DynaCoV

WP5: Final Feasibility Report on DWPT Deployment within the UK

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Western Power Distribution 2021

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Executive Summary

DynaCoV Project Scope:

The DynaCoV project was a desktop feasibility study which involved:

- A literature review looking at the available technologies and electricity network impacts of Dynamic Wireless Power Transfer (DWPT) (WP2),
- Demand and electrical impact modelling and simulation of a case study stretch of DWPT at Kenilworth Road in Coventry (WP3),
- Business case modelling investigating the economic case of a range of potential national rollout scenarios (WP4),
- Demonstrator site determination, physical feasibility assessment and costing (WP4), and
- Desktop review of considerations for deployment such as system and security requirements (WP4) and supply chain assessment (WP2).

DWPT is an immature technology

Dynamic Wireless Power Transfer (DWPT) technology is in the early stages of maturity. There have been just eight demonstrations or deployments around the world in the last decade. The system consists of three main physical components: the Ground Assembly (GA), the Vehicle Assembly (VA) and the Management Unit (MU) which work to provide energy from the grid to the vehicle via electromagnetic induction while the vehicle traverses a section of a DWPT equipped road.

Compared to traditional conductive chargepoints DWPT has the characteristics and potential to accelerate the decarbonisation of larger, harder to electrify vehicles; to support large-scale autonomous transport, and drive new revenue models for urban and highway transport corridors.

The business case for DWPT is best for HGVs on motorways

The ability to charge while in motion is particularly advantageous to commercial vehicles. From an infrastructure, return on investment point of view the vehicles (and fleets) to target would be those, such as city buses and logistics vehicles, operating on fixed or semi-fixed traffic corridors or highways. Of the scenarios assessed in the business case modelling, DWPT rollout catering for HGVs on motorways looks to represent the lowest marginal cost per kWh, close to the marginal cost of ultra-rapid conductive chargers (11p/kWh). This modelling accounted for the fact that shared DWPT resource reduces the need for (often private in the case of fleets) conductive charging and reduces the size of the battery required to cover the same journey lengths. Across half of the 36 scenarios (six baseline scenarios and five additional sensitivities on each) tested, the marginal cost of DWPT was at least three times more expensive than conductive charging. (The limitations of the modelling are described in WP4).

DWPT could reduce local network reinforcement costs although the demand at any location will vary according to key externalities

Additionally, there is some evidence from the identified case study site at Kenilworth Road in Coventry that DWPT could reduce the need for costly and time-consuming electricity network reinforcements required to support high power depot charging at depots (in this case at the National Express depot in Coventry). This is because the nature of DWPT distributes energy demand more evenly over time and space than conductive charging. For example, this project's modelling indicates that the peak power demand for buses on the Kenilworth Road in Coventry would not exceed 75 kW, although this could rise to as high as 650 kW in the worst case scenario for a mixed fleet (in standstill traffic).

The specific demand on the network at any individual point is dependent on many factors. Six key externalities were identified in three groups to determine if:

a) a charge event is possible with 1) a compatible vehicle and 2) available DWPT infrastructure,

b) a charge should be initiated by 3) a requirement to charge and 4) an acceptable price,

c) the resulting power and energy transfer based on 5) traffic conditions and 6) the way in which the vehicle is driven.

More work is required to determine the frequency distribution of demand, however, the physical characteristics of the system point to high diversity. The connection capacity required will be much lower than the theoretical maximum demand because of the very low probability and frequency of the theoretical maximum demand and particularly as the MU distributes the energy across in-use coils in the GA if the MU rating is exceeded.

Standardisation will be critical to the success of DWPT

For a rollout to be successful it will be important to have consistent international or even national standards for DWPT (they are being developed but are likely some years away from being agreed). 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. In particular, all DWPT hardware should comply with Electromagnetic Compatibility (EMC), Electromagnetic Field (EMF), IEC and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines, with a consideration of SAE J2954, ISO 6469 and ISO 26262. Furthermore, DWPT systems should employ proactive and reactive protection mechanisms to ensure safe operation under a variety of disruptive conditions.

DWPT is unlikely to take-off without government policy and financial support

A key piece of the puzzle that is missing to support a DWPT rollout is high-level, government support from both a policy and a funding perspective. The current targets of phasing out non zero emission HGVs by 2040 do not specify a vehicle or infrastructure technology for this decarbonisation or dedicated funding. To support and optimise any funding that does become available for infrastructure it would be important to carry out geospatial analysis of different vehicle traffic flows and understanding the energy infrastructure capacity at these locations to supply the transport sector. On a more regional basis some key selection criteria are identified that were used to identify a site in Coventry. At a national level, a holistic, systems-based approach is essential to deciding the future pathways.

A potential demonstration site in Coventry could answer some outstanding questions

The partners required to support a pilot at the identified demonstrator site at Kenilworth Road (an ‘A’ Road on the Key Route Network) are engaged in this project and geared to progress that quickly. It is estimated that this demonstrator could be delivered for around £1.5m and could help identify some of the missing information with regards to the impacts on the electricity network to help the understanding of, for example, the harmonics of the system and its’ effects on power quality. On the other hand, based on the outputs of the business case work which highlighted HGVs on motorways as being of greatest interest, the specific demonstrator location examined in this report may not be best to test the most beneficial scenario. In addition, it has been identified that further work is needed to compare DWPT against other competing low carbon technologies for heavy vehicles, such as conductive charging (for example via catenary systems) and hydrogen, from an economic point of view.

More work is required to overcome hurdles

In summary, it is likely that a proportion of the HGV fleet will be electrified by 2040 to meet decarbonisation targets (the exact proportion will depend on how successful hydrogen HGVs are). This implies that there will be a significant increase in electricity demand. DWPT offers the opportunity to smooth demand peaks over the whole day and lower network impacts (because charging can happen when the vehicle is in use). However, this study has not been able to quantify a benefit for DWPT from the perspective of a Distribution Network Operator like Western Power Distribution. In addition to the areas of work identified the above, further work is also needed to improve:

- technological maturity and increase power transfer,
- clarity over harmonic and power quality impacts,
- marginal costs.

1. Introduction

1.1. Introduction to Project

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 (CCC), in partnership with Coventry University, Cenex, ElectReon, Hubject, Midlands Connect, National Express, Ricardo Energy & Environment, and Transport for West Midlands (TfWM).

The overall aim of the DynaCoV project is to determine the feasibility of installing and operating Dynamic Wireless Power Transfer (DWPT) equipment in the UK.

1.2. Project Overview

This report is the final of four reports being produced by the DynaCoV project (Figure 1), summarising the work completed in Work Packages 2, 3 and 4.

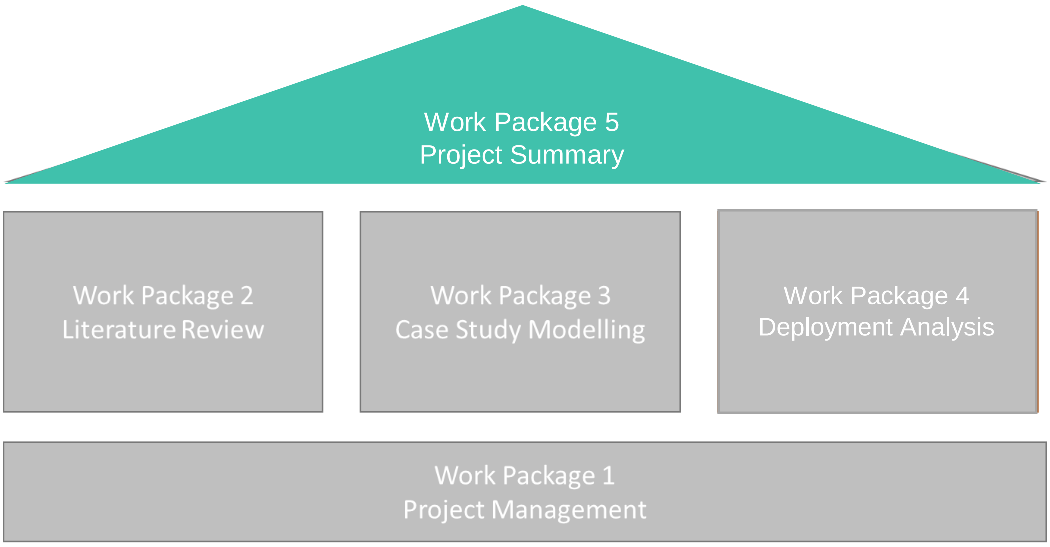


Figure 1: This report's contribution to the project

The structure of this report is as follows:

- Section 2 is aligned with the WP2 report and describes the key findings of the literature review.
- Section 3 covers content from WP2 and WP3 discussing what is known about the electricity network impacts and what remains to be explored.
- A summary of the electrical modelling and simulation carried out in WP3 is included in Section 4 while Section 5 summaries the business case modelling carried out in WP4.
- Section 6 highlights the considerations for demonstrators (and deployment) in the UK focusing on the case study site identified at Kenilworth Road.
- Finally, Section 7 summaries the key findings and the potential next steps identified during the course of this project.

1.3. Background to Dynamic Wireless Power Transfer Technology

Dynamic Wireless Power Transfer (DWPT) technology offers the potential to allow Electric Vehicles (EVs) to recharge whilst in motion. It is based on the wireless transfer of power by electromagnetic induction between two copper coils - a primary coil installed under the road surface (also known as the Ground Assembly, GA) and a secondary coil placed in the vehicle (also known as the Vehicle Assembly, VA). The VA (or the receiver) is installed under the chassis of the vehicle and it is responsible for transmitting the power directly to the battery.

The main potential benefit foreseen from DWPT is to help overcome some of the limitations currently associated with EVs. These limitations are:

- a lower maximum range compared to similar Internal Combustion Engine (ICE) vehicles, meaning that the latter can be driven further before needing to refuel
- a considerably longer period of time needed for recharging, compared to the time required to refuel a similar ICE vehicle. This is the case even when connected to rapid charging infrastructure.

DWPT technology has the potential to lessen or remove these limitations. This, in turn, may help to accelerate the transition to EVs, particularly among larger, high mileage vehicles, where these barriers are generally considered hardest to overcome. This is essential if the UK is to achieve its legally binding target to achieve 'net-zero' carbon emissions by 2050.

2. Technology Research

2.1. DWPT system and standards

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.

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.

Safety and Security

DWPT systems are likely to be classified as critical infrastructure, requiring appropriate levels of security and failsafe mechanisms, as well as General Data Protection Regulation (GDPR) compliance where personal data are collected. All DWPT hardware should:

- Comply with Electromagnetic Compatibility (EMC), Electromagnetic Field (EMF), IEC and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines, with a consideration of SAE J2954, ISO 6469 and ISO 26262 (all international standards that cover safety, more in the DynaCoV WP2 report[1]).
- Be deployed with a hierarchy of proactive (i.e. live object protection and foreign object detection features) and reactive (i.e. only transmitting power when a compatible vehicle is available) protection mechanisms.

2.2. Deployments and Providers

A total of eight DWPT demonstrations or deployments have been identified around the world in the last decade. Most projects have focused on supplying power to heavy vehicles, such as trucks or buses, and 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 metres, with more recent deployments stretching from hundreds of meters to a few kilometres.

Four key providers have been identified in the literature review (WP2), although three of these (KAIST, IPT and WiTricity) appear to have been acquired or retired. Only ElectReon appears to be active in the market at present. ElectReon's DWPT system is described in more detail below.

2.3. DWPT System Components

Examining the existing solutions, all DWPT solutions consist of the components shown in Figure 2.

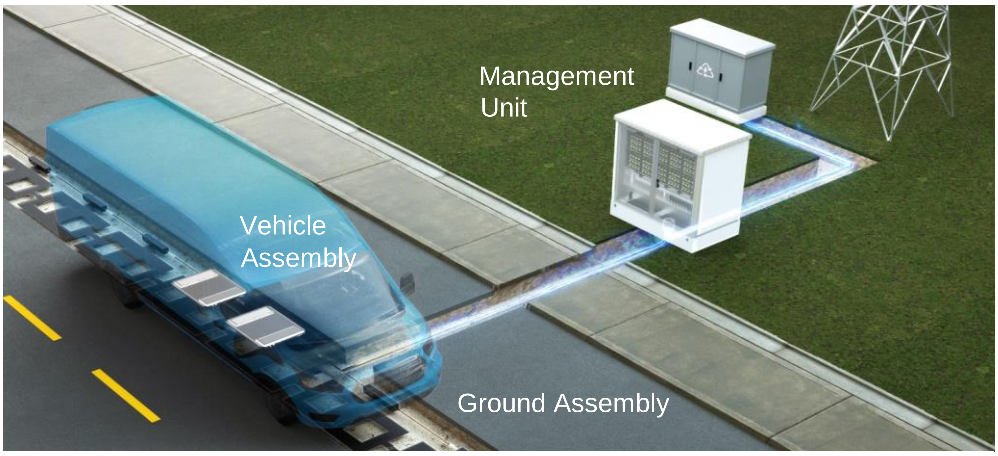


Figure 2: DWPT system illustration showing the three physical components.

[1] https://www.westernpower.co.uk/downloads-view-reciteme/397042

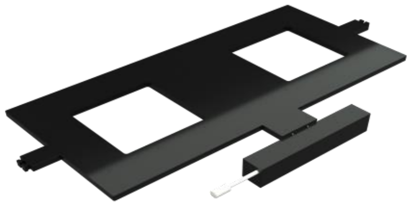


Figure 3: Coil segment of the Ground Assembly

Ground Assembly (GA)

Figure 3 shows an illustration of a coil segment. These copper coil segments~~a~~ make up the GA which is installed underneath the road surface. The GA emits the electromagnetic fields toward the Vehicle Assembly (VA) when the vehicle authorises a charge. The GA is controlled by the Management Unit (MU).

Management Unit (MU)

MUs are located at the side of the road, above or below the ground according to the customer's requirements. Each MU can support up to 60 coil segments that form ElectReon's Wireless Electric Road section of about 100 meters in length. Figure 4 show illustrations of different MUs (above and below ground designs) developed by the company and deployed in existing pilots. The MU is responsible for communication with the Vehicle Control Unit.

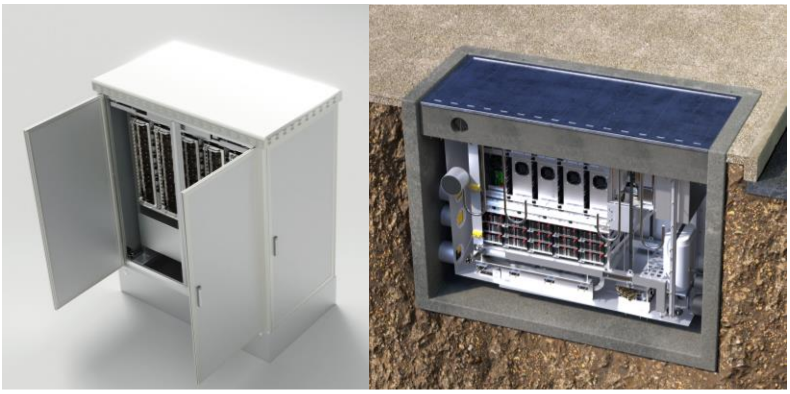


Figure 4: Above ground (left) and below ground (right) Management Unit

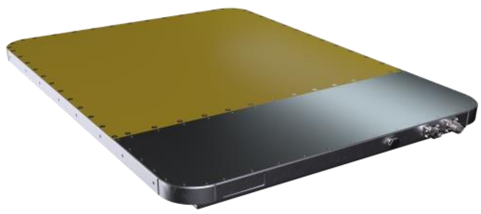


Figure 5: Example of Vehicle Assembly

Vehicle Assembly (VA)

The VA (or the receiver) is installed under the chassis of the vehicle and it is responsible for transmitting the power directly to the battery. VAs are modular and include a control unit. All VAs can charge any type of battery at voltages of up to 800 volts. There are three categories of receivers. The first is made for heavy-duty vehicles that have high-power energy consumption, such as buses and trucks, and have a charging capacity of up to 25kW. The second category supports commercial vehicles also with charging capacities of up to 25kW. And the third suits private vehicles as it allows for the power transfer to be adapted to the requirements of the vehicle and provide either 7 kW, 11 kW, or 22 kW.

Software

A cloud-based charging management system is used to orchestrate the connected charging infrastructure in real-time and to provide a customised graphical user interface (GUI) to the fleet operators. ElectReon's fleet charging software enables the metering of the energy transferred to the vehicle, to be performed at the Vehicle Control Unit. This functionality allows for multiple vehicles to charge at the same time from several underground coil segments that are connected to the same MU. Each vehicle can be associated with a different account and billed separately.

3. Electricity Network Impacts

WP2
WP3

In this section the practicalities associated with the deployment of the ElectReon DWPT system on the electricity network are presented.

3.1. Connection Interface and Architecture

The key features of the electricity network interface are as follows:

- 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 to interface with the High Voltage line (1 kV – 22kV) in the UK.
- DWPT deployments should adopt a modular design to allow for scalability and reduce distribution network impacts.

Connection Architecture

Each MU requires its own 3-phase low voltage (LV) electricity network connection (Figure 6 or Figure 7).

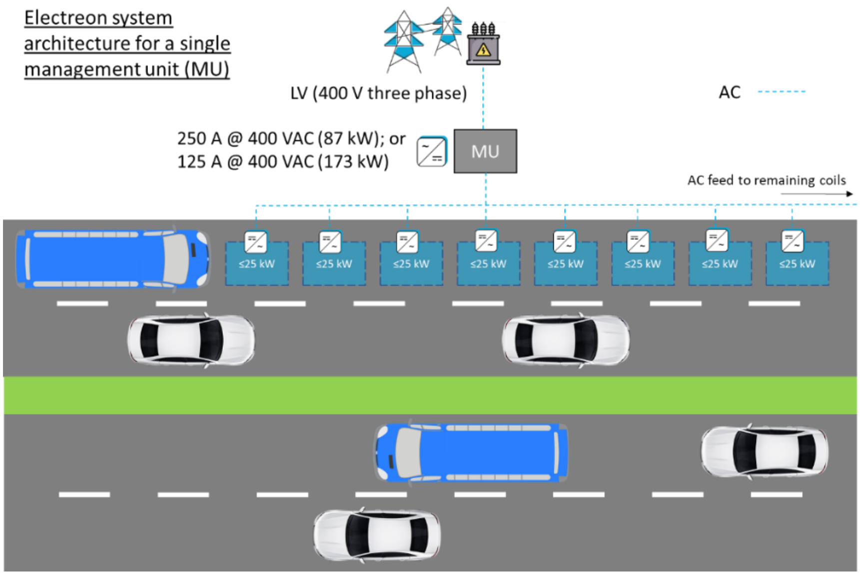


Figure 6: Single MU network interface - direct to dedicated substation (note: not to scale).

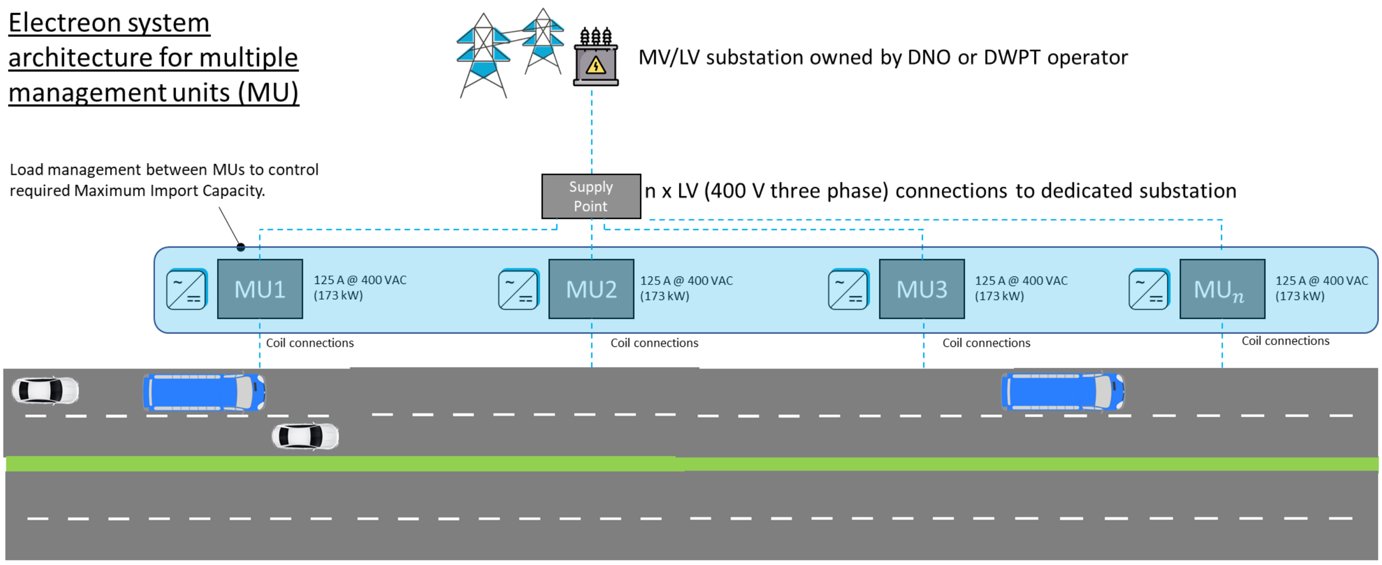


Figure 7: Multiple MU network interface - direct to substation.

At some locations, 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. 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 further erodes the business case.

3.2. 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:

- 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 State of Charge (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 management – may be required to ensure charging adheres to the agreed import capacity from the distribution network and meets the relevant technical standards (e.g. Engineering Recommendation P28 Planning Limits for Voltage Fluctuations Caused By Industrial, Commercial and Domestic Equipment in the UK).
- Efficiency - the network will need to supply more power than is received by the vehicle. Coil-to-coil efficiency is expected to be above 85% and even 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 (WP2).

3.3. Power Demand Profile

A single vehicle using a DWPT system is assumed to create a high frequency square wave of power demand on the network (see example from WP3 in Figure 8). The receiver is rated at 25 kW [this the real time peak power], whilst the mean power transferred is different and dependent on the vehicle speed. The shape, frequency and amplitude of this square wave is affected by:

- Transmitter coil length and spacing – changes shape of square wave
- Vehicle speed – changes frequency of square wave
- Transmitter coil/receiver coil rated power and real-time demand – changes amplitude of square wave.
- Misalignment (including by positioning of the vehicle in the road and also of the receiver on the vehicle (affecting the air gap))

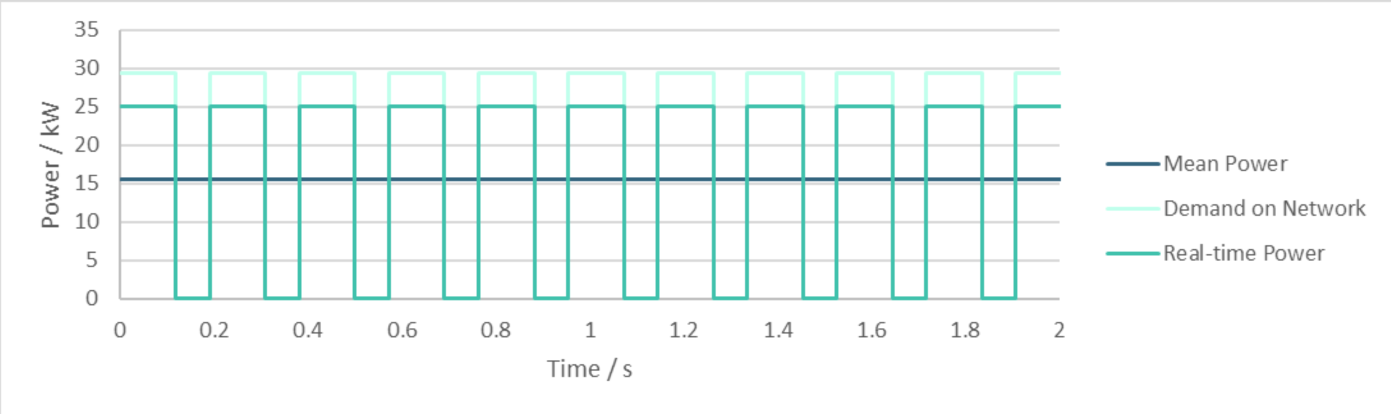


Figure 8: Example square wave for 1.65 m transmitter coil length; 1 m spacing; vehicle speed of 50 km/h.

The temporary fall in power from switching between sequential coils (as the vehicle travels along the road) makes the mean power transfer 80% of the peak value. This reduces the energy transfer during a charge event without reducing the peak power transfer. In a deployment, it may be possible that multiple vehicles are using a DWPT system simultaneously, and the real-time power demand on the system will be a combination of the square waves of each vehicle. Note that due to varying real-time vehicle spacing the square waves of different vehicles are unlikely to collate perfectly, as the individual vehicles pass over coils at different times.

On larger vehicles with multiple receiver coils, ideally the size and spacing of the receivers needs to be designed to match that of the transmitter coils. This ensures that the demand from each coil-pair combines to create a single waveform of an amplitude that is simply a factor of the number of coil-pairs.

Also, note that when multiple vehicles are using a single segment, the maximum power will be limited by the rating of the MU. ElectReon has confirmed that power is managed between in-use coils in a scenario where the MU rating is exceeded by distributing the energy equally between each coil.

3.4. Other Factors

The effect of harmonics and power quality from the ElectReon DWPT system is not yet known. With regards to earthing, as the regulations of BS 7671 are not applicable to wireless charging, it is suggested that the requirements of Engineering Recommendation (EREC) G12[2] are used to ensure that the ElectReon system is earthed in a way that is compliant with relevant technical standards.

[2] Engineering Recommendation G12: Requirements for the Application of Protective Multiple Earthing to Low Voltage Networks.

4. Modelling and Simulation to Support Electrical Impact

WP3

4.1. Externalities

A taxonomy of externalities – the factors that impact negatively or positively – relevant to DWPT in a UK context has been generated through DynaCoV stakeholder workshop.[3] The taxonomy classifies the externalities / factors into six categories, which are split in three groups described below:

Externalities to determine *if a charge event is possible*:

I. **Vehicle**: the vehicle must be equipped with a receiver and the condition of the vehicle (battery State of Charge (SoC) or instantaneous power demand) must permit a charge;
II. **Infrastructure**: the route selection must include charging infrastructure and the charging infrastructure must be available for use.

Externalities to determine *the decision to charge*:

III. **Journey**: the difference between the available energy and the required energy to complete a journey will influence the decision to commence a charge event;
IV. **Economic**: the cost of access and the cost of energy compared to the alternatives (for example, to stop at a charging station) will influence the decision to commence a charge event.

Externalities to determine *the power and energy transfer that result from a charge event*:

V. **Traffic**: the demand upon the system based on external factors, e.g. the density and mix of traffic that flows across the system, will determine the power available to an individual user and the energy transfer.
VI. **User**: the behaviour of the user, for example, along a fixed length of charging infrastructure the speed and alignment of the vehicle will determine the power and energy transfer result.

The above externalities are applied to the location to determine, from the vehicle count, which of those vehicles will start a charge event and what the associated power and energy transfers would be.

4.2. Simulations

The ambition of the simulation activity was to establish a model that would track the rate of energy transfer with time for a DWPT system at the case study location on Kenilworth Road. Two scenarios (Public Service Vehicle (PSV) and a mixed fleet) were developed for the purpose of determining energy and power demands. The simulation used a combination of Vissim and MATLAB® to predict the energy demand from the vehicles passing over the DWPT section of road and based on the conditions/constraints established as part of the scenario generation. The full details about the scenarios and simulation activity are in WP3 and a summary is provided below.

Scenario Generation

For the feasibility study two scenarios, or distinct possibilities, where explored and adopted the following constraints:

The PSV scenario considered the following:

- A captive fleet that is restricted in terms of routing and/or time of operation
- A homogeneous fleet in terms of vehicle design – voltage, energy consumption, etc.
- Additional vehicle count based on bus frequency per hour: low (4 vehicles per hour) and high (8 vehicles per hour).

The mixed fleet scenario considered the following:

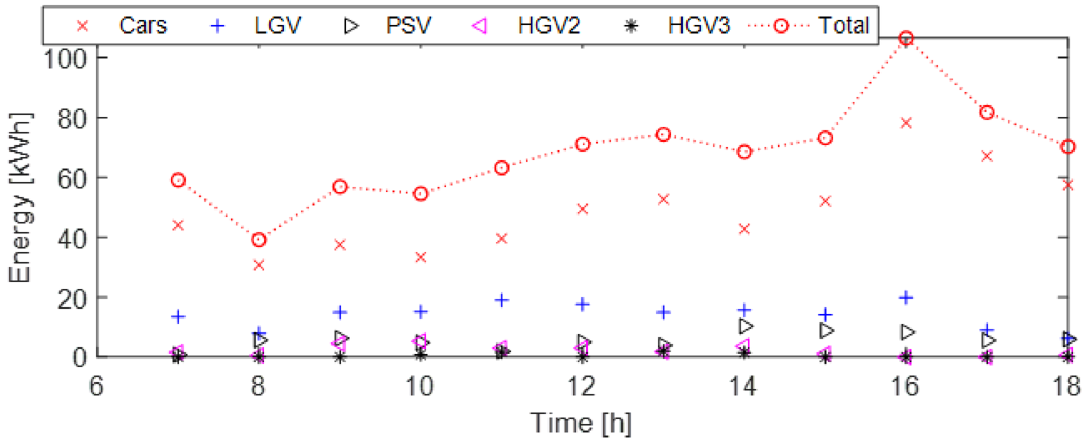
[3] An online workshop titled "Determining Stakeholder Involvement in EV Charging Innovation" was held on 24th February 2021. The event was hosted by Coventry City Council and supported by other DynaCoV partners, including Coventry University, Cenex and ElectReon.

➢ All vehicle types – cars, PSVs and freight (Light and Heavy Goods Vehicles)
➢ An independent fleet that has no restriction in terms of routing or times of operation
➢ An inhomogeneous fleet in terms of vehicle design – energy consumption, vehicle size (number of receivers dependent on size), etc.

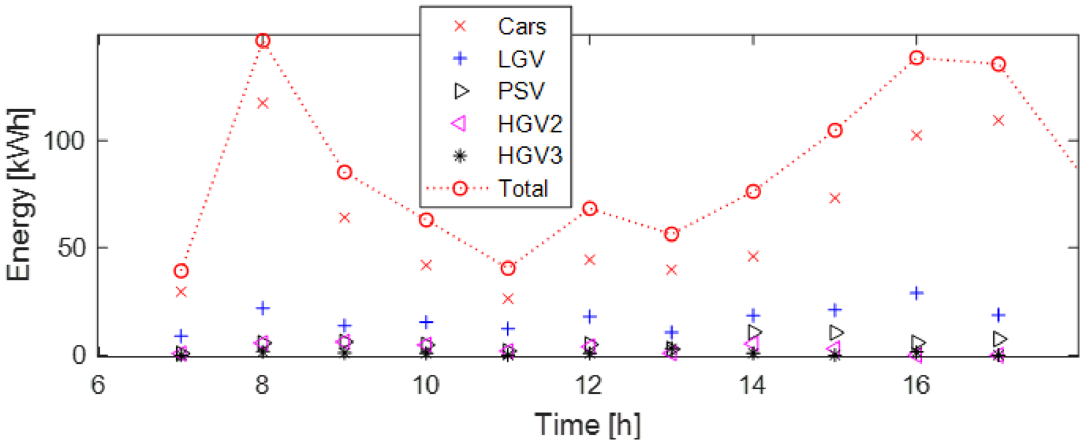
Some assumptions were common to both scenarios, including whether or not the vehicle would accept a charge (related to SoC), vehicle speed and transit time[4] (of DWPT section):

➢ Vehicles require charging if SoC at the end of the 100m or 400m DWPT sections is below 80%
➢ Vehicle counts from 7:00 until 18:00 based on data from TfWM
➢ Vehicle speed based on recorded averages recorded in 2021.

An example of the results of the energy demand resulting from the simulation activities are shown in the Figure 9 – note that this result relates to the mixed fleet scenario that included cars, light and heavy goods vehicles, and PSV.



a) Section 1 – 400m, 50mph speed limit



b) Section 2 – 100m before signalised intersection, 30 mph speed limit

Figure 9: Illustrating the impact of signalised intersection (Section 2) on energy usage compared to a free-flowing traffic section (Section 2), for a typical vehicle distribution on the Kenilworth road (A429)

[4] Two sections of road were part of the case study location for this feasibility study; one section was selected based on fixed transit time (free-flowing – Section 1, 400m long) and one based on variable transit time (traffic-controlled signals and bus stand – Section 2, 100m long).

Vehicle Demand Modelling

The key observations were as follows:

- For PSVs (buses), the peak power demand from the vehicles passing over the DWPT section would be unlikely to exceed 75 kW for the road sections selected as part of the feasibility study. This was due to the low number of PSVs (between 7 and 13 per hour).
- For a mixed fleet (PSV, HGV, LGV and cars), the peak power demand would be higher than for PSV alone. As a worst case the peak power demand could be as high as 650 kW (leftmost point on the graph in Figure 10), but it is unlikely this would be realised due to a combination of external factors. A peak value of 400 kW would be realisable (based on observed vehicle numbers at Kenilworth Road), but this would occur infrequently.
- For PSV, energy consumption would be skewed, with a little (or no) demand for DWPT in the morning (due to high SoC of PSV) and higher demand later in the day (as SoC falls). This could exacerbate the evening peak demand of the distribution network.
- The amount of energy transferred would be higher during the periods of high traffic volumes – due to the lower vehicle speeds.

The theoretical maximum demand is indicated by the orange line in Figure 10. Any point on or below this line represents a realiseable possibility i.e., when the speed is zero (traffic stationary) we can have a demand anywhere from 0 to 650kW. However, there are certain possibilities that will occur more frequently than others – for example, 650kW demand when the speed is zero requires that all vehicles will be charging, whereas, for the PSV example, each PSV will arrive at a different time and hence the demand will not exceed 75kW. If the system was capped at 75kW and demand was increased than the MU would distribute the available power equally across in-use coils in the GA or as a more intelligent approach could allocate the power across vehicles based on their SoC (those with lower SoC being served in preference to those with high SoC).

More work is required to determine the frequency distribution of demand however, the physical characteristics of the system point to high diversity.

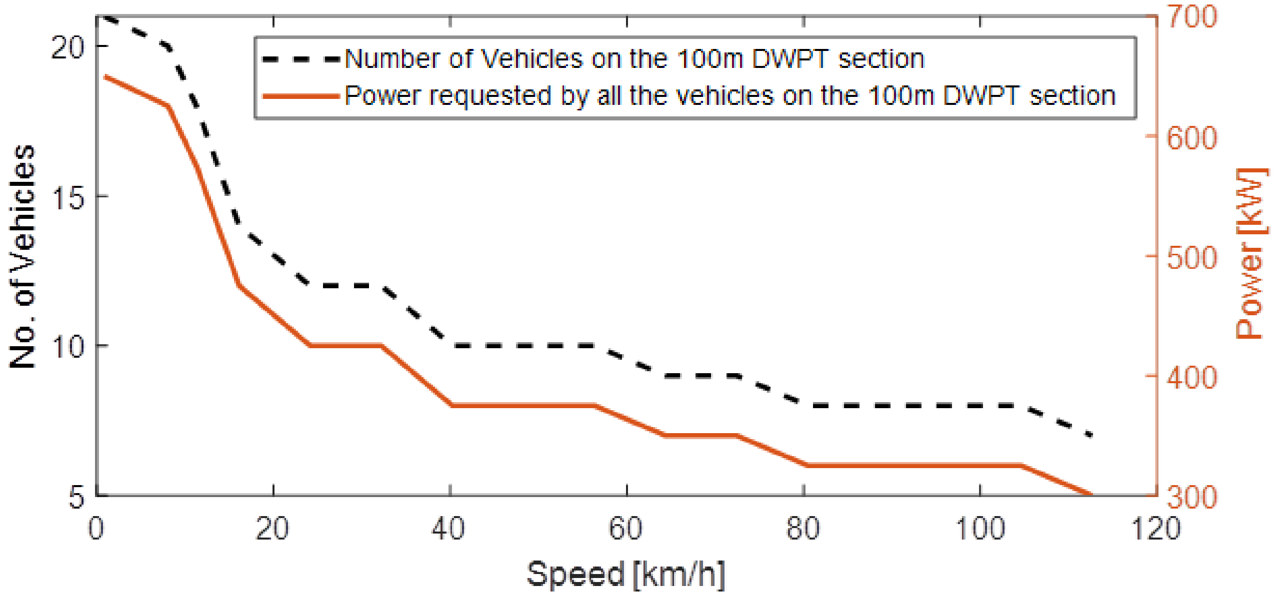


Figure 10: Illustrating the decreasing power requested from the DWPT section as the vehicle speed increases in case of queuing traffic characterised by a minimum time headway of 1s and a minimum distance headway of 2m whichever is the largest.

5. Business Case Assessment

WP4

The dilemma of which rollout needs to happen first - chargepoints or EVs - is more critical with DWPT because of the higher capital costs on both the vehicle and infrastructure side. It is therefore important for the two rollouts to happen simultaneously as much as possible. The modelling considers the whole ecosystem of the infrastructure, the vehicle retrofits/integration and the savings from the counterfactual costs of conductive charging and larger batteries.

5.1. Costs

DWPT capital costs are relatively well-known for civil works, installation and hardware. (Software costs are negligible after development and when technology is deployed at scale.). Network connection costs will vary by location. Operational costs such as electricity supply will depend on local conditions so should be analysed in any future DynaCoV demonstrator. Understanding how costs will be recouped and by whom is key to fully assessing the benefits of DWPT and constructing a robust business case. Note that to save customers from the large upfront capital costs, ElectReon are offering bespoke Charging-as-a Service packages.

5.2. Uptake Scenarios

A shared public DWPT network could supplement private charging stations. The nature of the in-road installation, the high capital costs, the potential impact and interaction with all road users means that the rollout would need to have high-level strategic support via government policy and funding for a rollout.

To model DWPT uptake, a top-down approach based on road lengths and percentages of DWPT cover was used. The statistics for the length of the roads are clear-cut. The modelling simplicity of a top-down approach looking at road coverage rates make the assessment more transparent and the results easier to consider. The scenarios that were modelled for the DWPT business case assessment are presented in the next section of this report.

To make DWPT economically viable, it is important that it is installed on the roads with the most traffic - the motorways and 'A' roads also known as the Strategic Road Network (SRN). One-third of all motor vehicle miles are made on the SRN, and that rises to two-thirds for HGVs.[Error! Bookmark not defined.] In Great Britain there are:

2) 2,300 miles of motorway (99% trunk, 1% principal[5])
3) 29,500 miles of 'A' road (18% trunk, 82% principal)[6]

Figure 11 shows the geographic layout of the SRN controlled by National highways and other major roads demonstrating clustering around major cities and conurbations controlled by local authorities. It serves to showcase the opportunity for scaling DWPT across the nation.

Based on a high-level assessment of the political and market situation and emerging trends (refer to the DynaCoV WP4 full report for further details), while there may be incentives to introduce an electrification enabler such as DWPT, other potential solutions (such as hydrogen, better batteries and ultra-rapid chargepoints) will compete for attention and funding and this is the key risk to the future of DWPT.

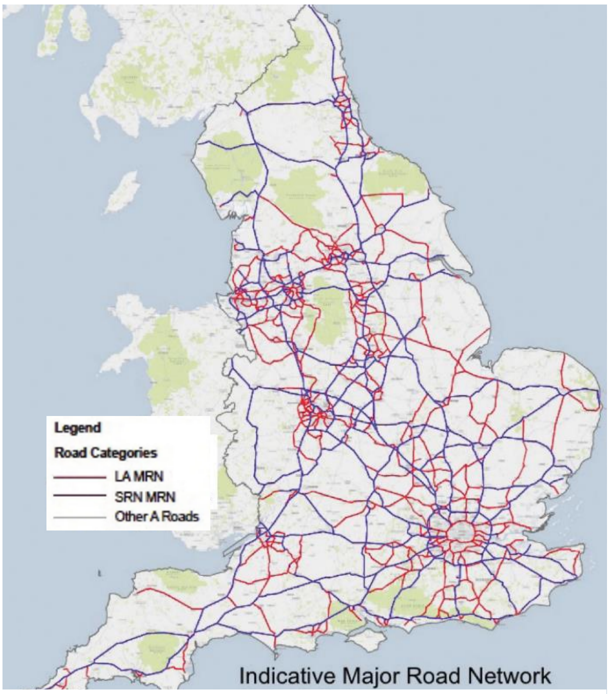


Figure 11: Major roads in England.

[5] Trunk roads are maintained by National Highways whereas principal roads are maintained by a local Highway Authority
[6] [Road Lengths in Great Britain: 2020 - GOV.UK (www.gov.uk)]

5.3. Modelling

5.3.1. Methodology

An Excel based model has been developed to quantify and assess the business case of a range of DWPT rollout scenarios at the GB level. The detail of the model is shown in WP4. The key output metric of the model is the £/kWh of energy delivered by the charging system over its expected lifetime. This metric allows comparisons between DWPT and other technologies, e.g. conductive charging.

The spreadsheet can model scenarios built from different combinations of inputs for:

- Vehicle types – Bus & Coach, HGVs, Cars & Light Commercial Vehicles (LCVs), All Vehicles;
- Road types – Urban ‘A’ Roads, Motorways, Trunk Roads, Urban ‘A’ Roads (Traffic Lights);
- Percentage of vehicles fitted with DWPT; and
- Percentage of road length installed with DWPT.

Scenarios (defined in Table 1) were created to assess different use cases of DWPT within the model.

Table 1: Scenario Definitions

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Road Network in Scope	Urban 'A' Roads	Urban 'A' Roads (Traffic Lights)	Urban 'A' Roads	Trunk Roads	Trunk Roads	Motorways
Percentage of Road Network with DWPT	90%	5.5%	50%	90%	90%	50%
Vehicles in Scope	Bus & Coach	Bus & Coach	All Vehicles	HGVs	All Vehicles	HGVs
Percentage of Vehicles Equipped with DWPT	70%	70%	50%	50%	50%	50%

Note that Scenario 2 represents DWPT being installed on Urban ‘A’ roads, but only on the approach (50m) to traffic lights (assumed to be 5.5% of road length). This results in lower average speeds for vehicles over the DWPT strips, and relatively more energy being delivered.

A key limitation of the model is that it cannot consider geospatial data; it assumes an even distribution of traffic along road lengths and road types. For example, the model assumes that all vehicles of a given type cover the same mileage on the road network in the scenario. This will not be the case and this generalisation will cause errors in the values of how many vehicles would be best to have DWPT capability fitted, and how much mileage on the road network these vehicles will cover. Due to the necessary assumptions made at this stage, the actual business case for DWPT will also vary by location, within the explored scenarios. However, at this stage of feasibility assessment, a homogenised national view is sufficient to support a decision on whether to proceed to the next stage of investigations and a possible demonstrator. The modelling provides a starting point from which DWPT can be compared with other charging solutions. It also gives a clear indication of which scenarios for DWPT are most promising and which are less so.

5.3.2. Results

Figure 12 shows that between scenarios, the split of lifespan DWPT costs and vehicle integration costs vary significantly. The bulk of the total lifespan DWPT cost (over 10 years) comes from the capital infrastructure costs derived from aspirational figures of what the technology costs could be in a few years’ time with further technology developments and when economies of scale are reached. Cost savings associated with a reduction in conductive charger capacity requirements and reductions in battery costs are shown below the axis in Figure 12. The vehicle integration cost is significantly higher in the ‘all vehicle’ scenario because of the significantly higher number of vehicles when considering the vehicle parc.

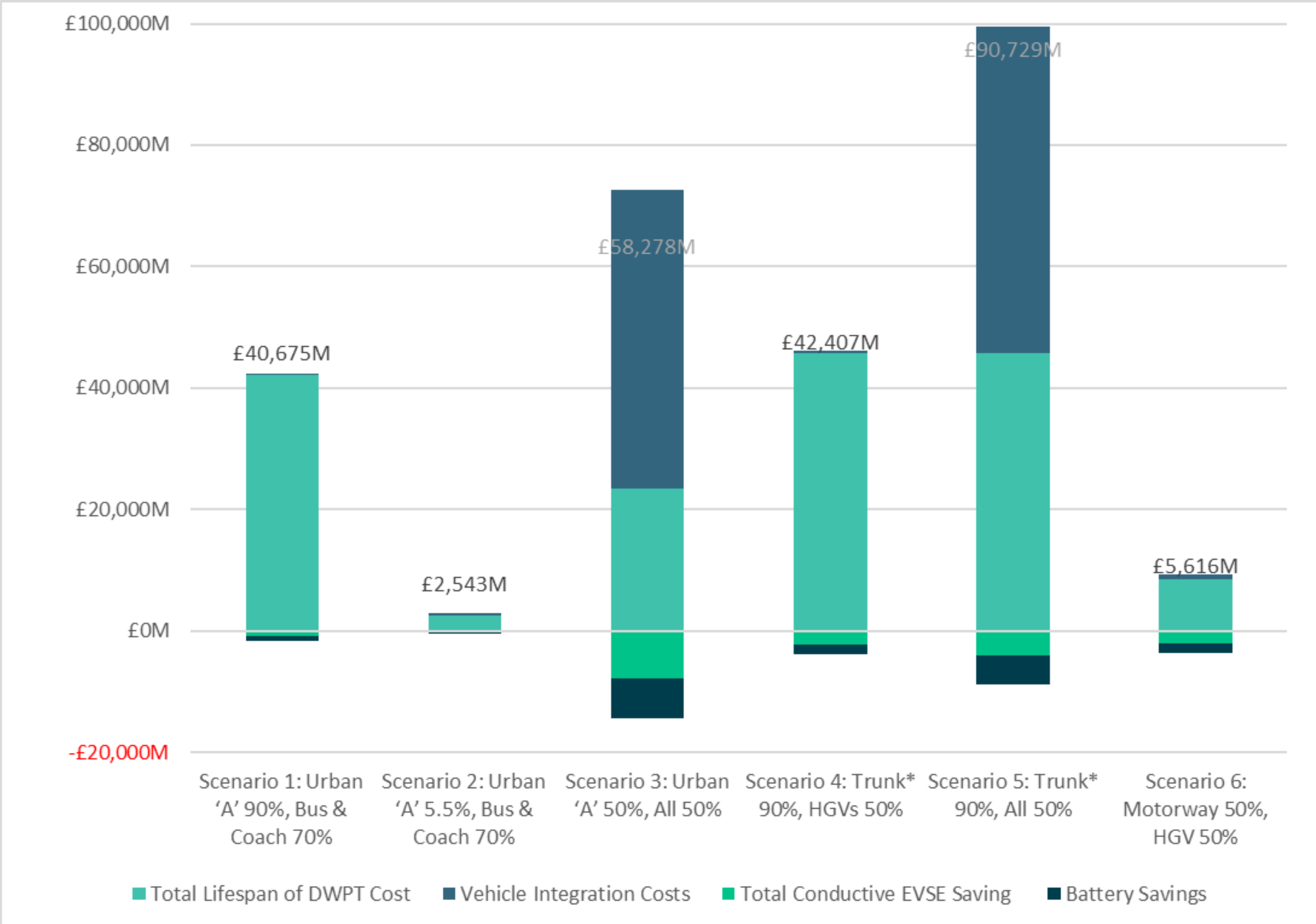


Figure 12: Modelling results costs summary.
*(*Trunk roads form part of the Strategic Road Network and are maintained by National Highways.)*

Figure 13 shows the costs for each scenario expressed on a marginal kWh basis. In other words, the value when the total cost is spread out evenly across all energy delivered to vehicles over the lifespan of the infrastructure. On this basis, scenario 6 is the best value at around 12p/kWh. The high energy demand from the HGV fleet over a relatively short road network contributes to this value. The most expensive scenario is scenario 1, with a cost around fourteen times higher, which represents the opposite case of a long road network with relatively low vehicle mileage.

In addition, the lowest DWPT lifespan cost is in scenarios 3 and 5. In these scenarios, the high utilisation of the DWPT infrastructure (from having all vehicle types covered) reduces the marginal cost. The vehicle integration cost appears cheapest in scenarios 1 and 4. These more targeted scenarios maximise the energy charged on a per vehicle basis.

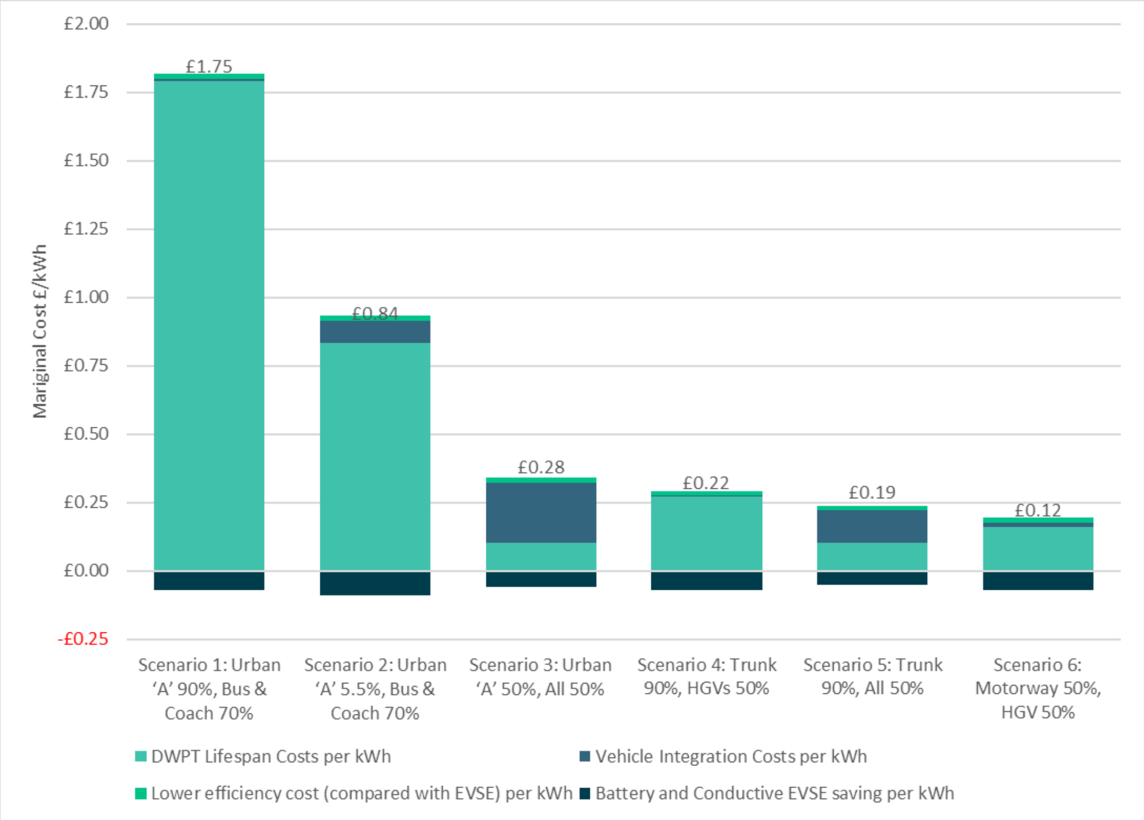


Figure 13: Modelling results marginal costs per kWh.

These costs can be compared with the costs of facilitating the electrification of vehicles through conductive chargepoints. The Cenex internal chargepoint deployment investment model calculates 11p/kWh for ultra-rapids.

A sensitivity analysis was carried out in which various parameters were altered to assess the impact on the per kWh cost of DWPT. The parameters were assessed independently; each row in Table 2 represents a specific and independent change from the baseline.

Table 2: Scenario results from sensitivity analysis.

	Scenario (DWPT coverage: Roads and Vehicle Mileage)					
DWPT (inc. cost offset) per kWh delivered	**Urban 'A' 90% Bus & Coach 70%**	**Urban 'A' 5% Bus & Coach 70%**	**Urban 'A' 50% All 50%**	**Trunk Roads 90% HGVs 50%**	**Trunk Road 90% All vehicles 50%**	**Motorway 50% HGV 50%**
Baseline	£1.75	£0.84	£0.28	£0.22	£0.19	£0.12
Lifespan increased from 10 to 15 years	£1.22	£0.59	£0.19	£0.16	£0.13	£0.09
Power per receiver increased from 30 to 35 kW	£1.49	£0.71	£0.23	£0.18	£0.16	£0.10
Half road coverage	(Urban 'A' 45%) £ 1.76	(Urban 'A' 2.8%) £0.93	(Urban 'A' 25%) £ 0.50	(Trunk 45%) £ 0.23	(Trunk 45%) £ 0.31	(Motorway 25%) £ 0.14
Half DWPT equipped vehicle	(35% Bus & Coach) £3.54	(35% Bus & Coach) £1.68	(25% all) £ 0.38	(25% HGVs) £0.50	(25% all) £ 0.29	(25% HGV) £ 0.29
Half road coverage and DWPT equipped vehicle	£3.55	£1.76	£0.60	£0.50	£0.41	£0.30

This sensitivity analysis shows that the Cost Benefit Analysis (CBA) is highly sensitive to scale; if the number of equipped vehicles is lower and the percentage of road network equipped is lower, then the cost per kWh is higher. This would suggest that in the initial years of deployment, where the number of equipped vehicles and amount of road network equipped with DPWPT will be lower, the costs could be significantly higher than the theoretical CBA in the baseline presented above.

5.4. Business Case by Stakeholder

In general, there is the potential for total network connection cost savings associated with a DWPT rollout, as the demand is distributed more evenly around the distribution network area, resulting in reduced connection capacity requirements at charging depots. However, quantifying this potential saving has not been within the scope of this early feasibility study.

For vehicle users and operators, having DWPT installed along the route can mean:

- they can travel further without needing to stop and plug-in;
- depot charging needs can be met with a smaller capacity connection; and
- reductions in the vehicle battery size and weight, meaning they can transport greater payloads in less time and fewer journeys.

In order to access these benefits, fleet operators will have to bear two costs:

- the capital costs for the vehicle integration; these are expected to be passed through to consumers via the vehicle OEMs, who are likely to also add a margin to the costs; and
- the charging costs, which will likely be higher than other forms of charging.

Unlike the centenary systems that could only ever work with HGVs, DWPT systems can work across a range of LCVs and HGVs. If National Highways were to upgrade their road networks with DWPT this would provide justification to introduce tolls for these roads offering a potential pathway to recoup costs lost from petrol and diesel tax revenues.

6. Considerations for Deployment in the UK

6.1. Site Selection

The process used to identify the demonstrator site is shown in Figure 14. This process could also be adapted and used to identify sites for DWPT rollout.

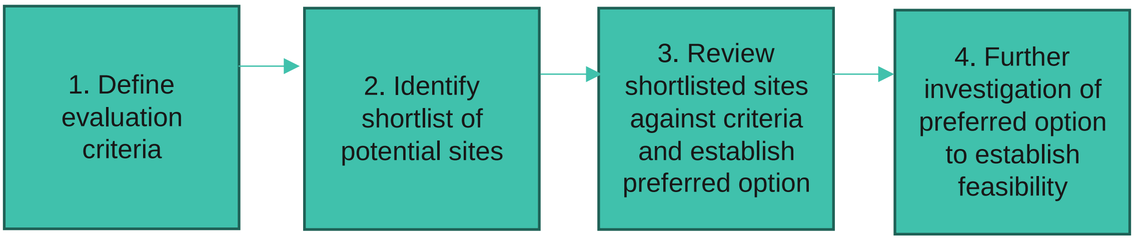


Figure 14: Site selection process.

The evaluation criteria defined in step 1 of the process are shown in Table 3; again, this set of criteria could be adapted to be used more broadly. The 'further investigations' required as step 4 are detailed in the next sub-section.

Table 3: Evaluation criteria for potential sites.

Site criteria	Rationale for inclusion	Essential / Desirable
Part of the Connected Autonomous Vehicles (CAV) Testbed[7]	• To enable different technologies to be tested simultaneously • To ensure ease of access for organisations based outside of Coventry	Essential
Part of a National Express bus route, due to be electrified before the end of 2022	• To enable the use of a National Express bus in real-world testing	Essential
Unlikely to generate objections from local residents (i.e. not in the immediate proximity of homes, schools etc)	• To minimise the risk of objections causing delays to the project, or preventing it from occurring entirely	Essential
No other significant works already planned	• To avoid testing being disrupted by other works	Essential
Likely to be physically suitable for the installation (e.g. carriageway of sufficient width)	• Essential to ensure successful installation	Essential
Attracts a good mix of different vehicle types	• DWPT technology primarily aimed at larger vehicles	Desirable
Attracts a high volume of traffic overall	• Maximises chances of other organisations making use of the technology during the trial period • Ensures 'real world' nature of test	Desirable
Provides opportunities to easily test the technology in both free-flowing and stop-start conditions.	• Ensures different levels of performance at different vehicle speeds can be properly understood	Desirable

[7] A network of 300km of roads across Birmingham, Coventry and Solihull which is enabled for the testing of CAV technology.

The Red/Amber/Green assessment of the the potential sites (in light blue in Figure 15) is shown in Table 4. Kenilworth Road (in navy blue in Figure 15) scored the best and hence was selected for further investigations.

Table 4: Desktop evaluation of shortlisted sites.

Criteria		Holyhead Rd	Warwick Rd	Kenilworth Rd	London Rd	Allesley Old Road	A45 option a	A45 option b
ESSENTIAL	CAV testbed							
	Suitable NX bus route							
	Low risk of resident objections							
	No other planned works							
	Carriageway likely to be suitable for installation							
DESIRABLE	Good mix of vehicle types							
	High volume of traffic overall							
	Ease of testing in both free-flowing and stop-start conditions							

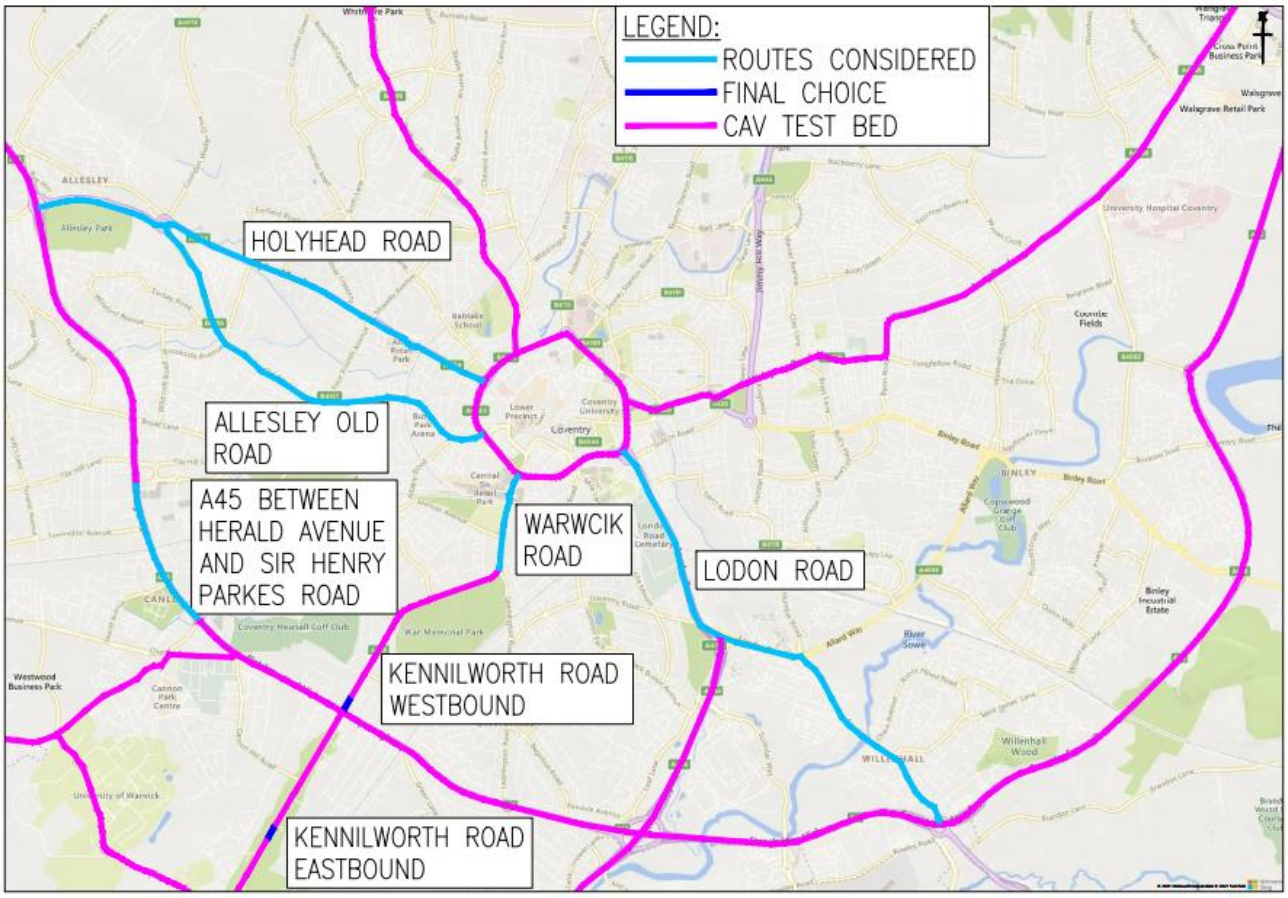


Figure 15: Location of shortlisted sites.

6.2. Physical Feasibility

An electricity network capacity assessment is required to establish whether existing infrastructure would be sufficient to supply the level of power required. This requires a calculation of the maximum power demand, which may be the maximum number of vehicles across the DWPT strips and charging at one time. Each 100m stretch of DWPT will normally have its own connection to the distribution network. WP3 details how power demand can be calculated based on the chosen uptake scenario.

A topographical survey and trial pits are required to determine above-ground features and underground utility apparatus (along with the depths) that could negatively impact the installation of DWPT infrastructure. The results of these surveys for the identified case study location are detailed in WP4, Section 2.2.

The principle constraints associated with the installation of the MUs are:

- Their size: the dimensions of the ElectReon MU are 1,808mm (height) x 1,678mm (width) x 970mm (depth). If the MU is installed underground (Figure 4 image right), these dimensions increase by a further 300mm in every direction, due to need to encase the MU securely; and
- Their proximity to the underground coils: The MU can be installed a maximum of 55m from the coils.

Each coil is 1,650 mm (length) x 580 mm (width) x 20 mm (depth). Coils are placed 1.5 m apart, meaning that a total of 66 coils will be required for each 100 m stretch of road identified as part of the demonstrator project.

The deepest total depth of the trench is 240 mm from the road surface. If the coil segments are placed exactly 100 mm beneath the road surface - the additional depth (from the coil segment layer) is 140 mm at its deepest point to accommodate the cables connecting the coil segments to the MU. The trench width (from the end of the coil segment) is 100 mm (Figure 16).

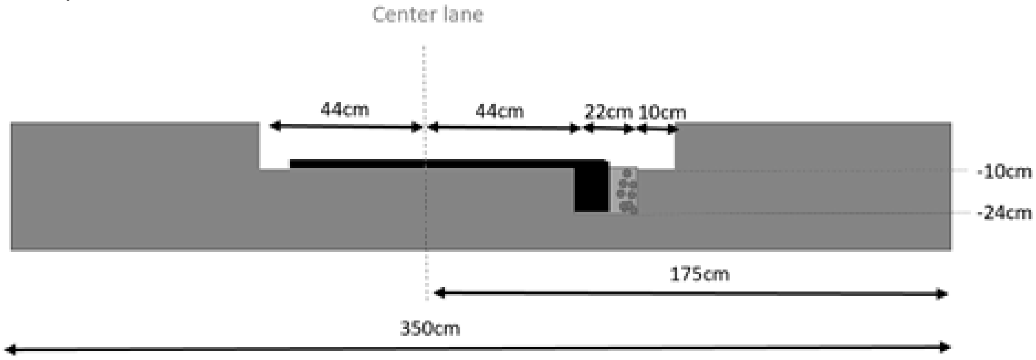


Figure 16: Cross-sectional diagram showing depth of coil

Figure 17: Photo from the ElectReon deployment in Italy in November 2021.

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.

6.3. Demonstrator Costs

This section provides details of the expected cost of installing DWPT technology on Kenilworth Road (an A Road part of the Key Route Network[8]) and equipping two vehicles (one bus and one van) with the necessary receivers, as part of the proposed demonstration project. Costs are based on:

- ElectReon supplying the DWPT technology and providing support to ensure that it can be installed and operated effectively;
- No significant change to the budget estimate for the connection cost provided by WPD;
- CCC carrying out the installation, including all necessary traffic management and public consultation; and
- An estimate of the project management costs from CCC, although in practice these will be spread across the various organisations involved in delivering the project.

Table 5: Estimated costs for installation of a DWPT demonstrator project on Kenilworth Road.

Item	Total cost	Source
Technology costs		
Planning and design	£9,000	ElectReon
DWPT- 2 x above ground Management Unit for 100m	£221,000	ElectReon
DWPT – 10 x sections of inductive coils (20m each)	£495,500	ElectReon
Commissioning including integration with the grid	£45,000	ElectReon
12 months’ maintenance, operation support	£14,000	ElectReon
12 months’ data management	£4,000	ElectReon
Subtotal	*£788,500*	
Civils costs		
Installation (including staffing, equipment hire and all physical works)	£130,000	CCC
Traffic management	£21,000	CCC
Site Management, site supervision and welfare	£22,500	CCC
Public consultation	£1,500	CCC
WPD connections - Eastbound	£15,000	WPD
WPD connections – Westbound	£68,000	WPD
Subtotal	*£258,000*	
Project Management (Activity Breakdown)		
PM Installation of physical works (10%)[9]		
Backoffice software development[10]		
Data collection and analysis		

[8] Collection of the busiest roads in a combined authority

[9] In accordance with https://www.routledge.com/Spons-Civil-Engineering-and-Highway-Works-Price-Book-2022/AECOM/p/book/9781032052205

[10] Development of a secure authentication and authorisation protocol sequence.

Item	Total cost	Source
Report writing		
Subtotal	*£300,000*	CCC
Vehicle Integration costs[11]		
Bus - Mechanical, Electrical, Software Components	*£67,000*	*ElectReon*
Van - Mechanical, Electrical, Software Components	*£62,500*	*ElectReon*
Subtotal	*£129,500*	
Grand total	***£1,475,000***	

Costs are likely to be broadly similar for any other comparable location. However, installing DWPT technology on the Strategic Route Network (motorway network) would be more expensive, due to additional traffic management requirements.

These costs are expressed in 2021 prices. For any future installations, they would need to be index linked to allow for inflation.

Once the demonstrator phase is complete, the equipment will be left in the carriageway even if it is not used. However, it is anticipated that the equipment will be made available to the electric vehicle manufacturers of all classification vehicles as a test route for them to a make strategic decision on whether to include this technology as a base functionality in their future EV production.

6.4. System, Safety and Security requirements

Electricity networks are critical infrastructure that must be secured to prevent possible tampering and cyber-attacks. Electricity network security is dependent on the security of all its gateways, including EV charging infrastructure. For this reason the DynaCoV WP4 report presents a concept for secure service access and exchange between EVs and on-road charging infrastructure. The proposed approach addresses the three main challenges identified in this DWPT technology:

- The lack of interoperable charging services and hardware;
- The insecure access to the electricity network; and
- Non-standardised communication between the actors involved.

The concept is based on the ISO15118[12] standard in combination with the Association for Electrical, Electronic & Information Technologies application guide for handling digital certificates for electric vehicles[1]. The actors involved are explained in the WP4 report, along with the software and hardware required to implement such a solution. A brief technical description of the realisation of the concept is also presented. The main results of the investigation can be summarised as follows:

- DWPT is still a young technology that requires standardisation of hardware and communication protocols;
- Standardisation is necessary to build a competitive, scalable market around this technology;

[11] These costs do not include decommissioning. Decommissioning would be carried out in conjunction with a local garage if requested and the cost would depend largely on the labour costs and time. Other factors including if there is a requirement for the specific OEM/auto manufacturer for the vehicle to undergo a lab evaluation process before being returned to full use after the pilot would also need to be considered.

[12] One of the International Electrotechnical Commission's group of standards for electric road vehicles and electric industrial trucks. It defines a vehicle to grid (V2G) communication interface for bi-directional charging/discharging of electric vehicles.

- The ISO15118 standards are the most complete and mature solution for secure and seamless access to the charging infrastructure and the provision of bi-directional services between the EV and the electricity network;
- Cooperation between the charging infrastructure operator and the utility is recommended to enrich the market and increase competitiveness.

In September 2021 ElectReon received ECE R10 certification – the UN and European Economic Community's Electromagnetic Compatibility Approval – for their deployments[13]. This approval pertains to the receiver coil and associated vehicle hardware and is concerned with being able to safely operate wireless charging equipment in a public environment, considering the impact of electromagnetic radiation on drivers, passengers and pedestrians.

6.5. Supply Chain Assessment

Part of the DynaCoV project involved conducting a supply chain assessment of the different components of DWPT, which highlighted the following opportunities to deliver UK-based activities (further information is available in the WP2 report). There is a mixed opportunity for a full UK supply chain, based on the observations below. 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.

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.

[13] ElectReon Receives UN and European EMC Board's Approval to Globally Integrate its Vehicle-side Technology (emc-directory.com)

7. Summary and Next Steps

The DynaCoV project was a desktop feasibility study that involved:

- A literature review looking at the available technologies and electricity network impacts of DWPT (WP2)
- Demand and electrical impact modelling and simulation of a case study stretch of DWPT at Kenilworth Road in Coventry (WP3)
- Business case modelling investigating the economic case of a range of potential national rollout scenarios (WP4)
- Demonstrator site determination, physical feasibility assessment and costing (WP4)
- Desktop review of considerations for deployment such as system and security requirements (WP4) and supply chain assessment (WP2)

For a rollout to be successful it will be important to have consistent international or even national standards for DWPT (they are being developed but are likely some years away from being agreed). 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. In particular, all DWPT hardware should comply with Electromagnetic Compatibility (EMC), Electromagnetic Field (EMF), IEC and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines, with a consideration of SAE J2954, ISO 6469 and ISO 26262. Furthermore, DWPT systems should employ proactive and reactive protection mechanisms to ensure safe operation under a variety of disruptive conditions.

Of the scenarios assessed in the business case modelling, a DWPT rollout to cater for HGVs on motorways looks to represent the lowest marginal cost per kWh, close to the marginal cost of ultra-rapid conductive chargers (11p/kWh). However, across half of the 36 scenarios tested (six baseline scenarios and five additional sensitivities on each scenario), the marginal cost of DWPT was at least three times more expensive than conductive charging. The modelling accounts for the fact that shared DWPT resource reduces the need for (often private, in the case of fleets) conductive charging and reduces the size of the battery required to cover the same the journey lengths, though it also has its limitations (described in detail in WP4).

The partners required to support a pilot at the identified demonstrator site at Kenilworth Road (an ‘A’ Road on the Key Route Network) are engaged in this project and geared to progress that quickly. It is estimated that this demonstrator could be delivered for around £1.5m and could help identify some of the missing information with regards to the impacts on the electricity network to help the understanding of, for example, the harmonics of the system and its’ effects on power quality. On the other hand, based on the outputs of the business case work which highlighted HGVs on motorways as being of greatest interest, the specific demonstrator location examined in this report may not be best to test the most beneficial scenario. In addition, it has been identified that further work is needed to compare DWPT against other competing low carbon technologies for heavy vehicles, such as conductive charging (for example via catenary systems) and hydrogen, from an economic point of view.

There is some evidence from the identified case study site at Kenilworth Road in Coventry that DWPT could reduce the need for costly and time-consuming electricity network reinforcements required to support high power depot charging at depots (in this case at the National Express depot in Coventry, see WP4). This is because the nature of DWPT distributes energy demand more evenly over time and space than conductive charging. For example, this project’s modelling indicates that the peak power demand for buses on the Kenilworth Road in Coventry would not exceed 75 kW, although this could rise to as high as 650 kW in the worst case scenario for a mixed fleet (in standstill traffic).

The specific demand on the network at any individual point is dependent on many factors. Six key externalities were identified in three groups to determine if:

a) a charge event is possible with 1) a compatible vehicle and 2) available DWPT infrastructure,

b) a charge should be initiated by 3) a requirement to charge and 4) an acceptable price, and;

c) the resulting power and energy transfer based on 5) traffic conditions and 6) the way in which the vehicle is driven.

More work is required to determine the frequency distribution of demand, however, the physical characteristics of the system point to high diversity. The connection capacity required will be much lower than the theoretical maximum demand because of the very low probability and frequency of the theoretical maximum demand and particularly as the MU distributes the energy equally across in-use coils in the GA if the MU rating is exceeded.

A key piece of the puzzle that is missing to support a DWPT rollout is high-level, government support from both a policy and a funding perspective. The current targets of phasing out non zero emission HGVs by 2040 do not specify a vehicle or infrastructure technology for this decarbonisation or dedicated funding. To support and optimise any funding that does become available for infrastructure it would be important to carry out geospatial analysis of different vehicle traffic flows and understanding the energy infrastructure capacity at these locations to supply the transport sector. On a more regional basis some key selection criteria are identified that were used to identify a site in Coventry. At a national level, a holistic, systems-based approach is essential to deciding the future pathways.

In summary, it is likely that a proportion of the HGV fleet will be electrified by 2040 to meet decarbonisation targets (the exact proportion will depend on how successful hydrogen HGVs are). This implies that there will be a significant increase in electricity demand. DWPT offers the opportunity to smooth demand peaks over the whole day and lower network impacts (because charging can happen when the vehicle is in use). However, this study has not been able to quantify a benefit for DWPT from the perspective of a Distribution Network Operator like Western Power Distribution. In addition to the areas of work identified the above, further work is also needed to improve:

- technological maturity and increase power transfer,
- clarity over harmonic and power quality impacts,
- marginal costs.

Glossary

Abbreviation	Term
BEV	Battery Electric Vehicle
CBA	Cost Benefit Analysis
CCC	Coventry City Council
DWPT	Dynamic Wireless Power Transfer
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GA	Ground Assembly
GDPR	General Data Protection Regulation
HGV	Heavy Goods Vehicles
ICE	Internal Combustion Engine
kWh	Kilowatt hour
LGV	Light Goods Vehicles
MU	Management Unit
OEM	Original Equipment Manufacturer
PSV	Public Service Vehicle
SoC	State of Charge
SRN	Strategic Road Network
TfWM	Transport for West Midlands
VA	Vehicle Assembly
WP	Work Package
WPD	Western Power Distribution

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