Lowering your emissions through innovation in transport and energy infrastructure

PROJECT

REPORT

DynaCoV

Workpackage 2 Report:

Literature Review Dynamic Wireless Power Transfer

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1	First draft for review by DynaCoV project group.	05-May-21
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Executive Summary

Introduction: This is Deliverable D2-6 of the DynaCoV project.

This report documents an industry-focused literature review of Dynamic Wireless Power Transfer (DWPT) technology, gathering information and findings from existing studies and projects to:

- Produce an overview of available DWPT technology solutions (D2-1);
- Assess different use-cases (D2-4);
- Collect learnings from existing solutions and projects (D2-2);
- Explore the impact of DWPT on the electrical grid (D2-3); and
- Assess the UK's current and potential future supply chain for DWPT (D2-5).

Headline: DynaCoV has a significant opportunity to build-on and contribute-to DWPT literature.

Solutions. DWPT is at an early stage of demonstration and deployment, with only a few current and proposed projects identified around the world. ElectReon is the only active provider in the market, with other companies having been acquired or focusing their technologies on non DWPT scenarios.

- ➢ DynaCoV has a significant benefit from having ElectReon as a partner in the consortium.

Use cases. Although DWPT may be applicable to a range of use cases, most projects provide power to heavier vehicles as these stand to benefit the most.

- ➢ By focusing on buses, DynaCoV is targeting a strong use case.

Existing learnings. Existing projects have delivered insights into key considerations for deployments, including the business case, system performance, installation coordination, safety, security and standards.

- ➢ There is reasonable evidence to support the planned modelling and feasibility work packages that follow this one, and DynaCoV should build upon the existing evidence base.

Impact on the electricity distribution network. The literature does not fully describe the overall impact of DWPT on the electrical grid. DynaCoV will be able to build-on specific conclusions about the Voltage Level, Frequency, Modularity, Efficiency, Power Quality and Role of Storage for DWPT. However, more work is needed to understand the sensitivities of the grid impact to short-term, long-term and road characteristic variables. There are not expected to be unmanageable issues for the network. Data from Electreon's demos are expected to be available within the project timelines.

- ➢ With appropriate and evidenced assumptions, DynaCoV's modelling work package has an opportunity to contribute significantly to the literature.

UK supply chain. There is mixed opportunity for a UK supply chain, depending on whether hardware, software, installation, maintenance or operations are considered. There are good opportunities for downstream activities such as installing the Ground Assembly (GA) (made of copper coils in vulcanised rubber) and Management Unit (MU) (power electronics unit connecting to the power supply, fitted at the roadside); connecting the DWPT solution to the grid; designing and installing Vehicle Assemblies (VA) (comprising of receiver coil and power electronics mounted on the underside of the vehicle) and maintaining this hardware.

- ➢ Any future DynaCoV demonstrator will be able to test these parts of the supply chain.

Supporting evidence.

Existing Solutions

Eight DWPT demonstrations or deployments have been identified from the past decade. Most projects have taken place on single-lane private, curated or bespoke test tracks, although three involved public roads. Initial infrastructure distances have been of the order of tens of meters, with more recently deployments stretching from hundreds of meters to a few kilometres. The majority of projects focus on supplying power to heavy vehicles as these have the most to gain from DWPT systems resulting from their higher utilisation, greater payloads and longer journeys.

Only ElectReon is active in the market at present, other developers and providers have either been acquired or appear to be refocusing their efforts on different areas of power transfer technology.

! More information can be found in Section 2 on page 13.

Considerations for Deployment

The literature review found:

- The capital costs are relatively well-known for civil works, installation and hardware, ranging from £750,000 to £1,600,000 per km. For a national roll-out, this cost can be reduced by timing DWPT installation with other planned roadworks.
- Network connection costs however will vary by location. Connections to higher voltage networks are expected to be the most cost-effective.
- Operational costs such as electricity supply will depend on local conditions so should be analysed in any future DynaCoV demonstrator.
- Software costs have not been published but can be defined in discussions with ElectReon.
- Maintenance costs are anticipated to be low, around $1,700/year per MU.
- Current demos are funded mostly through public innovation funding, in the future ElectReon intend to finance the manufacturing, deployments and vehicle integration offering the system users Charging-as-a-Service.

System performance:

- Variations in air gap, lateral alignment and longitudinal alignment between the VA and GA, mean that DWPT systems must be designed to give acceptable power transfer efficiency when misaligned.
- Coil to coil efficiency (i.e. between the VA and GA) is expected to be above 85% and up to 90-95%.
- Early laboratory research indicates a lower bound grid-to-battery efficiency of 70% with the expectation of this increasing to 80-85% as DWPT technology matures.

System Installation:

- DWPT installation and maintenance contracts should align with road maintenance cycles.
- There is likely to be a considerable need for training to educate stakeholders involved with the maintenance of highways.
- Standardisation of the VA will be necessary to drive greater uptake of DWPT.

Safety and Security:

- All DWPT hardware should comply to EMC, EMF, IEC and ICNIRP guidelines, with a consideration of SAE J2954, ISO 6469 and ISO 26262.
- DWPT system should be deployed with both proactive and reactive protection mechanisms.
- DWPT systems are likely to be classified as critical infrastructure, requiring appropriate security and failsafe mechanisms, as well as GDPR compliance to protect personal data.

Equipment and Industry Standards:

- The lack of comprehensive standards across all the elements of technology, installation and use of DWPT is currently a risk for future deployment.
- To avoid problems of interoperability, tailored standards on the type and placement of receiver coils, compliance with roadway construction and safety regulation to standards of service, information sharing, data collection and payment will be required.

! More information can be found in Section 3 on page 18.

Electricity Network Impacts

Electricity Network Interface:

- At-scale deployments are expected to interface with the Medium Voltage network in the UK.
- DWPT operates at frequencies between 10 and 100 kHz, often centred on 85 kHz, and requires AC/DC and DC/AC converters to increase the frequency of power supplied (expected to be 50 Hz for a deployment in the UK).

- DWPT deployments should adopt a modular design to allow for scalability and reduce distribution network impacts.

Load:

- The maximum theoretical load is a factor of the transmitter coil ratings, number of coils per road segment, number of segments per substation and vehicle type. In reality, the maximum theoretical load is never attainable because of a range of variables, mentioned below. In practice, the MU rating becomes the main limiting factor on the theoretical load. Variables impacting on the load include:
    - Efficiency - the network will need to supply more power than is received by the vehicle.
    - Load management – may be required to ensure charging adheres to any system constraints if a DNO is unwilling to accept the connection of a highly variable load. DWPT systems should leverage existing protocols such as OCPP and OSCP within their communications infrastructure. However, varying the timing, power or direction of power transfer through smart charging or vehicle-to-grid will undermine the business case for DWPT and should not be a focal point for future research.
    - Use case – targeted use cases will increase vehicle-side benefits and manage load variability but it must be noted that targeting multiple use cases will improve the business case.
    - Short-term - vehicle SoC, current power demand, type and headway will all impact the instantaneous rate of power transfer.
    - Long-term - traffic speeds, road type and traffic variations all impact overall power transfer.
    - Road characteristics – environment, lanes, slope, planned routes, junction proximity, coil length and overlap, charging system length and layout all impact on the distribution of load.

Load modelling:

- Most previous modelling into the variation of load allows general conclusions to be drawn but the specific results and range of outputs are highly dependent on the inputs.
- Traffic volumes impact both the overall system demand and fluctuations in demand, whether across the year, in the week or within the day.
- Demand can vary significantly over short timescales (i.e. five to ten second windows).
- This project should deliver further modelling of the real-time short-term or long-term loads for a generic DWPT system with the key variables from this chapter as configurable inputs.

Power Quality:

- The impact of harmonic distortion on local electrical infrastructure must be addressed.
- Existing research indicates strong harmonics from static charging systems, which required filters to be fitted so DWPT systems should include high-frequency harmonic filters and test harmonics during operations.
- DWPT systems must be compliant to EREC P28 and will need to control inrush currents during the coil start-up in the pick-up phase of power transfer.
- The frequency of disturbances depends on vehicle speed and coil length, although key modelling outputs from previous studies appear to use unlikely coil lengths.
- DWPT projects should measure power and quality factors to improve the knowledge base.

Storage and On-Site Generation:

- A suitable high power, fast discharge, low-capacity Energy Storage System can reduce the impact of DWPT on the distribution network.
- Supercapacitors are currently a well-suited technology when included in the DC bus.
- On-site generation and storage solutions may offer options to smooth the demands of DWPT on the distribution network, although they introduce additional complexities when exporting and may add cost that erodes the business case.

! More information can be found in Section 4 on page 28.

Supply Chain

The supply chain assessment shows there is mixed opportunity for a UK supply chain, particularly at this early stage of DWPT market development. The UK's post-Brexit trading relationship with the EU weakens the attractiveness of a UK base. When considering the global supply chain, the UK does not offer any competitive advantage for manufacture and assembly of the MUs or GAs. There are good opportunities for the design, manufacture, assembly and installation of VAs, whether as retrofits or as part of the UK automotive manufacturing industry. There are also good opportunities to install and maintain the other hardware components and the grid connection.

Although there are fewer barriers to the development of digital assets as compared to physical assets, UK labour costs and a skills shortage mean there are limited benefits from the DWPT supplier's perspective for the design, testing or maintenance of equipment firmware, back-office management systems or front-end user interfaces. The latter two software components do however present an opportunity for the UK particularly as they relate to DWPT compatible vehicle development.

! More information can be found in Section 5 on page 58.

1 Introduction

1.1 Context

Dynamic Wireless Power Transfer (DWPT) technology offers the potential to allow Electric Vehicles (EVs) to recharge whilst in motion, which could contribute to overcoming some of the well-publicised shortcomings of Battery Electric Vehicle (BEV) technology. This, in turn, may contribute to accelerating the uptake of EVs, which is essential to achieving a reduction in carbon and pollutant emissions from road transport. This is consistent with the UK's legal obligations to achieve net-zero carbon emissions by 2050, and to reduce air pollution to safe levels across the country.

In their current stage of development, BEVs have two fundamental limitations when compared to Internal Combustion Engine (ICE) vehicles. Firstly, BEVs have a lower range than ICE vehicles. An EV with a fully charged battery currently has a smaller range than a similarly priced ICE vehicle, meaning the latter can be driven further before needing to refuel. Secondly, the process of recharging an EV takes considerably longer than that of refuelling an ICE vehicle, even when connected to rapid charging infrastructure.

DWPT technology holds the promise of lessening or removing these limitations. The ability to recharge a moving EV or provide power directly to the motor could allow the EV to drive further or reduce the need to recharge mid-journey.

1.2 Introduction to this Report

This report documents an industry-focused literature review of DWPT technology, gathering information and findings from existing studies and projects to achieve the following **research objectives**:

- Produce an overview of available Dynamic Wireless Power Transfer technology solutions;
- Assess different use-cases for Dynamic Wireless Power Transfer technology;
- Collect and summarise learnings from previous studies of Dynamic Wireless Power Transfer;
- Explore the impact of Dynamic Wireless Power Transfer on the electrical grid; and
- Assess the UK's current and potential future supply chain for Dynamic Wireless Power Transfer.

This report has been produced primarily for an audience of technical and policy experts.

1.3 About DynaCoV

This report has been produced as part of the Dynamic Charging of Vehicles (DynaCoV) project. DynaCoV is being undertaken on behalf of and in partnership with Western Power Distribution (WPD), using Network Innovation Allowance (NIA) funding. The project delivery is being led by Coventry City Council, in partnership with Coventry University, Cenex, ElectReon, Hubject, Midlands Connect, National Express, Ricardo Energy & Environment, and TfWM.

The aim of the DynaCoV project is to determine the feasibility of installing and operating EV Dynamic Wireless Power Transfer equipment in the UK, using a real-world site – located in Coventry, United Kingdom - as a specific point of study. DynaCoV explores different use cases for Dynamic Wireless Power Transfer but is focussed predominantly on its benefits within a public transport use case. Subject to the outcome of the DynaCoV project, public transport is the intended focus of a potential future demonstration project, that will further study the feasibility of the DWPT in the UK.

This report documents the findings and brings together the key deliverables associated with work package two of the DynaCoV project.

These deliverables are, specifically:

- D2-1: Literature review of current Wireless and Dynamic charging solutions available from the worldwide supply chain;
- D2-2: A collection of learnings and available data from existing international Wireless and Dynamic charging solutions;

- D2-3: Evaluation of the power requirements compared with different Wireless Dynamic Charging Technology use cases;
- D2-4: Study of use cases for Wireless Dynamic Charging Technology including requirements and expected functional benefits;
- D2-5: Evaluation of UK supply chain; and
- D2-6: A comprehensive report detailing all of the above requirements.

Work package two has been delivered by Cenex, with thanks and acknowledgements for contributions made by DynaCoV project partners, ElectReon, and for the guidance provided by Denis Naberezhnykh and Claire Newton of Ricardo Energy & Environment.

1.4 Introduction to Cenex

Established in 2005, Cenex is the UK's Centre of Excellence for Low Carbon and Fuel Cell technologies.

Today, Cenex focuses on low emission transport & associated energy infrastructure and operates as an independent, not-for-profit Research Technology Organisation (RTO) and consultancy, specialising in project delivery, innovation support and market development.

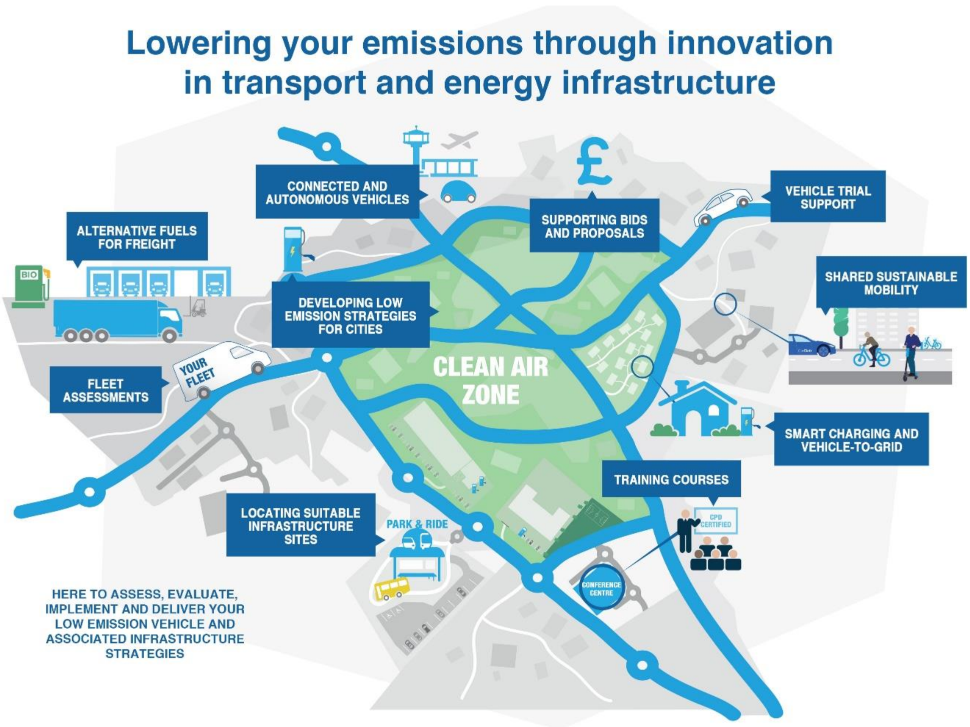
We also organise Cenex-LCV, the UK's premier low carbon vehicle event, to showcase the latest technology and innovation in the industry.

Our independence ensures impartial, trustworthy advice, and, as a not-for-profit, we are driven by the outcomes that are right for you, your industry and your environment, not by the work which pays the most or favours one technology.

Finally, as trusted advisors with expert knowledge, we are the go-to source of guidance and support for public and private sector organisations along their transition to a zero-carbon future and will always provide you with the insights and solutions that reduce pollution, increase efficiency and lower costs.

To find out more about us and the work that we do, visit our website:

www.cenex.co.uk



2 Existing Solutions

2.1 Introduction

2.1.1 Scope

Dynamic Wireless Power Transfer (DWPT) is distinct from static wireless charging in that it supports charging or powering of a vehicle that is in motion. Although, many static wireless charging solution providers and start-ups present ‘charging on the go’, this is not considered DWPT in this report. For instance, these solutions only work when the vehicle is stopped at least for a few minutes while loading or unloading goods (LGVs and HGVs) or picking up and dropping passengers (buses).

Within the DWPT arena, this report notes that some solution providers or demonstrators have not reported any updates for several years. This may be down to disruptions from the global pandemic but recent acquisitions may also be to blame. Much of the Intellectual Property around wireless charging and DWPT now resides in WiTricity. This leaves IPT group, who for EVs are focused on static charging, KAIST, who are exploring wireless power transfer in railway system, and ElectReon, who are partners in this project and whose technology features heavily in this report.

At the time of writing, ElectReon is the only known active DWPT system provider for EVs. They design and manufacture all components of the system, including inductive coils for the Ground Assembly (GA), management units and vehicle receiver units, as well as the software systems that operate them. They have passed TRL7 having conducted a Proof of Concept both at the company’s facility in Israel and in Sweden, and anticipate being TRL8 by the end of 2021 and TRL9 at the beginning of 2022.

This Section intends to describe the typical components of a DWPT and the recent past, present and planned deployments of the technology.

! Note that prototype equipment that is not at-market in some form is not considered.

2.2 Typical Components

The main components of a DWPT system are shown in Figure 1 and described beneath:

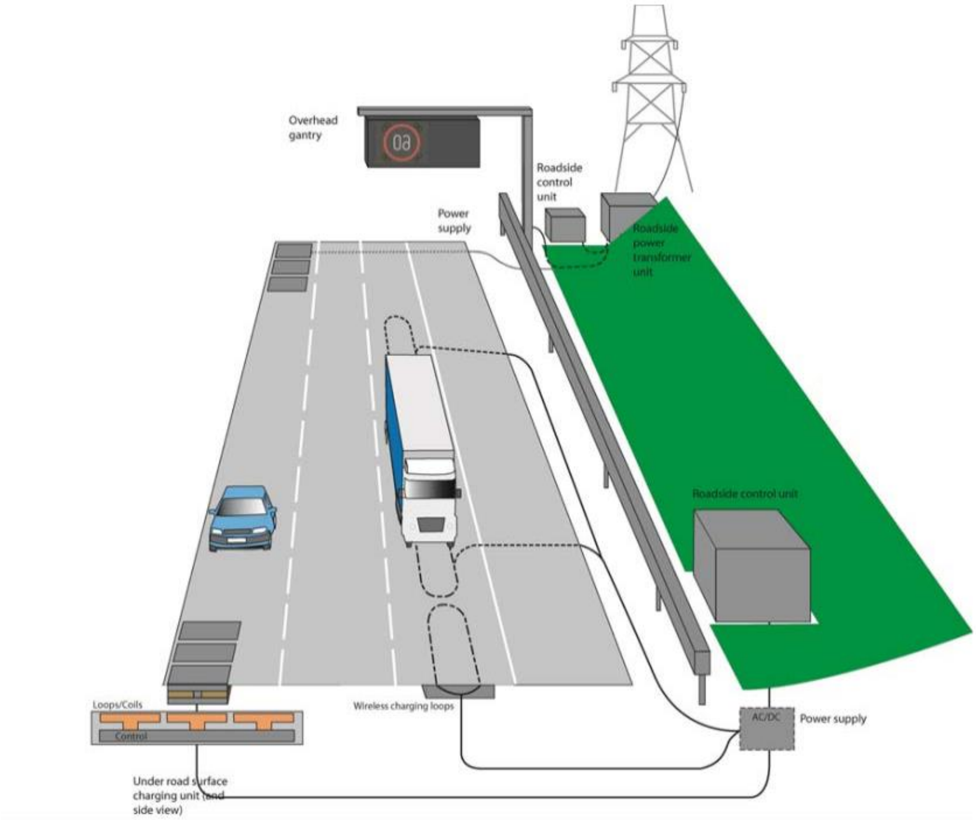


Figure 1: DWPT topology [1]

- Management unit (MU): An assembly of communications and power electronics equipment that is typically installed above ground, adjacent to the road under which the inductive coils are installed. This manages the supply of electricity to the inductive coils of the ground assembly.
- Ground Assembly (GA): Metal inductive coils, typically made of copper, that are installed underneath the road surface, generating a magnetic field when a high-frequency alternating electrical current is passed through them.
- Vehicle Assembly (VA): An assembly mounted to the undercarriage of an EV. When exposed to the magnetic field generated by the inductive coils, it generates a direct electrical current to provide power to the vehicle motor or battery. This assembly consists of a set of coils and associated power electronics.

Further detail on the technology configuration is provided in Section 4.2 (page 28) and on the supply chain components in Section 5 (page 58).

2.3 Deployments

2.3.1 Past

Table 1 shows three deployments in recent years that have showed promise, even though they are no longer operational.

Table 1: Past DWPT demonstrator high-level technology outcomes summary.

DWPT Provider	Year	Site	Key Results
Korean Advanced Institute of Technology (KAIST) [2]	2011- 2014 (after which the wireless technology was used in a static capacity)	372.5 m (16%) of 2.2 km route Seoul Grand Park (2011) 60 m (1.6%) of 3.76km route OLEV shuttle Bus at KAIST (2012)	100 kW of power provided to two buses through the application of Shaped Magnetic Field in Resonance (SMFIR) Maximum efficiency: 85%. EMF level: below 6.25 µT.

		144 m (0.6%) of 24 km inner city route Gumi, South Korea (2014)	Air gap: 20 cm.
Bombardier Primove (since acquired by IPT)	2013 (after which the technology was used in a static capacity)	80 m off-road test track in Mannheim, Germany	Provided up to 200 kW of power to the truck
Qualcomm Halo (partnered with Vedecom) (since acquired by WiTricity)	2017	100 m strip at an off-road test track in Versailles, France	Provided up to 20 kW of charge at speeds of over 100 km/h, and to two vehicles simultaneously

2.3.2 Current

Gotland, Sweden

Since 2018, ElectReon has been working in partnership with Smart Road Gotland and the Swedish Government to install and assess a demonstrator consisting of 1.6 km of DWPT infrastructure along a 4.1 km stretch of road on the Swedish island of Gotland. Two electric heavy vehicles were retrofitted with DWPT receiver units to enable them to utilise this infrastructure: an electric bus, used as a functioning shuttle service, and an electric heavy goods vehicle.

The purpose of the project is to evaluate DWPT technology and determine the feasibility and value of installing DWPT infrastructure across the 2,000 km network of highways in Sweden. The project is predicted to cost approximately $12.5m, of which $10m is being contributed by the Swedish Government.

Karlsruhe, Germany

In partnership with Eurovia, ElectReon was appointed in 2019 by German energy company, Energie Baden-Württemberg AG (EnBW), to provide a DWPT system along a bus route intended to connect the EnBW training centre in Karlsruhe to the rest of the local transport network. The bus service is to be operated by VBK, Karlsruhe's public transport operator. The first phase of the pilot has been deployed and the bus is charging from the installed system which includes 10 meters of static charging and a 100-meter test track at the EnBW training centre. The second phase of the project will install DWPT infrastructure along a further 600 metre stretch of public road, linking the training centre to Karlsruhe city centre. The intention is that VBK will use the infrastructure to recharge their electric buses.

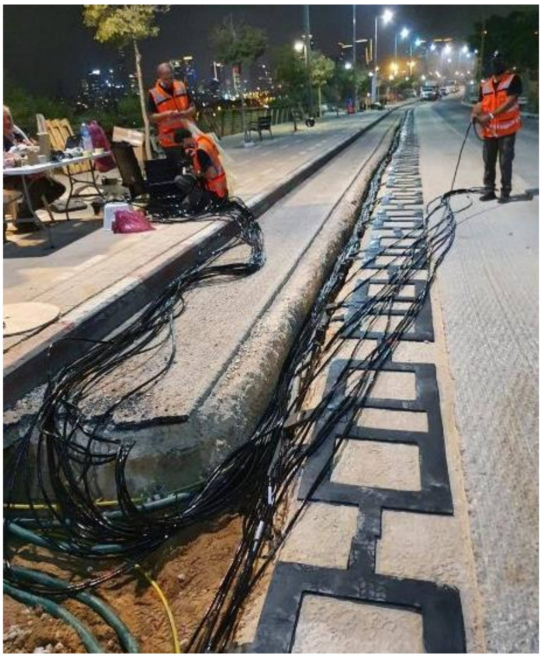


Figure 2: Photograph of works being undertaken to install Dynamic Wireless Power Transfer equipment beneath a road in Tel-Aviv, Israel.

Tel-Aviv, Israel

ElectReon began installing DWPT infrastructure in its home nation of Israel in January 2020, and subsequently began a pilot of its technology in September 2020. The pilot involved the installation of around 600 m of DWPT equipment, along a 2 km route between Tel-Aviv University Railway Station and Klatzkin Terminal in Ramat Aviv. ElectReon is delivering the pilot in partnership with the Dan Bus Company, a local public transport operator that runs bus services in and around Tel-Aviv. As part of the pilot, an electric bus, fitted with a super-capacitor (as opposed to a conventional lithium ion battery), was equipped with three DWPT receiver units, allowing it to charge along its service route. ElectReon also installed a static wireless charging station at the bus depot, to allow the DWPT-enabled bus to charge when not in operation.

2.3.3 Planned

ElectReon have two more projects in the pipeline, the key partners and aims of these are shown in Table 2.

Table 2: DWPT projects announced in early 2021.

Key Partners	Aims	Site	Reference
German Federal Highway Research Institute (BASt) - €1.9m financing Volkswagen Eurovia (subsidiary of Vinci group) Omexom *grid connection* VIA IMC *project management* Braunschweig University	▪ To develop an economical and functional solution for inductive charging of electric vehicles while driving. ▪ Testing issues such as: road integrity, connection to a renewable energy source, the billing interface and the systems' integration with vehicles, as well as analysing different business cases for the German mobility market.	DuraBASt, the German national road test facility, located near Cologne, Germany.	[3]
14 organisations including: Brembi toll road operator IVECO, Stellantis *Automotive OEMs* TIM Business *5G and connectivity provider* FIAMM Energy Technology *energy storage provider* Three research institutions	▪ Demonstrate static and dynamic WPT technology with two passenger vehicles and Iveco's intercity bus. ▪ Examine road construction optimization to increase road durability while not interfering with the efficiency of inductive charging systems. ▪ Demonstrate how a toll-road can be transformed into a charging asset for all road users. ▪ Explore advanced Internet of Things connectivity technologies to ensure road safety and maximum productivity of commercial vehicles.	1,050 m asphalt ring road fed by 1 MW of power 50 km from Milan near the Chiari Ovest exit of the A35 Motorway	[4]

2.4 Conclusions

Examining the existing solutions, the following conclusions can be drawn:

Solutions:

- All DWPT solutions consist of a Management Unit (MU), Ground Assembly (GA) and Vehicle Assembly (VA).
- Details of the variations of load and power specifications are found in later chapters.

Deployments:

- A total of eight DWPT demonstrations or deployments have been identified around the world in the last decade.
- Most projects focus on supplying power to heavy vehicles such as trucks or buses.
- Most projects have taken place on single-lane private, curated or bespoke test tracks, although three involved public roads.
- Initial infrastructure distances have been of the order of tens of meters, with more recently deployments stretching from hundreds of meters to a few kilometres.

Providers:

- Four key providers have been identified, although three of these (KAIST, IPT and WiTricity) appear to have been acquired or retired.
- Only ElectReon is active in the market at present.

3 Considerations for Deployment

The previous section has highlighted that DWPT solutions are still at an early stage of demonstration and deployment. The nature and significance of the challenges that need to be overcome to achieve mass-market adoption have fuelled research interest. Furthermore, the desire to place DWPT equipment in the public realm means that additional care is required to ensure a safe and compliant solution.

Feasibility studies and small-scale demonstrator projects have been undertaken to answer some of these key questions. This section will draw on their findings to identify key considerations to be accounted-for when implementing DWPT solutions.

3.1 Use Case

In principle, DWPT technology has the potential to allow EVs to drive further using smaller batteries, and either reduce or eliminate the need to spend time stationary while physically connected to a chargepoint. This could present a range of benefits, including:

- Convenience;
- Reduction of lost revenue by limiting downtime;
- Logistical ease by using pre-set routes and schedules; and
- Addressing large energy needs.

However, the degree to which the benefits can be accessed varies according to use case, as summarised in Table 3:

Table 3: Vehicle use case type against four potential DWPT benefits.

	Convenience & Accessibility	Limiting downtime	Logistical ease	Energy demand
Private Vehicle	✓ *			
Commercial Vehicle	✓	✓		
Bus	✓	✓	✓	
Truck	✓	✓	✓	✓

** Particularly for those without access to off-street residential parking/charging.*

Private vehicles are likely to benefit least from DWPT. For example, private drivers do not tend to worry about downtime (so long as charging is done relatively quickly) and the uses of a private vehicle are such that pre-set routes and schedules do not make sense. Furthermore, in comparison to heavier vehicles, the overall energy load is relatively small.

If there was no need to plug in to charge, the experience of owning and running a private EV would be more convenient than at present. Wireless charging (including DWPT) could then lower the barriers to adoption of private EVs for those without access to off-street parking at home (around 40%, though some of these users will have access to charging at work or destination). DWPT can also address accessibility challenges associated with the handling and use of conductive charging.

The heavier vehicles will see convenience benefits in the same vein. In some cases, where the only alternative method to charge is by installing chargepoints in cramped depots or by leaving cables trailing across public footpaths, further health and safety benefits could be accrued (see Section 3.5 on page 24).

On top of this, commercial vehicles, buses and trucks often have high utilisation so any downtime or diversions for charging during work hours is likely to incur lost revenue (or increased costs) for their operators. In this case, DWPT offers the benefit to limit downtime by charging whilst the vehicle is moving.

This is further underlined when the capital costs of DWPT installations are considered (see Section 3.2.2 for more details). The viability of this technology is dependent on at-scale roll-out of compatible vehicles. This should be more easily achieved by the fact that 54.2% of commercial vehicles are in fleets of 21 vehicles or more [5], and decisions about commercial vehicles are often made in a centralised manner.

Both buses and trucks are likely to move between fixed locations and the former also have pre-set routes and schedules. The deployment of DWPT infrastructure onto these common routes could provide shared infrastructure which would further reduce the need for opportunistic or depot charging.

Furthermore, trucks have the highest payloads and longest journeys, which will make their overall energy demand the greatest. DWPT could bring benefit to these vehicles by powering the vehicle *en-route* or ensuring it reaches its destination with a meaningful charge. Electric heavy vehicles with access to DWPT could reduce the need for [6]:

- Additional costs associated with larger batteries;
- Compensation of payload or capacity due to allocation of weight to the battery;
- The installation of high-power charging equipment at their depot; and
- Providing the electrical grid connection required to support high-power charging infrastructure.

DWPT has the potential to allow electric heavy vehicles to drive greater distances, without the need to increase battery sizes or provide high-power charging infrastructure.

Taking this together, DWPT carries advantages for all types of vehicles but the benefits are most clearly focused on buses and trucks. This conclusion is corroborated by the fact that many of the projects researched have also focused on these use cases.

Use cases with larger vehicles such as buses or trucks that carry greater payloads over longer journeys are best-placed to benefit from DWPT.

3.2 System Performance

There are many factors that affect how well a DWPT installation provides the specified energy to compatible vehicles. Figure 3 shows the factors influencing the system performance, (including those identified in [2]) along with signposts to sections with further information (in blue) and considerations for the deployment stage (in green).

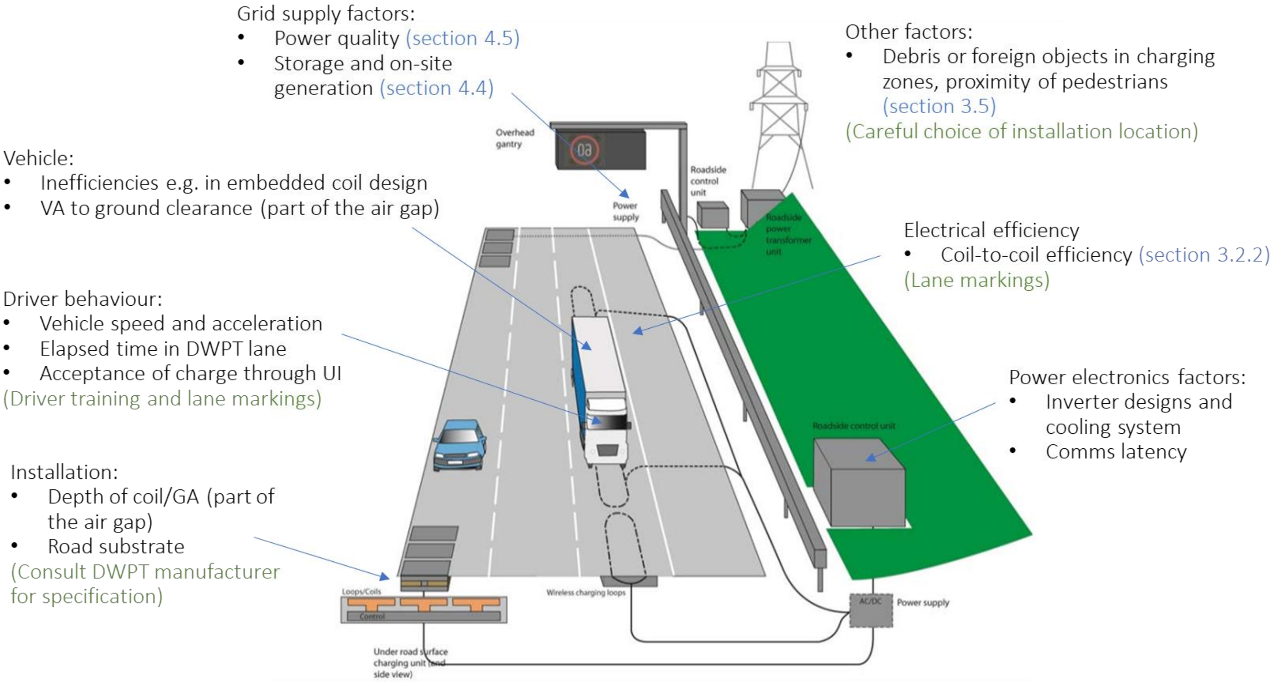


Figure 3: Factors affecting DWPT system performance, considerations for the deployment stage in green, signposts to further information where available in blue.

The sub-sections, below, explain the key factors in more detail.

3.2.1 Coil to Coil Efficiency

The main contributing factors to the efficiency of a wireless charging system are the transmission distance and the coil alignment. A DWPT system will achieve optimum efficiency when the two coils are perfectly aligned and separated by the designed air gap.

In static wireless charging, these variables are relatively easy to control as the vehicle can be positioned carefully when parking over the transmitter coil. SAE J2954 specifies a minimum efficiency of 85% for perfectly aligned coils and 80% for coils that are misaligned [7].[1] In practice, under ideal conditions, efficiencies of 90% and above are common. Witricity systems for example can go up to 93%.

In DWPT, the air gap between coils can be reasonably well controlled by the design of the transmitter coil within the GA and the receiver coil in the VA. There will be disturbances due to vertical movement of the vehicle suspension and imperfections in the road surfaces. However, this can be limited by a flat, well-maintained road surface. Variations in ground clearance between different vehicles could be somewhat compensated-for in the system design, although this may have cost or complexity implications for the production and installation processes.

Lateral alignment (horizontally across the road width) is much more complicated to control in a DWPT system. Whilst measures can be taken to encourage vehicles to drive in the prime lane position, in reality this will be affected by many factors including:

- Driver behaviour;
- Road geometry;
- Lane changes;
- Avoidance of debris or obstacles; or
- Deviations due to wind or imperfections in the road surface.

Additionally, longitudinal alignment (along the road length in the direction of travel) will vary naturally as the vehicle drives along the road and passes between coils.

Laporte et al. [8] reported results on alignment and resulting power transfer efficiency from coil to coil for the FABRIC Qualcomm/Vedecom DWPT system tests. The efficiency was reasonably robust to misalignment, with efficiency of >85% achieved in all but one of the tests with up to 15 cm misalignment.

The OLEV project [2] also produced results showing the impact of lateral misalignment on power transfer efficiency, it is not clear from the material whether this is coil to coil or overall system efficiency:

[1] Note that the SAE J2954 limits are intended for static applications only but are a good guideline of satisfactory efficiency for DWPT applications.

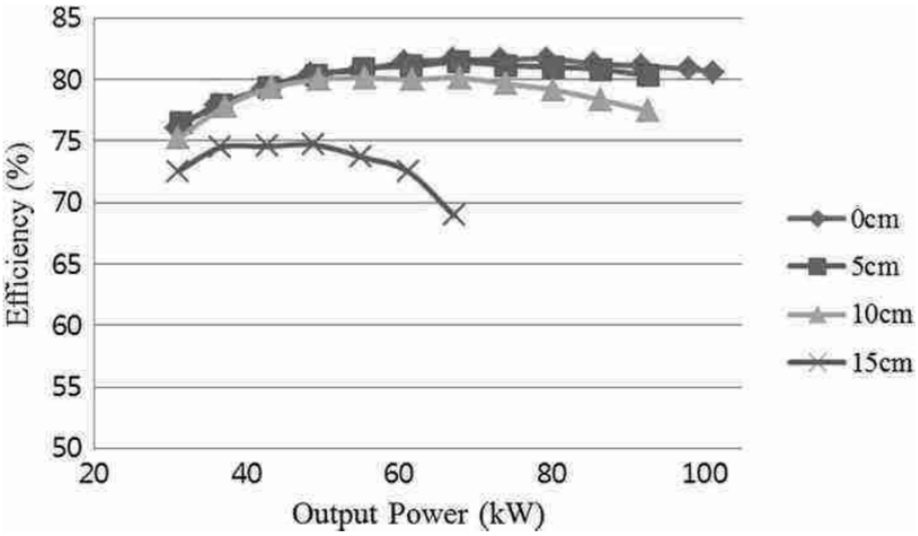


Figure 4: OLEV power transfer efficiency results [2]

Table 4 provides the maximum efficiency levels achieved across a number of DWPT demonstrations and tests [9]. Efficiency is calculated by the power input (usually measured at the inverter) versus the power output (at the vehicle receiver).

Table 4: Comparison of key equipment specifications, including efficiencies of dynamics wireless charging research projects. Source: Laporte (2019) [9]

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
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

! The literature is not clear on the boundaries across which the efficiencies are measured.

As a result of likely variations in air gap, lateral alignment and longitudinal alignment, DWPT systems must be designed to give acceptable power transfer efficiency when misaligned.
Coil to coil efficiency is expected to be more than 85%.
It is recommended to use boundary diagrams to make the efficiency calculation clearer in future research.

3.2.2 Overall System Efficiency

The overall system efficiencies (that is between the distribution network grid and vehicle battery) will be impacted by other losses in the GA power distribution system, infrastructure power electronics and the vehicle charging system. Stephane et al [8] reported a grid to battery efficiency of 70% (using only one AC converter for several distributed coil emitters). However, mature technologies could realistically increase this to 80-85%. For instance, Section 4.2 (page 28) shows how using a high voltage DC bus to connect the transmitter coils to the grid can minimise distribution losses.

> Laboratory figures indicate a lower bound grid-to-battery efficiency of 70% with the potential to increase this to 80-85% as DWPT technology matures.

3.3 Costs

[10] recognised that the cost of commercially available static wireless charging systems are greater than for an equivalent power conductive system, but also highlighted that research into the economic feasibility of dynamic systems is scarce. The overall business case for DWPT will be based upon downsizing vehicle batteries and enabling electrification of certain vehicle types that would otherwise not be viable.

However, the big challenge is that even a small-scale system requires a large capital investment due, in particular, to the significant civil works required. Figure 5 from [11] shows that over a 20 year period the infrastructure is the second largest expense, more than three times larger than the other components of the system.

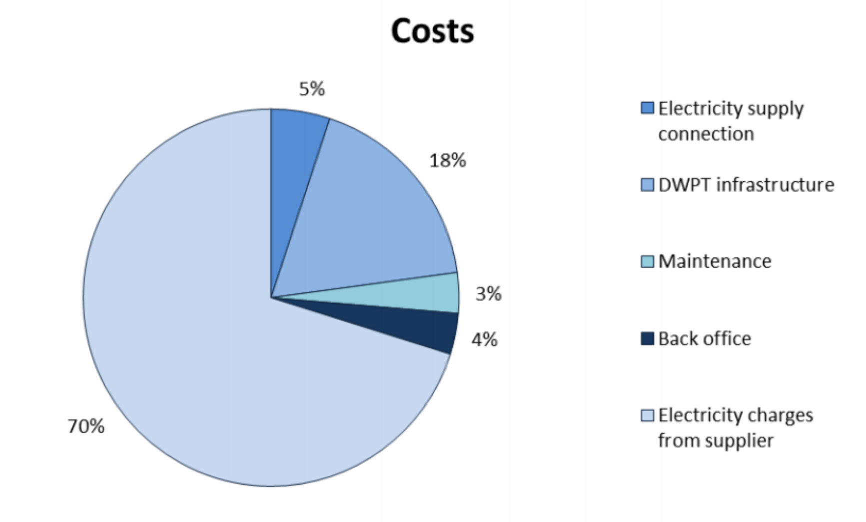


Figure 5: Breakdown of the NPV costs per km over 20 years under the select scenario [11].

Some estimates of the overall cost per km of DWPT systems were presented in [10]. In the OLEV project, these ranged from $850,000 per km to $1,069,000 per km. The Highways England report [11] estimated a cost of around £1,600,000 per km (for one lane) to buy and install DWPT equipment.

A brief description of the breakdown of the capital and operational cost categories is included below. Numbers are only provided where they are available and relevant, calculations for DynaCoV will be done in WP3.6 which will also cover different means of recouping costs. It should be noted that ElectReon's plans for future deployment involve financing the manufacturing, deployment and vehicle integration offering the system users Charging-as-a-Service (CaaS).

3.3.1 Capital costs

Civil works and installation - the civil engineering construction process includes roadside trenching for cables to cabinets, project management, site office and traffic management. The Fabric project estimates that total installation costs per installed km to be between €800,000 and €1,600,000 in a mature market [12]. Highways England [11] estimated £1,000,000 per km for installation of the equipment in the road. Streamlining DWPT installation with other planned roadworks can reduce the apportioned costs for the technology.

Hardware – including the vehicle assembly, ground assembly and management unit, have an estimated price of £600,000 per km [11]. ElectReon also state that they have a target price of around $650,000. This price will obviously vary depending on the number of vehicles.

Connection to the electricity network – this is highly dependent on the proximity to existing infrastructure and the required maximum power demand in comparison to the available capacity on the network at the desired location. The Highways England report [11] included an estimate of £455,000 per km from Western Power Distribution (WPD) when a separate connection to the grid is made for each 1 km of road (see section 4.7 on page 53 for more information about network connection costs).

Software - costs for the integration of the DWPT with electricity network operators, suppliers and users as necessary have not yet been estimated.

3.3.2 Operational costs

Electricity supply – this is a variable cost based on tariff structure, use case and uptake of compatible vehicles. Particularly for commercial vehicles, the demand for charging on the road would be in the day when renewable energy generation is highest and wholesale energy costs are likely to be lowest, which will help to reduce costs.

Software – ongoing licensing and hosting costs. ElectReon's software is hosted on Azure cloud services. Costs are unknown as the pricing structure is dependent on the architecture of the software and the size of the deployment.

Maintenance - providing the installation and commissioning are done well, the maintenance requirements should be very low, around $1,700/year per MU[6]. Retrofitted VAs are the most susceptible to damage although the probability of needing servicing is unknown and highly dependent on the routes covered and driver behaviour.

DWPT capital costs are relatively well-known for civil works, installation and hardware, ranging from £750,000 to £1,600,000 per km.
Network connection costs will vary by location and integration costs are difficult to estimate based on the current state of the literature.
Operational costs such as electricity supply will depend on local conditions but could be analysed in any future DynaCoV demonstrator.
Software costs have not been published but can be defined in a service level agreement.
It should be noted that ElectReon's plans for future deployment involve financing the manufacturing, deployment and vehicle integration offering the system users Charging-as-a-Service (CaaS).

3.4 System Installation

By virtue of being mounted beneath stretches of the road surface, the installation of DWPT infrastructure introduces new challenges, requiring coordination between stakeholder groups that have historically had little reason to do so. This coordination is essential to reduce disruption to road users, and optimise the integrity and durability of the road surface.

The embedded coils must be installed in a way that meets the same regulations of the road they are integrated to. This means different road surfaces may require different depths, as older roads will have a different structure to newer ones. This in turn can be problematic for the air gap and therefore reduce efficiency [13]. The coils must be kept at a consistent temperature meaning that they will require heating in the winter months to prevent freezing and cooling in the summer [12]. Installation of infrastructure should therefore aim to capitalise on a planned road maintenance programme to avoid additional disruption. However, most road maintenance is scheduled around every 10 to 12 years, whereas it is estimated that the life of the coils will be 20 years. Therefore, coils must be designed and installed to withstand any road maintenance that is required. Building standards for the road maintenance and surfacing regime with the installation procedures is critical here.

There is likely to be a considerable need for training to educate stakeholders involved with the maintenance of highways.
Contract length of infrastructure installation and maintenance should be aligned with realistic road maintenance cycles.

While this report focuses largely on DWPT infrastructure, it important to consider that only EVs fitted with receiver units will be able to use the infrastructure. Standardisation of receiver units will be essential for the adoption of the technology. There are several challenges on the placing of receiver coils such as capacity and space on the vehicle for pads. For instance, there is limited space on passenger vehicles for receiver pads but HGVs have more space to accommodate the VA. The current prevalent VA design is efficient but expensive and more than one would be needed to get the desired power transfer for larger vehicles [5].

The MU parts are expected to last 5-10 years of daily use but they are designed for easy access and maintenance.

Standardisation of the VA will be necessary to drive greater uptake of DWPT.

3.5 Safety and Security

In addition to the user and system considerations discussed so-far, health, safety and security risks needs to be evaluated carefully.

! It should be noted that the installation process itself is similar to other electrical equipment installations. Current industry processes for managing these risks are well understood and widely adopted, so are not discussed in detail here.

Instead, this section focuses on the impacts of the wireless aspect of the technology which have a novel application in DWPT.

The risks associated with Electromagnetic Field (EMF) interference are mitigated firstly through the design of the hardware components. Systems should be built and then independently tested against international guidelines and standards. EMF and Electromagnetic Compatibility (EMC) tests have been conducted on the ElectReon system in Israel by Hermon Labs (an independent body) and in Sweden by the RISE institute. Additionally, the system has been proven to be compliant with the IEC standards and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. The ICNIRP is an international organisation that published updated EM exposure guidelines in 2020. IEC 62233 and IEC 62311 both assess and guarantee the human exposure safety for EMR and EMF hazards.

Further standards cover safety:

- SAE J2954 (revised October 2020) standard establishes an industry-wide specification that defines acceptable criteria for interoperability, EMC, EMF, minimum performance, safety, and testing for Wireless Power Transfer (WPT) of light-duty plug-in electric vehicles;
- ISO 6469 (revised April 2019) contains safety specifications for electrically propelled road vehicles; and
- ISO 26262 (revised December 2018) is a functional safety standard for road vehicles, addressing potential failures in electrical and electronic systems.

Secondly, risks should be mitigated through the design of the system. For instance, live object protection and foreign object detection will shut off charging if any human, animal or metal object is in the vicinity of the coils. Added protection is provided by the Management Unit whereby each coil segment only transmits energy after the system identifies that a compatible vehicle is in place above the segment.

As DWPT technology distributes power, the system would be classed as critical infrastructure which is potentially a target for cyber attacks. For example, an attack in 2015 to 2016 on an Eastern European power-distribution grid resulted in a power cut to 230,000 people. In this case, attackers compromised a third-party vendor’s network, which was connected to an energy company’s operational technology network, allowing the attackers to make changes to the control system [14].

Cyber security risks for the back-office solutions in DWPT need to be identified and mitigated and this will be covered in WP4 by project partners Hubject. Key areas of concern relate to billing transactions and control of power transfer from the electricity network to the GA and the VA. UK and EU residents are covered by the General Data Protection Regulation (GDPR) which covers how personal data is gathered, used and managed by organisations. In order not to fall foul of this regulation, it is imperative that the communications architecture that handles the billing of individuals is secure. For this, penetration testing should be carried out both internally and by specialist organisations who are experienced in simulating cyber-attack against IT systems to check for exploitable vulnerabilities. The UK government website contains helpful information including on how to select a third party tester[2] and to handle security reports[3], the Energy Networks Association (ENA) and Department for Business, Energy and Industrial Strategy (BEIS) have produced tailored guidance for Distributed Energy Resource cyber security connections to the distribution network[4].

All DWPT hardware should comply to EMC, EMF, IEC and ICNIRP guidelines, with a view to SAE J2954, ISO 6469 and ISO 26262.
DWPT system should be deployed with a hierarchy of protection mechanisms including proactive options (i.e. live object protection and foreign object detection features) and reactive options (i.e. only transmitting power when a compatible vehicle is available).
DWPT systems are likely to be classified as critical infrastructure, requiring appropriate levels of security and failsafe mechanisms, as well as compliance with the GDPR where personal data are collected.

3.6 Equipment and Industry Standards

The lack of consistent international or even national standards for DWPT has been identified by several research projects. Standards are important to ensure that equipment remains safe to the user and the general public, especially as the industry expands. Standards are also important in facilitating technical interoperability between the systems of different manufacturers, which contribute to avoiding some of the pitfalls encountered during the early development of conventional EV charging infrastructure. There are two standards in development at stage 4 (approved for Committee Draft):

- IEC 63381 - Communication requirements of dynamic wireless power transfer (D-WPT) for electric vehicles, forecast publication in December 2023, and;
- IEC 63243 - Interoperability and safety of dynamic wireless power transfer (WPT) for electric vehicles, forecast publication in August 2022 [15].

IEC members will shortly be invited to give comments and approvals (stage 7 is publication stage).

In Table 5, Hutchinson *et al*. provide a summary of the standards that currently cover wireless charging technology [13]. Some of the standards for stationary wireless power transfer could be applied or built on for dynamic applications. For example, the frequency of the systems may be kept the same to allow interoperability when used in the stationary mode.

However, elements like power levels, coil dimensions and spacings become very important for DWPT, along with elements around switching times and activation profiles. Standards and regulations that are in place or in development for intelligent transport systems can be applied to the information communication technologies for DWPT.

[2] UK Government advice on Vulnerability and penetration testing - Service Manual - GOV.UK (www.gov.uk).

[3] The National Cyber Security Centre (NCSC) Cyber Assessment Framework 3.0 provides a systematic and comprehensive approach for assessing and hence improving cyber resilience.

[4] ENA and BEIS Distributed Energy Resources – Cyber Security Connection Guidance

Table 5; Wireless charging and relevant technology standards, Hutchinson et al.

Standard	Topic
ISO 19363	**electrically propelled road vehicles – magnetic field wireless power transfer – safety and interoperability requirements**
ISO 15118	road vehicles – vehicle to grid communication interface
ISO 17409	connection to external electric power supply
ISO 12405	Li-ion battery system – performance testing and safety performance
ISO 6469	electrically propelled road vehicles – safety specifications
IEC 61980	**electric vehicle wireless power transfer systems**
IEC 62840	electric vehicle battery swap system
IEC 61851	electric vehicle conductive charging system
SAE J2954	**wireless charging of electric and plug-in hybrid vehicles**
SAE 1772	electric vehicle and PHEV conductive charge coupler
SAE J1773	electric vehicle inductively coupled charging
SAE J2836/6	use cases for wireless charging communication for plug-in electric vehicles
SAE J2847/6	communication between wireless charged vehicles and wireless EV chargers
SAE J2931/6	signalling communication for wirelessly charged electric vehicles
BS EN 61851-1	electric vehicle conductive charging system: general requirements

! IEC members (including those with observer status) will shortly be able to review and comment on the two DWPT standards in development IEC 63243 and IEC 63381 (December 2021) – this is deemed the most important commenting stage in the development of the standards.

The lack of comprehensive standards across all the elements of technology, installation and use of DWPT is currently a risk for future deployment. To avoid problems of interoperability, tailored standards on the type and placement of receiver coils, compliance with roadway construction and safety regulation to standards of service, information sharing, data collection and payment will be required.

3.7 Conclusions

Examining the considerations for deployment, the following conclusions can be drawn:

Solutions:

- Use cases with larger vehicles such as buses or trucks that carry greater payloads over longer journeys are best placed to benefit from DWPT.

System Performance:

- Variations in air gap, lateral alignment and longitudinal alignment, mean that DWPT systems must be designed to give acceptable power transfer efficiency when misaligned.
- Coil to coil efficiency is expected to be above 85% and up to 90-95%.
- Laboratory figures indicate a lower bound grid-to-battery efficiency of 70% with the expectation of increasing this to 80-85% as DWPT technology matures.
- It is recommended to use boundary diagrams to make the efficiency calculations clearer in future research.

Costs:

- Understanding how these costs will be recouped and by whom is key to fully assess the benefits of DWPT and construct a robust business case.
- DWPT capital costs are relatively well-known for civil works, installation and hardware, ranging from £750,000 to £1,600,000 per km.
- Network connection costs will vary by location and integration costs are difficult to estimate based on the current state of the literature.
- Operational costs such as electricity supply will depend on local conditions so should be analysed in any future DynaCoV demonstrator.
- Software costs have not been published but can be defined in discussions with ElectReon.

System Installation:

- There is likely to be a considerable need for training to educate stakeholders involved with the maintenance of highways.
- Contract length of infrastructure installation and maintenance should be aligned with realistic road maintenance cycles.
- Standardisation of the VA will be necessary to drive greater uptake of DWPT.

Safety and Security:

- All DWPT hardware should comply to EMC, EMF, IEC and ICNIRP guidelines, with a consideration of SAE J2954, ISO 6469 and ISO 26262.
- DWPT system should be deployed with a hierarchy of proactive and reactive protection mechanisms.
- DWPT systems are likely to be classified as critical infrastructure, requiring appropriate levels of security and failsafe mechanisms, as well as GDPR compliance where personal data are collected.

Equipment and Industry Standards:

- The lack of comprehensive standards across all the elements of technology, installation and use of DWPT is currently a risk for future deployment.
- To avoid problems of interoperability, tailored standards on the type and placement of receiver coils, compliance with roadway construction and safety regulation to standards of service, information sharing, data collection and payment will be required.

4 Electricity Network Impacts

4.1 Introduction

As with any other load, the design and operation of the DWPT system will have an impact on the energy system. This section identifies these impacts, the variables that can affect them, and the existing literature in which they have been studied. Data from Electreon's demos are expected to be available for review within the project timelines.

! Note that it is assumed that the DWPT system will source power from a connection to the electricity network.

The electrical design of DWPT systems are presented in order to explain the **grid interface requirements**.

Then, the impacts on the distribution network are analysed using the following categories:

- **Load** – the demand placed upon the distribution network will have a theoretical limit. However, many variables will affect how the load varies temporally and spatially.
- **On-site Generation and Storage –** as part of the DWPW system, it may be beneficial or even necessary to deploy on-site generation and/or storage.
- **Power Quality** – DWPT systems are made up of various electronics that will have an impact on the power quality at the point of connection to the network. Impacts such as harmonics are discussed in this section.
- **Smart Connectivity –** as with static conductive charging systems, smart systems may be applied to DWPT in order to manage the grid impact in real time. This section will look at how such systems can mitigate the impacts that will be discussed in the previous sections.
- **Cost –** deployment of DWPT at scale is likely to require expansion and reinforcement of distribution networks. This section will evaluate the scale of the likely upgrade costs.

4.2 Electricity Network Interface and Supply Characteristics

Prior to going into the impacts on the distribution network, it is imperative to understand how a DWPT system is constructed and therefore how systems are likely to be connected to the network. This builds upon the summary presented in Section 2.2 (page 13).

4.2.1 System Design

Modern wireless charging systems for Electric Vehicles (EVs) rely on the principle of Inductive Power Transfer (IPT) between two magnetically coupled coils. The difference between IPT and alternative methods for wireless power transfer is discussed in [16]. IPT relies on high frequencies in order to achieve the required power transfer with satisfactory efficiency through significant air gaps between transmitter and receiver. The standard operating frequency for interoperable systems is defined as 85 kHz (see standard SAE J2954) [7]. However, all systems identified by Pancha *et al.* [16] operate with frequencies in the range of 10-100 kHz.

Consequently, all wireless power transfer systems – dynamic or otherwise - require power electronics to increase the grid frequency of 50 or 60 Hz by multiple orders of magnitude. This conversion is done using AC/DC and DC/AC converters, as shown by Figure 6:

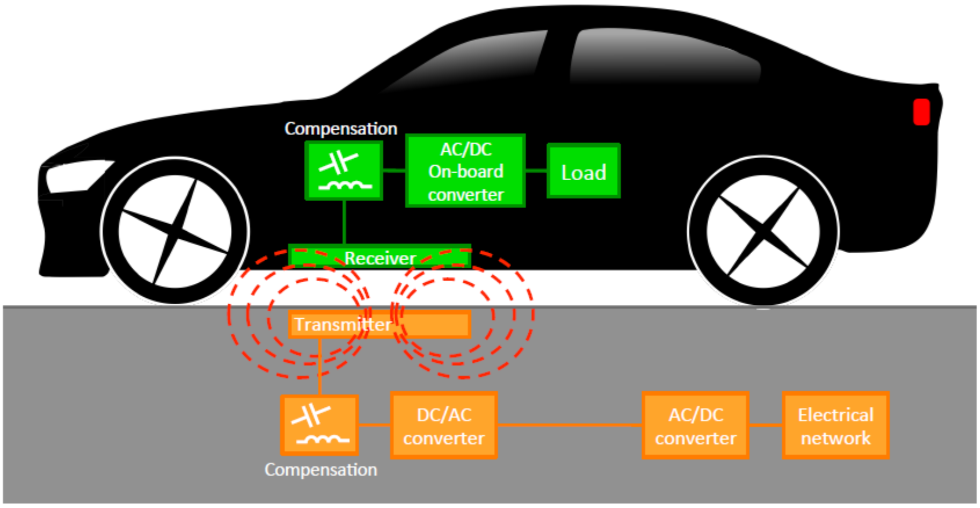


Figure 6: Simplified Wireless Charging Schematic [17]

Typically, the AC/DC and DC/AC converters are not co-located, meaning that the primary transmitter coils are connected to a high voltage DC bus. For example the PRIMOVE demonstrator project used 750 V (a common voltage used for tramways [18]) to minimise distribution losses. An example configuration with DC distribution from the road-side electrical infrastructure to the transmitter coils, proposed by Politecnico di Torino's Charge While Driving (CWD) concept in the FABRIC project, is shown by the schematic of Figure 7:

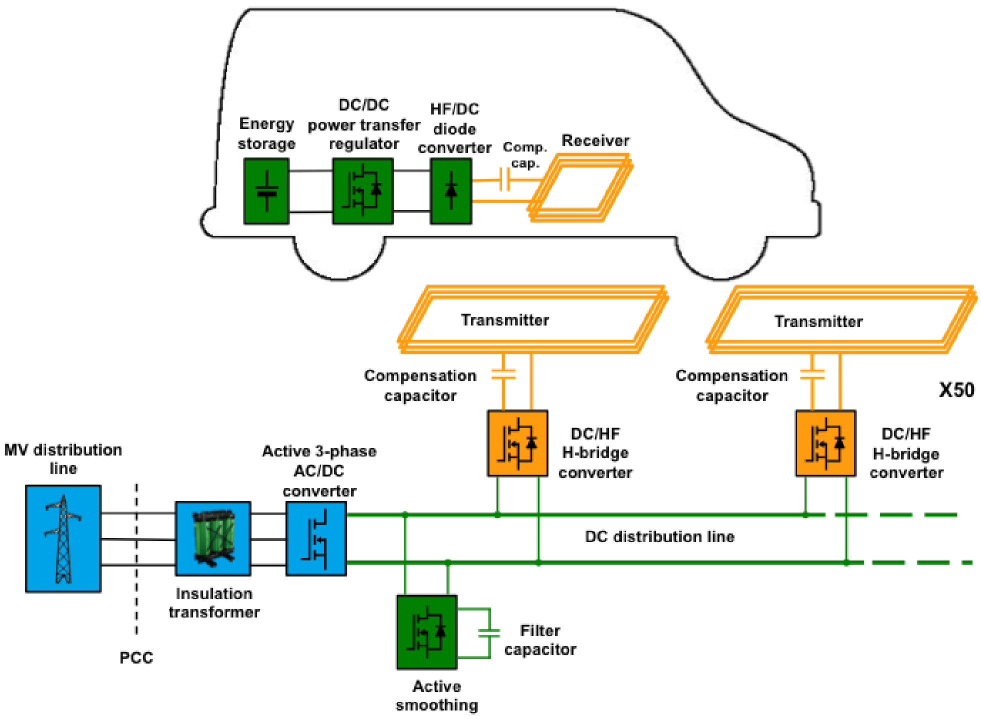


Figure 7: DWPT Schematic with DC Bus [17]

DWPT systems use operating frequencies between 10 and 100 kHz, often centred on 85 kHz.
AC/DC and DC/AC converters are needed to increase the frequency of the power supplied.

4.2.2 Connection Voltage and Supply Points

The FABRIC project reviewed the network connection topologies of existing projects including the KAIST and PRIMOVE solutions, as well as the concept proposed by Turki et al in [19]. The KAIST solution – which is a working deployment with little available documentation – is believed to be connected to the Low Voltage (LV) system according to [18]. Although each coil is capable of transferring 100 kW, the system has been designed to charge only one bus at a time and hence the maximum load is not scalable and can be supported by an LV network connection.

The FABRIC demonstrators also connected to an existing LV network as sufficient power was available at LV level at the test sites. – Figure 8 shows the scheme for the Satory site:

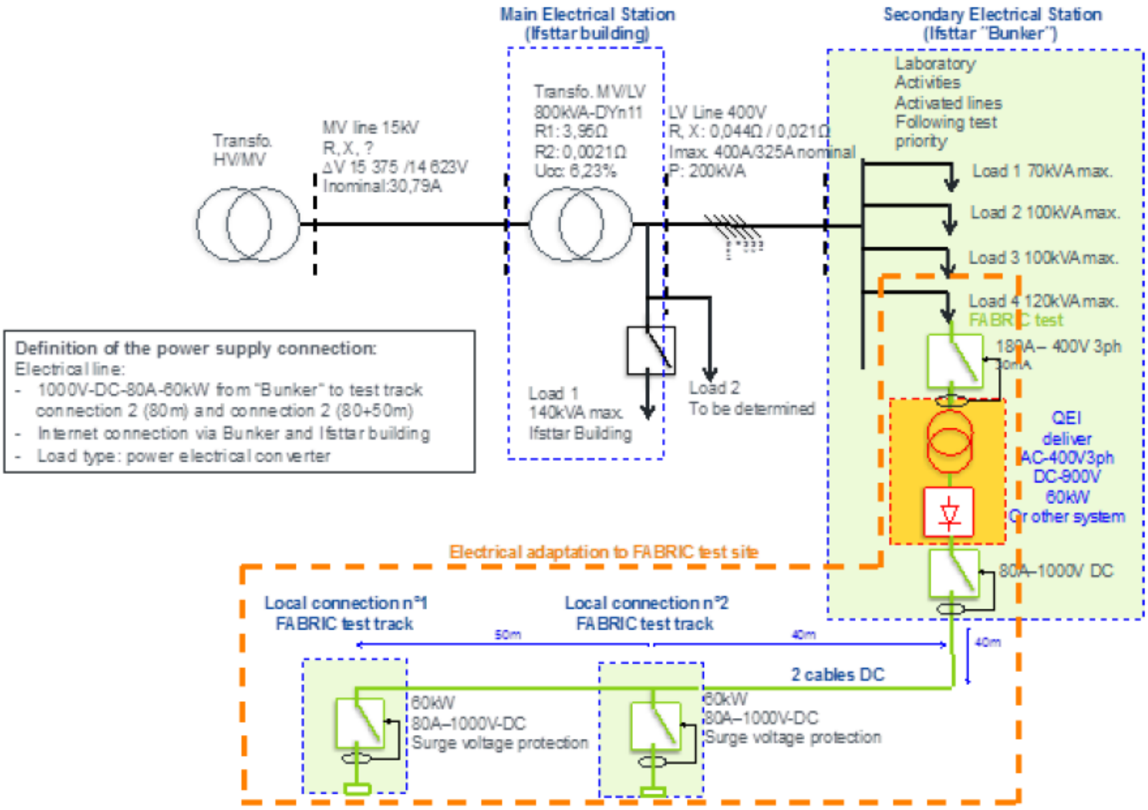


Figure 8: FABRIC Satory Site Electrical Schematic [18]

However, the project proposed an architecture for DWPT with a network interface at the Medium Voltage (MV) with the exact voltage depending on the country of deployment. In the UK this would be 11-33 kV. The topology proposed by FABRIC for the DWPT network connection interface is shown in Figure 9. The architecture includes a "road converter station" owned by the DWPT provider, which includes the MV/LV transformer.

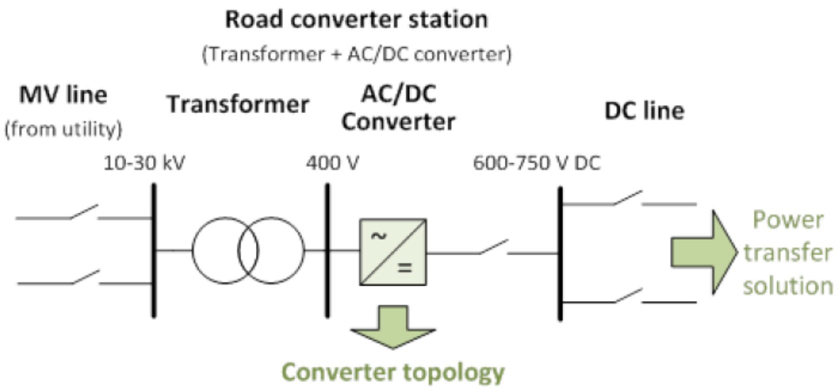


Figure 9:DWPT network connection, FABRIC [18]

Figure 10 shows how this architecture could work at scale with multiple road converter stations serving adjacent DWPT deployments. Note that the network connection (referred to as the "grid connection" in the figure) is depicted at MV level where the transformer is included in the road converter station. For a demonstrator with a single "road converter station", this is the pragmatic solution. However, for larger scale deployments, it is possible that the DWPT solution provider would also own the MV network and the point of connection would be at the High Voltage (HV) level (i.e. the conversion from 110-130 kV to 10-30 kV in Figure 10).

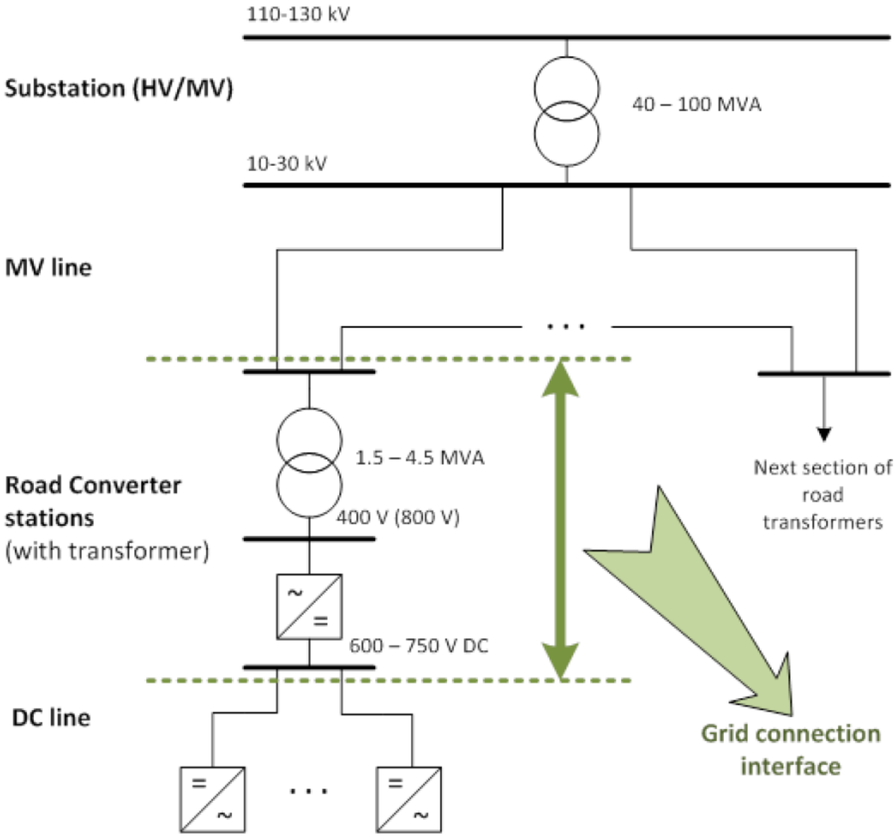


Figure 10: Wireless Charging System Network Connection [18], [12]

The Highways England report [11] also proposed three options for connecting a DWPT system to the network as part of a cost study, which is described in more detail in Section 4.7 (page 53).

At-scale deployments are expected to interface with the Medium Voltage line in the UK.

4.2.3 Modular Deployment

As can be seen from Figure 10, DWPT systems are modular by design. Each set of transmitter coils is connected to the Management Unit (MU), which sits at the side of the road and includes the power electronics and control systems. Each MU can then be connected to existing or new MV substations, allowing for multiple “modules” to be deployed. Connecting in this way will require a transformer at the roadside to reduce the AC voltage before rectification to DC.

The length of road which can be “electrified” and the number of modules that can be connected to each substation will depend on the system characteristics, which shall be discussed in this section, and the local energy network.

The FABRIC report on architecture definition [18] compares and contrasts the proposed DWPT network connection architecture with similar systems in rail, light rail and other conductive electrified road systems.

DWPT deployments should adopt a modular design to allow for scalability.

4.2.4 Frequency

Existing DWPT systems are designed to operate at the frequency of the Grid of the target market, 50 or 60 Hz.

UK DWPT systems will need to be designed for a nominal input frequency of 50 Hz.

4.3 Load (Demand)

In this sub-section, the variables that can influence the real-time load on the network are discussed.

4.3.1 Max Theoretical Load Limit

Any DWPT system has a maximum theoretical load limit although it must be noted that this is unlikely to be achieved in reality. However, it is important to outline this hypothetical limit first before discussing the variables which affect it.

Each transmitter coil will have a rated load. The majority of demonstrator projects and deployable systems have a rated coil power in the region of 20 - 25 kW, as seen in Table 6:

Table 6: Wireless Charging System Transmitter Coil Ratings

	Status	System Type	Power Rating / kW	Reference
ElectReon	Deployed, commercial	Dynamic	25	[20]
Charge While Driving (CWD), eco-FEV & FABRIC	Demonstrator	Dynamic	20	[21]
Induction Powered Vehicle (IPV), FABRIC	Demonstrator	Dynamic	100[5]	[21]
Primove (car)	Demonstrator	Dynamic	22	[21]
Primove (bus)	Demonstrator	Dynamic	200	[21]
Qualcomm / Vedecom System, FABRIC	Demonstrator	Dynamic	20	[21]
On-Line Electric Vehicle (OLEV), KAIST	Deployed	Quasi-dynamic[6]	100	[2]
UNPLUGGED	Prototype	Stationary	3.7, 2 x 25	[22]
ZeEUS	Demonstrator	Stationary	2 x 50	[23]

DWPT systems consist of coils laid back-to-back in, on or underneath the road surface to provide a near continuous charge as a vehicle passes from one coil to the next.

[5] Saet-Spa IPV system was designed for 100 kW but is believed only to have operated at 30-50 kW in FABRIC project [15].

[6] The OLEV project system only provides charging when the buses are stationary at or accelerating away from bus stops.

Figure 11: CWD Prototype (left, [17]); ElectReon SmartRoad Gotland Project Deployment (right, [24])

A key limiting factor is the vehicle length, so the maximum power transfer would be achieved when vehicles are parked bumper-to-bumper (ignoring any potential alignment issues between transmitter and receiver coils). When considering the average car length of around 4.5 m, it might be reasonable to expect two vehicles to be able to charge for each 10 m of road, each using a proportion of the available coils in that segment.

Furthermore, DWPT system architectures consist of a number of coils connected to a single road-side MU. The number of coils that are connected to each MU varies by manufacturer and deployment, so the limiting factor may be the MU, rather than the number of compatible vehicles that can be physically charged at once. Early demonstrations were limited to only one vehicle per segment although more recent systems allow multiple vehicles to receive a charge from a single segment simultaneously [25].

There is limited information available on the rating of the MU for the systems listed in Table 6. The internal electronics, cables, safety systems, rectified and transformers will need to be sized for a specific rating, which means that the MU will place limitations on the maximum theoretical load.

Bringing all these factors together, Table 7 gives a worked example of how this is accounted for in an ElectReon system designed for the private vehicle use case:

Table 7: Example Theoretical Load for Private Vehicles

	ElectReon [26]	SAET-SPA IPV
Power per coil	25 kW	40 kW
Number of coils per management unit (per DWPT segment)	60	20
Total length of electrified road	100 m	25 m
Theoretical number of charging vehicles[7]	20	5
Maximum theoretical load	500 kW	200 kW
Management unit rating	180 kW[8]	100 kW

[7] Assuming two vehicles per 10 m section for 4.5 m vehicle length and ignoring any alignment issues with coils.

[8] ElectReon's management unit has a configurable rating – for systems where the expected load is greater – as a result of more vehicles using a single segment, for example, then a higher rating can be specified. The 180 kW management unit rating was used for the Gotland, Sweden deployment.

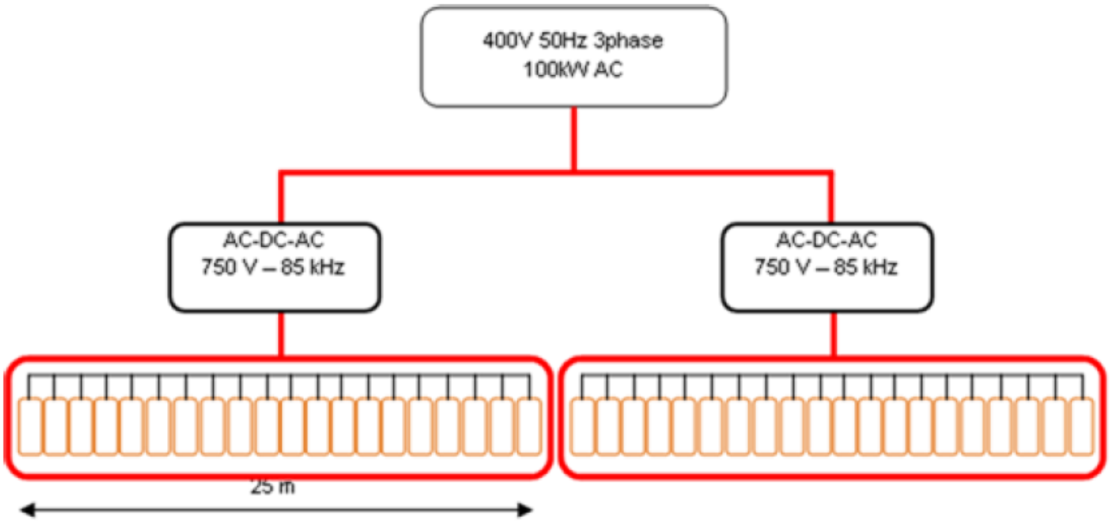


Figure 12: SAET SPA Test Site Layout [18]

By limiting the maximum MU power to 180 kW, ElectReon have reduced both the total cost of the system and the potential grid impact in terms of overall load. This system allows seven coils to be in use at 25 kW maximum power at once.

Table 7 showed the maximum theoretical load for private vehicles but the type of vehicle using the system will also impact the maximum demand. ElectReon currently foresees four use cases, as shown in Table 8:

	Number of receivers	Current Total Vehicle Transfer Power / kW	Planned Future Total Vehicle Transfer Power (2022) / kW
Private (light) vehicle	1	25	30
Commercial vehicle	2	50	60
Bus	3	75	90
Truck	5 - 7	125 - 175	150 – 210

Table 8: Electreon System Power Ranges by use case (courtesy of Electreon)

Although larger vehicles receive greater power as a result of having more receivers fitted, the power transfer per receiver in ElectReon's design is consistent at 25 kW per transmitter/receiver pair in the current design and 30 kW for the future design. The packaging of multiple receivers on a single longer vehicle therefore increases the maximum power transfer possible, as shown by Table 9:

	Number of receivers	Maximum Power Transfer per Vehicle / kW[9]	Vehicle Length / m	Maximum Power per 100 m DWPT road / kW[10]
Private (light) vehicle	1	30	4.5	660
Commercial vehicle	2	60	7	840
Bus	3	90	12	750
Truck	5 - 7	210	16.5	900-1260

[9] Using the rated power of Electreon's future system for 2022.

[10] Assuming that vehicles are nose to tail with zero spacing.

Table 9: Maximum theoretical load for different use cases

! The effect of different vehicle use cases is discussed in more detail in Section 3.1 (page 18).

> The maximum theoretical load is a factor of the transmitter coil ratings, number of coils per road segment, number of segments per substation and vehicle type.
> In reality, the maximum theoretical load is never attainable because of vehicle type and the need for cost-effective deployments.
> In practice, the MU rating becomes the main limiting factor on the theoretical load.

In reality, the demand of a DWPT system will be less as discussed in the subsequent sub-sections.

4.3.2 Effect of Efficiency

When analysing network impact, it is imperative to understand the difference between the power received by the vehicle battery (which is commonly what is advertised by the DWPT supplier) and the power delivered by the energy system.

As an example, ElectReon's system which has a maximum power transfer to the vehicle of 25 kW is approximately 85% efficient, meaning that the network will need to supply at least 29.4 kW for each ground coil running at maximum power.

> The effect of efficiency is such that the distribution network will need to supply more power than is received by the vehicle.

4.3.3 Use of Load Management

The need for load management was recognised by the FABRIC project. A potential communications architecture was proposed in [27] and given as a "use case" in [28] by which to control charging power to adhere to both the constraints of the system and the network in real time.

How this is achieved will depend on the communications infrastructure that is deployed. However, load management is a technique that is widely adopted in the EV charging industry that could be readily applied to DWPT systems. The complexity with DWPT is the inherent variability of the real-time demand, which will be discussed in the following sub-sections.

> A load management system is required to control the charging power of individual coils in real time, to ensure charging adheres to any system constraints.

4.3.4 Single vs Multiple Use Cases

The vehicles that are the targeted users of the DWPT system will have an impact on the real-time load, as well as its variability and predictability. In Highways England's "Preparing the Strategic Road Network for increased use by electric vehicles report" 2014 [29], power transfer levels of 20-40 kW and 100-180 kW were proposed for light vehicles and trucks and coaches respectively.

Section 2.3 (page 14) and 3.1 (page 18) have already reviewed the variation in vehicle-side benefits by use case.

However, on the system-side, whilst targeting a single use case greatly simplifies the process of evaluating the system's use, there is the obvious disadvantage that the infrastructure and associated civil engineering works will only be used by a limited number of users and hence for limited periods of time. Hence, to commercialise wireless charging systems, it may be necessary to target a greater range of use cases. For instance, the Smart Road Gotland project has deployed a system that is in use for both an electric bus and an electric HGV [30]. The real-time load of a system used for HGVs would be more variable and unpredictable.

> A tension exists between increasing vehicle-side benefits and managing load variability by targeting a single use case, and improving the business case by designing the DWPT system for multiple use cases.

4.3.5 Temporal Load Variations

Two documents from the FABRIC project are especially useful for evaluating the variability of the load of a DWPT system. A gap analysis of the network requirements was completed as part of [25] whilst [12] investigated the network impact of upscaling systems. These concluded that variability can occur on both short-term (second by second) or long-term (time of day, week, year) basis.

Individual Vehicle demand (Short-Term)

The real time charging demand of the vehicle will vary depending on:

- The current battery State of Charge (SoC). If the battery is already at a high SoC, then the maximum allowable charging power may be reduced by the vehicle to protect the battery.
- The current driving power demand. This can vary greatly from the vehicle's maximum propulsive power to its maximum regenerative braking power. This will be dependent on several other variables such as traffic state, speed and gradient. [12] presented a graph showing the effect of speed on energy consumption for a 2016 Nissan Leaf:

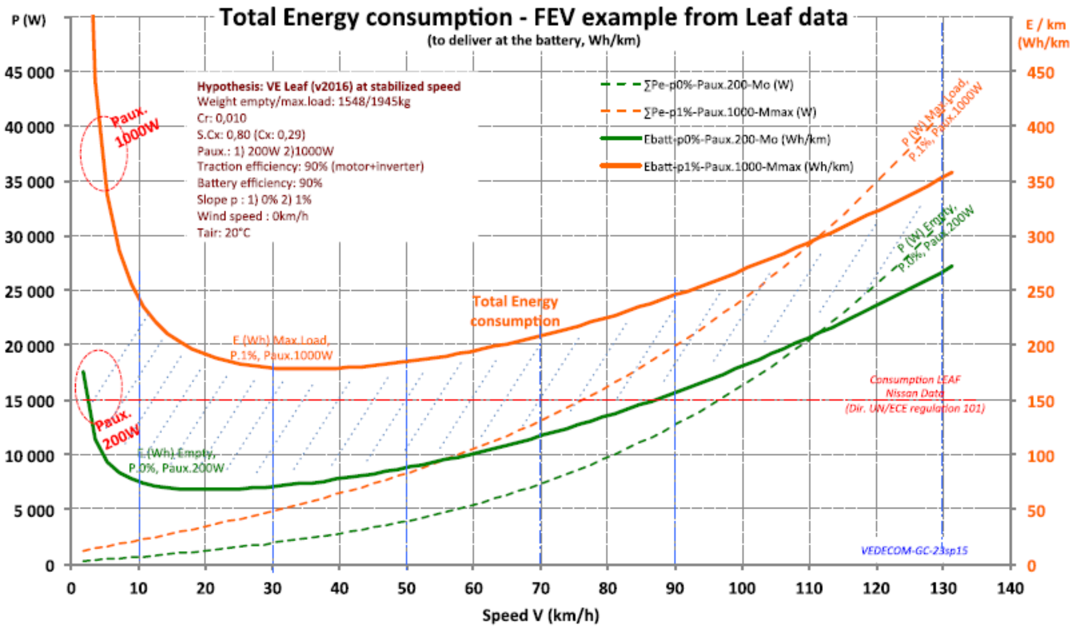


Figure 13: Effect of Driving Speed on Energy Consumption [12]

Figure 13 shows that whilst there is an optimum driving speed of 30-40 km/h where the auxiliary power requirement is 1 kW, the power required increases at a greater than linear rate.

The driving power demand is also affected by the vehicle type, with larger vehicles requiring greater power. The power requirements for private vehicles and HGVs at constant speed was presented by [11] and is shown in Table 10. The demand on the network is calculated assuming a 73% DWPT efficiency.

	Light Vehicles			HGV		
Speed / mph	Power requirement for traction / kW	Traction energy per km / kWh	Power demand from the network / kW	Traction energy per km / kWh	Power demand from the network / kW	Traction energy per km / kWh
10	1.1	0.067	1.5	0.73	16.1	0.73
20	2.2	0.067	3.0	0.80	35.1	0.80
30	3.7	0.076	5.0	0.92	60.7	0.92
40	5.8	0.09	7.9	1.09	96.2	1.09
50	8.8	0.11	12.0	1.31	144.7	1.31

60	12.8	0.13	17.6	1.59	209.7	1.59
70	18.1	0.16	24.8	1.91	294.4	1.91

Table 10: Light vehicles and HGV DWPT power demand [11]

Figure 14 shows that the relationship between speed and network demand is non-linear, primarily as a result of air resistance increasing with the square of the vehicle velocity. This highlights the importance of both the system use case and chosen road type (to be discussed in section 4.3.6 on page 39).

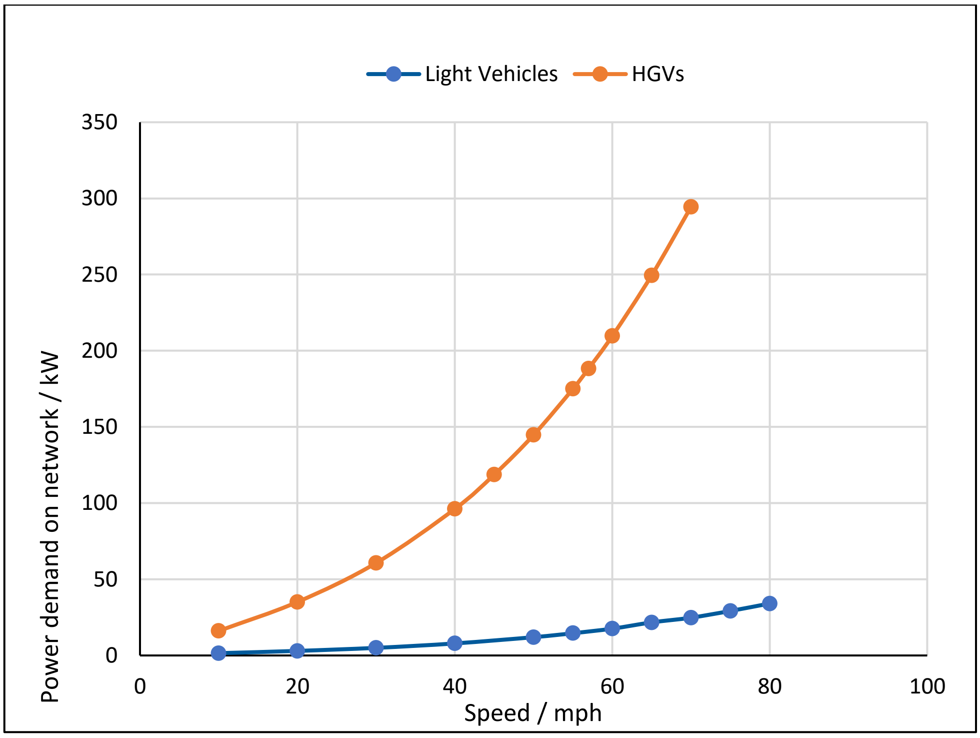


Figure 14: Change in Network Demand with Vehicle Speed

Traffic Speed (Short-Term)

The driving speed of the DWPT vehicle is of great importance to the system real-time load and overall efficiency. We have seen that the GA consists of individual transmitter coils laid adjacent to each other along the length of the road. For each coil, a connection must be established before the coil is energised. Any delay in activating and resonance calibrating the subsequent coil, as well as physical gaps between adjacent coils, creates pulses of demand proportional to the driving speed. If the vehicle is to be able to receive power whilst driving at any significant speed, the software and power electronics associated have to be able to establish the pairing between coils as quickly as possible to maximise the power transfer time.

Each ground-side coil is typically between one and two metres in length[11] and are therefore passed over in fractions of a second. At 60 km/h, a 2 m ground-side coil will be passed over in 0.12 s. Many of the existing demonstrators had a cut-off speed at which DWPT is not activated due to a poor system efficiency (as a result of the low proportion of time that power transfer is active at higher speeds). The systems demonstrated in the FABRIC project were designed with maximum speeds of between 50 and 80 km/h [21].

To minimise delays energising individual coils and the resultant loss of system efficiency, DWPT control systems implement processes to detect arriving vehicles and energise coils prior to the vehicle receiver being in position. [18] discusses the Vehicle Detection Segment Control (VDSC) system used in PRIMOVE and the equivalent systems for the FABRIC demonstrators. ElectReon's

[11] The Qualcomm hardware from FABRIC was 1.71 m [16] and the Charge While Driving (CWD) demonstrator was 1.5 m in length

system has a functionality to control how power transfer is "handed over" from one ground coil to the next which also works between the last and first coils in adjacent segments.

Headway (Short-Term)

In the maximum theoretical demand discussion, the headway (or distance) between vehicles was noted as another factor that will influence the system load. Whilst driving speed is the main contributing factor, headway is also affected by driver behaviour and can vary quickly. FABRIC studied this impact extensively, considering both a "coordinated" scenario where the headway is controlled (roughly equivalent to existing adaptive cruise control technology as well as a future autonomous driving scenario) and uncontrolled traffic.

In uncontrolled traffic, the two second safety rule can be used to estimate the number of vehicles that will be present for a length of road and the headway between them. However, in reality drivers often travel much closer to each other than this, and headway is highly variable, as shown by Figure 15 which shows headway for vehicles on a highway.

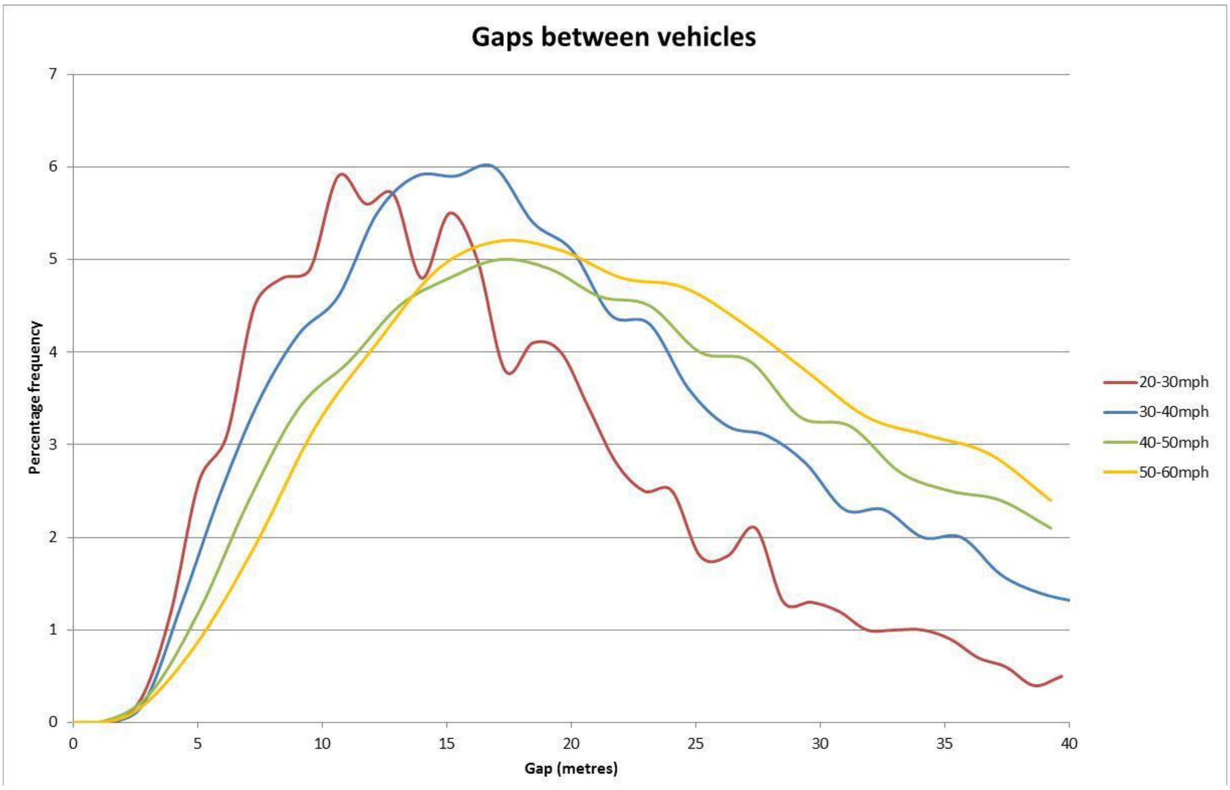


Figure 15: Vehicle Headway [31]

Traffic Intensity and State (Short-Term)

The volume of traffic will have an impact on the total demand on a DWPT system and can be affected by factors including:

- Time of day - morning and evening rush hours are likely to have greater traffic volumes for many roads;
- Day of the week - weekdays would be expected to have greater traffic volumes;
- Roadworks and obstructions – can cause temporary lane closures leading to greater volumes of traffic in other lanes in multi-lane roads. This could result in either increases or decreases in load depending on how the DWPT lane is affected; and
- Traffic collisions – can lead to lane closures and even temporary periods of stationary traffic.

In addition to these factors, whether the state of traffic is free-flowing or stop-start will determine the frequency and magnitude of short-term second by second variations in the load. High traffic volumes will be less likely to be free flowing and therefore more likely to produce greater system load variability.

Real-Time Power Transfer Efficiency (Short Term)

Whilst a DWPT system will have a peak efficiency, the variability of key factors such as alignment will impact how the system efficiency – and therefore network load – varies in real time. (See section 3.2 on page 19 for more details)

Intra and Inter-day Variations (Long Term)

DWPT load will have a positive correlation with traffic intensity. Therefore, there are likely to be peaks in demand during weekday rush hour traffic, which can coincide with existing peaks in demand on the network. This is discussed further in 4.3.7 (on page 40).

> An individual vehicle's battery SoC and current power demand will impact the overall rate of power transfer in the short-term.
> Vehicle type will greatly impact the short-term power demand on the network.
> Vehicle headway will vary the short-term power demand of the system.
> DWPT systems will need to be designed to handle a range of traffic speeds and thus be matched to the road type and likely traffic throughout the day and week.

4.3.6 Variations due to Road Characteristics

The characteristics of the road selected for DWPT will affect the load and its variability between segments on the same road and segments on different roads. The variables include:

- **Environment –** DWPT systems have been proposed for urban, intra-urban and highway scenarios. The different road types will have an impact on the traffic intensity, speed (due to driver behaviour, traffic management systems and speed limits) and likelihood of stop-start traffic flow.
- **Number of lanes** – both the number of lanes in total and the number of electrified lanes (all current demonstrators and deployments include a single "charging lane" only) will influence the vehicle types and nature of traffic flow that use the DWPT system.
- **Slope** – An often-ignored factor that will have a large impact on the real-time individual vehicle demand. A flat road is most likely to encourage free-flowing traffic and therefore most likely to be suitable.
- **Planned routes –** As already mentioned, some DWPT systems have been designed to be used by vehicles use designated routes, only. Deploying a system that coincides with these routes can give an assured, predictable use case.
- **Proximity to junctions –** Junctions on highways can cause disruptions to traffic flow as vehicles leave and merge onto the carriageway. Likewise, stop-start flow is enforced on intra-urban and urban roads with roundabouts or traffic lights. [31] acknowledged that although traffic speed is likely to be lower, and therefore power transfer efficiency increased, if deploying a system within close proximity to such features, it is imperative to understand the impacts. It is preferable to deploy on a clear stretch of road if possible.
- **Ground-side coil length and overlap –** The length of the ground-side coil, the gaps between adjacent coils and how the power transfer is transferred from one coil to the next affects the nature of rapid load fluctuations.
- **Charging system length and layout –** Clearly there is a correlation between the length of the charging system deployment and the potential load. However, in addition to this there are two potential layouts for a scaled system:
  - **Continuous –** The charging system is deployed as a single continuous charging lane.
  - **Distributed –** The charging system is deployed as discrete lengths with non-electrified sections between. The FABRIC project defined a parameter – the e-road penetration δ – in [12] to describe the proportion of a road that has DWPT deployed in order to evaluate the extended vehicle range:

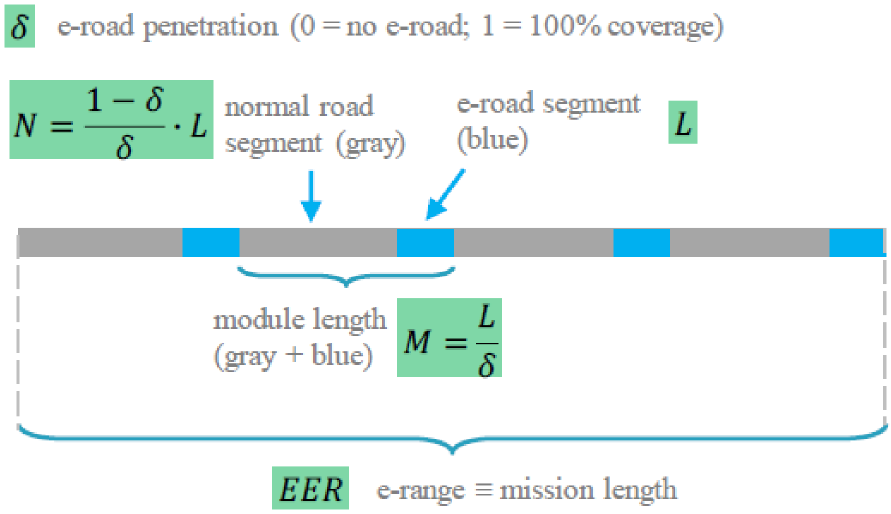


Figure 16: E-road penetration parameter [12]

For the DynaCoV project, it will be necessary to evaluate the road characteristics to understand their impact on system load.

4.3.7 Previous Load Modelling

The load variation of a DWPT system has been studied in a number of projects:

- FABRIC – technical requirements [31], gap analysis [25] and report on effect of upscaling to vehicle fleet and energy grids [12]
- UNPLUGGED – Technical feasibility of en-route charging technical report [32].
- ZeEUS – Grid impacts of electric bus system based on bus stop charging [33].

FABRIC modelling

The FABRIC project [31], [25] modelled the potential impact of traffic intensity and environment on system load using two models; one from the Institute of Communication and Computer Systems (ICCS) and a second from the Politecnico di Torino (POLITO).

The ICCS model first looked at a coordinated scenario with vehicles travelling at 36 km/h with a headway of 30 m (equating to 3 second intervals) over 267 50 kW power transfer modules on an 8.01 km route. This concluded that the maximum power demand was 13 MW.

Next, an uncoordinated traffic scenario was considered using a probabilistic model. The probability of a vehicle interacting with any transmitter coil was varied between 15%, 50% and 75% to model light, medium and heavy traffic. In addition, both urban and intra-urban environments were considered where the speed and minimum headway was changed. The simulation parameters used are shown in Table 11:

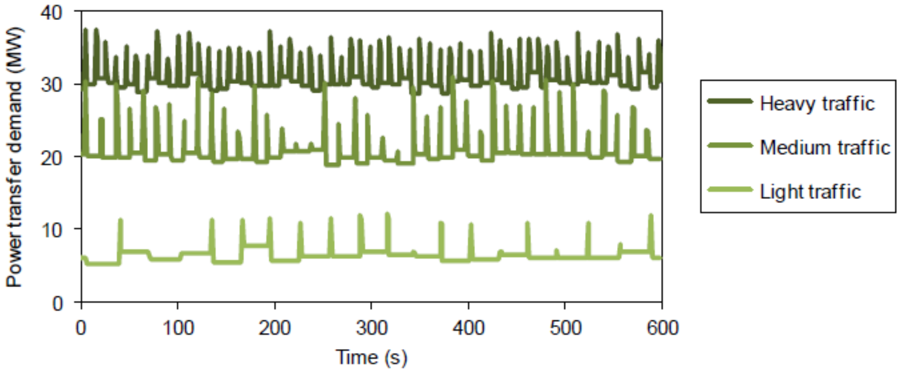
Table 11; Uncoordinated traffic simulation parameters, ICCS model, FABRIC [1]

Scenario	Pad entrance probability (%)	Vehicle speed (km/h)	Min. head-way (m)	Vehicle length (m)
		urban / inter-urb.	urban / inter-urb.	
Light traffic	15	36 / 108	5 / 10	5
Medium traffic	50	36 / 108	5 / 10	5
Heavy traffic	75	36 / 108	5 / 10	5

The results over a 10-minute interval are shown in Figure 17 for each environment.

! Note that the load was not constrained by the charging equipment, each module of the charging system was set at 30 m in length, with all interfacing vehicles assumed to demand the maximum power of 50 kW from each transmitter coil. This means that rapid changes in instantaneous vehicle demand is not considered). It is not clear how the fluctuations were modelled from the reported results.

Urban



Intra-urban

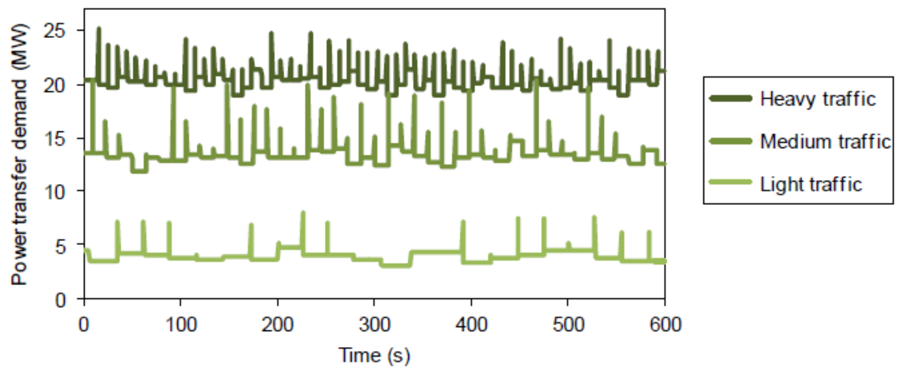


Figure 17: Load Simulations from ICCS model - urban and intra-urban environments, FABRIC [31]

As expected, it can be seen that increasing the volume of traffic increases the system load and higher traffic volumes create more fluctuations in demand. The urban scenario creates greater loads and more fluctuations because there are lesser minimum headways.These results are summarised in Table 12.

Scenario		**Average [MW]**	**STDEV [MW]**	**MAX [MW]**
Urban	Light traffic	6.33	1.07	12.05
	Medium traffic	20.61	2.18	31.05
	Heavy traffic	30.80	1.88	37.50
Inter-Urban	Light traffic	3.95	0.52	8.20
	Medium traffic	13.29	0.89	20.30
	Heavy traffic	20.15	0.82	25.15

Table 12: Summary of ICCS Simulation Results, FABRIC [31]

The second model reported in [31] from POLITO showed the short-term demand fluctuations for a simulation with very similar input parameters for the traffic flow and infrastructure as the ICCS model. The results are shown in Figure 18; the demand was found to vary between 2 and 8 MW repeatedly over a short five second period.

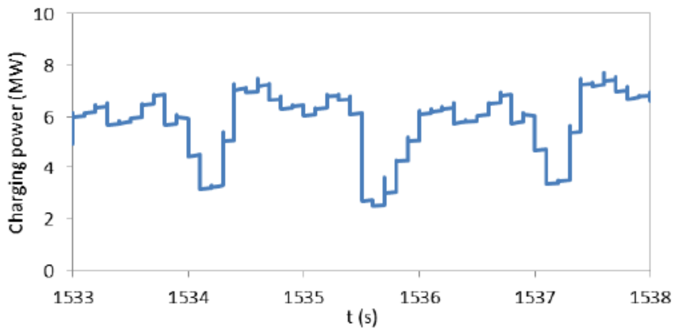


Figure 18: POLITO model simulation results, FABRIC [31]

[12] investigated the potential impact of DWPT systems at scale on the energy systems further. A method was devised to determine the power requirement for the grid connection as a result of the number of vehicles per km, by the following equation:

$$P_{km}[kW] = N_{vpk} P_{ch}[kW]$$

Where P_{km} is the power requirement per km, N_{vpk} the number of (compatible) vehicles per km and P_{ch} the charging power of the vehicle.

For modelling purposes, the charging power was set at a certain level for different environments, as shown in Table 13:

Scenario	Motorway E-Corridors/E-Road	Periurban (E-Launchers)	Urban (Bus)
Power per vehicle	50 kW	100 kW	100 kW

Table 13: Charging power parameters, FABRIC [12]

The number of vehicles per km in the Motorway scenario was set using an assumed security distance of 2 s and vehicle length of 4 m. This yielded the following values for N_{vpk}:

Vehicle speed v_{veh} (km/h)	Number of vehicles per km N_{vpk}	Distance between cars (m)
10	104.7	9.6
30	48.4	20.7
50	31.5	31.8
60	26.8	37.3
80	20.6	48.4
90	18.5	54.0
100	16.8	59.6
110	15.4	65.1
120	14.2	70.7
130	13.1	76.2

Table 14: Number of vehicles per km, FABRIC [12]

Despite Table 14 showing that much higher numbers of vehicles per km are possible, even with vehicles using a safe headway based on a 2 s security distance, results are proposed for 10-15 vehicles per km. This suggests that at low speed the charging power to each vehicle can be limited as more time is available for charging.

Charging power (per vehicle) P_{ch} $[kW]$	Grid power per km (Road converter station) P_{km} $[MW]$		Grid power per 25 km (HV/MV substation rating) P_{25km} $[MW]$	
	$N_{vpk} = 10$	$N_{vpk} = 15$	$N_{vpk} = 10$	$N_{vpk} = 15$
20	0.25	0.38	6.3	9.4
50	0.63	0.94	15.6	23.4
100	1.25	1.88	31.3	46.9

Table 15: Grid power requirements for motorway environment, FABRIC [12]

Table 15 shows that the power requirement for a 25 km stretch of DWPT could be in the range of 6 – 47 MW for these lower vehicle numbers. Alternatively, 30 vehicles per km at a charging power of 20 kW would yield a total load of 18.8 MW for a 25 km length with 80% transfer efficiency. The author suggested that these are reasonable values for a HV/MV substation transformer and proposed a modular deployment as per the network interface architecture shown in Table 16 to support DWPT lengths of 1 km.

The "peri-urban" environment was also considered but limited to heavy vehicles only. The lower numbers of vehicles per km yielded lesser power requirements:

Charging power (per vehicle) P_{ch} $[kW]$	Grid power per km (Road converter station) P_{km} $[MW]$		Grid power per 10 km (HV/MV substation rating) P_{10km} $[MW]$	
	$N_{vpk} = 5$	$N_{vpk} = 7.5$	$N_{vpk} = 5$	$N_{vpk} = 7.5$
50	0.31	0.47	3.1	4.7
100	0.63	0.94	6.3	9.4
150	0.94	1.41	9.4	14.1

Table 16: Grid power requirements for peri-urban environment, heavy vehicles only, FABRIC [12]

This was extended to consider the use case of buses, building upon the work that had previously been completed in the UNPLUGGED project. This considered the power requirement on a power density basis for three potential solutions: a continuous 50 kW DWPT lane, 25 m 100 kW DWPT "tracks" at each bus stop (similar to the OLEV solution [2]), and stationary 150 kW charging at each stop (as per the ZeEUS demonstrations [23]).

UNPLUGGED modelling

UNPLUGGED demonstrated static/stationary charging systems only and therefore the majority of the work was done considering the impact of introducing static/stationary wireless charging on specific areas – London, UK and Firenze, Italy.

However, one of the project's key deliverables was a feasibility study into "en-route" wireless charging and its use in urban environments. As part of this feasibility study, a very early modelling exercise was completed to investigate the impact of such a system on extending battery range by looking at the potential individual vehicle demand if vehicles were charged during idle phases of either the NEDC or WLTP drive cycles. Unfortunately, this is hypothesising static charging rather than DWPT and therefore not in-scope of this report.

Highways England

Highways England used inductive motorway (MIDAS) traffic flow data from a single term-time weekday (Monday 7th October 2013) to simulate the network load for two DWPT system layouts. The layout parameters are summarised in Table 17:

	Layout 1	Layout 2
Maximum number of charging vehicles	2	1
Coil length	8 m	9 m
Coil separation	5 m	0 m
Segment length	50 m	40 m
Segment separation	25 m	Short (order of 2-5 m)
Maximum power transfer per coil	100 kW	140 kW
Maximum power transfer per segment	200 kW	140 kW

Table 17: Highways England DWPT Layouts [11]

Two scenarios with varying levels of assumed vehicle compatibility penetration were simulated for each layout:

- Scenario A (medium penetration):
    - Light vehicles 30%
    - Heavy vehicles 50%
- Scenario B (high penetration):
    - Light vehicles 50%
    - Heavy vehicles 75%

The results are shown in Figure 19. The maximum power is calculated using the maximum measured traffic flow whilst the average power flow is calculated using the average measured traffic flow.

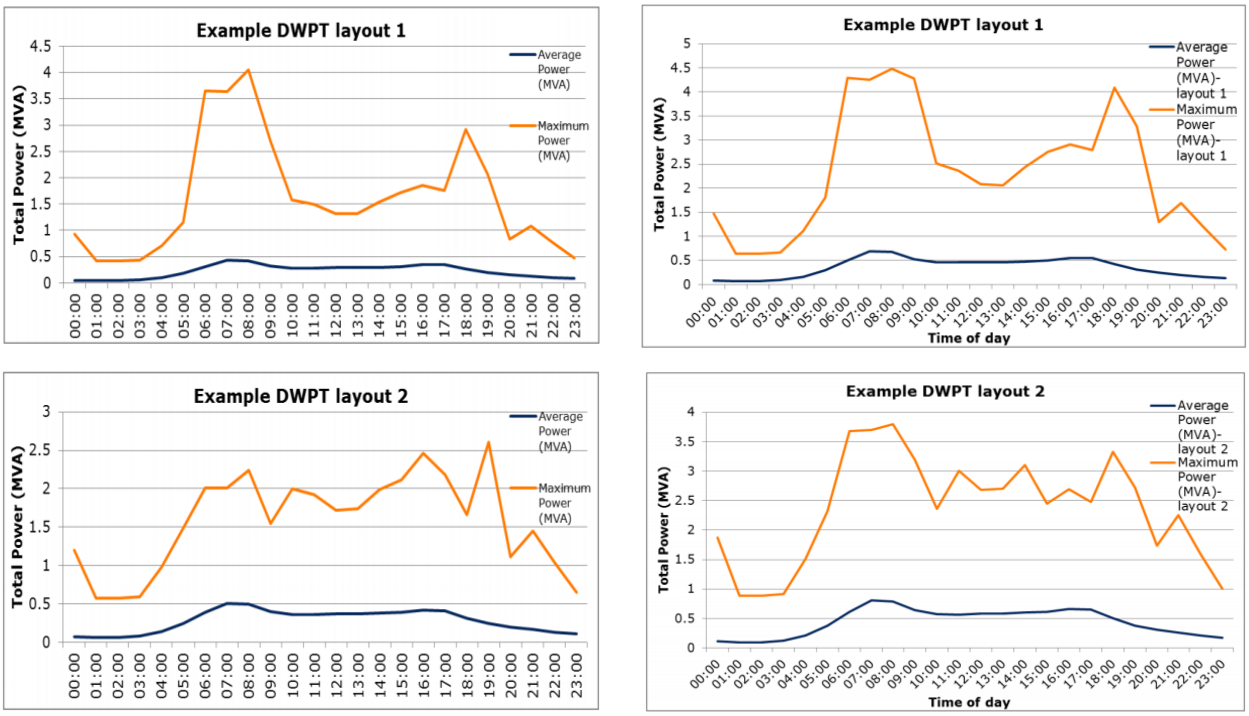


Figure 19: Predicted load profiles, clockwise from top-left: Layout 1 Scenario A; Layout 1 Scenario B; Layout 2 Scenario A; Layout 2 Scenario B

The results show that layout 1 allowed greater maximum demand for both scenarios but during times of high demand, layout 2 could only provide a limited amount of power.

Drawing conclusions is difficult as a result of the large number of variables changed between the two layouts. In both cases only the long-term load changes are modelled – the rapid load fluctuations as a result of coil and segment separation is not considered. The report summarised that high peaks and variations in power demand were possible due to traffic conditions, the layout and the maximum power supply capability of the DWPT system deployed.

[11] extended the study of DWPT system demand by applying it to a specific location on England's Strategic Road Network (SRN). A section between junctions 5 and 6 on the M6 in the West Midlands was selected as a 'typical' road section to evaluate the network impact. The evaluation predicted a maximum load of 4.04 MVA for the use case of 16 HGVs on a 1 km road length with a system efficiency of 75% and power factor of 0.95.

Other studies

Deflorio and Castello [34] presented the results of a traffic model based on POLITO's Charge While Driving (CWD) system. The model accounted for key variables such as headway, battery state of charge (SOC), traffic density and vehicle speed to simulate the use of DWPT for a freight route on the slow lane of a multi-lane highway. This report focussed on how traffic flow would affect usage but not the impact this would have on the electricity network.

Meanwhile, Karakitsios et al [35] created a process to identify the amount of DWPT that could be deployed without exceeding a local electricity network constraint, in addition to conductive home-based charging and static inductive charging. A single primary transformer in the area of Katerini, Greece was investigated as a case study. The assumptions used in the modelling are not clear, however the result indicates how DWPT can cause long-term temporal shifts (see Section 4.3.5) in demand for EV charging, as shown by Figure 20:

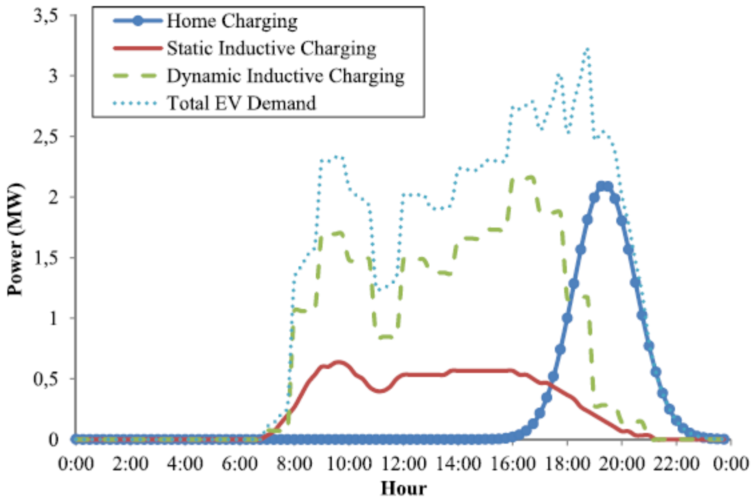


Figure 20: Modelled EV Charging Demand from [35]

Garcia et al [36] studied DWPT for three road types: motorway, highway and urban stretch using Cadiz, Spain as the case study. The study used real traffic data to investigate the real time energy demand for DWPT from hypothetically compatible vehicles, modelling annual and intra-day demand variation. An example output for the urban stretch case study is shown in Figure 21:

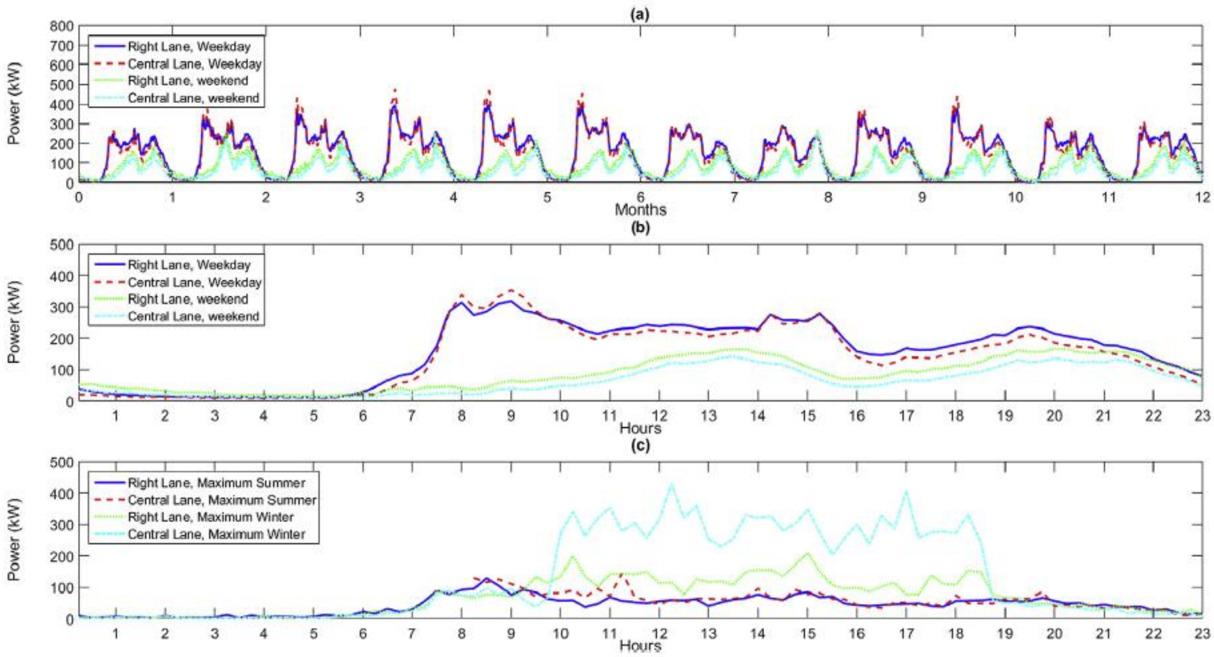


Fig. 15. Power required by the entire DWPT system in the urban stretch: a) Monthly average; b) Annual average; and c) Days of maximum intensity.

Figure 21: Urban case study power requirement for DWPT [36]

Most previous projects have completed modelling into the variation of load required by DWPT; general conclusions can be drawn but the specific results are highly dependent on the input assumptions and the range of results is high in some cases.
Increased traffic volumes increases both the overall system demand and fluctuations in demand, whether across the year, in the week or within the day.
Urban DWPT creates the greatest system demand due to smaller headway between vehicles.

Demand can vary significantly over very short timescales (i.e. five to ten second windows).

4.4 Storage and On-site Generation

Due to the high peak loads and highly variable demand of a DWPT system, it may be desirable to reduce the impact on the distribution network. This sub-section investigates how Energy Storage Systems (ESS) and on-site generation could be integrated with DWPT.

! It is important to note that if the local DNO is willing to connect a system with highly variable loads, then these measures will not be necessary. If not, the costs associated with the additional technology would have to be included in the DWPT business case.

4.4.1 Energy Storage Systems (ESS)

The FABRIC project modelled the smoothing effect of an energy storage system (ESS) on the urban and intra-urban simulation cases shown in section 4.3.7 (page 40). The results, shown in Figure 22, are given for 5, 20 and 60 second smoothing windows over a 10-minute period:

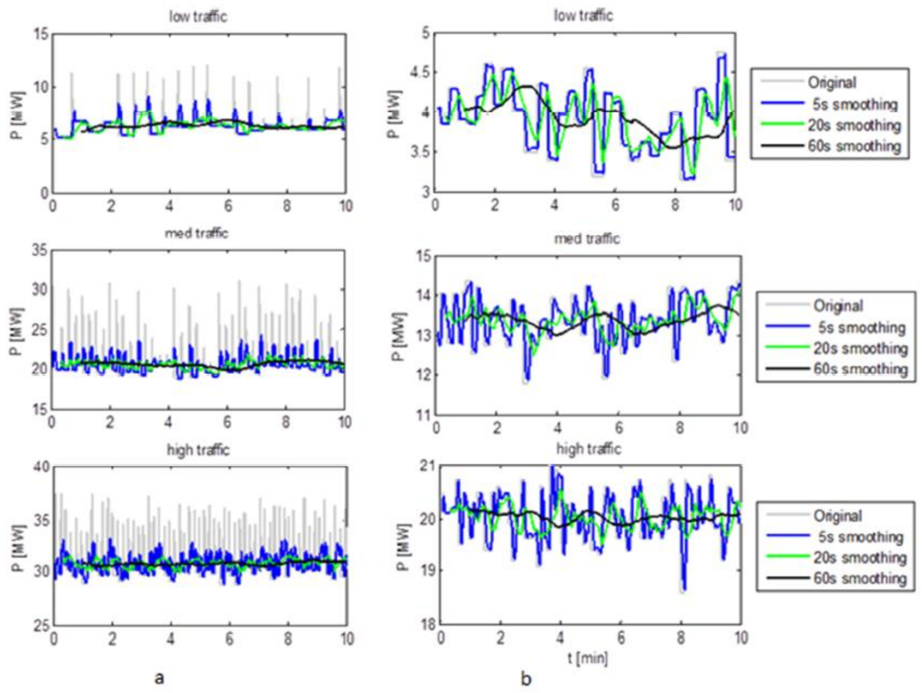


Figure 22: Energy Storage System demand smoothing results, FABRIC [25]

The project concluded that:

- where fluctuations are very high in the urban case, a 11.4 MW, 8.2 kWh ESS is required with a smoothing window of 5 s and typical discharge time of 2.6 s; and
- where fluctuations are lesser in the intra-urban case, a 2 MW, 8 kWh ESS is required with a smoothing window of 60 s and typical discharge time of 20 s.

Whilst noting that these requirements are based on preliminary unverified models, [25] acknowledged that a suitable ESS is a key requirement for a DWPT system deployed at scale.

The suitable technologies identified at the time were supercapacitors and flywheels due to the requirements for high power, fast discharge time and low capacity. The recommendation was for a supercapacitor system, as this could be integrated into the system DC bus to reduce losses and therefore more easily co-located with other grid infrastructure. Whilst Battery Energy Storage Systems (BESS) have been developed considerably since the FABRIC project concluded, current technology is still not appropriate for this application. For instance, while a high-power system could be designed, it would need to be grossly oversized in order to achieve the required power.

A suitable high power, fast discharge, low capacity Energy Storage System is likely to be needed to reduce the impact of DWPT on the distribution network.
Supercapacitors are currently a well-suited technology as they can be incorporated into the DC bus to reduce losses.

4.4.2 On-site generation

The FABRIC project also investigated the possibility of integrating sustainable generation with a DWPT system.

Solar generation was evaluated first, based on the hypothesis that solar power generated during the day would coincide somewhat with periods of higher vehicle driving demand. Two case studies were considered: Madrid (32.5 MWp installation) and Stockholm (49 MWp installation). Contrary to the initial hypothesis, the project found that solar power has only limited effectiveness in reducing peak early morning and late afternoon rush-hour loads. Furthermore, it exports large loads during the middle of the day when traffic is lighter. This could be problematic depending on the nature of existing loads on the local network and if it already has generation constraints.

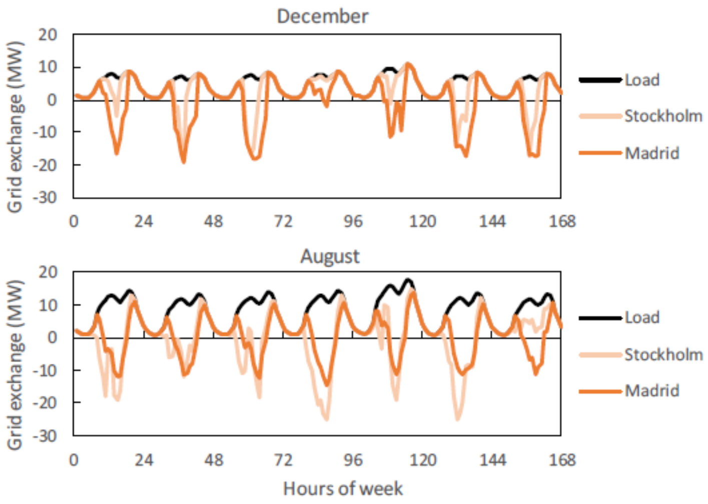


Figure 23: Integration of Solar PV, FABRIC [12]

Wind generation was also studied with the caveat that real wind generation is very location dependent.

Finally, the integration of a BESS with solar and/or wind was studied as a natural progression to provide smoothing between the peak DWPT system loads and the peak generation times.

Self-sufficient micro-grids were considered. However, the conclusion was that for the 25 km DWPT system, prohibitively large storage capacity would be required for this to be possible.

Consequently, a 24-hour smoothing model was run in an attempt to optimise the system to limit the import and export from the network. Whilst this resulted in much more feasible storage system sizes, the order of magnitude was still hundreds of MWh for a 25 km stretch of electrified road. The results are shown in Figure 24 and summarised in Table 18. Note that for each of these cases a BESS is included.

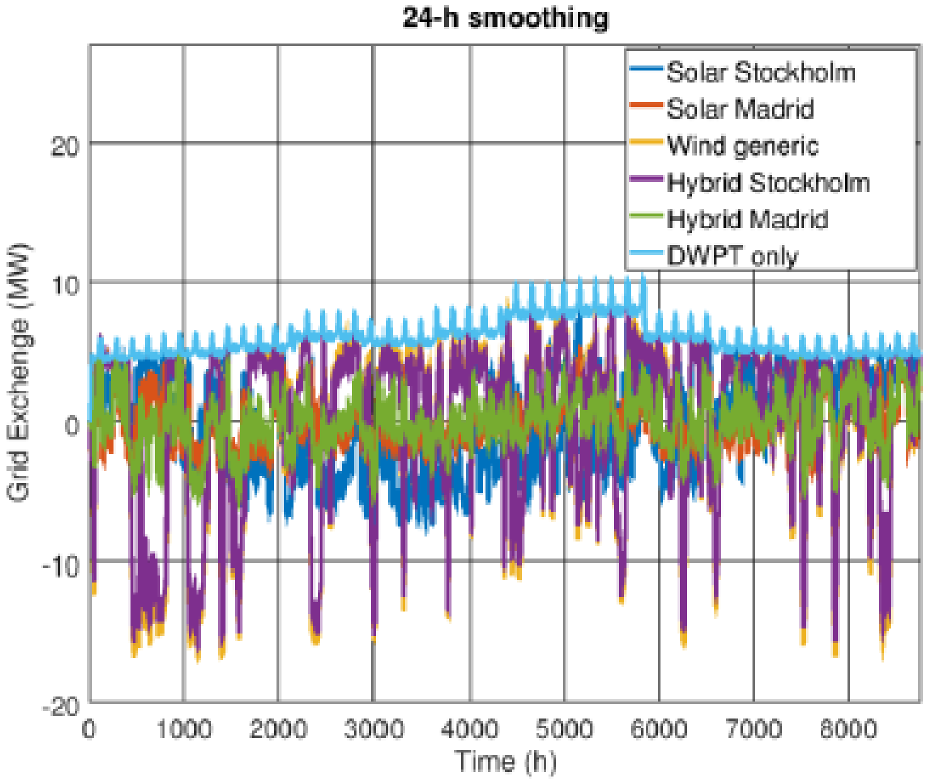


Figure 24: BESS and On-Site Generation Results, FABRIC [12]

Table 18: Grid connection results, FABRIC [12]

E-road RE show case	RE P_{inst} (MW)	P_{ESS} (MW)	E_{ESS} (MWh)	Annual grid exchange (GWh)	System demand peak (MW)	System back-feed peak (MW)	RE Self-consumption ratio (%)
Only e-road	0	9.5	136	52.3	10.1	0.0	0%
Solar PV Stockholm	49.0	27.8	266	27.7	8.1	7.4	73%
Solar PV Madrid	32.5	24.0	183	13.4	5.2	3.5	87%
Wind Spain	22.5	27.9	425	46.1	9.8	16.8	56%
Solar-Wind Stockholm	24.5	26.1	397	42.8	9.2	16.1	59%
Solar-Wind Madrid	31.0	18.4	196	13.8	5.2	5.7	87%

On-site generation combined with storage options may offer options to smooth the demands of DWPT on the distribution network, although they introduce additional complexities when exporting and may add costs that erode the business case.

4.5 Power Quality

DWPT also have an impact on the power quality of the local electricity network. For instance, Highways England's feasibility study on DWPT for the SRN [11] acknowledged the possibility that this might adversely affect other road electrical infrastructure (such as road loops, radar, communications, cabling and utilities) either through physical connections or transmitted electromagnetic fields.

The ZeEUS project produced a summary of the characteristics that could be impacted by DWPT:

Table 19: Voltage characteristics of public distribution networks, from ZeEUS [33]

	Voltage characteristics according to EN 50160
Power frequency	50 Hz ± 1 % during 99.5 % of a year 50 Hz + 4 % / -6 % during 100 % of the time
Supply voltage variations	At least 99 % of the 10 min r.m.s values of the supply voltage shall be inside the limits of ±10 % None of the 10 min r.m.s. values of the supply voltage shall be outside the limits ±15 % NOTE: The percentages above refer to a measuring period of one week (i.e. to 1 008 intervals of 10 min)
Rapid voltage changes and flicker	Plt ≤ 1 for 95 % of week
Supply voltage dips and swells	The dip threshold is equal to 90 % of the reference voltage The swell threshold is equal to 110 % of the reference voltage
Harmonic voltage	3rd ≤ 5 %, 5th ≤ 6 %, 7th ≤ 5 %, 9th ≤ 1,5 %, 11th ≤ 3,5 % THD ≤ 8 % of week mean 10 minutes r.m.s values
Supply voltage unbalance	During each period of one week, 95 % of the 10 min mean r.m.s. values of the negative phase sequence component of the supply voltage shall be within the range 0 % to 2 % of the positive phase sequence component

As mentioned previously (Section 3.5 on page 25) the ElectReon system has undergone independent tests for EMC and EMF, so this appears to be less of an issue for the current solutions on the market.

4.5.1 Harmonics

The non-linear loads in high power charging systems create harmonic currents and cause harmonic distortion to the system voltage. Harmonics are controlled in order to protect other devices connected to the network as well as for the efficiency and safety of the network itself. DNOs require systems to be in accordance with certain standards such as IEC 61000, IEEE 519-2014 or Engineering Recommendation (EREC) G5 in order to connect to their networks. This applies to conductive and wireless charging systems. If a dedicated MV transformer were to be provided for a DWPT system, then standards may be less critical, but harmonics should still be considered and controlled.

Highways England [11] identified the sources of non-linear loads that could cause network disturbance:

- Solid state inverter often used for controlling variable speed drives and variable frequency loads.
- High power inverters used to convert the DC power supply to ground coils to AC for DWPT.

In addition, [11] presented the expected harmonics from the IPT technology equipment used for static wireless charging of electric buses in Milton Keynes. The system produces strong 5th and 7th current harmonics, as shown by Figure 25, although the voltage harmonics were within the recommended levels of G5/4.

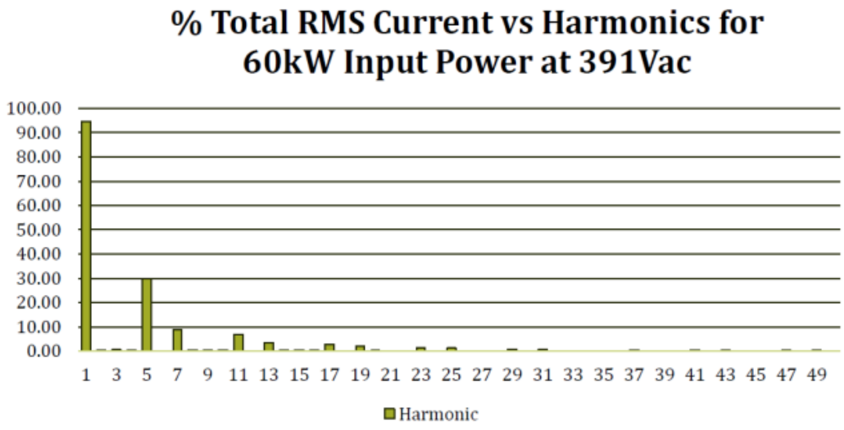


Figure 25: Milton Keynes Static Wireless Electric Bus Charging - Current Harmonics [11]

The ZeEUS project [33] simulated the harmonic distortion on the distribution networks in Münster and Helsinki resulting from deploying DC conductive chargers. Whilst this is not a study of a DWPT system, the peak loads are of a representative order of magnitude (16.5 MW). The result was that the current Total Harmonic Distortion (THD) was very close to the applied local limit of 5%.

This report acknowledged that the studies were done using zero assumed grid THD, which is not representative. Had this been applied, the THD of the modelled systems may have been found to be above the acceptable limits. [11] stated that UK Power Networks recommended that harmonic filters be fitted as part of the ZeEUS project installation, which used the same IPT Technology hardware as the Milton Keynes electric bus project.

The FABRIC project [25] recognised the requirement to meet the European IEC standard 61000-3-12 for systems connected to LV with currents equal to or above 16 A, and that the state-of-the-art on-road solutions did not have test results for harmonics. As part of this gap analysis, the recommendations were:

- To design high-frequency harmonics filters that were not overly detrimental to system efficiency; and
- Complete harmonics testing during the project.

[21] presented the compliance with electromagnetic compatibility regulation as part of a review of the existing charging solutions – both static and dynamic wireless, and dynamic conductive. This information is summarised in Table 20:

Table 20: Electromagnetic Compatibility compliance summary [21]

	System Type	Total Harmonic Distortion (THD)
POLITO CWD	Dynamic wireless	No information given
Saet-Spa IPV	Dynamic wireless	No information given
Primove	Dynamic wireless	"The PRIMOVE system has been show to meet EN standards for electromagnetic compatibility except at the primary power transfer frequency, where it has been demonstrated and accepted that no harm arises from the exception. The TUV SUD has confirmed that the Primove systems complies with the regulations and requirements regarding [electromagnetic] compatibility."
Qualcomm / Vedecom	Static wireless (then used for dynamic wireless)	No information given.

Volvo ERS	Dynamic conductive	Not measured (expected to meet IEC 61000-3-4)
ORNL	Dynamic wireless	Current harmonics <4%
OLEV	Dynamic wireless	No information given
Conductix Wampfler	Static wireless	IEC EN 61000-3-4 applies
Plugless Power	Static wireless	V THD: 4% I THD: 112%
Siemens e-Highway	Dynamic conductive	No information given
Elways	Dynamic conductive	“As wanted – depending on specification”

The impact of harmonic distortion on local electrical infrastructure must be addressed in DWPT systems.
Existing research indicates strong harmonics from static charging examples, which required filters to be fitted.
DWPT systems should include high-frequency harmonic filters and test harmonics during operations.

4.5.2 Supply Voltage Variations

The high localised loads and rapid demand variations from a poorly controlled DWPT system could have adverse effects on the supply voltage. Connected equipment will need to be in accordance with EREC P28.

This was acknowledged in [17] for rapid voltage fluctuations due to the change in absorbed power as an individual vehicle moves from one transmitter coil to the next. This summary report references a method of using a smoothing architecture with a bidirectional converter to reduce harmonic emissions [37].

Highways England [11] also investigated the potential for DWPT systems to introduce voltage fluctuations as a result of “sharp variations in demand” as vehicles pass over primary coils. This report describes the power transfer from each individual coil in three stages: pick-up, steady state and drop off. It is stated that a DWPT supplier would need to understand and control potential inrush currents during coil start up during the pick-up phase. This report produced a demand profile for a vehicle passing over a 20 m coil at 80 km/h in 0.9 s.

! Note that the coil is much larger than those used in current solutions and this research is only theoretical, and not based on a real system or validated by testing.

The frequency of disturbances clearly depend on vehicle speed and coil length. [11] gave an additional example of a 5 m primary coil and vehicle speed of 90 km/h producing 5 Hz fluctuations, noting that this would be subject to the harmonic limits of EREC G5/4.

[11] also analysed the HGV use case against the requirements of EREC P28 for voltage change and flicker severity, acknowledging this would require a case-by-case assessment by the DNO to understand whether the system was permissible at that specific point of network connection. The report stated that the DNO is likely to connect peaky loads such as that shown in Figure 27 at HV with a dedicated section of network, potentially owned by the DWPT operator.

Figure 26: Illustrative DWPT Demand Profile for a Single Primary Coil [11]

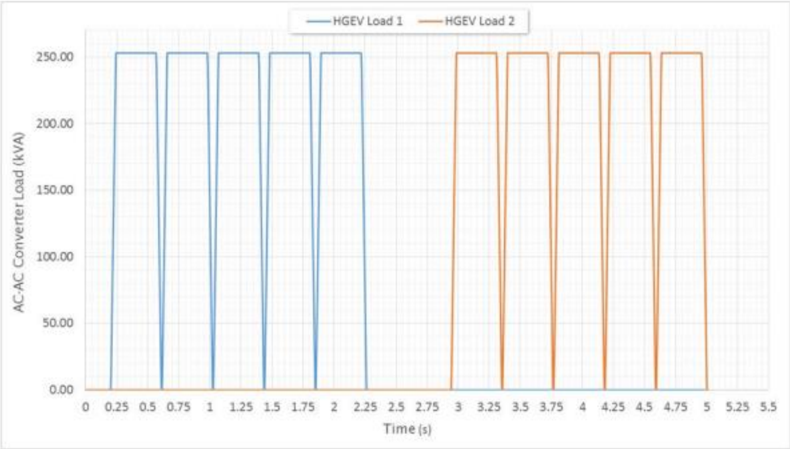


Figure 27: HGV Use Case Load Profile for Power Quality Assessment [11]

The ZeEUS project's modelling exercise [33] on the impact of deploying high powered conductive charging, as introduced in 4.5.1, found that supply voltage impact will be greater on substations with lower MVA ratings and lower X/R ratios. Typical X/R ratio was 4-7 but values under 2 could give problems "due to high resistance induced voltage sag".

DWPT systems must be compliant to EREC P28 and will need to control inrush currents during the coil start-up in the pick-up phase of power transfer.
The frequency of disturbances depends on vehicle speed and coil length, although key modelling outputs appear to use unlikely coil lengths.

4.5.3 Power and Quality Factor

As part of the conversion from AC power at grid frequency to high frequency wireless power transmission, wireless charging systems employ power factor correction to ensure a high power factor and low harmonic content. Machura and Li [10] reviewed the compensation topologies for wireless charging systems, stating that "the main purpose of the system's primary compensation network [is] to reduce the reactive power rating (Var) or the power supply by cancelling out the reactive component of the primary coil". They also provided diagrams of system topologies and equations for power factor and quality factor.

Despite this, limited information is available on the power factor and quality factor of existing wireless charging systems in the review completed by the FABRIC project in [21]. This is partly due to limitations obtaining proprietary commercial information and also the relatively early state of the market at this time.

DWPT projects should measure power factor and quality factor to improve the knowledge base.

4.6 Smart Systems

As with any public-use EV charging, DWPT systems will require a communications infrastructure in order to authenticate and bill users. ICT can also facilitate smart systems which can be used to better control the charging power to support the local grid. The discussion and modelling results shown in Section 4.3 (page 32) have shown that is likely to be necessary.

However, if a dynamic charging system is being used to ensure the operation of fleet vehicles or extend vehicle range, then reducing charging power in real-time is likely to be highly complicated to manage. The users may have much less flexibility in comparison to static conductive charging systems where the vehicle is parked for long periods of time. In fact, the principle of reducing power or deferring charging through either smart charging or V2G diminishes the business case for DWPT.

The FABRIC project studied how demand side management could be introduced to DWPT and highlighted the applicability of existing protocols Open Charge Point Protocol (OCPP) and Open Smart Charging Protocol (OCSP) [38].

Bidirectional wireless charging is also a theoretical possibility which could be used to mitigate risks of the grid impact of DWPT systems. However, Vehicle-to-Grid (V2G) systems are not yet fully understood for static systems, regardless of whether they are conductive or wireless, and business models tend to rely on long dwell times of vehicles. Consequently, bidirectional DWPT is not expected to be a key research area.

DWPT systems should leverage existing protocols such as OCPP and OSCP within their communications infrastructure.
However, varying the timing, power or direction of power transfer through smart charging or vehicle-to-grid will undermine the business case for DWPT and should not be a focal point for future research.

4.7 Cost

It is likely that a DWPT deployment of significant scale will incur significant network upgrade costs and/or need a new connection point. These costs will vary greatly depending on location and the exact deployment specifications. The vast majority of DWPT cost studies have focussed on the cost of the DWPT hardware, installation and highways infrastructure costs, rather than the network infrastructure costs.

The only known network infrastructure cost study was done as part of [11]. Three network connection ownership architectures were proposed, as shown by Figure 28.

! Note this research does not differentiate between MV and HV voltages.

- Option A: DWPT operator connects at LV with a meter provided for each DWPT segment;
- Option B: DWPT operator connects to the LV side of a HV/LV (possibly MV/LV) substation owned by the DNO; and
- Option C: DWPT operator owns the HV (possibly MV) network and connects to the MV side of the DNO's HV primary substation.

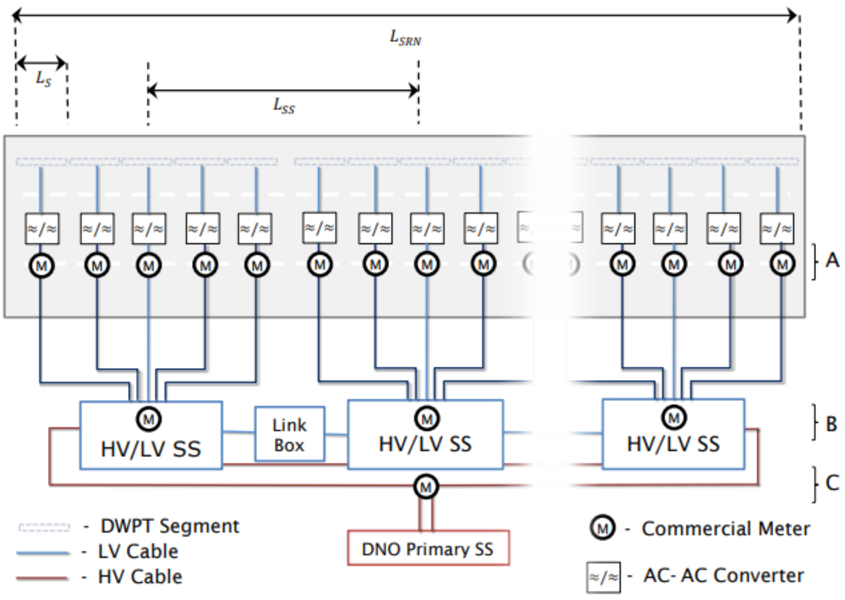


Figure 28: Highways England Cost Study Network Connection Architecture Options [11]

The following tables show the estimated cost payable to the DNO for connecting each of options for a 1 km stretch of DWPT road, again using the M6 between junctions 5 and 6 as the case study. Costs were provided by WPD for the 2015 Highways England report [11].

The key conclusion is that each subsequent option has less up-front costs payable to the DNO as a result of increased DWPT operator system ownership.

Item	Description	Cost
LV Cable	1km of 300mm^2 Combined Neutral and Earth (CNE) LV cable, ducted, with civils costs excluded. Includes cost for 3 off LV link boxes.	£25,000
HV Cable	1km of 11kV 300mm^2 aluminium cable, ducted, with civils costs excluded.	£30,000
4 off 1MVA substations	11kV/0.4kV 1 MVA substations.	£120,000
HV cabling Security of Supply	A length of HC cable laid from the primary substation and an extra Ring Main Unit (RMU) provides security of supply and back feeding capability in case of a network fault.	£200,000
20 off 3 Phase Supply	250kVA 3 phase service (cable and cut-out).	£50,000
Total Cost		£425,000

Table 21: Cost table with WPD providing infrastructure to meter points in Option A

Item	Description	Cost
HV Cable	1km of 11kV 300mm^2 aluminium cable, ducted, with civils costs excluded.	£30,000
4 off 1 MVA substations	11kV/0.4kV 1MVA substations.	£120,000
HV cabling Security of Supply	A length of HV cable laid from the primary substation and an extra Ring Main Unit (RMU) provides security of supply and back feeding capability in case of a network fault.	£200,000
Total Cost		£ 350,000

Table 22: Cost table with WPD providing infrastructure to meter points in Option B

Item	Description	Cost
HV cabling Security of Supply	A length of HV cable laid from the primary substation and an extra Ring Main Unit (RMU) provides security of supply and back feeding capability in case of a network fault.	£170,000
Building Cost		£10,000 - £20,000
Total Cost		£ ~190,000

Table 23: Cost table with WPD providing infrastructure to meter points in Option C

Only one study has been completed on the distribution network costs aspect of DWPT installations, so more research is needed.
Highways England and WPD concluded that the network connection costs will decrease as the DWPT operator ownership (point of connection) moves up the voltage levels of the network.

4.8 Conclusion

Examining the evidence presented above, the following conclusions can be drawn:

Electricity Network Interface:

- DWPT operates at frequencies between 10 and 100 kHz, often centred on 85 kHz, and requires AC/DC and DC/AC converters to increase the frequency of power supplied.
- At-scale deployments are expected interface with the Medium Voltage line in the UK.
- DWPT deployments should adopt a modular design to allow for scalability and reduce distribution network impacts.

Load:

Maximum theoretical load:

- The maximum theoretical load is a factor of the transmitter coil ratings, number of coils per road segment, number of segments per substation and vehicle type.
- In reality, the maximum theoretical load is never attainable because of a range of variables, mentioned below.
- In practice, the MU rating becomes the main limiting factor on the theoretical load.

Variables impacting on the load:

- Efficiency - the network will need to supply more power than is received by the vehicle.
- Load management – may be required to ensure charging adheres to any system constraints if a DNO is unwilling to accept the connection of a highly variable load.
- Use case – targeted use cases will increase vehicle-side benefits and manage load variability but it must be noted that targeting multiple use cases will improve the business case.
- Short-term - vehicle SoC, current power demand, type and headway will all impact the instantaneous rate of power transfer.
- Long-term - traffic speeds, road type and variations in traffic will all impact the overall rate of power transfer.
- Road characteristics – environment, lanes, slope, planned routes, junction proximity, coil length and overlap, charging system length and layout all impact on the distribution of system load in space.

Load modelling:

- Most previous modelling into the variation of load allows general conclusions to be drawn but the specific results and range of outputs are highly dependent on the inputs.
- Traffic volumes impact both the overall system demand and fluctuations in demand, whether across the year, in the week or within the day.
- Urban DWPT creates the greatest system demand due to smaller headway between vehicles.
- Demand can vary significantly over short timescales (i.e. five to ten second windows).
- This project should deliver further modelling of the real-time short-term or long-term loads for a generic DWPT system with the key variables from this chapter as configurable inputs.

Storage and On-Site Generation:

- A suitable high power, fast discharge, low capacity Energy Storage System is likely to be needed to reduce the impact of DWPT on the distribution network.
- Supercapacitors are currently a well-suited technology as they can be incorporated into the DC bus to reduce losses.
- On-site generation and storage solutions may offer options to smooth the demands of DWPT on the distribution network, although they introduce additional complexities when exporting and may add cost that erodes the business case harder.

Power Quality:

- The impact of harmonic distortion on local electrical infrastructure must be addressed.
- Existing research indicates strong harmonics from static charging systems, which required filters to be fitted so DWPT systems should include high-frequency harmonic filters and test harmonics during operations.
- DWPT systems must be compliant to EREC P28 and will need to control inrush currents during the coil start-up in the pick-up phase of power transfer.
- The frequency of disturbances depends on vehicle speed and coil length, although key modelling outputs appear to use unlikely coil lengths.
- DWPT projects should measure power factor and quality factor to improve the knowledge base.

Smart Systems:

- DWPT systems should leverage existing protocols such as OCPP and OSCP within their communications infrastructure.
- However, varying the timing, power or direction of power transfer through smart charging or vehicle-to-grid will undermine the business case for DWPT and should not be a focal point for future research.

Cost:

- Only one study has been completed on the distribution network costs aspect of DWPT installations, so more research is needed.
- Highways England and WPD concluded that the network connection costs will decrease according to increasing interaction of the DWPT solution provider with the Medium or High Voltage networks.

5 Supply Chain Assessment

At its present stage of development, demand for DWPT technology is limited, with most deployments being attached to research & development projects, often supported by public funding. At this scale, it is most economical for the DWPT provider to carry out the upstream activities close to the supplier's base of operation and the downstream activities close to the deployment site and where possible using local staff. Opportunities to create a more distributed supply chain may develop as the DWPT marketplace achieves greater scale.

At time of writing, there are no DWPT OEMs or suppliers headquartered in the UK. Even were this to be the case, it is likely that several elements of the DWPT supply chain would still be outsourced to organisations based overseas for manufacturing and distribution cost competitiveness. In order to determine the potential economic value that DWPT could add to the UK economy, this section considers which elements of the DWPT supply chain *could* be fulfilled within the UK economy and, with that considered, which elements *should* be fulfilled within the UK economy, were DWPT technology to achieve mass market scale.

This section explores the key components of the DWPT supply chain identified during the literature review and provides an assessment of how feasible or beneficial it would be to fulfil each element within the UK economy. Of any of the solutions mentioned in this report ElectReon's DWPT product has the highest Technology Readiness Level and is closest to being commercially available. Hence, the red, amber, green assessments are based primarily on their system from discussions with ElectReon staff and Western Power Distribution consultants Ricardo Energy and Environment.

The security of the supply chain is of great importance, particularly for a fledgling industry that needs to build trust in its customers. In recognition of this, ElectReon use the Risk Exposure Index (REI) created by MIT to keep their supply chain resilient. The REI analyses supply chain resilience, identifies hidden risks, and suggests mitigation strategies to address these risks. An example of a mitigation activity identified and hence carried out by ElectReon was carrying stock of 'Class A' components which are expensive or hard to source, such as the chips used in the MUs.

5.1 Approach

5.1.1 Key Supply Chain Components

For the purposes of this report, the DWPT supply chain has been divided into four key categories, each containing several components, as shown in Figure 29. Although the categories apply to any DWPT solution, the assessment is tailored to ElectReon's solution for the reasons stated above.

Each component is broken down into specific business activities (for example, design, manufacturing, assembly), in order to provide an assessment of the different activities involved within the supply chain.

! Customer service is not considered a formal part of the supply chain, though it would contribute to the success of a DWPT system installation. Delivering customer services from within the UK would be beneficial for the end users and the DWPT providers who could use the information gathered in the field for improvements to their system.

Hardware

- Management Unit
- Ground Assembly
- Vehicle Assembly

Software

- Firmware
- Back-office management systems
- Front-end user interface

Installation

- Fitting GA coils
- Grid connection
- Receiver unit retrofit

Maintenance

- Hardware
- Software

Figure 29: Supply chain analysis categories and components

5.1.2 Assessment Method

The early stage of the development of the DWPT industry means that there is limited direct evidence available to determine such scores. Therefore, red/amber/green scores have been attributed on a comparative basis, informed by the desk research undertaken previously in this report and by discussions with DWPT industry stakeholders and experts.

Each business activity has been rated against five criteria, with a sixth criteria reflecting the overall feasibility of fulfilling that specific business activity within the UK. The criteria that have been considered are:

Criteria:	Explanation:
GVA (Gross Value Added) Potential	The potential economic value of the business activity to the UK.
Employment Potential	The potential number of jobs created through undertaking the business activity in the UK.
Feasibility	The capability of the UK to undertake the business activity based on existing expertise and capacity.
Benefit	The benefit of undertaking the business activity in the UK, from a DWPT supplier's perspective (in this case ElectReon).
Short-Term Prospects	The extent to which any of the potential for this business activity could be realised in the UK within the next five years.
Overall	The overall value and feasibility of undertaking the business activity in the UK.

5.2 Hardware

The hardware associated with DWPT is broadly split into three components as described in Section 2.2 (page 13) and expanded in Section 4.2.1 (page 28): the Management Unit (MU); the Ground Assembly (GA); and the Vehicle Assembly (VA).

Additional hardware may be required in order to establish an electrical supply to a DWPT installation, but this hardware is not unique to DWPT and therefore not considered a key hardware component. The major raw materials are copper and different alloys of ferrite material.

5.2.1 Management Unit

The MU is typically mounted above ground, adjacent to a DWPT-enabled road. It contains 12 subassemblies, power electronics, data processing and communications equipment required to manage the delivery of power to the inductive coils fitted beneath the road surface. The components that make up the unit can each have different origins based on the value and/or quality requirements of the system. It is therefore important to make a distinction between component-level manufacturing and the overall management unit assembly when considering the supply chain.

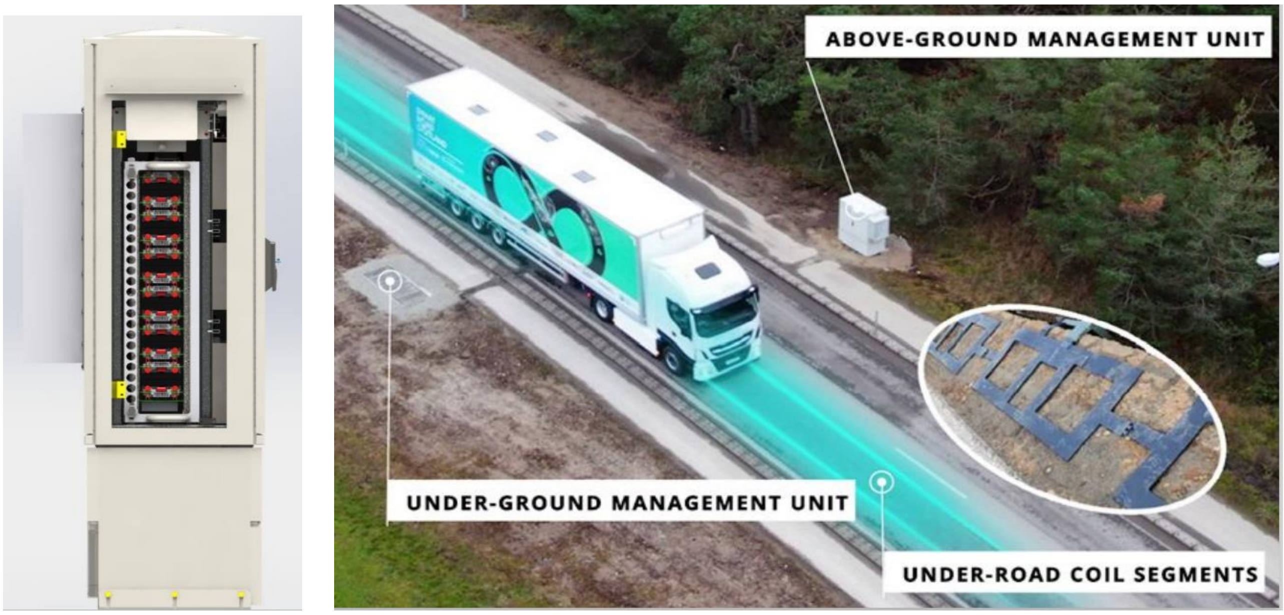


Figure 30: Electreon Management Unit (left) and two types of installations of MU at Gotland, Sweden [45].

Design

Since this analysis is based primarily on the ElectReon solution, no design activities are foreseen to be needed for the MU.

Manufacture

The manufacturing of components included within the MU offers greater potential for GVA and job creation, especially considering that many components are not unique to DWPT management units and may therefore have wider economic value. However, the UK is assessed to be unlikely to compete against component manufacturers in South East Asia who hold the majority of the market as shown in Figure 31.

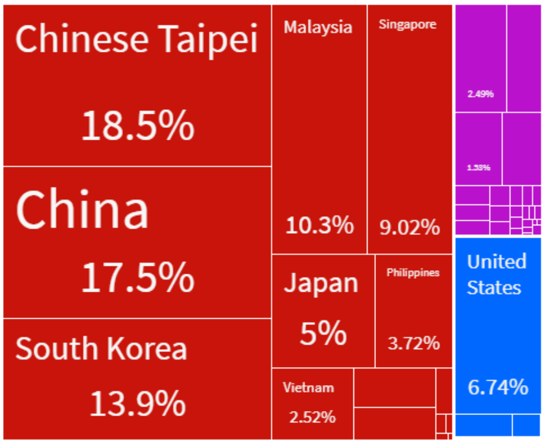


Figure 31: Exporters of Integrated Circuits (2019) expressed as a percentage of all global exports. Source: OEC (https://oec.world/en/profile/hs92/integrated-circuits)

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Assembly

The assembly of DWPT MUs may be feasible within the UK economy, and this may become a beneficial means of reducing cost. However, the economic case for UK assembly is contingent on significant UK-based demand for DWPT infrastructure. There would also be concerns relating to the export of assembled MUs from the UK into Europe, as the componentry would mean the assembled units would not conform to the post-Brexit rules of origin required for tariff-free trade between the UK and Europe. With this considered, a DWPT OEM is likely to favour the EU over the UK were it to consider assembling MUs outside of its base of operations – this is corroborated by ElectReon's assessment and choice of suppliers from the region.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.2.2 Ground Assembly

GAs are mounted a few centimetres below a road surface and, when an alternating electrical current is passed through them, they create a magnetic field that is used to transmit energy wirelessly. These coils are typically constructed of copper, owing to its electrical conductivity, alongside ferrite-based magnets, which are used to alter the magnet field in order to remove any health and safety risks. Vulcanised rubber protects the core components from the environment.

Design

Since this analysis is based primarily on the ElectReon solution, no design activities are foreseen to be needed for the GA.

Manufacture

For DWPT to achieve scale, inductive coils will need to be mass manufactured. In the short-to-medium term, centralised manufacturing is likely to remain the most cost-effective means of producing inductive coils, reducing the potential for manufacturing activity to take place in the UK. Figure 32 shows that the second largest exporting region (i.e. mining) of copper ore is Asia, and Asian countries are also the biggest importers (largest manufacturing of copper based products). These markets have the capacity and capability for large scale, low-cost manufacturing – this is corroborated by ElectReon's assessment and choice of suppliers from the region.

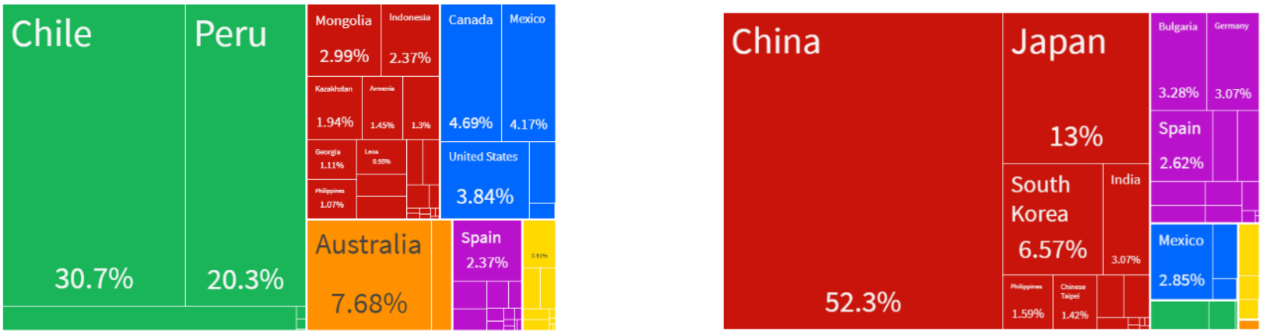


Figure 32: Exporters (left) and importers (right) of copper ore in 2019, expressed as a percentage of all global imports. Source: OEC (https://oec.world/en/profile/hs92/copper-ore) Key: Asia (Red); S. America (Green); Europe (Purple), N. America (Blue); Oceania (Orange), Africa (Yellow)

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.2.3 Vehicle Assembly

The VA is a receiver unit assembly fitted to an EV that allows it to receive charge from DWPT infrastructure. At present, these units are typically designed and manufactured by the same organisations who provide DWPT infrastructure to ensure compatibility between the infrastructure and the vehicles using it. In the future there will be two distinct supply chains depending on whether the VA is an aftermarket retrofit or an integration within the EV manufacturing process by the OEM.

Design & Integration

The skills and expertise required to design DWPT receiver units and integrate them into existing EVs are available within the UK. There may be benefit in undertaking design activities in the UK, as doing so would provide proximity to various automotive research institutions (e.g., Warwick Manufacturing Group) and industry associations (such as the Society of Motor Manufacturers and Traders). Such proximity may assist the process of integrating DWPT receiver units with current EVs and allow DWPT providers to work more closely with vehicle OEMs.

There are already 500,000 EVs on the roads in the UK. ElectReon expect to reach TRL 9 in 2022, by which time EV uptake is projected to be in the millions. Modular design along with interoperability standards in development will mean the technology could be applied to different vehicle types, makes and models. However, as there are differences in every vehicle make and model, it will be beneficial to have local expertise to assess the individual vehicle needs and to offer tailored design and integration services for the VA. Vehicle adaption is a service provided by a number of organisations in the UK, including Ricardo.

ElectReon have commercial Joint Ventures (JVs) with a growing number of automotive OEMs including: Higer, IVECO, VW and Stellanitis. These JVs offer an accelerated means to design, integrate and manufacture compatible VAs whether as retro fits for demonstrators or, in the longer term, as part of the vehicle coming off manufacturing lines.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Manufacture & Assembly

When it comes to vehicles being produced with DWPT compatibility built-in there are opportunities for the UK to form a part of this supply chain. In 2019, the United Kingdom exported $39.4 billion in cars, making it the seventh largest exporter of cars in the world. The main destinations were United States, China, Germany, Belgium and Italy. The second fastest growing market for car exports from the UK was to Israel (after US and before Canada) [39]. This evidence suggests that there is potential for the UK to be involved in the DWPT compatible EV production supply chains if the UK makes investment in the new capabilities required, particularly when considering that there are already five electric bus manufacturers and an electric taxi (black cab) manufacturer in the UK.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.3 Software

The software component of DWPT equipment has been divided into three categories: firmware, back-office management systems and front-end user interface. These categories cover the operation, management and use of a DWPT system.

Generally the barriers to entry for software development are lower than for hardware manufacturing. However, labour costs are linked to cost of living and currency exchange rates, so they remain higher in the UK than in other countries. Furthermore, there is a lack of capacity in programming and software development, with 48.1% of existing vacancies being classed as hard-to-fill due to applicants lacking relevant skills, qualifications or experience [40]. This skills shortage however is likely to exist globally due to rapid growth in demand for these skills.

5.3.1 Firmware

Firmware is a layer of software that directly interfaces with and controls hardware, effectively sitting beneath the user interface and providing a foundation for user-facing software to be developed. Firmware is installed directly onto hardware devices but can potentially receive and respond to commands sent using cloud-based software. Firmware is important to ensure that devices function correctly and safely.

Design & Testing

The development of DWPT device firmware is likely to be most cost effectively undertaken near to or on the same site as the design of device hardware. This provides an environment where both hardware and software faults can be identified and remedied through unit and system, testing. Whilst the UK has a supply of skills in software design, it would not be practical to undertake firmware design and testing apart from a DWPT provider's base of operations.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.3.2 Back-Office Management Systems

Back-office systems are software that allow DWPT infrastructure owners and operators to monitor and manage the use of the infrastructure, potentially also managing financial transactions made by users of the infrastructure. This software can be cloud-based, connecting to hardware via an internet connection.

Design & Testing

The UK has the capability to design back-office software systems and there may be some benefit to undertaking these design and testing activities within the UK economy. Undertaking such activities in the UK would assist in developing software that is designed with the needs of the user or distribution network in mind. It may also help in designing software systems which meet the requirements of evolving UK regulations for EV charging infrastructure (e.g., for collecting and sharing data on equipment location and status). This is particularly important as there are currently no specific UK regulations governing DWPT. However, such regulations are likely to be forthcoming were DWPT to achieve scale in the UK. Until greater scale is achieved and such regulations are introduced, it is likely to remain more cost-effective for DWPT providers to conduct back-office systems development within their base of operations.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.3.3 Front-End User Interface

The front-end user interface is required to enable EV drivers to activate a charge when driving over DWPT infrastructure, and also make payment for the use of the infrastructure. This system interacts with both the VA and the GA.

Figure 33: The commercially available Higer bus which includes the Electreon VA, picture shows the interior - the yellow boxes highlight where (a) the notification for 'DWPT available' is displayed and (b) the buttons the user needs to press to accept the charge. [41]

The interior setup shown in Figure 33 within additional buttons for the interface is appropriate for buses and possibly trucks. However for private vehicles, notification of availability and user acceptance in one UI in the central infotainment screens may also be possible.

Design & Testing

As with back-office system design, the UK has the capability to undertake the design and testing of front-end user interfaces for DWPT systems and there may be some benefit in undertaking these activities within the UK. The primary benefit of designing in the UK is that the products would more easily be tailored to the needs of UK users, especially were different interfaces to be designed for different use cases and adaptation to the UK market (i.e. for left-hand drive vehicles). However, in the short-term, this software design could be more economically undertaken centrally at a DWPT provider's base of operations where the knowledge of the core software and technologies resides.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.4 Installation

The installation of DWPT equipment draws upon different supply chain capabilities than its design and manufacture. The installation component of the DWPT supply chain has been divided into three categories: fitting the GA, grid connection and the VA.

5.4.1 Fitting the Ground Assembly

DWPT is fitted beneath the surface of a road and therefore requires roadworks to be undertaken to remove the road surface prior to the fitting of the coils, followed by further roadworks to reinstate the road surface.

Roadworks

Roadworks represent a pre-existing activity that have long been routinely undertaken by UK-based suppliers. Therefore, the supply chain for equipment, materials and labour are well established within the UK economy. It is likely that, in any eventuality, a DWPT provider wishing to install equipment in the UK will contract roadworks to a UK-based supplier. This would be a cost-effective approach, as the DWPT provider avoids the need to recruit, train, certify and relocate staff to legally undertake the roadworks.

In the short-term, using UK-based suppliers to undertake roadworks is particularly beneficial, as initial deployments of DWPT infrastructure are likely to be small in both number and size, therefore not justifying the ongoing revenue expenditure associated with building in-house or bespoke capabilities.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Equipment Fitting

Figure 34: GA installation in Tel Aviv.

Following the removal of the road surface, DWPT inductive coils would then be fitted, alongside the MU. Whilst there is no known existing capability to undertake this work within the UK, there will be benefit for a DWPT provider to train a UK-based contractor to fit equipment, rather than to rely on and require personnel to travel overseas for this. As DWPT installations are likely to be small in both size and number in the short-term, it may remain more cost-effective to sub-contract rather than to develop in-house resources until a pipeline of installations is generated. ElectReon has already signed a deal with transport infrastructure company Eurovia, a subsidiary of the VINCI Group, one of the world's largest construction companies, to collaborate on the installation of wireless electric road systems in Germany, France and Belgium [42].

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.4.2 Grid Connection

Providing an electrical supply to DWPT infrastructure requires an electrical connection to be established between the equipment and the distribution network. Some of the activities required to establish this connection can be undertaken by any accredited provider (so-called "contestable works")[12], whereas others are referred to as "non-contestable" and must be undertaken by the local Distribution Network Operator (DNO).

[12] Also known as an Independent Connections Provider or ICP

Contestable Works

There is a well-established industry for conducting contestable grid connection works, including civil and electrical engineering required to run electrical cabling underground to a point of connection with the distribution network. As part of a DWPT infrastructure installation, these works can be undertaken by the local DNO or by a privately appointed accredited supplier. In either case, the works would be undertaken by UK-based staff, potentially employed by UK-based organisations. Utilising the existing capabilities within the UK would be beneficial to DWPT infrastructure providers, as it removes the need to recruit, train and certify staff to deliver the services in-house.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.4.3 Vehicle Systems

Once manufactured, DWPT vehicle receiver units require additional work to be fitted to an EV, thereby enabling it to receive wireless charge from DWPT infrastructure.

Receiver Unit Retrofit

Retrofit solutions are always best provided by a local installer for a number of reasons. The shorter the distance between the vehicle and the installer, the quicker and more cost-effective the service. The installer is more likely to have a better knowledge of local rules and regulations for vehicle adaptation, as well as the terrain and environmental conditions. In addition, there is a higher likelihood for a need for aftersales support and maintenance for novel solutions like this. In the UK, around two million new vehicles are purchased every year and, even if only a small proportion of these vehicles were retrofitted with DWPT receiver units, it is likely to be impossible to meet demand without utilising UK-based labour and/or contractors.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.5 Maintenance

Once the DWPT infrastructure is installed and receiver units fitted to the vehicles of those who wish to receive a wireless charge, a further supply of skills and labour is required to ensure that the equipment continues to function correctly. This covers both the hardware and software components of the equipment.

5.5.1 Hardware

Ensuring that all DWPT hardware, whether it be the GA or the VA, remains safe and functional will require an ongoing commitment of resource. The required will vary between components, depending on the amount and the nature of maintenance needed.

Management unit

Correcting faults in the DWPT MUs may require repair staff to attend a specific site. This is particularly the case if a fault is developed that potentially presents a hazard to the pubic (for example if the unit is exposed after a vehicle collision). In instances such as this, it is not uncommon within the context of EV charging infrastructure that repair staff would be expected to attend the site within a small number of hours. Delivering this level of service necessitates a UK-based operation.

However, in the short-term, the limited number and scale of DWPT infrastructure installations would be unlikely to justify a dedicated maintenance team. Instead, the responsibility for maintaining DWPT management units would likely to be deferred to a suitably trained, UK-based electrical engineering contractor. At mass-market scale, it may become cost-effective for DWPT providers to recruit, train and certify their own UK-based maintenance teams.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Ground Assembly

As inductive coils have no moving parts and are completely enclosed beneath the surface of a road, they require little maintenance. The exceptions to this would be where either the road surface is compromised or where other roadworks need to be undertaken. In these instances, it may become necessary for DWPT providers to work with local highways authorities to ensure that the inductive coils are either not disturbed by the roadworks or, if this is unavoidable, to attend the site to ensure that any damage caused to the coils can be remedied before the road surface is reinstated. The need for such intervention is likely to be infrequent and somewhat predictable, and it could therefore potentially be undertaken without the need for a specific UK-based maintenance contractor.

This would be especially true in the short-term, where a small number of DWPT infrastructure installations are undertaken on roads that are not anticipated to require any foreseeable additional roadworks. At mass-market scale, it may become necessary for a UK-based maintenance operation to co-ordinate with local highway authorities and ensure that planned roadworks are monitored and responded to.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Vehicle Assembly

The VA is arguably the component of the DWPT system that is most liable to failure, owing to its exposure to the elements beneath a potentially fast-moving vehicle. It is therefore most likely to require maintenance and repair. When the technology is at market, a UK-based maintenance and repair function will inevitably be required in order to offer a positive customer experience. This would be especially important for business vehicles with heavy duty cycles, as a malfunctioning receiver unit could prevent the vehicle from being used and therefore the response time for a technician to attend the vehicle could result in a loss of earnings for the business. Therefore, for DWPT to be deployed successfully in the UK, a UK-based maintenance function would need to be established.

In the short-term, this function could potentially be contracted to a small number of UK-based suppliers but, in the longer-term, it may require more widespread training to equip a network of vehicle repair centres with the knowledge required to conduct maintenance and repair to DWPT receiver units.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.5.2 Software

Software faults can potentially render DWPT systems unusable and potentially unsafe. Its successful operation therefore requires software to be actively monitored, maintained and updated. Part of such activities should involve identifying potential software vulnerabilities and addressing them to defend DWPT systems from cyber-attack. The assessment here is inherently dependent on the assessment in section 5.3.

Firmware

Once DWPT is at market, the frequency of firmware updates should be low, as stable and functional firmware should have been developed during the trial stages of the technology. The skills may exist within the UK to identify and correct faults in firmware or improve firmware to add features, but these functions benefit from remaining centralised by the DWPT provider. A decentralised approach would risk firmware becoming fragmented across a network of DWPT infrastructure and receiver units, thereby introducing inconsistency and potentially leaving areas of a DWPT network more at risk of fault or cyber-attack.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Back-Office Management Systems

EV infrastructure back-office management systems are typically cloud-based software, meaning that software can be monitored, maintained and updated centrally, from any location, without significant difficulty. The UK possesses the capability of undertaking such activities, but there would be little benefit gained from doing so, as they could more effectively be undertaken within the DWPT provider's base of operations, even if it were overseas.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

Front-End User Interface

As is considered to be the case for DWPT back-office management systems, were a DWPT front-end user interface to be cloud-based (as is typical for EV charging infrastructure front-end software), the software could be effectively maintained remotely, from any location. As such, the opportunities for these activities to be undertaken in the UK is limited, regardless of the UK's capabilities in this sector.

GVA Potential	Employment Potential	Feasibility	Benefit	Short-Term Prospects	Total

5.6 Summary

While wireless charging technology has been available for decades, the industry for providing DWPT for electric vehicles is in its early stages of development. As such, a common theme of the DWPT supply chain is that business activities such as equipment design, manufacturing or software development, can be undertaken more cost-effectively where they are centralised to a provider's base of operations.

At time of writing, there are no DWPT providers with a base of operations in the UK. Within that context, this supply chain assessment has explored the feasibility of fulfilling elements of the DWPT supply chain within in the UK, and the benefit that this might offer to DWPT providers.

There is limited opportunity, particularly in the short-term, for DWPT hardware design, manufacture, or assembly within the UK for the GA. Whilst the capability to deliver these activities is likely to exist

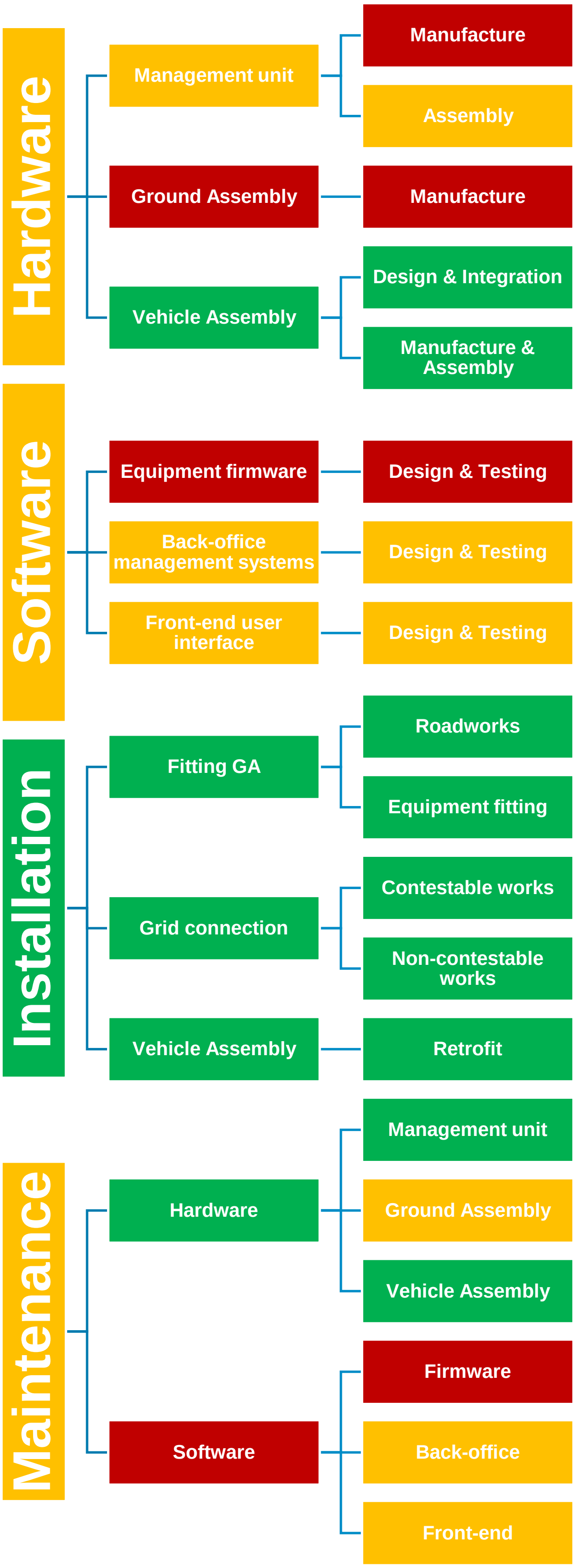


Figure 35; Summary of key components of the Dynamic Wireless Power Transfer supply chain, coloured in red, amber or green depending on the feasibility and benefit of fulfilling supply chain components within the UK.

in the UK, the benefit of doing so would be limited. A key factor that limits the attractiveness of the UK for DWPT hardware production is its current trading relationship with the EU and, in particular, its requirements for rules of origin. Many components and raw materials used to produce DWPT hardware are sourced from outside of the EU. As such, were DWPT hardware manufacturing or assembly to take place in the UK, a DWPT OEM may need to pay import tariffs to bring raw materials and components into the UK, and potentially a second round of import tariffs to export manufactured DWPT hardware into the EU. Alternatively, were a DWPT provider to conduct equipment manufacturing in the EU, only a single round of tariffs would be due for equipment manufactured in and exported to any of the 30 nations within the European Economic Area (EEA).

It is therefore considered that the design, manufacture and assembly of the MU or GA hardware is unlikely to take place within the UK, unless it could be justified by demand.

The demand for VA design, manufacture and assembly is much more likely to be present should DWPT infrastructure be rolled out. For each GA there could be demand for hundreds of VA units depending on the number of EVs using the roads where the DWPT GA installations are made.

The tailoring of the GA for the different makes and models and the installation need make this an attractive option to place in the UK market.

Similar to hardware, the capability to design and test software for DWPT equipment is likely to be available in the UK, but it is considered that there would be little or no benefit of undertaking these activities in the UK. The exact location where software is produced is of less importance than for hardware, as it is not dependent on a physical supply chain of raw materials and components. The most cost-effective location to design and test DWPT software is therefore likely to remain at a provider's base of operations, or at least within that nation.

As there is no present indication that any DWPT providers intend to establish a formal base of operations in the UK in the short term, little or no opportunity is considered to exist for designing and testing DWPT software in the UK.

Most of the services and skills associated with DWPT hardware installation are currently available in abundance in the UK. Business activities involved in roadworks and electrical grid connection are not only highly feasible to be undertaken by UK-based organisations but there are also distinct benefits in doing so. Specifically, utilising UK-based suppliers to support the installation of DWPT hardware in the UK removes the need for DWPT providers to recruit, train and certify their own staff within the UK. This would save cost, particularly in the short-term when demand for DWPT is very low.

> There is little doubt of either the capability or the benefit of conducting installation operations in the UK.

The ongoing maintenance required to ensure that DWPT equipment continues to function correctly and safely is another area where there is considered to be opportunities within the UK supply chain. Some of the capabilities of undertaking DWPT maintenance activities are already available in the UK (e.g., maintenance and repair of power electronics), but the skills to maintain and repair equipment that is unique to DWPT is likely to require a DWPT provider to train and certify a UK-based supplier. However, this assessment finds that there would be considerable benefits in doing so and, in some cases (e.g., repair of faults that cause a potential hazard), it would be a necessity. In the short-term, the economic opportunity presented by the maintenance of DWPT hardware is limited, but this would grow proportional with demand for DWPT.

> Conducting DWPT hardware maintenance within the UK would have lasting economic value, as maintenance is an ongoing activity.
> This assessment finds that the same opportunities would not exist for DWPT software to be maintained and updated within the UK, as these activities can be more practically and cost-effectively undertaken elsewhere in the worth or at a DWPT provider's base of operations.

5.7 Conclusions

Examining the supply chain assessment, the following conclusions can be drawn about the opportunity to deliver UK-based activities:

Hardware:

- There is limited opportunity for manufacture and assembly of MUs or GAs.
- There are good opportunities for the design, manufacture and assembly of VAs, whether for integration into vehicles in UK automotive manufacturing plants or as retrofits.

Software:

- There is poor opportunity for the design and testing of equipment firmware, back-office management systems or front-end user interface.

Installation:

- There are good opportunities for installing all the hardware components of the system and for making the connection to the electricity network.

Maintenance:

- There is good opportunity to maintain the hardware.
- The opportunity to maintain the software is highly dependent on where it was developed.

General observations:

- There is a mixed opportunity for a full UK supply chain, based on the observations above.
- The UK's post-Brexit trading relationship with the EU is unfavourable, weakening the attractiveness of a base in the UK to cater for a European market.
- All opportunities for UK-based supply chain activities are predicated on uptake of DWPT solutions.

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7 Abbreviations

AC	Alternating current
ANPR	Automatic number plate recognition
BESS	Battery energy storage system
BEV	Battery electric vehicle
CO_2	Carbon dioxide
CWD	Charge while driving
DC	Direct current
DNO	Distribution network operator
DSRC	Dedicated short-range communication
DSM	Demand-side management
DWPT	Dynamic Wireless Power Transfer
ECU	Electrical control unit
EEA	European Economic Area
EM	Electromagnetic
EMC	Electromagnetic compatibility
EMF	Electromagnetic frequency
EMS	Electromagnetic susceptibility
ESS	Energy storage system
EU	European Union
FOD	Foreign object detection
GA	Ground Assembly
GVA	Gross value added
HDV	Heavy duty vehicle
HGV	Heavy goods vehicles
HV	High voltage
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
IPV	Induction powered vehicle
ISO	International Organisation for Standardisation
KVA	Kilovoltamp
kW	Kilowatt
kWh	Kilowatt-hours
LCS	Lane control signals
LCV	Low carbon vehicle
LOD	Living object detection

LV	Low voltage
MLTB	Millbrook London Transport Bus test cycle
MU	Management unit
MV	Medium voltage
MVA	Megavoltamp
MW	Megawatt
NEDC	New European drive cycle
NIA	Network innovation allowance
OCPP	Open charge point protocol
OEC	Observatory for Economic Complexity
OEM	Original equipment manufacturer
OLEV	On-line electric vehicle
ORNL	Oak Ridge National Laboratory
PV	Photovoltaic
RTO	Research and technology organisation
TCO	Total cost of ownership
THD	Total harmonic distortion
TRL	Transport Research Laboratory OR Technology readiness level
UI	User Interface
VA	Vehicle Assembly
VAC	Volts over alternating current
VMS	Variable message signs
WLAN	Wireless local area network
WLTP	Worldwide-harmonised light vehicles test procedure
WPD	Western Power Distribution

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8 Appendix

8.1 Summary of Demonstrators

Qualcomm Halo (since acquired by WiTricity)

As part of the EU-funded FABRIC research programme, Qualcomm worked in partnership with French technology company Vedecom, to develop and install a DWPT system, based on Qualcomm Halo's static wireless electric vehicle charging equipment. The DWPT equipment was built in Munich, Germany, and installed along a 100 m strip at an off-road test track in Versailles, France. In 2017, the DWPT equipment was used to undertake a research study that proved the equipment capable of providing up to 20 kW of charge at speeds of over 100 km/h, and to two vehicles simultaneously. In 2019, Qualcomm Halo were acquired by WiTricity, who now hold over 1,500 patents and patent applications relating to wireless charging technology.

Figure 36; Photograph of the Qualcomm/Vedecom Dynamic Wireless Power Transfer equipment, in use during a research project under the FABRIC programme.

Bombardier PRIMOVE (since acquired by IPT group)

Bombardier worked with Scania in 2013 to conduct a controlled test of DWPT technology on a heavy truck. The test took place on an 80 m off-road test track in Mannheim, Germany. During the trial, Bombardier PRIMOVE's DWPT equipment was able to provide up to 200 kW of power to the truck. In 2015, Bombardier PRIMOVE deployed its wireless charging technology at a series of four bus stops along an active bus route in Mannheim. In this deployment, Bombardier PRIMOVE's technology was utilised as static wireless charging, rather than DWPT, as the electric buses using the route would only recharge when stationary at one of the bus stops fitted with wireless charging infrastructure. Electric buses were required to stop for 30 seconds to recharge at each bus stop equipped with the infrastructure, with a longer five-minute stop required to recharge at the end of the bus route. The equipment was powerful enough to provide sufficient charge during these stops to enable the electric buses to continue their route. Bombardier PRIMOVE installed similar systems in Braunschweig, Germany; Bruges, Belgium; and Södertälje, Sweden. A similar system was also installed in Berlin and operated from 2015 to 2019 before being discontinued. In January 2021, IPT Group acquired PRIMOVE from Bombardier.

8.2 Summaries of Notable Research Projects & Programmes

Several research projects and programmes have explored the concept of Dynamic Wireless Power Transfer. The most notable of such are included in this sub-section. Findings from these projects and programmes are referred to throughout this report.

FABRIC

FeAsiBility analysis and development of on-Road chargIng solutions for future electric vehiCles

The FABRIC project ran between 2014 and 2018, and received €9m funding from the EU under its 7^{th} Framework programme for research, technological development and demonstration. It examined the technological feasibility, economic viability, and socio-environmental sustainability of wireless charging for EVs. Specifically, FABRIC was intended to achieve the following objectives:

- Collection of end-user requirements and industry demands that determine the potential success of such technologies in various application sectors;
- Identification of technology drivers and challenges that impact the implementation of wireless charging technology and the widespread installation of wireless charging infrastructure;
- Determination of product and technology development activities by technology developers, EV makers and other key stakeholders;
- Proposal of partnerships and collaboration between key stakeholders for implementation of technology;
- Survey of governmental policies, regulations and public & private funding activities impacting the progress of wireless charging infrastructure;
- Evaluation of technology penetration potential for wireless charging in public transportation in addition to the passenger car segment;
- Bridging the technological gaps and proposal of a rational solution for both the grid and the road infrastructure.

INCIT-EV

Commencing in January 2020, INCIT-EV is an EU-funded research programme exploring innovative EV charging solutions including: smart charging, V2G (vehicle to grid), superfast charging; large EV charging hubs; static wireless charging; and Dynamic Wireless Power Transfer. INCIT-EV received €15m funding from Horizon 2020, contributing to a total project cost of €18.6m. The project is being led by Groupe Renault, alongside 32 project partners from across eight countries including Estonia, France, Germany, Italy, the Netherlands, Slovenia, Spain, and Turkey. The programme is due to run until December 2023 and is broadly split into two phases: an initial research & development phase, followed by a demonstration phase.

Scheduled from mid-2022, INCIT-EV will demonstrate DWPT technology in two new environments:

- A central urban environment, involving the installation of 50 m of DWPT infrastructure, split on either side of a purpose-built signal-controlled junction. The DWPT equipment will be specified to provide up to 120 kW across its 50 m extent, allowing EVs to charge quickly whilst waiting at the traffic signals. This is being done to understand the challenges of integrating DWPT charging with other smart road infrastructure (e.g., traffic signals). This demonstrator is being led by Groupe Renault.

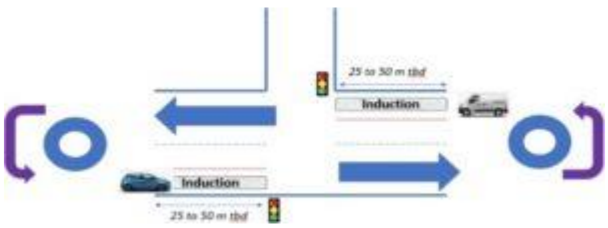

Figure 37; Diagram of INCIT-EV urban demonstrator. Source: https://www.incit-ev.eu/demonstrations/

- A long-distance driving environment, involving the installation of an 80 m strip of DWPT equipment on a high-speed test circuit in Versailles, France. The DWPT equipment will be specified to provide up to 90 kW of charge at speeds of up to 120 km/h, designed to further understand the viability of DWPT infrastructure in a high-speed, long-range use case. This demonstrator is being led by Vedecom.

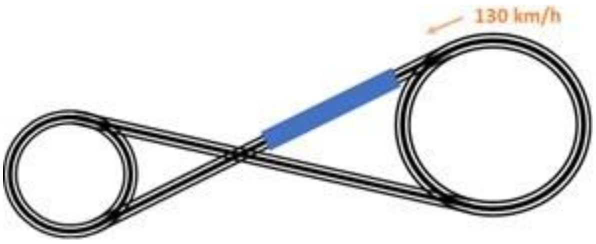

Figure 38; Diagram of INCIT-EV long-distance demonstrator. Source: https://www.incit-ev.eu/demonstrations/

Unplugged

Unplugged was a wireless charging research project led by Circe, an innovation and technology centre based in Spain. The project took place between 2012 and 2015 and was funded by the European Commission and Horizon 2020. This project aimed to investigate how the use of inductive charging of EVs in urban environments improves the convenience and sustainability of private car use. The key challenges that the project aimed to address were to:

- Increase the energy transfer efficiency and speed;
- Optimize the vehicle/coil positioning;
- Plan the possible expansion of the power grid to be capable of deal with the new fleet;
- Ensure the magnetic field and crash safeties as well as the protection of all devices;
- Reach economically feasible solutions;
- Determine the proper placement for the charging points;
- Find a secure and fair way to bill the user for the provided energy;
- Develop a secure wireless communication between the EV and the grid; and
- Ensure the interoperability of the communication and the inductive charging systems.

ZeEUS

__ZE__ro __E__mission __U__rban Bus __S__ystem

Project ZeEUS took place between 2013 and 2017, and was co-funded by the European Commission to demonstrate electric and hybrid bus technologies in ten European cities. London was among these ten cities where a static wireless charging system was trialled, using three 10m double-decker plug-in hybrid electric buses on one specific route. At both ends of the 11 km bus route, buses parked over a 100 kW inductive charging plate. Overnight, plug-in charging took place at the depot. The project therefore concerned static, rather than Dynamic Wireless Power Transfer, but focused on the public transport use case, making it of interest to DynaCoV.