FeAsiBility analysis and development of on-Road charging solutions for future electric vehicles

Reporting

Project Information

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Final Report Summary - FABRIC (FeAsiBility analysis and development of on-Road charging solutions for future electric vehicles)

Executive Summary:
The FABRIC project aimed to analyse the feasibility of dynamic wireless power transfer (DWPT) for electric vehicles at typical driving speeds.

Two charging solutions (e-roads) were developed and demonstrated at the Susa test site in Italy. The first consisted of a series of 46 multi-windings coils and the second of a series of 22 simple single turn coils, all at a resonance frequency of 85 kHz. The coils were embedded at 6/7 cm deep and covered by asphalt. Both systems shared the same receiver installed on the testing vehicle. A third prototype based on the
QUALCOMM HALO system was developed and integrated along 100 m in a concrete trench with removable covers in the Satory test site in France. In the Italian test site 81 tests were performed with the instrumented FCA-CRF vehicle. For the first solution the power efficiency was > 80% at 50 km/h with a physical air gap in the interval [20 ±5] cm. For the second solution it was > 62% at 30 km/h with similar air gaps. In the French site the maximum efficiency measured in 54 tests was 60.1% at 50 km/h. Significant improvements in efficiency can be achieved if using bespoke components designed to operate at conditions of peak efficiency. Charging two cars at the same time was demonstrated in France at 18 kW. In both sites, the electro-magnetic exposure was below ICNIRP 2010 recommendations and the grid side power was pulsed the same way as the on-board battery.

The FABRIC feasibility analyses show that e-roads with DWPT have a clear advantage in a future where electricity is produced green (2050) and where the battery size of a vehicle can be shrunk to a fraction (10%) of a regular battery-powered vehicle. However, the lower Well-to-Wheel (WTW) efficiency of DWPT compared to regular charging can easily undo any savings from the lower battery weight. It is therefore key to look further into increasing the efficiency of DWPT. Another positive aspect found is that the introduction of DWPT infrastructure contributes very little to the overall emissions of the transport system, as utilisation rates have the potential to be very high in metropolitan areas and major corridors (TEN-T). The scenarios also found that having few DWPT e-roads available does not really provide a chance for battery size reduction, as the relative amount of energy gathered on the e-road compared to the routes travelled is relatively small. Improving capacity of DWPT is a key aspect to overcome this, but it also has consequences for the deployment options available. The major advantages of DWPT will only be gained after large-scale e-roads have been deployed and batteries are shrunk. In the medium-term, it is therefore feasible as an emission reducing option for vehicles with very regular travel patterns, like urban buses and specific point to point cargo routes.

From an investment point of view, e-roads are expensive. A comparison of the total costs of ownership of diesel powered, battery powered and DWPT-enabled vehicles show that only in case of low speed scenario (high energy transmission per meter of infrastructure) and maximum battery reduction (busses with regular routes), DWPT can be beneficial. In all other scenarios, major incentives from the government would be needed.

At the start of the FABRIC project, significant questions were raised regarding the options to integrate DWPT technology in real-world roads. A range of experimental and computational tests have proven that DWPT can be safely integrated in the road, when using high quality, currently available, binder materials. Construction methods can be chosen such that low-temperature asphalt can be used to cover the coils. Constructions with concrete gutters for placing coil pads can be integrated into the pavement when paying good attention to the boundary layers. Further work is needed with more production ready coil constructions to develop final pavement designs for e-roads.

Analysis of usage patterns of energy for DWPT has shown that even with a very large uptake of e-roads, electricity grids do not significantly block the deployment. Due to the expected usage patterns, e-road deployment may even be beneficial for local integration of solar power.

Deployment locations for e-roads need to be carefully chosen, as simulation studies have shown significant effects on travel routes when few e-roads are available for general passenger vehicles. This leads to important questions regarding stepping stones of e-road deployment.

If there is a system, like urban buses, for which e-roads can be a beneficial option, then it is positive to deploy DWPT technology, as this can be used by many types of vehicles, unlike conductive overhead
wires. Other vehicles being equipped with DWPT technology can opportunistically use compatible infrastructure where available but could get their main power from other solutions.

A final extensive review of ongoing standardization activities in general wireless power transfer for transportation has been performed and suggestions for consideration of DWPT solutions in the discussions have been prepared.

Project Context and Objectives:

Electromobility is an important component in the pursuit of the decarbonisation of road transportation and mobility. An important factor for the commercial success of electric vehicles is considered to be the convenience of their charging from the point of view of the final user.

EV Wireless charging technologies are a potentially promising alternative compared to plug-in solutions, as they would alleviate the users from uncomfortable plug-in procedures. At the start of the FABRIC project such technologies were at the verge of commercialisation by various manufacturers for static charging of vehicles. At that time some prototypes of dynamic (on-the-road) charging were reported, although at rather low speeds. But beyond static charging, wireless technologies may allow opportunistic charging of vehicles during short stops, for example at traffic lights, or while driving on specific lanes. It is expected that wireless charging (if widely available) will enable the use of smaller and lighter on-board batteries and will shorten travel times for long trips, as there will be no longer any need for long stops for charging.

In this concept, the principal motivation for the FABRIC project was to analyse the feasibility of Dynamic Wireless Power Transfer (DWPT) for electric vehicles at typical driving speeds. The objective was to provide insights about the technology potential to stakeholders, manufacturers and policy makers, taking into consideration all the factors that may impact the technology adoption by stakeholders and the users.

In more detail, the main project objectives were to:

- design and develop prototype DWPT solutions, based on the magnetic coupling, along with their accompanying communication, control and interfacing software, which will meet the stakeholders’ and users’ requirements
- implement the solutions in two test sites in France and Italy, in order to collect data from tests at typical driving speeds
- analyse the grid infrastructure at the two sites via power flow analysis to detect issues as regards the grid connection and study the feasibility of integration of renewable sources and storage
- propose grid adaptations in the test sites in order to support the charging solutions and deploy the necessary grid elements and modifications at the test sites
- assess the impact of mechanical loading on the pavement after the integration of the road components of the charging solutions and prepare the road infrastructure in the test sites
- design an overall software architecture and interfaces between road and grid infrastructure and develop ICT solutions to support the driver in maintaining a steady vehicle position over the road component in order to optimise energy transfer, to guide and inform the driver about the charging procedure while driving and to optimally plan charging considering the grid restrictions
- install the vehicle-side components of the charging and ICT solutions on the French and Italian test vehicles
- integrate the infrastructure-side components of the charging and ICT solutions in the Italian and French
test sites

- specify a common validation methodology for both test sites and collect data from various driving scenarios at typical speeds for a highway
- analyse the data collected and evaluate the performance of the integrated systems at typical driving speeds
- create a feasibility framework to systemically evaluate different future deployment scenarios of DWPT considering all dimensions of sustainability
- determine an integrated LCA/LCC system for the evaluation of e-roads and conduct a detailed assessment of environment and cost impact of e-roads
- prepare technical specifications for the construction, maintenance and operations of e-roads
- analyse the effects of up scaling of DWPT solutions to vehicle fleet and energy grids
- analyse the maturity, reliability, efficiency and stability of supply chain and review security threats as regards DWPT solutions for electric vehicles
- assess the impact on traffic operations and management from the deployment of DWPT solutions
- conduct cost-benefit analyses, environmental life-cycle assessment and propose business models for infrastructure owners, for the final users and for public authorities for the large-scale deployment of DWPT technologies
- propose items for consideration in relevant standardisation work to ensure the future interoperability of environmental life-cycle assessment

Project Results:
Extracting system specifications

The work started with the identification of the main stakeholders, which included road and grid operators, vehicle manufacturers, municipal and transport authorities, and the evaluation of their acceptance of DWPT solutions for electric vehicles. Their requirements relevant to such technologies were collected, covering safety, EMC and EMF issues. In parallel, existing charging prototypes, ICT components and communication protocols were reviewed and prioritised for consideration in the FABRIC development. Charging solutions were prioritised according to their performance, EMC, Closeness to market, Cost, Maturity, Safety, Scalability in terms of vehicles and road coverage. ICT solutions were prioritised according to Easiness of implementation, Interoperability, Cost, Security, Safety, Efficiency, Maintenance, Usability and Closeness to market. The final users’ requirements were captured by defining the expected real-life use cases of DWPT charging solutions.

The use cases and a gap analysis between the stakeholders’ requirements and the functionalities of existing systems was the basis for extracting the FABRIC solutions specifications. As regards the vehicle DWPT charging components, no structural problems due to the charging prototypes were expected in normal vehicle operation conditions, but the system weight should be reduced as far as possible. Power ramps must be limited to make sure that the battery management system is able to detect them properly. A system to support the driver in maintaining a good alignment between the road (primary) component and the vehicle (secondary) component was considered essential, although future vehicle automation could be integrated with DWPT systems to enable automated alignment.

As regards the road DWPT charging components, power should only be transferred while a vehicle able to
receive it is over the power transfer area. So, the DWPT equipment should be disabled when either a non-equipped vehicle or any other object could be affected by the power. The components need to be embedded in such a way as not to compromise the structural integrity of the road, while maintaining a reasonable efficiency of power transfer. As regards embedment, several techniques were available at the moment and it was not clear what the optimal embedment method is. A main concern regarding the installation of the road components was the high temperature of up to 200ºC experienced during the laydown process of the upper layers (asphalt) of the road structure.

It was expected that the interface to the electricity grid will depend mainly on the power level of the installation, for up to 150 kV it should satisfy the requirements of EN 50160. It can be expected that any DWPT solution will include a power converter which rectifies in a first step the AC current from the grid to DC, implying an intrinsic compatibility or interoperability of the grid-tied converter with any subsequent power transfer option. The integration of energy storage systems directly connected to the DC distribution line will be beneficial, reducing power peaks and thus power rating of the grid connection. Three-level topologies were recommended in order to reduce the size of passive elements in the grid-side filter, but if a strong grid connection is available, simple pulse width modulation converters will satisfy current standards. Long runs of power cables carrying high-frequencies and high-power should be avoided to minimise losses, hence power controllers should be positioned close to the segments they feed. Long runs of low voltage power should also be avoided to minimise losses in the power cables used, hence the sub-stations feeding the power controllers should not be too far from the controllers.

For communication, it was decided to follow the data model of the Open Smart Charging Protocol and to implement a low latency transport protocol (RFC 6455) to enable low latency responses to grid capacity emergencies or intermittent power supply.

Specific emphasis was given on specifications to ensure safe operation of the DWPT solutions. High-quality 3D simulations with the prototypes gave first estimations of the EMF fields and showed that lateral shielding is effective, even considering lateral misalignment between primary and secondary coils, and that wide emitter coils entail design challenges for shielding.

Developing the prototype DWPT solutions

The FABRIC DWPT prototypes were designed to meet the specifications. Two charging solutions were developed for integration and testing at the Italian test site, and a prototype based on the QUALCOMM HALO system was developed for the French test site.

The road components of the French prototype consist of a series of Base Area Network (BAN) units, including coil and controller. The AC/DC power supply is connected to the grid (400 V AC, three phase) and rated for maximum of 64 kW installed power. The vehicle components of the French prototype include two pads, a vehicle controller unit and a communications controller, which connect to the battery, battery management system and universal controller unit. Each vehicle is capable of charging up to 20 kW average power to the battery at 85 kHz.

The vehicle component of the Italian prototype is a structure of 140 x 80 x 15 cm which contains the
secondary coil (30 x 70 cm), the resonant capacitor and the ferrite cores. The housing meets the requirements of shielding of stray magnetic field for human protection and magnetic compatibility respect to electronic devices on vehicle board and in proximity of the vehicle. The shield is made of an aluminium plate designed after a process of optimization oriented to the maximization of the coupling with the transmitting section, minimization of induced losses and respect of ICNIRP limits for field exposure. Blocks of ferrite act as flux concentrators. They improve the coupling with the transmitting coil and enhance the tolerance to the misalignments with respect to the emitting coils during the dynamic WPT mode operations. The receiving coil and ferrite cores are placed on a Lexan polycarbonate plate that guarantees good mechanical properties without impacting on the magnetic efficiency of the device. The receiver structure is fixed to the bottom surface of the vehicle through silent blocks in order to minimize the vibrations from and to the vehicle.

The road components of the two Italian prototypes consist of a series of coils of 1.5 m length x 0.5 m width, installed with an inter-space of 0.5 m. Each transmitter coil is supplied by a dedicated DC/HF H-bridge converter with a nominal power of 20 kW working at 85 kHz with no forced cooling.

The first Italian prototype by Politecnico di Torino (POLITO) was based on multi-windings coils to be directly connected to the LV DC distribution network through the H-Bridge converter. The system is designed for 85kHz using the power generator board and a special series capacitor, designed by POLITO, also embedded in the road, completes the resonance system with the coil. The second Italian prototype by SAET was based on simple single turn coils 1.5 m length x 0.5 m width, to reduce the coils cost and increase practical feasibility. The original design was larger but it was decided to reduce the dimensions in order to increase the power transfer rate and to meet EMF requirements. It was also decided to avoid a magnetic shielding beneath the in-ground inductor. The SAET prototype includes a custom designed transformer which reduces the voltage by 1:10, while a series resonance capacitor matches the primary coil inductor impedance. Both road components are to be placed into the asphalt layer at 40mm from the ground level using a technique like the one for traffic-light inductive loop sensors.

Next, a common testing methodology was proposed, in order to verify in a laboratory environment that the FABRIC prototype charging solutions meet their specifications. The main objective of the tests was to verify the charging efficiency under different operating conditions. Secondary objectives were to check for any interference from the charging systems to the electricity grid, measure the temperature of the devices during operation, the generated EM field in respect to health effects, and the EMC as regards the vehicles. The tests were performed at nominal operating conditions of each charging prototype. Additionally, the effect of misalignment between primary and secondary device, of partial input power and of a moving secondary device was analysed. No standards currently exist as regards verification and testing of DWPT systems. Therefore, the FABRIC methodology and lessons learnt are useful for consideration in future standardisation works in the area.

Based on the verification methodology, tests were done in laboratory conditions in five test conditions and 16 different test setups, where each test condition defined a horizontal (y-axis) or vertical (z-axis) offset position of the secondary coil relative to the primary coil. The data were analysed and recommendations on further improvements and modification were extracted for the solutions providers. Some key findings are:
• The efficiency of the POLITO solution was greater than 80% for the majority of the test setups, apart from those where the horizontal offset was 200mm or more.

• The efficiency of the SAET solution was below 80% for the majority of the test setups, apart from those where the vertical offset was -50mm and horizontal offset was 0mm. Further improvements will be needed in the future to achieve at least 80% efficiency at perfect alignment and nominal airgap.

• The rectifiers on the primary side for the POLITO and SAET solutions required further development and modification in order to ensure that the solution is capable of providing 20kW at the DC out on the vehicle. As a result, the SAET solution has been realized with a 12pulse Transformer Rectifier Unit providing the power and voltage levels. The POLITO solution has finally adopted the AC/DC power supply with appropriate voltage but limited power.

• The Total Harmonic Distortion (Voltage) met the specifications as it was below 8% for all test setups. But the Total Harmonic Distortion (Current) was high for both solutions, i.e. 61.9% for perfect horizontal alignment at the nominal air gap. A 12-pulse rectifier has been employed at the test site to strongly reduce this level.

• The power factor for POLITO solution was 0.84 and SAET solution was 0.87 for perfect horizontal alignment at the nominal air gap, below the specification level of 0.95. It is expected that improving the current harmonics could increase the power factor.

• No abnormal voltage fluctuations were observed during testing with POLITO and SAET solutions.

• The EM field for the POLITO solution was 7.02 μT and 12.96 μT for the SAET solution at nominal airgap with no misalignment, below the limit of 27 μT recommended by ICNIRP 2010 for all the test setups. The EM field level is expected to be below ICNIRP 2010 specification for the fully developed solutions when the solutions will be shielded.

In parallel, theoretical studies were conducted on the feasibility of applying the FABRIC charging prototypes to higher charging power, higher travelling speeds and to different types of vehicles. Studies were also carried out on the feasibility of applying two existing charging solutions for heavy vehicles and highway applications to passenger vehicles and urban environments.

Finally, an analysis of interoperability aspects regarding inductive charging systems was performed. The main outcome is that the FABRIC DWPT solutions are interoperable with other prototypes solutions. Specifically, there are physical areas where interoperability is not a major issue, such as power rating, secondary component voltage, coil geometry and operational frequency. On the other hand, air gap and tolerance, secondary coil voltage and operation frequency may create interoperability problems while more work is needed as regards magnetic field intensity, position tracking, achievable velocity and communication protocols.

Developing support ICT solutions

Based on the derived specifications, two on-board ICT modules were developed: an on-board information system for the driver and a Lane Keeping Assistance application, providing information to the driver via custom-made HMIs.

Due to the specificities of the French test site, the information provided related to charge authorization
procedure and parameters, namely car at the entrance of the charging track (phase 1), car driving on the track at a distance greater than 30 m to the Base Charge Unit (BCU) (normal driving mode - Phase 2), car driving at the distance less than 30 m to BCU (beacon mode- Phase 3), car driving on BCU (charge mode-Phase 4) and after charge operations (post charge mode – Phase 5). As regards the Italian test site, there was a need for a wireless communication between the vehicle and the electric vehicle supply equipment (EVSE), in order to manage the charging processes. The EVSE should be able to authenticate each vehicle moving above the coils in the charging lane. The main phases of the power transfer process were: car at a distance greater than 100 m from the charging station (Phase 1 – Idle state), car at a distance between 100 m to 20 m from the charging station (Phase 2- Prepare for charging state), car at a distance between 20 m and some meters from the charging station (Phase 3 - Authorization state), car driving over the coils (Phase 4 – Power transfer state) and end of power transfer process (Phase 5 – End of power transfer state).

The aim of the Lane Keeping Assistance application (LKA) was to support the driver in maintaining a good alignment of the road and vehicle charging components. A vision system detects lane markings and calculates the lateral distance. If misalignment increases an optical warning is given to the driver.

A third, off-board ICT system was developed, to support load balancing which is specifically needed for dynamic charging and where conventional methods for load balancing for static charging cannot be applied due to the very fast transitions from charging pad to charging pad, and the discrete, rather than continuous charging process. Because of this, a technique for managing the information flow in TCP/IP environments was investigated where the charging sessions could be considered as packets of information in a network. The system is composed of the Load Balancing module performing control operations, the charging infrastructure services related to load balancing and finally the on-board client load balancing module. Simulations have been conducted to assess the functionality of the proposed method, using the VEINS simulation environment where communications and traffic flows can be modelled. Simulations have shown that the Additive Increase Multiplicative Decrease (AIMD) method could support fast durability strength and misuse (DSM) operations and integration of highly variable sources of energy to the charging infrastructure. This facilitates the increased penetration of renewable sources to the grid in a secure way. The simulation scenarios revealed the effect of parameters such as the gap between the charging pads and the maximum number of vehicles charging simultaneously in relation to the maximum available supply. These parameters should be considered when deploying a dynamic charging infrastructure in order to integrate means such as on-site energy storage systems that facilitate smoother DSM operations and better integration of locally deployed renewable sources. Additionally, simulations revealed that current communication stacks such as 802.11p and WAVE can enable distributed DSM in e-roads. However higher layer application protocols for smart charging should be amended to include the broadcasting of DSM information to electric vehicle in a global manner.

The developed ICT solutions with their components were tested and verified in order to check that the specifications are met.

Preparing the test sites

Two sites were equipped with the FABRIC prototypes. The test site in France was located in Satory near
Versailles while the test site in Italy was located by the A32 Torino-Bardonecchia motorway, near Susa.

Initially, an analysis of existing grid infrastructure per test site took place. Models that were used for power flow analysis were constructed per each site and guidelines for grid adaptations for increasing power supply capacity were provided.

The Italian test site did not allow the connection of an 80 kW charger but only permitted 48 kW complying with voltage and current restrictions. A completely new design for the power distribution has been designed and implemented, including AC and DC distribution lines, as the existing one was too short and there was no storage available. The Italian site can serve an 100 m long area equipped with the POLITO solution, served by a transformer with a nominal power of 125kVA and a second 50m long area equipped with the SAET solution, served by a transformer with 60kVA output.

Internal grid adaptations were needed in the French site, in order to guarantee the proper supply of the FABRIC test track. It was decided to build a direct 250 kVA connection to the French grid network. The 100 m long active charging track is decomposed in 4 sections (stubs) of 25 m length each. 14 Base Area Network (BAN) units (BAN controller + BAN coil) were installed per 25m stub. The stubs were each powered in AC at 85 kHz by a 25 kW DC/AC converter in each of the four roadside cabinets. The roadside cabinets were connected to the grid cabinet through 1000 V DC line. In an existing shelter, the AC/DC power supply is connected to the grid (400 V AC, three phase) and rated for a maximum of 64 kW installed power. The grid cabinet contains two rectifiers 30 kVA each taking power from the grid (400 V tri-phased) and powering the roadside cabinet at 900 V DC. A control room hosted the infrastructure supervision workstation and measurement equipment. Off board QUALCOMM-HALO components have been implemented in the control room. Communication to the vehicles was performed through dedicated short-range communication (DSRC) from the Supply Equipment Communication Controller (SECC) with a proprietary protocol implementation, derived from the current draft standards proposal for wireless electric vehicle charging (WEVC) static systems. Each roadside cabinet worked independently and could start transferring power upon valid vehicle detection; only one interconnection was made between the roadside cabinets to synchronize power phase. Only one vehicle can charge per 25 m stub in this implementation and a minimum distance of 28 m must be kept between vehicles in 2-vehicle scenarios.

The harmonics analysis showed the importance of adequate power electronics architecture and harmonics filters. It was shown also that a weak feeding grid is much more sensible to voltage distortion than a strong grid. Regarding harmonic distortion, no grid adaptation was needed. Nevertheless, if the grid connection is weak, advanced inverter topologies such as pulse width modulation (PWM) or multi-level are required in order to maintain voltage total harmonic distortion (THD) below 8%.

The main lessons learned regarding the grid infrastructure are:
• The Qualcomm solution required a 1000 V DC wiring which is the standard voltage used for public transport and photovoltaic electric infrastructure.
• An active rectifier should be considered for deployment in real conditions.
• An Energy Storage system will be necessary on the DC network to avoid power peaks in the network in case of discontinuous energy demand.
• The pre-charge circuitry should be designed to limit the overvoltage level, as this may severely damage
An insulated power supply should be used to feed the equipment. Additionally, a feasibility analysis for integration of renewable energy and storage to the test sites was conducted. Photovoltaic systems (PV) as renewable energy sources connected to the DC bus of the test site have a potential to decrease the energy losses and hardware costs. An energy management system will be needed to optimise the flow of renewable energy sent to the charging units and increase the overall energy quality. In parallel, a cross-country comparison of standards took place in order to clarify interoperability aspects related to smart grids. The findings were that high level principles can be applied across Europe in order to foster the necessary grid environment for electromobility.

Integrating the charging components in the test vehicles

Two vehicle prototypes were prepared in FABRIC: a Renault Kangoo (for the French test site) and an electric IVECO Daily light duty van (for the Italian test site). Both vehicles were adapted mechanically to host the secondary coils from QUALCOMM and POLITO respectively. Electrical adaptations had also been implemented while electronics (such as tablets) for the necessary HMI had been added to assist and guide the driver during the charging process.

Some of the lessons learnt from this integration work are:

- Integrating a “black box” type of prototype DWPT system on a serial car is a real challenge, as the real root cause of the encountered failures could not be identified with 100% certainty.
- The integration affected several aspects such as the management of the vehicle, the modification of the HV and LV wiring harness, and the communication between the new subsystems and the existing on-board networking, typically based on CAN protocol.
- In the future, the mechanical integration of DWPT on board components could be optimized (pads and shielding).
- Thermal impact when charging at 20 kW was not noticeable with the additionally implemented cooling system in (short time) dynamic conditions.
- An independent protection against unwanted overvoltage that may occur on the DC link during the operations of the vehicle is a must.
- The receiver coil housing shall meet the requirements of shielding of stray magnetic field for human protection and magnetic compatibility respect to electronic devices on vehicle board and in proximity of the vehicle.
- The BMS HV insulation monitoring system needs to be enhanced in order to keep into account the new WPT components vehicle integration and their high frequency operation that may induce parasite circulation currents through the vehicle chassis.
- The receiving coil housing shall guarantee good mechanical properties (robust enough for normal use condition during the life cycle and extreme condition during for example a crash) without impacting on the magnetic efficiency of the device and its positioning on vehicle shall assure no interference with other components and sufficient ground clearance.

Integrating the charging components in the test sites
Laboratory tests on small scale e-road pilot samples using dummy charging pads but with similar characteristics as the ones developed in FABRIC were carried out to investigate the e-road structure, based on which some potential structural optimization solutions were further studied. The conduction of small-scale pilot tests was intended to simulate different locations of the e-road pavement with the aim of obtaining a better understanding of the structural behaviour of e-roads, typically the critical locations around corners and joints. The main conclusions were:

- An analogous general response was observed in all the critical locations. Thus, there are no significant load capacity problems related with embedding the Charging Unit (CU) in the pavement (which is consistent with the results from the FEA).
- When subjected to cyclic tension-compression testing, there was significant failure of the asphalt/CU interface with particularly more rapid failure of e-road samples in comparison with conventional samples.
- X-Ray Computed Tomography (CT) scanning after repeated dynamic loading revealed a significant increase of voids and interlinking along the interface indicating a loss of bonding between materials.
- The asphalt/CU interfaces along the driving direction and the corners of the CUs are subjected to higher deformations. Consequently, these are considered as critical areas of the structure (especially the corners), and thus are susceptible to suffer premature damage. Measures to reduce the stress and strain concentrations in these areas should be taken (e.g. using proper joint materials or interlayer systems).
- From a visual perspective, cracks appeared to be located above the interface with same orientation (orthogonal to the driving direction) and also above the corners. Moreover, vertical cracks were observed in the binder course layer adjacent to the CU.
- In terms of compaction, the X-Ray images highlighted the lack of homogeneity and higher air void content next to the interfaces with the CU and small fractures founded in this rigid module suggest that these defects might occur quite often due to the lack of experience in this type of structure and can be responsible of distress failures during early stages of operation, causing important reconstruction or rehabilitation actions.

To further investigate the effectiveness of potential structural optimization solutions, a sensitivity analysis of the overlay was performed to evaluate the influence of overlay thickness and stiffness in the response of the pavement. In addition, the presence of a silicone rubber joint between adjacent CUs was simulated to compare the reactions of the structure with and without this consideration. Both simulations were subjected to a static load with 800 kPa (typical tyre pressure of heavy vehicles), and the main conclusions are:

- The influence of the thickness of the overlay (surface layer) is much more relevant for the structure integrity than the increase of its stiffness or resistance. This fact shows a restriction on the overlay thickness, that is to say, from a structural perspective it is not recommended to reduce excessively the thickness of the surface layer. However, this fact will be also dependent on the efficiency of the WPT equipment.
- The incorporation of joint materials provides significant stress relief at the base of the asphalt layer, the critical location which is focused on by mechanistic pavement design principles.

In addition to the laboratory tests, a detailed Finite Element Analysis (FEA) simulation of the behaviour of e-roads was carried out. The conclusions are as follows:
• Static analyses showed that differences between the examined e-road solution and standard t-roads (traditional roads) arise essentially in the short term, when the viscous effects have not yet started. Indeed, as far as horizontal strains are concerned, differences in stress and strain distributions would become negligible for high values of accumulated strain. Refined non-linear models would allow for accurate predictions on the risk of failure in the form of cracking, rutting, de-bonding etc.

• The results underline that it is essential to analyse the infrastructure as a whole in order to obtain more realistic stress distribution in the technology components. This is true especially in dynamics, as measured damping values usually refer to realistic structural dimensions.

• There are no significant structural problems with the copper cables or aluminium box. A further assessment is however required at the life-cycle assessment stage.

• Regarding the longitudinal stress induced by the braking force, a static analysis showed orders of tensile normal stress in the wear layer of the pavement almost equal to 1-3 MPa. The actual values will depend on the friction coefficient between the wear layer and coil-box. Frictional resistance to braking tyres certainly constitutes a factor to be considered in the selection of materials to be used for the e-road construction. Regarding this, emphasis is to be put on the definition of appropriate friction parameters.

• The interface bonding strength of CU-overlay in terms of, e.g. sudden vehicle braking and accelerating suggest that when the interface between and the AC overlay is fully bonded, the critical horizontal stresses induced on the e-road surface are lower than that of a normal road, for both light car and heavy vehicle. This means the e-road surface could be resistant enough when a braking force is applied, if the structure is in good conditions. When the interface between and the AC overlay has zero bonding, the critical horizontal stresses induced on the e-road surface increase significantly when comparing with the fully bonded condition, especially for that in tension. This entails that more attention should be paid to the bonding properties of the interface CU-AC overlay of the e-road in future studies.

Based on above stress and strain analysis, recommendations for e-road structural design were given as follows:

• Given the problems related to differential settlement between coil-box and paving, a different solution would be to not bury the charging unit under the wear layer of the pavement. The wear layer could be differently incorporated in the coil-box, thus isolating the technology from the pavement. This would also be reasonable in view of a modular design of the technology. In this last case, it should possibly include special joints (injections, etc.) to prevent infiltration of water between coil-box and paving.

• As regards to the protection of the aluminium box from any local plasticisation or by the environmental actions, a polymeric material layer could be envisaged. Among the existing polymeric materials, ABS (Acrylonitrile-Butadiene-Styrene) or TPU (Thermoplastic Polyurethane) could be considered, as they appear to meet the mechanical and physical requirements for the road environment.

• For copper coil, the structural analysis did not reveal particular problems. It is recommended that a protective layer is introduced to avoid problems related to the digging operation of asphalt, during which the cables may be compromised. For the protective layer the same material as mentioned above may be used.

• If it turns out that the CU-AC interface bonding is weaker than that in a traditional AC-AC interface, some optimization solutions could be considered. For instances, 1) applying an optimum quantity of tack coat at the CU-AC interface. Traditionally, spraying tack coat e.g. asphalt emulsion, over the down concrete layer
before lying the surface course layer is a typical technique to ensure the sufficient bonding, making the layered structure act as an entirety to withstand the traffic and environment loads. 2) Improving the CU surface texture roughness by transverse or longitudinal tinning.

In summary, the laboratory test results suggest that although the overall structure of an e-road can withstand high vehicle loads, when subjected to cyclic tension-compression testing, there is significant failure at the horizontal interface and greater rates of deformation at the corners and asphalt/CU interfaces. X-Ray computed tomography results after cyclic loading confirmed these results by identifying large voids and along the vertical and longitudinal interfaces. However, further optimization studies suggest the effectiveness of using some techniques to improve the structural integrity and to help mitigate these concerns. Furthermore, if the joints are not located in the wheel paths i.e. between the wheel paths, they should not experience the levels of traffic loading required to cause premature failures.

An alternative solution would be to install the CU cables in micro-trenches and cover them with proprietary bituminous in-fill materials. The CU cables could be placed in narrow micro-trenches excavated within the pavement. The major benefit of this approach is that the structural integrity of the pavement is not compromised and there would be no damage inflicted on the surrounding pavement structure. Other potential benefits include:

- Shorter installation periods;
- Low volume of waste material excavated;
- The use of proprietary in-fill materials which protect the cables from loading and prevent ingress of water into the pavement;
- Ease of access to the e-road systems for maintenance / replacement.

The effects of temperature changes on the CU, both daily and those associated with the asphalt paving and maintenance processes, have been raised as key issues in the performance of e-roads. With regards to daily temperature changes, an e-road could be likened to a typical flexible-composite pavement whereby saw-cut and seal joints are incorporated to accommodate thermal movements. In terms of the CU operational system, the CU should be designed to perform adequately in various climate conditions. This could include the use of heat resistant materials to house the coils and insulate them from significant temperature changes. CU systems should be designed to operate efficiently over a range of temperatures. In this way, the CU would be more robust and adaptable for operating in almost any road environment. Concerning temperatures associated with paving and maintenance procedures on the operation of CUs, the use of low temperature asphalt (LTA) mixtures and proprietary bituminous in-fill materials would help reduce the effects of high temperatures on the CU performance.

Using the above findings, the French site installed the road charging components (pads) in a concrete trench with removable covers. This construction was chosen to facilitate testing and easy servicing/replacement of the road components and be reconfigurable for future studies. The test track pavement was built on 100m long stretch of 4m wide tarmac road, built according to roadway standards. As regards the French test site, the main concept was to build a track to ease experimentation and be reconfigurable for future studies. A central trench was built enabling 800*200 mm of free space for hosting the prototype systems (primary coils and their conditioning power electronics) with iron elements
sufficiently far from power electronic components (at least 15 cm). The cavity was to be covered by a layer of 30 mm of non-ferrous material. Following this concept, the in-ground elements of the charging solution were installed in a concrete trench with bolted-down glass fibre reinforced removable bolted covers (3 cm thickness) over the trench. Lateral protections (plastic boxes) located about 3 m from centreline were used to define the non-accessible zone during tests. The covers were custom designed in order to support the weight of vehicles and also not interfere with the magnetic flux of the coils. The number of necessary bolts used for the slab covers was determined based on the most unfavourable loads applied by a vehicle on the covers. Detailed analysis of the stresses imposed by vehicles has been carried out to ensure that the covers are adequate.

Several experiments were done in the Italian site embedding different coils with different materials and analysing impedance in relation to frequency, showing a big change in impedance behaviour starting from 20-30kHz. The asphalt at the test site, as well as the one that could be found in the area surrounding the university can be considered a material suitable for the embedding because it did not influence the coil behaviour. The high temperature of the asphalt standard placing is the only limiting element for the embedding with the actual coils and capacitors material. The embedding of the primary charging components in the Italian test site was done as follows:

1. Cutting holes in the existing asphalt with the following dimensions: 100m long x 1m wide x 6-7cm deep for the POLITO solution and 50m long x 1m wide x 6-7cm deep for the SAET solution.
2. Placing the power electronics and control equipment in manholes at the track side.
3. Connecting the main power and data transmission network to the grid infrastructure by a cable pipe beside (but outside) the charging lane.
4. Embedding the loops covering the whole cut with asphalt.

The POLITO charging area was composed of 46 coils and 23 manholes hosting two power boxes each. The SAET charging area was composed of 22 coils and 11 manholes. Both systems were based on a 650V DC distribution link (independent for each solution), controlled in the POLITO solution and simply rectified in the SAET solution and they both followed the “one coil, one power electronic” concept. Both systems share the same receiver installed on the FCA-CRF testing vehicle. For all coils the reference frequency was 85 kHz. The differences are the in-ground coil shape and embedding peculiarities, the ground coil was individually insulated for SAET and uninsulated for POLITO and there was a factor of 10 in voltage and current rating for in-ground resonant components between the two solutions. The AC/DC rectification stage was based on an active front end in the POLITO solution and a 12-pulse diode based solution in the case of SAET.

The complete integrated systems in the two sites were verified before the validation tests. A check-list was developed and used to verify that all components are in place and work properly. Some lessons learnt from the integration and verification are:

- The Qualcomm solution presents some complexity (as regards the embedded power electronics below the road surface) but presents the advantage of drastically reducing the number of converters needed per km.
- Some durability tests (mechanical, environmental, electrical) should be conducted
• The chosen cabling system for the POLITO and SAET solutions can be improved, as there are too many wires for a wireless system. A switched-mode power supply for each board should be realized and the communication should be sent on the DC power line.

Validation

A validation methodology was developed, so that the data collected can be used to extract comparable and significant results. The validation plan focused on assessing the functionality of the developed DWPT solutions, their efficiency, and impact on the grid and the road. Initially the processes for validating the physical aspects of the delivered systems were defined. This includes geometric characteristics on a component level (e.g. charging pad) as well as on system level to make sure that the system is installed as required. The second step was the definition of the parameters that need to be measured during the tests. The primary parameters were energy transfer efficiency for static, stationary and dynamic charging, EMF measurements inside and outside of the vehicle, EMC with the vehicle and surrounding equipment and EMF levels. Such testing protocols for DWPT can be a useful input for standardization bodies on static wireless charging (SAE TIR J2954) since DWPT has not yet been considered in its work.

At the Italian site near Susa, 81 tests were performed with the instrumented FCA-CRF vehicle at the end of 2017. Each test involved both POLITO and SAET solutions. The weather conditions were sunny and light fog. The on-ground power level was 7kW for POLITO to avoid permanent damage in the embedded coils and 11 kW for SAET so that comparisons could be made. The measured parameters were: voltages and currents at the grid, voltage and current for the DC-link distribution, voltage and current at the battery input and vehicle speed. No direct measurement of the misalignment was possible. The air-gap height was fixed before every test. For the POLITO solution the power efficiency was > ~ 80% at 10 km/h, 30 km/h and 50 km/h with an air gap in the interval [-5, +5] cm. For the SAET solution it was > ~ 62% at 10 km/h and 30 km/h with similar air gaps. The average power transferred to the battery was 5.2 kW for POLITO and 9 kW for SAET.

At the French site, results of 54 tests were collected and analysed. The tests were conducted with a fully instrumented demonstrator vehicle on 27 and 28/12/2017. The weather conditions were rainy and light cloud. The power was set to 18 kW. The target speeds were 20, 50 and 70 km/h. The measured parameters were: current and voltage on AC three phases line (50 Hz), current and voltage on DC output power supply (connected to grid), and current and voltage on the on-board DC output WPT system. Air gap varied in the range [-25 mm, + 6.5 mm] using additional masses. The average misalignment during charge was calculated by analysis of GPS-RTK high accuracy position data and it was in the [-20, +20] range. The maximum efficiency measured was 60.1% in full nominal conditions (no misalignment targeted driving, nominal air gap, speed 50 km/h). The maximum average power measured was 15.8 kWh. Additional tests were done, for example on 23/02/2018 with a power level of up to 20 kW and a speed of 20 km/h and one test at 6 kW in reverse driving. The analysis shows that:

• A “good alignment” zone is in the [-12; 12] cm range where variation of charge performance indicators is typically less than 10 %, while in the ranges [-20; 12] cm and [12; 20] cm the performance indicators decline significantly, in particular at high speeds.
• Air gap (in the functioning range) influence was not so significant for all the configurations tested.
• Speed impact was not noticeable in the range explored (up to 70 km/h) when driving in good alignment conditions.

Charging two cars at the same time was demonstrated on 16 March and 18 July 2017. The two cars were at a distance of 30-40 m (more than one stub length). The power was set at 18 kW and the target speeds were 20, 50 and 70 km/h. Simultaneous charging for both cars occurred for a little more than 5 seconds, i.e. about 30 m at 20 km/h.

Several improvements in the design have been proposed to improve the French efficiency results, an important one being to design the system knowing in advance the BMS specification and to use bespoke components designed to operate at conditions of peak efficiency, and not “off the shelf” modules and boards not specifically designed for such an application as was the case with the FABRIC prototype. It is expected by Qualcomm that the DC-DC dynamic charging efficiency could be increased to 80% for a production design. At both sites, the EM exposure was below ICNIRP 2010 recommendations (27 μT). Speed and misalignment were not found to cause the recommendations to be exceeded. In both sites the grid side power was pulsed the same way as into the on-board battery.

Assessing Societal Feasibility

The work started with an assessment of the feasibility potential of several scenarios for large-scale deployment of DWPT solutions. The analyses examined the topic from many aspects, namely the impact on energy efficiency and GHG emissions, the safety in relation to EMF exposure, the operation management and business plan, the impact on road infrastructure and the vehicle technology. Based on the analyses the most promising scenarios were outlined. The main objective was to analyse the societal perspectives towards on-road charging to provide a multi-dimensional framework, which will allow assessment from social, economic and environmental perspectives of DWPT solutions. Key barriers and drivers for uptake of DWPT from a political, economic, social, technological, environmental and legal (PESTEL) perspective have been identified and a corresponding assessment framework has been established. Ten different scenarios, comprising of different transport means (bus, taxi, cars, long and short-haul freight transport), as well as urban and highway scenarios, have been derived. For each of these scenarios, the defined criteria from the PESTEL assessment framework were used for a feasibility study. The main findings of this analysis showed that it seems likely to be feasible to apply dynamic on-road charging in four different scenarios, however comprising high risks:

• Metropolitan deployment of buses
• International freight corridors
• Long-haul national freight corridors
• Short-haul freight corridors

Consequently, from the 10 initial analysed scenarios, only one scenario involving passenger transport seemed likely, the scenario for buses. For this scenario, there are already existing mature solutions for using other types of electrical charging but a main risk is related to the incentives. The other three feasible scenarios were all related to freight transport. Two main reasons for the feasibility were the high likelihood of a positive return on investment for most stakeholders (depending to some extent on the incentives) and
the environmental impact, since the new vehicles would replace diesel trucks.

Assessing the Impact on Road Infrastructure

Tools and procedures that allow for the environmental life cycle assessment, the economic life cycle costs and the prediction of long term e-road behaviour have been developed. Specifically, an integrated Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) system has been defined, in which the system boundaries to enable comparisons between the e-road solutions as well as with non-electrified roads have been established.

Existing e-roads and the implementations in the FABRIC test sites have been then reviewed. The different methodologies for e-road construction have been described and the different materials and highways specifications that are applicable for e-roads have been reviewed. A finite element simulation of pavement rutting performance and parametric studies as regards lane capacity and traffic speed were conducted, which resulted in recommendations for e-road construction as regards effects of vertical and horizontal forces (including braking), cabling, roadside equipment, drainage, safety, risk management and maintenance of infrastructure.

A probabilistic recursive approach has been established to predict the lifetime of the road and the damage in the charging unit. The input parameters included: acceleration, axle load, number of axles inter arrival time, transverse position of the axles and vehicle speed. The transverse strain at the bottom of the asphalt layers should also be monitored. Strategies and protocols for monitoring and required maintenance and operations of the e-roads have been set out. As regards e-roads, a first estimate of the lifetime was based on structural analysis relative to costs. The analysis showed that the optimal design life of the wear layer results to be 34 months (2 years and 10 months), while the number of Equivalent Single Axle Loads to be guaranteed in that period (34 months) are 100270 and 2908620 axles for the 2030 and 2050 scenario respectively. In that situation, the average annual maintenance cost of POLITO solution would be 2.86 times that one of a t-road, while the SAET solution would have a maintenance cost of 3.81 times that one of t-roads. Technical specifications for planning and scheduling specific maintenance tasks of e-roads have been established. A cost study was also undertaken considering the depreciation of the e-road components for two scenarios, i.e. 2030 and 2050.

Finally, the environmental and economic performances of the e-road infrastructure were evaluated. The LCA/LCCA analysis framework was used for a series of calculations, using assumptions on system boundaries based on the FABRIC prototype solutions. The environmental performance of the e-road infrastructure was evaluated by analysing the potential energy usage, fuel usage and emissions. Results show that in the construction phase the most relevant components in terms of impacts are the WPT components, even though they represent only the 1% of the total amount of materials in the e-road. As regards traditional construction materials, the most relevant share is still covered by asphalt, more deep investigations are needed as regards recycled asphalt, as it may require thicker layer to ensure the same performance. Recycling may also be an issue when stronger binders with polymer modifications are to be used. Maintenance accounts for almost 50% of the impacts, transport wasn’t found to have an impact in the construction and maintenance phases.
As regards the LCCA, three representative scenarios were chosen, motorways with light and heavy vehicles, a peri-urban scenario with trucks and buses and an urban scenario with buses. Two construction alternatives were considered, the re-construction of an existing lane of a traditional road and the manufacturing of a new separated dedicated lane, and the total costs were calculated for the POLITO and SAET solutions at two timepoints i.e. 2030 and 2050.

Assessing the Impact from Upscaling

This part of the work aimed to assess the combinatory complexity when electric vehicles will be charged using on-road charging with large-scale deployed ICT, transfer and grid systems. A multitude of simulation approaches was used to project the impact of each solution as accurately as possible, while taking data on road ICT (ITS), transfer and grid systems from a sample of typical areas in Europe into the equation. A large set of comparative analyses have been set up with key data from different situations across Europe regarding current vehicle fleets. Costs, space, weight and energy consumption aspects have been analysed, with particular attention for the relation between weight and energy. A model has been developed to calculate the well-to-wheel (wtw) energy consumption and CO2 emissions comparing ICE drivetrains and electric vehicles with the option of DWPT.

Results show that electric drive trains typically have lower wtw energy consumption and CO2 emissions compared to ICE but the introduction of DWPT increases both due to the charging efficiency. The gains due to reduced vehicle weight are low for passenger vehicles, but substantial for heavy vehicles and buses. The well-to-tank (wtt) energy consumption of electric vehicles depends very much on the electricity mix. Given the adopted EU-mix (1 kWh of electricity requires 2.95 kWh of primary energy), EVs only show slight advantages over ICEs (at most 30%) and electric heavy-duty vehicles even consume more energy than ICE ones. Regarding CO2 emissions, the advantage of all electric options is more visible. The outcomes have been used as input for the integrated assessment framework on LCA / LCC for the whole of SP5.

As regards the effect on the electricity grid from upscaling DWPT, the global and local energy needs of e-road deployment scenarios from the perspective of the electricity grid have been assessed via simulations and comparative analyses for the three scenarios. The study shows that the expected electricity consumption will be modest at European level and will pose no significant problems for integration in the electricity grid. DWPT shows major advantages for integration with solar power, as demand occurs mainly during daylight hours. Local energy storage is able to smooth out fluctuations on a 24-h horizon, however seasonal availability of renewable energy needs to be addressed. Regarding CO2 emissions of electrified traffic, they will tend towards zero, as emissions for electricity generation are reduced.

In parallel, the feasibility of the dynamic EV charging technology was investigated as regards the supply chain and raw material procurement points. The objective of this work was to identify potential bottlenecks that may hinder the large-scale deployment of e-roads. Initially the FABRIC prototypes were decomposed to component level in an effort to identify the suppliers for each component and form the current primitive supply chain which is expected to evolve, be refined and optimized in the future, in case the technology picks up. In parallel to the identification of system component suppliers it was attempted to forecast the expected demand for the systems in the future. This study took into account existing studies on EV market
penetration vs time in order to estimate how many vehicles will be equipped with wireless dynamic charging technology in the future and also the European Union plans for the TEN-T road network. A questionnaire study among potential component suppliers was conducted. In general, no issue with the supply chain of materials was identified, although one response raised the issue of a potential lack of experts and engineers in e-road technology in the event of a rapid and wide deployment of e-roads.

Finally, the FABRIC ICT and charging solutions have been analysed for their vulnerabilities from two perspectives. First, the technical perspective in a world of cyber-threats has been analysed against the currently known best practices in cyber security management. Secondly, an analysis from a legislative perspective on how security can be governed for the e-road solutions has been carried out.

Assessing the business potential and societal consequences

The aim of this work was to assess the long-term implementation and operation of on-road charging systems in urban and extra-urban areas. A simulation model has been developed and demand scenarios have been analysed for the deployment of e-roads for a case study area using nine scenarios, with different mix of light and heavy vehicles, as regards the impact on travel times, emissions and energy consumption.

Results show that because of re-routing behaviour, part of the energy gains of an increased use of electric vehicles becomes lost, while the success of using dynamic charging largely depends on whether there will be a fast or a slow uptake of electric vehicles irrespective of whether e-roads will be developed throughout the EU. Several configurations about the e-charging lane and the potential effect of price differentiation were also explored.

An economic study of the three identified scenarios (motorway, peri-urban, urban) was carried out aiming to establish an order of magnitude for the system costs. A sensitivity study, modifying the system variables, was carried out. The analysis was done from the perspective of the investor in the e-road, the vehicle user and the public administration. Some highlights of the results are:

- It will be necessary to incentivize the deployment of such technologies at least for the highway and peri-urban scenarios until 2050.
- Motivation should be also given to vehicle users, still considering that a big threat to DWPT is the deployment of fast chargers.
- The urban bus scenario could be interesting as its cost would be lower than its direct competitors.

A system level social cost-benefit analysis has been iteratively carried out for the three scenarios, using as input the insights gained during FABRIC. The impacts were analysed for three vehicle typologies, a SUV, a heavy vehicle and a bus, being pure battery powered or equipped with DWPT and using the wireless energy to extend range with and without a reduction in the battery size. The impact on CO2 emissions by vehicle and battery production, wtw and infrastructure were calculated. The main findings are that the share of the infrastructure is negligible, while the three vehicle typologies would present similar environmental impacts.
A final extensive review of ongoing standardization activities in general wireless power transfer for transportation has been performed for 4 standardization bodies. An analysis has been made on how these efforts align with the needs from the deployment scenarios identified as feasible and suggestions for consideration of DWPT solutions in the discussions have been prepared.

Potential Impact:
The main aim of FABRIC was to assess the feasibility of on-road charging with special focus on DWPT. In this context, FABRIC successfully demonstrated the feasibility of DWPT charging of electric vehicles at 20 kW and typical highway driving speeds. FABRIC has also proven that e-roads with DWPT are technically feasible, and under certain circumstances even financially viable and with positive environmental effects. Further developments could focus on efficiency and capacity. Their exact role in the overall transformation of the European transport sector will depend on the developments of other electrification technologies.

The assessments and analyses performed focussed on three key scenarios as logical combinations of design parameters from today’s understanding of the transportation system. The scenarios have functioned as condensation points to gain insights into the sensitivity of the overall transportation system performance in terms of money, emissions, energy and a few other parameters. The findings from the development, demonstration and validation activities in FABRIC and the results of its feasibility studies and impact analyses will be a useful input to stakeholders for future activities in promoting DWPT solutions and electromobility in general.

Specifically, FABRIC is expected to have impact on the following areas related to electromobility.

Environment

The motivation for e-roads is to contribute to the European path towards zero CO2 emissions from the transportation sector. e-roads with DWPT have proven to show a clear advantage in a future where electricity is produced green (2050) and where the battery size of a vehicle can be shrunk to a fraction (10%) of a regular battery-powered vehicle. However, the lower Well-to-Wheel (WTW) efficiency of DWPT compared to regular charging can easily undo any savings from the lower battery weight. It is therefore key to look further into increasing the efficiency of wireless power transfer in general, and DWPT in particular for future use in the transportation system. Another positive aspect found in FABRIC is that the introduction of DWPT infrastructure contributes very little to the overall emissions of the transport system, as utilisation rates will be very high in metropolitan areas and major corridors (TEN-T). The FABRIC findings can be used by stakeholders when designing policies and measures to promote DWPT and e-roads.

Investment opportunities

From an investment point of view, e-roads are expensive. Their installation is predicted to be in the range of 2-4 million EUR/km, and their maintenance costs are estimated to be 2,5 – 4 times higher than from a regular road. The total costs of ownership of diesel powered, battery powered and DWPT-enabled vehicles have been compared and show that only in case of the scenario with low speeds (and therefore a high energy transmission per metre of infrastructure) and maximum battery reduction (buses with regular
routes), that DWPT can be beneficial. In all other scenarios, major incentives from the government are needed to make DWPT an attractive option compared to battery powered vehicles.

Deployment locations for e-roads need to be carefully chosen, as simulation studies have shown significant effects on travel routes when few e-roads are available for general passenger vehicles. This leads to important questions regarding the stepping stones of e-road deployment. If there is a system, like urban buses, for which e-roads can be a beneficial option, then it is positive to deploy DWPT technology, as this can be used by many types of vehicles, unlike conductive overhead wires. Other vehicles being equipped with DWPT technology could opportunistically use compatible infrastructure where available but could get most of their power from other solutions. Efficiency of DWPT is key to make such development steps a positive net reducer of CO2 emissions. Sufficient availability of other (ultra-fast) charging solutions is key to avoid lock-in to scarce e-roads. Such piggy-backing deployment could benefit from developments in static wireless charging if standards make the two modes of wireless power transfer compatible. There is however a significant gap between the current wireless standards and standardisation efforts and the needs of DWPT.

Infrastructure owners, regional and national authorities could use the FABRIC analyses to guide their decision making or to select locations or configurations for e-roads.

Commercialization of DWPT solutions

FABRIC experts feel confident that there is a lot of room for improvement as regards efficiency of DWPT by optimising design and components, and in the future efficiency could be comparable to other types of charging.

The FABRIC prototype solutions and the findings and lessons learnt from its development and integration activities can be used by vehicle manufacturers, solution providers and operators to further develop the FABRIC prototypes or to integrate them in their own development paths.

EV battery size

The FABRIC analyses found that having few DWPT e-roads available does not really provide a chance for battery size reduction, as the relative amount of energy obtained on the e-road compared to the routes travelled is relatively small. Improving capacity of DWPT is a key aspect to overcome this, but it also has consequences for the deployment options available.

The major advantages expected by DWPT will only be gained after large-scale e-roads have been deployed and batteries are shrunk. It is therefore feasible as an emission reducing option for vehicles with very regular travel patterns, like urban buses and specific point to point cargo routes.

e-roads construction

At the start of the FABRIC project, significant questions were raised regarding the options to integrate DWPT technology in real-world roads. A range of experimental and computational tests have proven that
DWPT can be safely integrated in the road, when using high quality, currently available, binder materials. Construction methods can be chosen such that low-temperature asphalt can be used to cover the coils. Constructions with concrete gutters for placing coil pads can be integrated into the pavement when paying good attention to the boundary layers. Not all construction materials proved to be neutral for wireless power transmission. Further work is needed with more production-ready coil constructions to develop final pavement designs for e-roads. National or regional assessments are needed with regards to the use of recycled material, as not all recycled material allows for thin top layer structures that are durable, and some countries limited the recycling in top layers of polymer modified binders. e-road construction procedures must meet current highway design and construction specifications. Any departures from these standards should clearly demonstrate that the structural integrity and service life of the road remains unaffected.

Analysis of usage patterns of energy for DWPT has shown that even with a very large uptake of e-roads, electricity grids would not significantly block the deployment. Due to the expected usage patterns, e-road deployment may even be beneficial for local integration of solar power, particularly in Southern Europe.

The outcome of these studies will become a basis on future assessments by the authorities and function as guidelines facilitating the decision-making process regarding large-scale implementation of DWPT and e-roads.

Renewable Energy Systems (RES) Integration

EVs can help to address the “underutilization” of generation and transmission capacity in a country. Peculiarities of electricity generation and distribution technology, combined with an extremely volatile demand that must be satisfied at every location and every moment, require that the capacity and infrastructure is available for unexpected or expected surges in demand. Several technologies for energy storage, capable of providing large peaks of energy when needed have been investigated in FABRIC and guidelines were given regarding the integration of RES in the system aiming to increase the secure operation and stability of the grid. These studies could facilitate micro-grid architectural design for future e-road deployment.

ICT Solutions for enabling DWPT

In FABRIC ICT solutions in three key areas to support dynamic wireless charging were developed. ICT that inform and guide the EV user about the charging process, ICT for optimizing power transfer by guiding the driver on the optimal path during charging and ICT for the balancing of the charging load in real time in order to satisfy restrictions posed by the supply availability and the vehicle battery management system (demand). Standards such as OSCP and OCPP were followed for communication with grid operators, and gaps for supporting the dynamic charging technology were identified.

Even though ICT was not the primary objective of the project, studies on feasible use cases and ICT architecture for future dynamic charging systems were conducted, which can form a basis for more specialized ICT projects on dynamic charging and for standardization bodies.

Wider Societal implications – Health and Safety aspects of DWPT
The technologies developed within FABRIC have also a societal impact relevant to implications for people’s health and safety. So, in terms of society, one primary focus of FABRIC was on the combined safety of the electric systems in the urban environment, where electromagnetic fields are already prominent, and if DWPT affects health of drivers and road users in general.

Dynamic charging presents an opportunity to reduce battery size, reorganise the internal architecture of the electric vehicles and redesign power electronics (new converters), etc. However dynamic charging, especially the wireless version entails some other health risks if the design is not done properly such as leakage flux which makes people hesitant towards the technology. FABRIC did extensive studies on this issue by simulating and actually measuring the induced magnetic field both inside and around the electric vehicles. It was found that with proper design, the exposure of people to the leakage flux is minimal and inside the limits set by current health and safety standards. This result when properly disseminated to the general public is expected to raise the confidence towards dynamic charging technology (but also static wireless charging technology).

Interoperability and standardisation

Dynamic charging is still a very innovative technology and it is still studied on a pre-standardization level by IEEE. FABRIC has identified several areas where existing relevant standards (e.g. for static wireless charging) could be extended to support the dynamic mode.

These areas can be considered in future activities of standardisation bodies, thus ensuring interoperability of DWPT solutions and thus their deployment.

Policy and stakeholder awareness of dynamic charging

Today, apart from certain countries such as the UK and Korea, the government does not directly support the development of wireless charging. Since wireless charging in general is a relatively new concept, potential investors perceive the return of investment on the technology in the short to medium term to be uncertain. Today companies are making cautious investments in research activities which must involve collaboration with technology developers and other stakeholders to enable dynamic charging to become a reality.

FABRIC has organized several events where experts and public authorities could be informed about the technical feasibility of the technology and discuss the foreseen business cases for large-scale deployment. In addition, FABRIC has established its External Reference Group where experts from public authorities and the industry are included and invited in discussions and project events. In addition, FABRIC used the network of its partner ERTICO to raise awareness on the technology and the project’s findings among stakeholders in the Intelligent Transport Systems (ITS) domain.

Main dissemination activities

Public awareness activities aimed to spread the information about the project to the broad community to
set the ground for exploitation of the results or possible technology transfer.

A project website (www.fabric-project.eu) has been developed in order to disseminate the project outcomes; it includes project objectives and background, significant achievements, technology news, consortium contacts, scientific publications and presentations, approved public deliverables, etc.

The FABRIC LinkedIn group (https://www.linkedin.com/groups/6700121) has more than 150 expert members.

Other major awareness/communication and dissemination activities included:

- Videos showing the FABRIC system in operation (YouTube);
- Press releases;
- Interviews given to Horizon-The EU Research and Innovation magazine and at popular national media;
- Presentation of FABRIC test sites through press briefings, on TV news and popular media (YouTube videos, articles in national and international printed and online media);
- FABRIC leaflets and posters;
- Presentations of results at large project workshops and special sessions organized within large conferences on transport systems and electromobility;
- Scientific publications;
- Formation of a group of external experts to assure that the project’s technical solutions properly addressed the requirements from the point of view of road operators, grid operators, public authorities, end users, OEMs and other potential stakeholders and to assess the deployability and acceptance potential of the FABRIC solutions;
- Liaison with many projects, associations/organisations and standardization bodies.

A description of the most important activities and some highlights are given below.

FABRIC events during the IEEE-IEVC 2014

FABRIC organized three events during the IEEE International Electrical Vehicle conference (IEVC’14) that was held in Florence, Italy on December 16-19, 2014: i) a FABRIC technical session presenting the project and its results, ii) a workshop entitled “Europe meets IEVC”, where 12 European and National research projects (FABRIC, ASTERICS, UNPLUGGED, FASTINCHARGE, GREEN eMOTION, ZeEUS, eCo-FEV, Ele.C.Tra EV CONNECT, STEEP, DOROTHY) were presented providing a great networking opportunity and iii) a workshop focusing on WPT standardization activities where ISO, EIC, WEVA and CUNA representatives presented the current status on electromobility standards, while several OEMs, ICT and services providers, suppliers etc. presented the current charging technologies. During a dialogue session that took place at the end of this workshop, the future needs and standardization issues were discussed among the participants.

In parallel, FABRIC, Green Emotion, ZeEUS, eCo-FEV and UNPLUGGED projects were exhibited at the “Europe meets IEVC” booth organised and coordinated by the FABRIC project.

The events’ documentation (presentations, reports, photos etc.) are available at: https://www.fabric-
FABRIC Midterm event (2016)

The FABRIC midterm event was organised on February 2, 2016 in Brussels, as a One-Day Conference, which focused on the challenges and concepts of the Wireless dynamic charging for EVs. The Conference was organized by ICCS and hosted by ERTICO-ITS Europe and gathered approximately 70 participants from 15 different countries, including policy makers, standardization experts, OEMs, solution providers as well as representatives of the academic and research community. The conference was structured as follows:

- Opening session: Introductory presentations by the European Commission, EUCAR, ERTICO-ITS Europe and ICCS as the FABRIC project coordinator.
- Session on FABRIC preliminary findings.
- Session on Policies and Standardisation in WPT. During this session well-known standardization experts (i.e. ISO, IEC, CUNA) as well as representatives from the TM2.0 Traffic Management Platform for harmonization topics, Qualcomm as a solution provider and others, discussed the drivers and the barriers towards wide implementation of WTP. This session was organized as a follow up of the FABRIC IEEE IEVC Standardization Workshop held in Florence on December 2014.
- Round Table discussion on “Wireless Charging: Is the solution for the range anxiety problems?”, during which key experts from industry and relevant authorities discussed the following topics: Trends and roadblocks towards the wide deployment of Electromobility; Which charging technology is the more likely candidate for deployment an as well as the potentials and bottlenecks of Wireless Charging as solution to the range anxiety problems.
- The Conference ended with a session focusing on Electromobility R&D initiatives where invited representatives from other R&D initiatives gave presentations.


FABRIC Deployment Scenarios workshop (2017)

A half-day workshop entitled “Deployment Scenarios for Dynamic Charging of Electric Vehicles” was organized by the FABRIC consortium (Qi Europe together with ERTICO and ICCS) on the 19th of June, 2017, in parallel to the 12th ITS European Congress in Strasbourg, France. The goal of this workshop was to bring together experts from the area of electromobility to discuss, improve and validate the different deployment scenarios for the most promising on-road (dynamic) charging solutions for EVs as proposed by the FABRIC partnership. The workshop was attended by 25 experts from key international companies and organisations. Discussions focused on the roadmap for the introduction of the dynamic charging technology in the next decades, the market opportunities for dynamic charging, the initial business models, and the identification of related market niches.

Information and documentation are available at: https://www.fabric-project.eu/index.php
The FABRIC Final Event and Demonstration was organised on 21-22 June 2018 in Turin and Susa Italy. During the first day of the Final Event a dedicated technical conference and exhibition took place in Turin, at the POLITO facilities, unveiling the project findings and providing opportunities for networking and discussion around key themes and issues towards the large-scale deployment of DWPT. The second day of the event was dedicated to the on-site demonstration of the two technological solutions developed and tested within FABRIC at the Italian test site in Susa. Other solutions were presented through videos and posters at the exhibition organised in the main building of the test site. The Final Event was organised by ICCS, with the help of the local partners, POLITO, TECNOSITAF and FCA-CRF. The Conference gathered approximately 130 participants and the second day demonstrations approximately 140 participants.


Presentations in Fora/Events/Conferences related to electromobility and dynamic EV charging

FABRIC organized and was presented in several technical special sessions on dynamic charging within large conferences. Indicatively the following are listed:

- Special Interest Session: “Deployment of EV-related services in practice”, 10th ITS European Congress.
- Special Interest Session: “Electromobility”, ITS European Congress in Helsinki, June 18, 2014.
- Special Interest Session: “Advances on innovative EV Charging Technologies”, 22nd ITS World Congress in Bordeaux, October 8, 2015.

FABRIC was presented to the EUCAR Sustainable Propulsion Program Board meeting every year since 2014, at the UNPLUGGED project final event and at the EEVC conference organised by AVERE every year since 2014. Additionally, the project was presented in two editions of the IET MedPower Conference in Athens (2014) and in Belgrade (2016), in two editions of the ApplePies International Conference (2016 and 2017) and at two editions of the Transport Research Arena Conference (2014, 2018).

Scientific Publications

The FABRIC work has resulted in 31 scientific publications, of which 3 in peer-reviewed journals, 25 scientific peer-reviewed papers and 3 as book chapters.
Other dissemination activities

A number of press activities and live demonstrations were held in the French and the Italian test site resulting in numerous articles in national and international news portals, TV clips as well as videos in YouTube. Some of the most important activities include the official launch to the press of the Qualcomm’s system organised by Qualcomm and supported by VEDECOM and Renault with the cooperation of FABRIC on 18 May 2018, the visit of the French Minister of Transport and of the VP of the European Commission at the FABRIC track in Satory in October 2017 and the press releases issued for the launch of the project activities. The press clippings are available here:


Videos and TV clips related to the project are available here: https://www.fabric-project.eu/index.php?option=com_k2&view=itemlist&layout=category&task=category&id=46&Itemid=224

In addition, several technical posters were produced and exhibited in Conference exhibitions and other events while approximately 25 posters (18 roll up banners and 7 A0 posters) were produced for the support of the FABRIC final Event and Demonstration activities.

The project leaflets were distributed in every available occasion (related national and international conferences, workshops and other events organised by the project or other partners events) while a final leaflet, including basic project findings was available for all the final event participants. The brochure is also published at the project website in: https://www.fabric-project.eu/index.php?option=com_k2&view=itemlist&layout=category&task=category&id=39&Itemid=229

The FABRIC project description was also included in all the issues of the EUCAR Project Yearbook published from 2014 and so on.

Liaison activities

Liaison has been established with International Standardization Bodies (IEC, ISO, CUNA, etc.) and the standards existing and under development by ISO, IEC and SAE related to Wireless Power Transfer have been reviewed.

Specifically, liaison has been established with the IEA HEV (Hybrid and Electric Vehicle) Task 26 on WPT for EVs. A project test site demonstration was held in conjunction with Task 26 wireless charging Standardization WG during 24-26/4/17 at Satory, France which was jointly organized with FABRIC. The FABRIC Project Officer and the IEA-HEV experts of EV dynamic charging visited the site and experienced a live demonstration at various speeds of two EVs charging at the same time.

FABRIC participated in the IEA's joint Task 26-Task28 workshop on Wireless charging and V2G market and grid integration, organised on 19-20 April 2018, in Newcastle, UK, where discussions took place with several stakeholders from Europe and the US. The IEA workshop on WPT was organised by POLITO on 25-26 June at their facilities, where the FABRIC results were presented and FABRIC demonstrations were re-organized at Susa for the workshop participants.
Additionally, FABRIC established contact with HyER (Hydrogen fuel cells and Electro-Mobility in European Regions), the EV Observatory (led by HyER), EGVI (European Green Vehicles Initiative) and eMI3 (eMobility ICT Interoperability Innovation platform), with exchange of information between these different platforms.

FABRIC participated in the ERTRAC/EGVIA Electrification Task Force aiming to include DWPT systems and e-road aspects into the 2017 ERTRAC European Roadmap on Electrification of Road Transport. Information about FABRIC was presented to stakeholders of other electromobility projects.

Exploitation of results

As regards exploitation, the partners have distinguished two types of results, prototypes and components that can be further developed in the future to possibly reach a level of industrial maturity and exploitable knowledge generated in FABRIC. For the first category of results, the partners have determined future development activities that will be needed per prototype in order to reach a higher technology maturity, so that the output becomes interesting for commercialisation. Despite the technical challenges due to the innovative nature of the technology, FABRIC was successful, as it achieved the demonstration of operational systems at several speeds and even demonstrated two vehicles charging simultaneously. The industrial partners and stakeholders in the consortium are interested to continue in the future the further development of these early prototypes and to use the knowledge and lessons learnt when planning the development of similar products in the future. Even more important, the results from the project impact analyses are a useful tool for stakeholders when considering the deployment of such technologies and e-roads. For the second category of results, the partners are interested to continue similar research activities and to widely disseminate the knowledge to the scientific and industrial communities.

List of Websites:
www.fabric-project.eu

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