a concrete road base.
- Layer debonding, due to the presence of interfaces between layers of materials with different mechanical properties.
- Thermally induced cracking, due to the different thermal expansion coefficients of the inclusions and surrounding pavement materials. This phenomenon has been clearly demonstrated by Hornych et al. (2020).

Most classical pavement design methods, like in particular the French pavement design method [3] are based on simplified mechanical models, considering homogeneous, multi-layered structures, and elastic behaviour. Because E-road structures are more complex, with the presence of inclusions and discontinuities, such simplified calculation methods may not be suitable for their analysis. Finite Element Modelling (FEM) is more appropriate, as it allows to take into account more complex geometries, and non-linear material behaviour.

A detailed study of the mechanical response of an E-road, using FEM modelling, has been conducted by Chen [5], in connection with the FABRIC project. In this study, an asphalt pavement, with charging loops integrated in a concrete slab, has been considered. The calculations have shown that the presence of the stiff concrete slab in the pavement modifies significantly the mechanical response under traffic loading, and can increase the risk of damage. In particular, high shear stresses are generated near the surfaces and at the corners of the concrete slab.

Other effects, not considered in the work of Chen, may have a significant influence on the durability of E-roads. They include:

- Temperature variations, which will lead to differential thermal expansion of the different materials, and can induce cracking
- The behaviour of interfaces between the road layers and inclusions. When these interfaces are insufficiently bonded, this can create significant tensile stresses above the interface, under wheel loading, which can lead to fatigue and cracking of the upper layer.
- Deterioration associated with water infiltration in the cracks and discontinuities.

5.3 Review of existing wireless power transfer solutions.

In deliverable D4.4 of INCIT-EV, a detailed review of different existing wireless power transfer solutions has been carried out, with a focus on pavement integration aspects. In particular, solutions developed by Polito [6], Bombardier (Primove system , [7]), by the Fabric project [8, 9], by KAIST-OLEV [10,11], by CIRCE (Victoria project, [4]) and by Electreon [12] have been studied. Only a summary of the conclusions of this study is presented in this section.

A summary of characteristics of some of these charging systems is given in table 2 below [18].

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Table 2. Comparison of characteristics of different WPT systems [18]

Year	Project	Veh. Type	Driving Cond	Air Gap cm	Max Power kW	Op. Freq. Hz	Eff. %	Ref. and Outcomes
1980s	PATH UC Berkeley	Bus	Dynamic	5–10	200	20	60	Ref. [29] Project Stopped
1997	Conductix-Wampfler	Bus	Static Stationary	4	30	15		Patents [30,31] First commercialized static WPT
2011	SELECT Utah State University	Bus	Static Stationary	15–25	25	20	90	Ref. [32] Commercial activities (WAVE)
2011	PRIMOVE Bombardier	Bus	Static Stationary Dynamic		200	20	>85	Ref. [33] Commercialization static systems in Mannheim, Berlin
2011	KAIST Olev	Bus	Static Stationary Dynamic	15–20	100	20	85	Ref. [34] First commercialized dynamic wireless charging bus
2016	ONRL	Pass. car	Slow dynamic		20	22–23	90	Ref. [35] Research Laboratory conditions
2017	FABRIC Versailles-Satory Site	2 serial Pass. cars	Stationary to highway speed (100 km/h)	17.5	20	85		Ref. [36] Experimental representative road

From the point of view pavement integration, the review of different inductive charging systems has led to the following main conclusions :

- The tested systems include both urban and interurban applications.
- The primary coils (integrated in the road) vary greatly in length, from less than 1 meter to 24 m long.
- Some systems are dedicated to buses or heavy vehicles, whereas others are suitable for different types of vehicles, from cars to heavy goods vehicles.
- Different architectures are also used, with one inverter controlling only one coil or several coils.
- Easy access to the electronics seems important to facilitate maintenance and adaptation of the systems
- Typical air gaps between the primary and secondary coil seem to range between 15 cm and 25 cm
- Integration in both bituminous materials and concrete materials has been tested, and both seem possible. Several projects have used prefabricated concrete solutions, which present the advantage of a good control of the geometry of the components and easy installation.
- The most frequent mode of construction seems to be the trench-based construction, where the system is installed in a trench (about 0.6 to 1 m wide), milled in the centre of the road lane, and then covered with a wearing course extending over the whole road lane, to ensure a smooth riding surface, without joints. This type of solution limits the volume of construction works.

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- Problems of electromagnetic influence of the road materials are mentioned in some projects; it is clearly necessary to avoid materials containing ferrous elements, and moisture also has a negative effect. A solution to reduce these problems is to protect the coils with a dielectric insulating material.
- The heat generated by the system in operation can be significant, and can affect materials sensitive to temperature (in particular bituminous materials).
- Practically no information could be found about the long-term durability of the pavement solutions, and observed deteriorations, probably because these applications are too recent.
- Finally, metallic object detection in the charging area (due to the heating effect of induction) is mentioned as a very important issue in the Bombardier demonstration.

5.4 Description of the VEDECOM and CIRCE charging systems

For WPT charging, the objective of INCIT-EV is two develop charging solutions for passenger cars and light utility vehicles (<3,5 T), and for 2 different use cases: an urban use case, and an interurban use case. The urban solution is developed by VEDECOM, and the interurban solution is developed by CIRCE. This section presents some of the main characteristics of the two developed systems, and of the associated demonstrators. Only the transmitter part of the systems (also called the primary system), which is installed in the road, is described.

5.4.1 VEDECOM system description

A schematic description of the primary system of the Vedecom solution is shown on figure 15. The primary includes:

The DC power source: Connected to the grid, this AC-DC converter will power the whole system with a constant DC voltage and current.

The inverter module: This module is composed by electronics and power electronics circuits and it is responsible for the power electronics command, electrical measurements and communication with the next and previous inverter modules of the track but also with a track supervisor interface. In the VEDECOM primary system, each coil is connected to one inverter module.

The coils: They are the wireless power transmitters and are composed by an inductance and a capacitance. The VEDECOM coils are 1m long, and have a power of 30 kW.

A detailed description of the VEDECOM system, including its electrical characteristics, can be found in deliverable D 3.4 of INCIT-EV.

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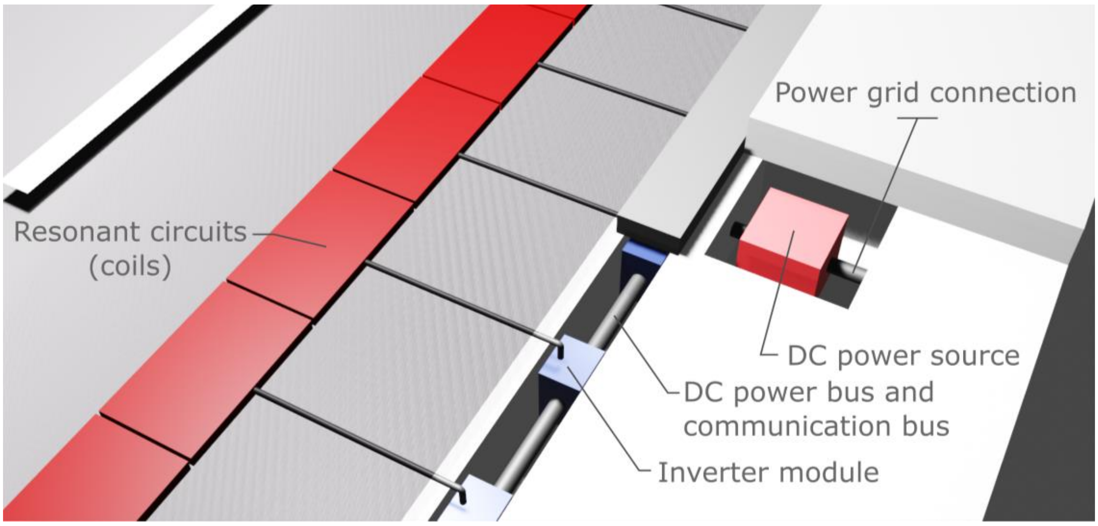

Figure 15. Schematic description of the VEDECOM primary charging system.

The coils developed by VEDECOM are rectangular in shape and are made of Litz wire (several loops), the dimensions of the coils are shown in Figure 16. Theses coils must ensure an acceptable coupling factor, an easy road integration and a good electromagnetic field exposure protection (provided by the shielding).

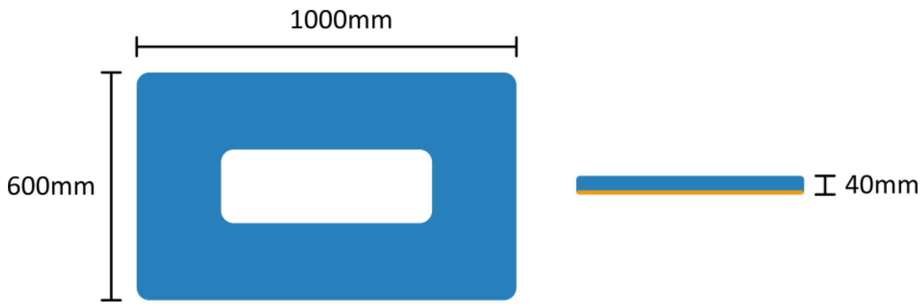

Figure 16. VEDECOM coil dimensions (first design).

Ferrite plates are used below the primary coils and above the secondary coils, theses ferrite plates must allow the passage of the magnetic field with a minimum of loss. The coils will be protected and held in their position, by a dielectric insulating material

For the urban demonstrator, it is planned to install two 25 m long charging sections, with a total installed power per section of 120 kW (30 kW per coil), and the experiments will be performed with two vehicles : a passenger car, (ZOE, charging power 30 kW), and a light utility vehicle (MASTER, charging power 90 kW). The operating speeds will be between 0 and 50 km/h.

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5.4.2 CIRCE system description

The charging system developed by CIRCE for inter-urban applications represents a challenge according the current technical literature as It consists to feed up to three possible 30 kW secondary coils while running at high speed (130 km/h). The solution is based on 10m long and 45 cm wide coils, with a power of 90 kW per coil and the total length of the charging section will be between 80 and 90 m. A schematic description of the CIRCE primary system is shown on figure 17. The primary includes:

- One AC/DC converter, for the supply of all the coils;
- 4 DC /AC high frequency converters (1 for two coils);
- 8 coils (10 m long), made of Litz wire, each coil consisting of only 1 loop of Litz wire, with a large section (around 200 mm^2), and associated capacitors.

The CIRCE system is designed to simplify as much as possible installation, and to reduce costs, for the long-distance application. The objective (still to be validated) is to use no ferrite and no aluminium in the road structure, and no cooling system. A detailed description of the CIRCE system, including its electrical characteristics, can be found in deliverable D 3.4 of INCIT-EV

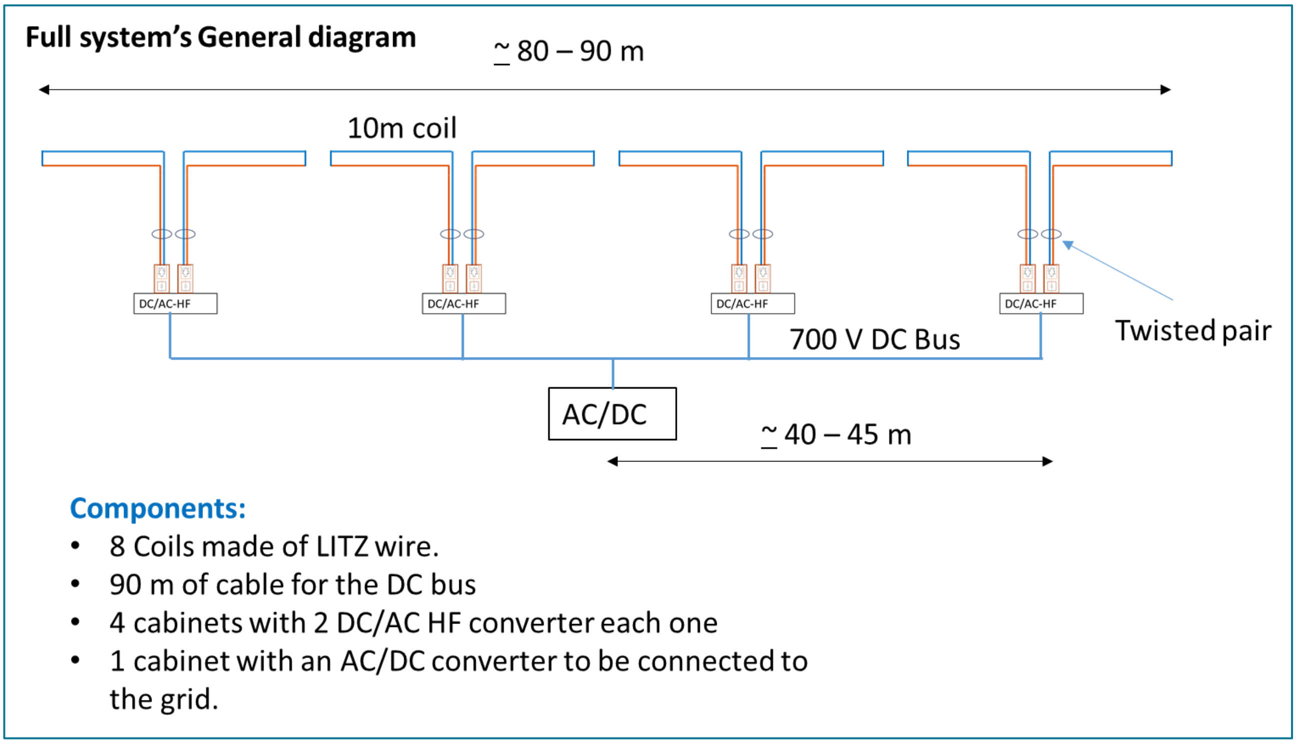

Figure 17. Schematic description of the CIRCE primary charging system.

The inter-urban demonstrator will be a dedicated test track, built on the site of VEDECOM, in Satory. The charging section will have a total length of about 80 meters, and will include eight 10 meter long coils. The total installed power will be 360 kW (90 kW per coil), and the experiments will be performed with the same

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vehicles as for the urban demonstrator : a passenger car, (ZOE, charging power 30 kW), and a light utility vehicle (MASTER, charging power 90 kW). The operating speeds will be between 0 and 130 km/h.

5.5 Work program for road integration of WPT systems at laboratory scale

Based on the state of the art, a methodology has been defined for designing and validating suitable solutions for road integration of WPT systems. The general methodology is similar for the two urban and interurban use cases, but the test programs will be adapted to each use case (characteristics of each charging system, pavement structure, materials, other constraints).

This section presents :

- the general methodology that will be followed for road integration,
- the integration solutions proposed for each use case and associated charging system,
- the program of laboratory tests, and modelling, started to validate the proposed solutions.

5.5.1 Methodology for road integration of WPT systems

From the state of the art and review of existing solutions, a methodology has been proposed, for the study of the integration of WPT systems in pavement structures, at laboratory scale. This work is carried out in collaboration with task 3.4, in charge of the design of the WPT systems, because the electrical design and the integration in the pavement are interdependent. The main steps are the following:

- **Definition of the type of pavement structure**. Depending on the characteristics of the primary coils, on the use case and type of pavement structure, a first initial design is proposed, for the integration.
- **Selection of appropriate materials**. The second step consists in selecting a suitable protective and insulating material for the coils, and suitable pavement materials. This requires in particular to verify that the electromagnetic properties of the pavement materials do not affect the performance of the system.
- **Electromagnetic modelling**. The objective is to model the electromagnetic performance of the charging system, as installed in the road, and validate the power transmitted and the EMF level in the vehicle and around the vehicle, to adjust the design if necessary (shielding, materials, geometry...).
- **Laboratory testing**. The objective is to evaluate, in realistic laboratory conditions, the performance of the primary coils, embedded in pavement materials. Several aspects need to be studied :
    - The operating temperatures of the system.
    - The electromagnetic performance of the coils embedded in pavement materials (dry and wet).
    - The resistance of the coils to the construction process, and the mechanical behaviour of the embedded coils.

Mechanical and thermal modelling. Modelling will be performed to evaluate temperatures in the E-road, and mechanical behaviour of the E-Road under vehicle loads.

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5.5.2 Proposed pavement structures

In task 4.4, the objective is to develop solutions for pavement integration with both bituminous and concrete materials. However, in the first year, only **bituminous solutions** have been studied, and are presented here.

5.5.2.1 Urban demonstrator

After examining different possibilities, the design described on figure 18 has been proposed :

The solution consists in milling a narrow trench in the existing pavement, just slightly larger than the coils, and installing and sealing the coil in this trench with an appropriate joint material (resin), and then covering this trench with a surface layer, covering the whole width of the road lane.

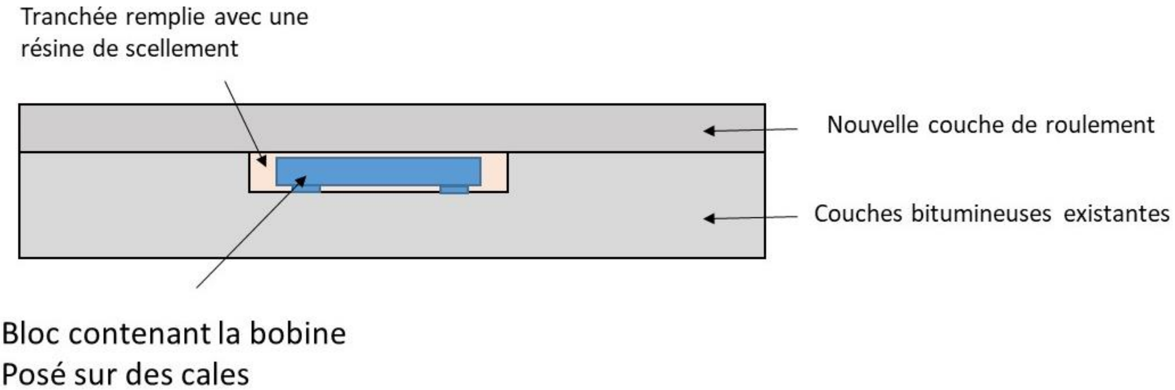

Figure 18. Narrow trench solution for pavement integration (urban demonstrator)

The following remarks can be made about this solution :

- This solution is simple to build, and the surface layer, covering the full width of the road lane avoids the presence of joints in the middle of the lane.
- The resin used for sealing the coils is a key element of this solution : it must ensure a good bonding with the coils and pavement materials, and it must be sufficiently flexible to limit risks of cracking due to the different properties of the pavement and coil materials.
- Because the asphalt materials are laid at high temperatures (about 160 to 180 °c), the resin, and the insulating material protecting the Litz wires must be able to resist to thee high temperatures.

5.5.2.2 Inter-urban demonstrator

The solution proposed for the inter-urban demonstrator is similar to the on proposed for the urban-demonstrator, and also based on a trench-type solution (see figure 19). This solution consists in milling a wide trench in the middle of the road lane (about 1 m wide minimum), fixing the coils to the bottom of the trench, and then filling directly the trench with asphalt concrete.

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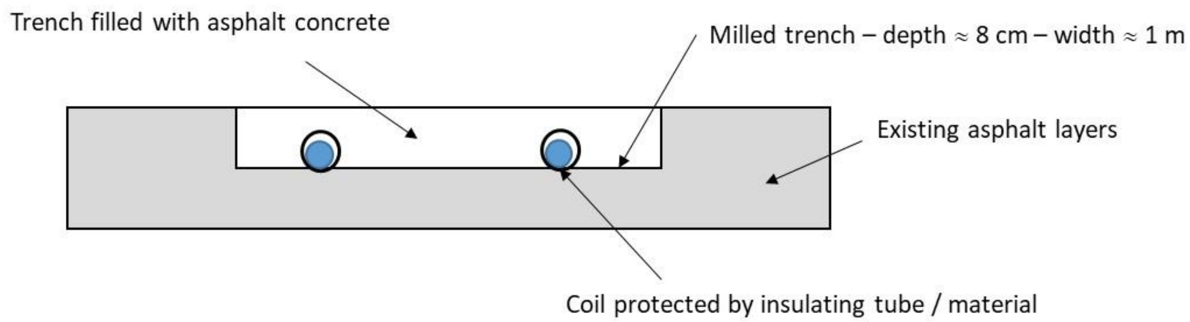

Figure 19. Wide – trench solution for pavement integration (inter-urban demonstrator)

The following comments can be made concerning this solution :

- This solution is simple to build : the trench (1m wide minimum) is easy to mill, and only asphalt material is used. Instead of a trench, it is also possible to mill and replace the whole width of the road lane, to avoid joints.
- The Litz wires need to be protected by a coating material which is waterproof, insulating and resistant to temperature (160 °C to 180 °C).
- During construction, the coil will be directly in contact with the hot bituminous materials (160 °C), and directly submittted to the stresses generated by the compaction of the bituminous material. It will be necessary to verify that the coil is sufficiently protected by the coating material, and will not be damaged by this process
- With this solution, it would be possible to place a shielding material below the coils, at the bottom of the trench (electromagnetic modelling will show if it is necessary).

5.5.3 Laboratory testing and modelling

After defining the pavement structures, a test program was started, first with the VEDECOM coils, to verify the compatibility with pavement materials and then the performance of the embedded coils (operating temperature, charging performance, mechanical performance). It is planned to perform similar tests with the CIRCE system.

These tests are carried out on a test bench, specificallly developed by VEDECOM for the testing of WPT systems. This test bench consists of a platform, where the primary coils are installed, and a robotized arm, which is used to move the secondary coil, to simulate the moving vehicle (see figure 20)

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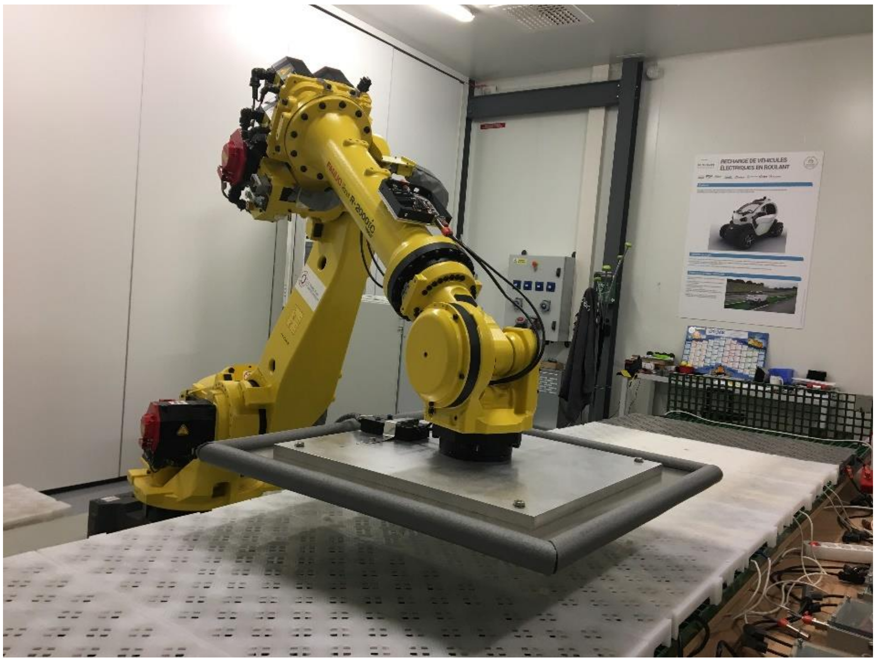

Figure 20. View of the VEDECOM test bench for testing of inductive charging systems

5.5.3.1 Compatibility with pavement materials

A first series of preliminary test was performed on the VEDECOM test bench, to evaluate the effect of pavement materials on the charging performance of the coils. For these first tests, plates of bituminous or concrete material were interposed between the primary and secondary coils. For this purpose, six plates of cement concrete and six plates of bituminous concrete were manufactured by Univ. Eiffel, with dimensions of 600 mm long x 400 mm wide x 50 mm thick.

The bituminous material was a standard wearing course bituminous concrete (EB-BBSG), of 0/10 mm grading, made with diorite aggregates. The cement treated material was a standard road concrete, made with gneiss aggregates (0/11.2 mm grading).

Charging tests were performed by varying :

- The distance beween the coils (10, 15, 20 and 25 cm)
- The alignement of the two coils (between -25 % and + 25 %)
- The material between the coils : bituminous concrete, cement concrete and air (used as reference).

During the tests, the input power, the output power, and the charging efficiency were measured. The results indicated that :

- the charging efficiency is only very slightly reduced (by about 3 %) when 5 cm plates of pavement materials are placed between the coils, compared to results obtained in air.
- The effect of the misalignement between the coils (+/- 25 %) is also very limited, with a decrease of about 3 % of the charging efficiency.

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In conclusion, in these tests, the influence of the pavement materials (bituminous concrete or cement conrete) on the charging efficiency appears very limited. However, this will need to be confirmed by tests with the coils embedded in the pavement materials.

5.5.3.2 Test with coils embedded in pavement materials

Aftre the first tests, a second series of tests was started , with the coils embedded in pavement materials. As a first step, it was decided to perform tests with the coils embedded in a granular material, without binder, identical to the granulal skeleton of the bituminous concrete. The advantage of using a granular material is that it has no cohesion, and that the coils can be easily embedded in the material and removed. This is not possible with a bituminous material, that will adhere to the coils, making the embedment irreversible.

The experimental setup for these tests is shown on figure 21. The granular material was placed in a plastic container. A first layer of granular material was placed at the bottom of the container and compacted. Then, the primary coil was placed over the granular layer, and covered again with a layer of 6 cm of granular material . During the embedment, 6 temperature sensors were placed in the container at different depths, to measure the operating temperatures during the charging. Finally the secondary coil was installed above the embedded primary coil, using plastic supports.

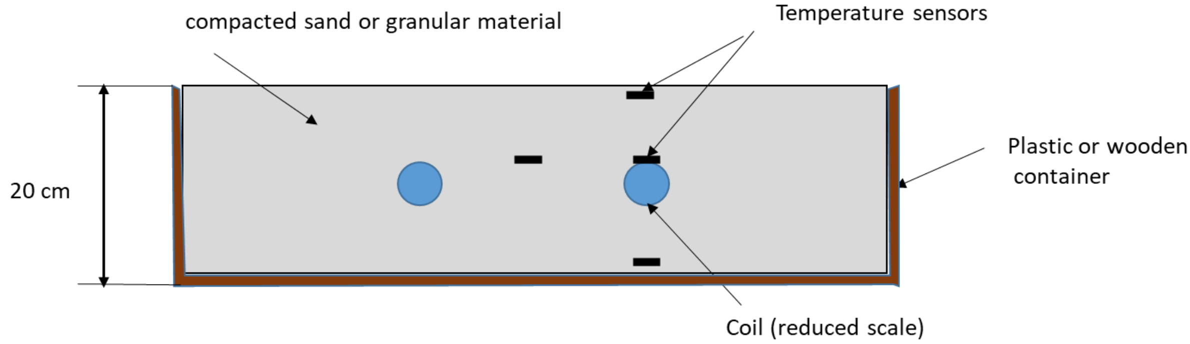

Figure 21. Experimental setup for the tests with a granular material

A program of charging tests is under way with this setup. Three types of tests are performed :

- Measurements of operating temperatures, with different charging sequences, simulating the operating conditions of the urban demonstrator;
- Charging efficiency measurements with a granular material (first dry and then wet), similar to those performed with the bituminous concrete plates.

If these first tests are satisfactory, a second series of tests will be performed with the coil embedded in bituminous material.

5.5.3.3 Thermal modelling

In parallel with the laboratory tests, modelling work has started, to model the thermal response of the bituminous pavement structure with the embedded primary coils

The modelling consists in performing finite element calculations, in 2D, with a model simulating the coil embedded in the pavement, and studying the thermal response of the pavement, due to the heat generated

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by energy losses in the embeded primary coil. The finite element mesh used for the simulations is shown on figure 22.

Simulations have been performed, first with the VEDECOM coil, embedded in a bituminous pavement structure. A charging power of the coils of 30 kW, and an energy loss (dissipation by Joule effect) of 4 % in the primary coil, embedded in the pavement, were assumed. The simulations were performed with :

- Different charging durations (1, 3 and 12 hours)
- Different pavement temperatures
- Different boundary conditions (convective exchange with air at the surface of the pavement).

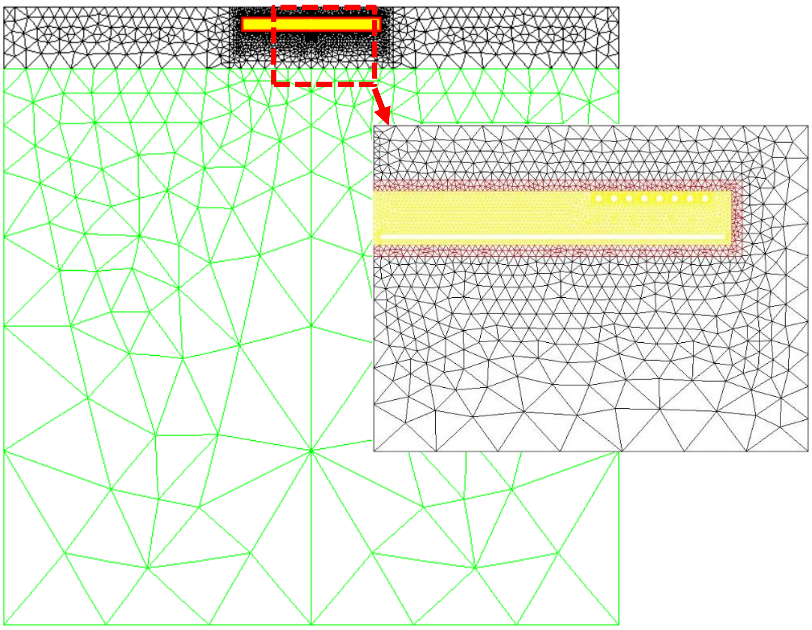

Figure 22. 2D mesh of the first finite element model of the VEDECOM coil, integrated in a bituminous pavement.

Figure 23 shows an example of simulation results. In this simulation, a continuous charging during 1 hour was simulated (extreme condition), with an initial pavement temperature of 15 °C. Only the evolution of the temperature in the asphalt concrete is represented, with a scale going from 15°C to 25°C. The results show that :

- After 1 hour of charging, the temperature reaches a maximum value of 24°C in the asphalt concrete, under the ferrite
- Then, the temperature decreases progressively, and after 3 hours of rest, the temperature is below 20°C in the pavement layer.

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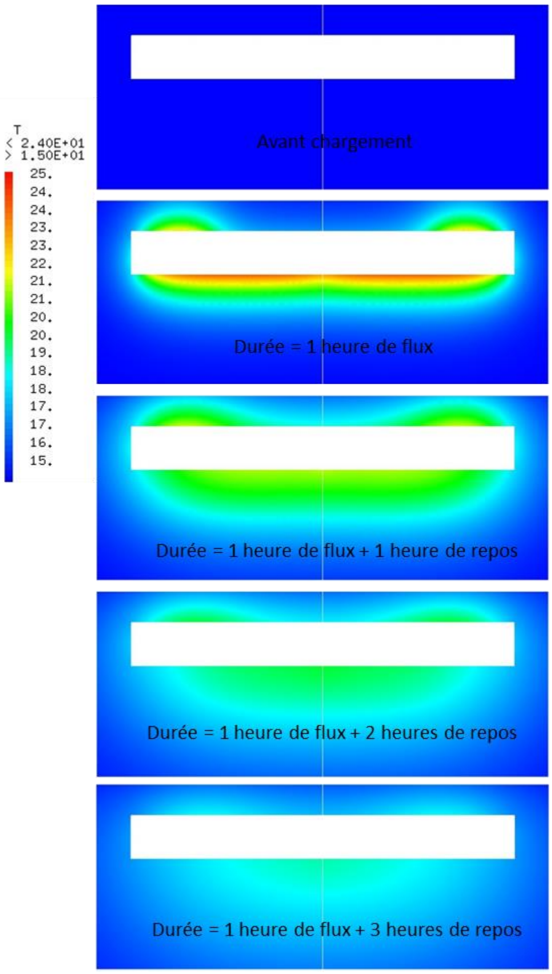

Initial temperature T

T after 1 hour of charging

T after 1 hour of charging
+ 1 hour of rest

T after 1 hour of charging
+ 2 hour of rest

T after 1 hour of charging
+ 3 hour of rest

Figure 23. Evolution of temperatures in the bituminous layer after one hour of charging (Temperatures after 1,2,3 and 4 hours – temperature scale 15 °C – 25 °C)

These first results, with an initial temperature of 15 °C indicate a moderate temperature increase in the bituminous layer around the charging system. However, it is only a first simulation. The model will have to be calibrated by comparison with the laboratory tests, in order to obtain accurate results. After that a parametric study will be performed with different operating conditions :

- Different power levels dissipated by the embedded coil
- Different charging times or charging cycles
- Different Ambient temperature conditions, and surface boundary conditions

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5.6 Perspectives of task 4.4

In the first year of the INCIT-EV project, a detailed review of existing WPT systems, and in particular of solutions for integrating these systems in roads has been carried out. On the basis of this state of the art, and of the characteristics of the two charging systems developed by VEDECOM (for urban applications) and by CIRCE (for inter-urban applications), possible solutions for their integration in bituminous pavements have been proposed. Then, a program of laboratory tests, and of associated modelling was defined, to validate the proposed solutions, and the materials to use for the integration.

This program includes the following steps :

- Selection of protective materials for the coils , and appropriate pavement materials, and evaluation of their electromagnetic properties.
- Electromagnetic modelling, to validate and if necessary adjust the design of the charging system, to ensure satisfactory charging performance
- Laboratory testing, to evaluate the performance of the primary coils embedded in pavement materials: different tests are carried out to evaluate the charging performance, the thermal effects, and the mechanical behaviour of the embedded coils under traffic loads.
- Mechanical and thermal modelling, which objective is to analyse the results of the laboratory tests, and then to predict the performance of the proposed pavement structures.

First tests have been performed on test bench developed by VEDECOM for testing of WPT systems, with the coils developed by VEDECOM. These tests consisted in evaluating the effect of pavement materials on the charging efficiency of the system, and on the thermal response. First test have been performed with plates of pavement materials placed between the primary and secondary coils, and then with the coils embedded in pavement materials. The first tests have indicated a low influence of the materials on the charging efficiency. The thermal tests will be continued to verify the temperatures attained in different operating conditions.

The test program will be continued during the second year of the project, with the VEDECOM and CIRCE primary systems, to verify the resistance of the embedded coils to construction , and then to traffic loads. Thermal and mechanical modelling of the performance of the systems in pavements will also be carried out. The objective, at the end of the task, is to propose reliable pavement integration solutions, for the urban and inter-urban dynamic wireless charging demonstrators.

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6 TASK 4.5 - DEVELOPMENT OF THEFT-PROOF PARKING AND CHARGING SYSTEM FOR ELECTRIC 2-WHEELERS

6.1 Objectives

This section concerns task 4.5 , which is carried out by IDNEO. On the basis of experience acquired with previous systems, IDNEO is in charge of developing a new, innovative parking system for two-wheelers (bikes and kick-scooters), which will combine secure parking and charging functions. The objectives are :

- To reduce the size, compared to current theft-proof systems, to minimize visual impact and facilitate installation
- To propose a wireless battery charger, compatible with a large variety of electric two-wheelers (interoperable), which can be used both for commercial vehicle fleets and for private use
- To provide an efficient locking system, to prevent theft, which is a major concern for these vehicles.
- To propose a solution which is easy to use, and of reasonable cost.

Over the last years, electric 2-wheelers have changed mobility in most large European cities with an important role in the reduction of NOx and CO2 emissions. Electric bicycles and scooters, both in private and shared use, represent a very interesting alternative to other vehicles in urban areas, especially in combination with public transport. The interoperability between the different types of 2-wheelers and public transport, and the facility for parking and charging these vehicles represent key factors in the success of these alternative mobility systems.

To develop this new parking and charging system, a state of the art review of charging and anti-theft solutions for 2 wheelers has first been carried out. After this review, the main characteristics of the new parking system have been defined, and will be presented in this section.

6.2 Review of existing parking and charging solutions for two-wheelers

6.2.1 Electric bike-sharing systems

The use of electric bikes and electric scooters has increased considerably over the last few years in the EU. in 2019, the number of e-bikes sold was close to 3 million, and the use of kick scooters is also increasingly popular, with more than 125 cities in Europe using these types of vehicles in sharing systems [14].

In many of these cities, the increase of robberies and vandalism of these 2-wheelers systems, either public for sharing use or for private use is a major concern. Novel anti-theft solutions combined with flexible and safe battery charging solutions are required by all the stakeholders of this new mobility era: end users, fleet operators and municipalities.

A review of European bike-sharing systems [15] indicated that the following cities in Europe have the most important systems, with the following daily uses of each bicycle :

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- **Barcelona** (10.8 trips per bike, 67.9 trips per 1,000 inhabitants)
- **Lyon** (8.3 trips per bike, 55.1 trips per 1,000 population)
- **Paris** (6.7 trips by bike, 38.4 trips per 1,000 inhabitants

The study also indicated that the following criteria are important to have a good bicycle sharing system :

- Having multiple stations ideally located within no more than approximately a 325-meter radius.
- Have multiple bicycles available (10-30 per 1,000 populations in the coverage area)
- A coverage area of more than 10 square km
- Solid bikes with hardware that discourages theft
- Easy to use payment systems and stations.

A very important points to take into account for electric 2 wheelers sharing systems, is the control of the battery charge cycle : how to ensure that users do not run out of battery power in the middle of a journey and how to charge the battery rapidly and safely, with minimum impact on the availability of the bikes.

However, the major concerns with these new mobility systems are risks of theft and vandalism. In the case of bikes for sharing use, two major types of locking technology are employed :

- Bikes lock to a rack or kiosk where users collect and drop bikes by means of a magnetic card (see figure 24) . These systems are generally simple to operate, making them accessible to the general public. This type of system is called dock based system. These systems present a better protection against theft, and also allow to combine parking with charging, but require to install dedicated dock stations. Such systems are often used for bikes.

Figure 24. Dock-based bike station in the city of Madrid

- Bikes are secured using an electronic lock mounted on the bike. Users must use a mobile phone to unlock the bike via a code received from the operator company. This type of system is known as Free-floating system or dockless. This system presents a better flexibility, because the vehicles can be parked anywhere, without the need to install dock stations; the vehicles are then located using

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their integrated GPS, which requires a smartphone application. However, because the vehicles are not attached to a fixed rack, there is a greater risk of theft or vandalism. Free floating systems are predominantly used for kick scooters.

In INCIT-EV, the objective is to combine parking and charging, and therefore the solution that will be studied is a dock-based system. For such systems, there are two main types of locking systems, depending on the part of the bicycle which is attached :

Fork lock systems :

Fork lock blocking is the most common and secure method found in docking based systems. This system can be used either with electric or mechanical bikes. In case of electric bikes, battery charger connections can be included in the blocking mechanism, to ensure protection of the power terminals (Figure 25).

Figure 25. Fork lock dock station of Madrid electric bike sharing system

Hub lock system :

Front hub blocking systems can be used as well in docking based systems for electric and mechanical bikes. In this case, battery charging terminals are more exposed to external disturbance than in the case of fork locks systems.

In INCIT-EV, as the objective is to propose a parking and charging system which can be used for both bicycles and kick-scooters, the fork lock system seems the most suitable.

6.2.2 Reference electric bike sharing solutions of European cities

To define the characteristics of the new parking and charging system that will be developed in INCIT-EV, different existing systems from major European cities and sharing services companies have been studied. A detailed analysis of these different solutions can be found in the deliverable D4.5 “Report on theft-proof parking and charging systems for two-wheelers” of INCIT-EV. The following systems have been reviewed :

- ***Bicing,*** the bike sharing service of the city of Barcelona.

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- ***Bicimad,*** the public electric bicycle service of Madrid
- The systems developped by ***Smoove,*** a French company which develops bike sharing systems implemented in 22 cities.
- The systems developped by **PBSC**, a Canadian company, also developing bike sharing systems for several large cities.

Most of the analysed systems are made only for bicycles (classical or electric), and use fork lock blocking systems. The lock also includes the connector for electric charging.

Recently, PBSC unveiled a more innovative solution, which also allows most types of kick scooters to dock and recharge at their smart stations**.** PBSC uses a triangular device to lock and charge the electric bikes. This system can also be directly mounted onto the frame of kick scooters, making these vehicles compatible with their docking points. It is thus the first charging and parking solution compatible with different 2-wheelers.

6.3 Innovative charging and parking system for two-wheelers developed by IDNEO

On the basis of previous experience and of the review of existing systems, IDNEO has defined several innovative characteristics for the new charging and parking system to develop in INCIT-EV :

- The locking system will be compatible with both bicycles and kick-scooters.
- The vehicles will be equipped with connectors for charging the battery, compatible with any kind of vehicle.
- The charging will be wireless, thus eliminating plugs, and reducing the risks of vandalism and reducing maintenance.
- The dock stations will be compact and adaptable, to allow installation in different strategic locations of the cities (kiosks, poles, walls, …).

The main characteristics of the system are detailed below.

Interoperable dock stations for bikes and kick scooters :

The objective is to develop an interoperable charging system that allows both electric bicycles and scooters to be used in the same charging station. The locking system must be compatible with both types of vehicles. On the vehicle side, a connector for charging the battery compatible with any kind of vehicle must be developed. A sketch of the proposed system is shown on figure 26.

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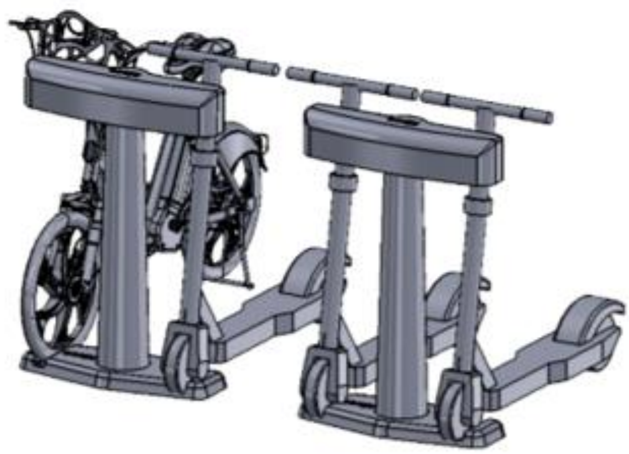

Figure 26. Concept of dock-station, compatible with e-bikes and kick-scooters

Compatible anti-theft charging connectors for e-bikes and kick scooter

Custom on-board battery chargers, adaptable to different vehicles will be developed (figure 27). When the vehicle arrives to the dock station and the battery charging process begins, the 2 wheeler vehicle will send its set points (maximum charge voltage and constant current value) to the electronic control unit of the dock station. The battery charging unit will also serve to lock the 2-wheeler to the dock station, using an electro-mechanical locking system

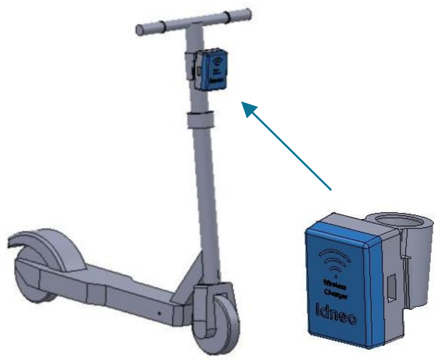

Figure 27. Concept of Wireless interoperable connector for 2 wheelers

Wireless battery charging to avoid mechanical connectors

The connector will allow wireless inductive charging, without the use of a physical connector. This provides a reliable solution, reducing vandalism problems and maintenance. In addition, the wireless technology allows modulating bidirectional communication signals for the exchange of data between the 2 wheelers and the dock station. The principle of the charging system is described on figure 28.

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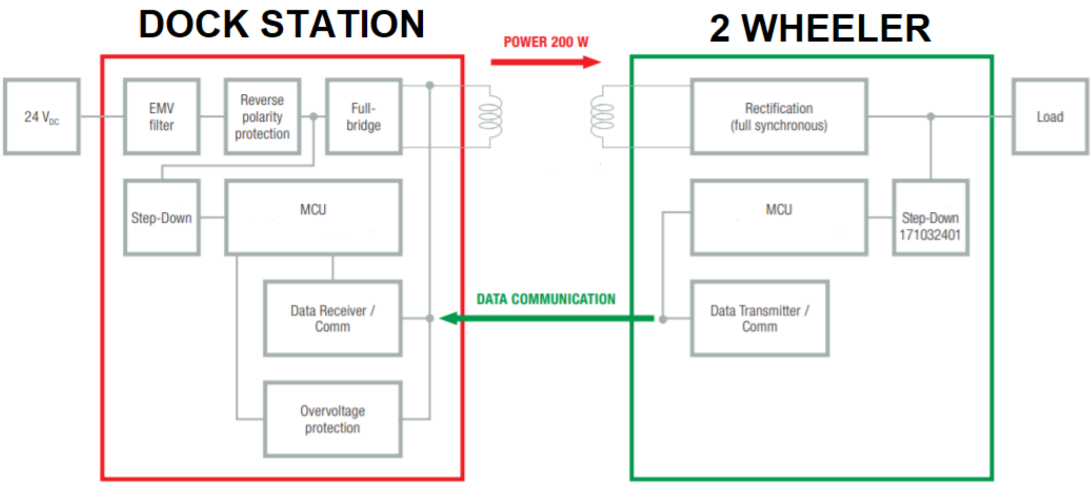

Figure 28. Principle of the wireless charging and communication system

Adaptable dock stations :

The objective is to develop compact dock stations which can be adapted to different types of use and different urban locations along the cities, such as shopping centers or kiosks, and also to different types of business models (renting, sharing, smart free floating, ...). A possible adaptation to a kiosk is shown on figure 29.

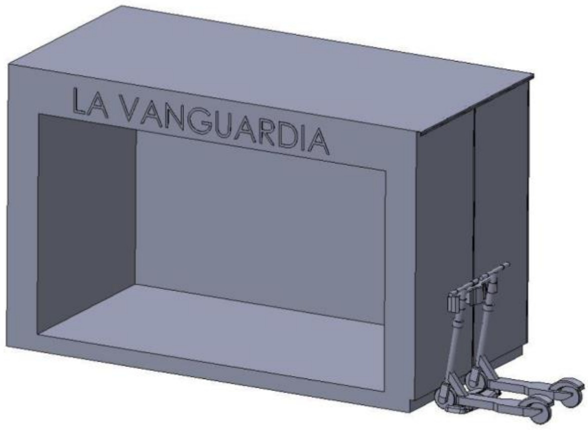

Figure 29. Concept of 2-wheeler charging dock station for kiosk (wall mounted)

6.4 Perspectives of task 4.5

During the first year of the project, the concept of the new charging and parking solution has been defined, and in the next year (2021), the detailed design of the prototype of the dock station and of the on-board charger will be carried out for at least one target vehicle of the project. To do this, all the innovative elements

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presented in this report will be introduced in the design, such as the intelligent locking system with IoT functionality and the wireless charging system with bidirectional communication that replaces physical connectors for battery charging, one of the weakest points of the 2 wheelers sharing systems.

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7 CONCLUSIONS

The following results were achieved in Work Package 4, during the first year of the INCIT-EV project.

- In Task 4.1 "Grid requirements for charging system deployment", a theoretical analysis of potential impacts that a large deployment of electric vehicles could have on the electric grid was performed. Then, in a second stage, simulations were carried out to analyse the effective impacts that could be expected in the context of different EV use cases (urban, inter-urban, peri-urban and parking frameworks). Finally, different measures that could be used to mitigate these impacts were discussed and evaluated.
- In Task 4.2 "grid services enabled by charging infrastructure and ESS deployment" a review of different grid services which can be provided by the charging systems and electric vehicles has been performed. Both services provided by grid operators and V2X services have been studied. Then, using the same scenarios as in task 4.1, first simulations have been performed to assess the expected impacts of these services on grid performance. These simulations will be continued during the second year of the project
- In Task 4.3 "Connection with DC networks and integration with tram / metro energy lines", potential advantages of using DC networks for charging of electric vehicles have been discussed, and different possible architectures of such networks have been analysed. A particular focus was made on connection with tramway or railway DC energy lines. A first simulation of connection of chargers with an electric substation of the Turin Tramway network has been performed, in connection with use case 4 of INCIT-EV.
- In Task 4.4 "Infrastructure upgrading for dynamic wireless charging", different existing dynamic wireless charging systems have been reviewed. On the basis of this review, solutions for the integration in pavements of the systems developed by Vedecom (for urban use) and by CIRCE (for inter-urban use) have been proposed. Finally, an experimental program, associating laboratory tests and modelling, has been started, to validate the proposed solutions. These tests are designed to validate the operating temperatures, the charging performance and the resistance to traffic of the primary coils installed in the pavement.
- In Task 4.5 "Theft-proof parking systems for two-wheelers", a review of existing parking and charging systems for 2-wheelers has first been performed. Based on this review, the characteristic of an innovative charging station, with wireless charging system, adaptable to both bicycles and kick-scooters have been defined, and its design is in progress.

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ANNEX 1 – TITLE OF THE ANNEX

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