FABRIC

Feasibility analysis and development of on-road charging solutions for future electric vehicles

Interoperability considerations

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LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
AC	Alternating Current
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CWD	Charge While Driving
D	Deliverable
DC	Direct Current
DIS	Draft international Standard
DSO	Distribution System Operators
eCo-FEV	Cooperative infrastructure for Fully Electric Vehicles
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field emissions
ERS	Electric Road System
ETSI	European Telecommunications Standards Institute
EV	Electric vehicle
EVCC	Electric vehicle Communication Controller
EVSE	Electric Vehicle Supply Equipment
FEV	Fully Electric vehicle
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPV	Induction Powered Vehicle
ISO	International Organization for Standardization
IST-G5	Intelligent Transportation Systems 5 Gigahertz
ITU	International Telecommunication Union
JWG	Joint Working Group
NWI	New Work Item
SC	Standardisation Committee
SECC	Supply Equipment Communication Controller
TÜV	German: Technischer Überwachungs-Verein, English: Technical Inspection Association
V2G	Vehicle to grid
V2V	Vehicle to Vehicle
WEVC	Wireless Electric Vehicle Charging
WLAN	Wireless Local Area Network
WP	Work Package
WPT	Wireless Power Transfer

REVISION CHART AND HISTORY LOG

REV	DATE	REASON
1	01/10/2014	Document and Table of content definition
2	24/11/2014	First draft proposal
3	05/02/2015	Final draft ready for internal review
4	13/02/2015	Final draft ready for peer review
5	20/03/2015	Submission to EC
6	31/08/2015	1st Update of the deliverable
7	01/07/2016	Content update
8	01/01/2017	Content update VICTORIA integration
9	01/10/2017	2th Update of the deliverable

EXECUTIVE SUMMARY

Within this document an analysis of interoperability aspects regarding inductive charging systems will be performed with a main focus on the developed FABRIC solutions. The overall considerations will not result in addressing solutions, but identify critical technical domains, in which interoperability can be determined as limited/restricted or even not available.

This document is a result out of an extensive analysis performed in different working documents (extract is shown in the appendix). The overall results as well as the interoperability analysis methodology are described in detail in this deliverable.

This interoperability analysis document has to be considered as a living document which grows hand in hand with the specifications and developments. The available required data for the interoperability analysis at the time of delivery of this document was about 70%. Assuming the missing data will be provided; an interoperability level (combination of interoperable solutions regarding each considered parameter, see Table 37) of over 80% is possible and thus can be rated as good.

After analysis of the different systems it can be stated that there are physical areas where interoperability is not a major issue, such as:

- Power rating
- Secondary coil voltage
- Coil geometry
- Operational frequency

As well as critical areas in which more research is needed:

- Magnetic field intensity
- Position tracking
- Achievable velocity

Regarding the interoperability of the FABRIC solutions with other systems, such as the UNPLUGGED solution a positive resumé can be drawn, as the systems are interoperable in a high degree.

1. INTRODUCTION

The FABRIC project addresses directly the technological feasibility, economic viability and socio-environmental impact of dynamic on-road charging of electric vehicles. This innovative, new technology however requires a detailed investigation of all technical aspects of possible on road charging solutions. For a successful mass roll out of these charging systems, a detailed technical benchmarking, definition of requirements, specifications and architecture is mandatory.

One of the milestones towards an overall customer acceptance is the interoperability of the different charging solutions. Within this deliverable this crucial technical topic is discussed. A methodology is presented to define the interoperability level and the different FABRIC solutions are evaluated together with other solutions as described in this document.

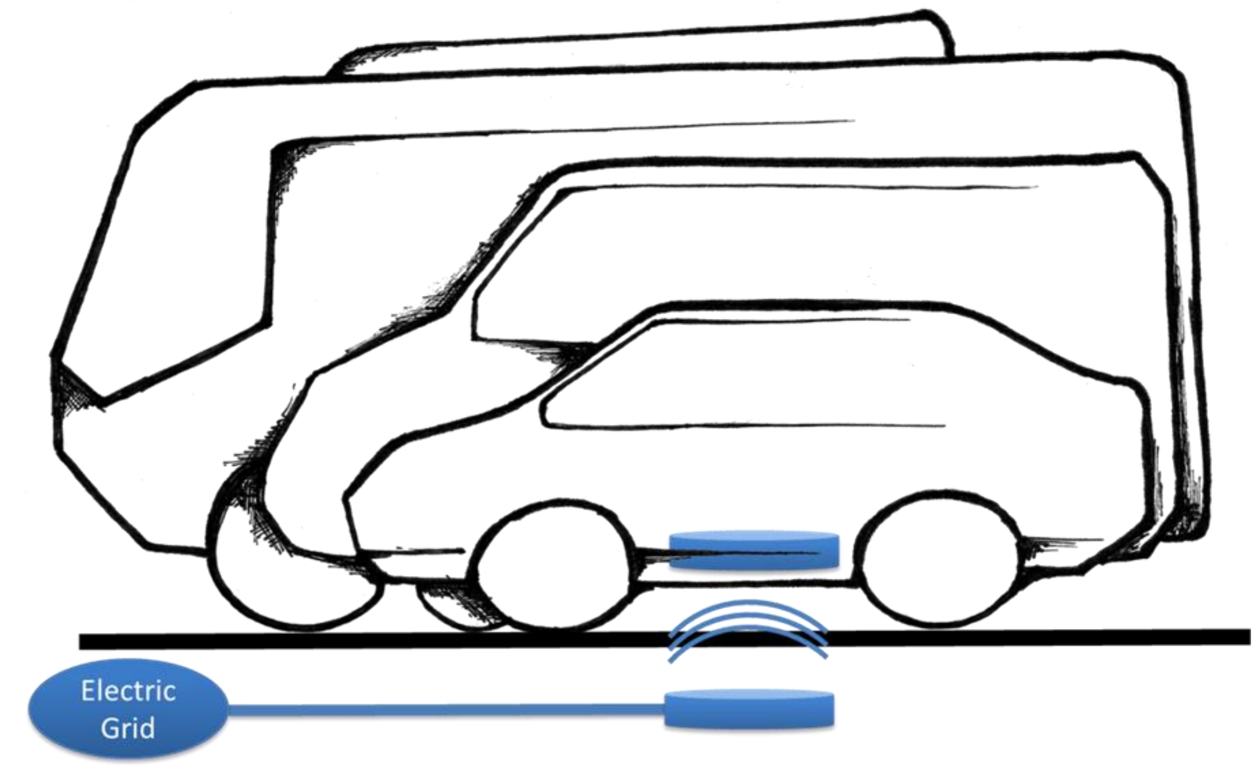

Figure 1: Only interoperability can lead to user acceptance.

The document is structured in the following way;

Section one gives an overview on the structure and partners involved in the FABRIC WP33 Task 3.3.4. Responsibilities and areas of expertise will be described briefly.

Within section two a complete overview is given on the definition of interoperability in general. The methodology used to analyse the interoperability of different technical systems is explained and the critical parameters for interoperability of an EV inductive charging system are listed. Standards concerning interoperability are listed and the methodology is configured in a way that all standards for interoperability (and the analysis) are fulfilled by defining them as the existing boundary conditions.

As an extract of the deliverable D33.1 an overview on existing solutions, in specific the characteristics of the critical interoperability characteristics is given in Section 3. This section is structured by interoperability properties regarding the different inductive charging solutions which are grouped thematically into: communication, construction and geometry, electromagnetic and other (which includes safety aspects).

The following section four, will give an overview on the interoperability considerations. The methodology as described in section two and the available input out of section 3 is combined and a chart analysis for every physical aspect is executed.

An overall conclusion in section 5 then describes gaps within the interoperability field, next steps for interoperability to improve, and technical areas where interoperability will never be possible.

2. METHODOLOGY

2.1. Interoperability in general

Interoperability is the ability of different systems, including those from different manufactures, to seamlessly work together (to inter-operate). In D3.3.3, a system of on road charging solutions is envisioned, where different kinds of electric vehicles, from small cars to heavy duty vehicles, can all be charged by all systems.

Interoperability enables synergy, extends product utility and increases the usability for different customers dramatically. Each participant in developing road charging solutions should accept and enforce the use of mutual standards and interface protocols. With those common standards a framework that ensures the interoperability for all upcoming developments exists. However, there is no finalized document since IEC 61980, which aims to provide standardization for inductive power transfer for EVs, and similar guidelines are still in development.

This leads to a situation, where all charging solutions that are currently tested were developed on almost no common standard. The question that has to be examined is, whether it is still possible to do an interoperable charging, and if not which components have to be changed at what costs in order to achieve interoperability.

2.2. Interoperability methodology considerations

For an inductive charging system (of an EV) many different parameters have to be considered for interoperability of a ground module of charging system A and an on-vehicle module of vehicle B. Different parameters can be analysed in a matrix which matches different ground modules and on-vehicle modules, always identifying the critical physical functions and components of a system. This is the basic concept behind a proper interoperability analysis and will be worked out in detail in the next sections.

Within this document the FABRIC solutions number 1,2,3,5, the UNPLUGGED project solution (FP7, EU Project), the FASTINCHARGE (FP7, EU Project), OLEV solution (KAIST) and VICTORIA (CIRCE) solution are analysed regarding different interoperability aspects. FABRIC solution 4 is not included in this analysis as this is a conductive charging system and there are no proper physical crossovers regarding interoperability with inductive systems. The UNPLUGGED, VICTORIA as well FASTINCHARGE project solutions are not part of the FABRIC project, but due to the fact that several FABRIC project partners are involved in the UNPLUGGED, VICTORIA and FASTINCHARGE project there is a very detailed and valuable physical input, thus including this system is valuable for the analysis. The OLEV solution from

KAIST is a well-known solution for some partners and detailed information is available in technical reports, so this solution is also included.

All compared on-road charging solutions in D 33.3 are shown in Table 1 and described in detail in section 3.

Compared on-road charging solution	Abbreviation	Corresponding FABRIC solution
The VEDECOM solution is provided by Qualcomm: "Qualcomm Halo™ Wireless Electric Vehicle Charging"	WEVC	FABRIC solution 1
Polytecnico di Torino/ Centro Ricerche Fiat- Charge While Driving	CWD	FABRIC solution 2
Saet Spa- Induction Powered Vehicle	IPV	FABRIC solution 3
Scania/ Bombardier Primove	PRIMOVE	FABRIC solution 5
UNPLUGGED en route charging solution	UNPLUGGED 50 kW	Non-FABRIC solution
UNPLUGGED en route charging solution	UNPLUGGED 3,7 kW	Non-FABRIC solution
UNPLUGGED follow up	FASTINCHARGE	Non-FABRIC solution
OLEV	KAIST	Non-FABRIC solution
CIRCE solution	VICTORIA	Non-FABRIC solution

Table 1: Overview of compared solutions.

Before starting a detailed analysis two major building blocks have to be identified and described properly. The first building block is the proper identification of physical and functional aspects of an inductive charging system for EVs. After detailed research and investigation, the results can be grouped into four categories, which are listed and described in detail in this section. The second building block is the data description of the inductive charging solutions used for the analysis executed in section three.

- The first category contains all **communication** aspects needed for recognising the EV, initiating and controlling the charging process.

- In the second category all physical **construction and geometry** aspects are considered e.g. the coil position and dimension and the achievable vehicle velocity as a result of construction and geometry aspects.

- The third category describes all essential **electromagnetic** aspects. For the interoperability this group of parameters is possibly the most critical due to the fact that the energy is transferred via an oscillating magnetic field.

- The fourth category, **other**, can be seen as a combination of the three physical categories (which are defined by the system), results out of (possible upcoming) standards as well as a subjective evaluation of the involved experts.

All identified parameters are listed in Table 2:

Communication
Communication method (wireless, Bluetooth, etc.)
Communication protocol (ISO 15118, IEC 61851 etc.)
Position tracking for primary coil activation

Construction and Geometry
Coil geometry
Lateral misalignment tolerance
Air gap and tolerances
Achievable vehicle velocity

Electromagnetic
Operational frequency
Magnetic field intensity
Achievable secondary coil voltage
Power rating and power

Other
Charging efficiency
Safety considerations (Shielding, EMC, Heating, etc.)
Costs to accomplish interoperability

Table 2: Overview on interoperability parameters.

Communication

Before an inductive charging process with different players can start, both systems have to be able to communicate. Using the Vehicle to Grid (V2G) communication the vehicle issues a charging request, which is then approved if all requirements are fulfilled. Therefore, the vehicle and the grid have to use the same communication methodology/system. For example, for the long-range communication the mobile phone network is often considered and for the short range V2G and possibly also Vehicle to Vehicle (V2V) the new IEEE 802.11p standard is applied.

An additional requirement is the usage of the same communication protocol, in order to exchange parameters in such a way that different systems use the same technical language.
Another communication aspect is the fact that all dynamic charging systems interoperate continuously with the vehicle to activate only those coils which are at that moment, aligned with the vehicle and available/needed for the energy transfer. For safety reasons, this last aspect is very important and needs to be analysed in detail (position tracking of the secondary coil and primary coil activation).

Construction and geometry

After a proper communication setup for the charging process, the next step is to physically align both coils, so that the oscillating magnetic field of the primary, ground coil couples with the secondary, vehicle coil and therefore construction and geometry aspects have to be investigated.

For construction and geometry analysis, primarily the analysis of coil geometry of different systems is required. Coil dimension and on vehicle/road positioning is crucial for interoperability (possible lateral misalignment tolerance etc.). Large primary coils can provide good energy transfer, even if the vehicle is slightly misaligned within its lane, however charging efficiency is also a boundary condition which has to be in a defined range to guarantee a proper charging process.

The air gap tolerance is a critical property regarding ground clearances of different vehicle types. Finally, all geometrical parameters combined determine the speed at which the ground coils can be switched on and off, and thus, are the basis for the analysis of the achievable vehicle velocity.

Electromagnetic

For the part of the analysis considering all electromagnetic conditions, the most important parameters are:

- Oscillation frequency used by the circuits. The power can only be transferred efficiently at the resonance frequency.
- Magnetic field intensity; to transfer adequate amounts of power the magnetic field intensity has to be high enough to achieve a proper voltage level in the secondary coil. On the other hand, it must not be too strong because it could damage the vehicle equipment if it is not designed for such a high induced current. However, if the magnetic field limits of the charged vehicle are known, the primary circuit could be powered down accordingly without significant design effort.
- Power rating; amount of power which can be transferred and certificated for the combination of the given systems.

Other

Regarding this section, the first parameter which is considered is the charging efficiency. Critical and most interesting for this conclusion/analysis is the consideration in which degree the efficiency, compared to a perfect arranged situation, will change in other, not physically perfect situations. E.g. misalignments, imperfectly matched frequencies or even bad weather.

The second parameter, safety, is extremely important in every aspect, especially since the confidence of the consumers in the EV is not established yet and an accident could reduce the sense of EV reliability in general. The general threat of high voltage has to be taken into account, as well as the electromagnetic compatibility with other vehicle systems (includes shielding), the heating of the vehicle due to eddy currents and more.

Last but not least the economic aspects have to be considered, in most cases interoperability could be achieved, but often only with a disproportional huge effort in time and money. However, some aspects need only small adjustments to achieve interoperability.

2.3. Analysis Methodology

For each of these parameters, as mentioned above, interoperability of every EV system part has to be "tested" on every road system part to identify the considered parameter's working area or - in case of not working interoperability – to disprove the system compatibility. The methodology matrix is depicted in Table 3.

Lateral misalignment tolerance		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC									
	CWD									
	IPV									
	PRIMOVE									
	UNPLUGGED 50 kW									
	UNPLUGGED 3,7 kW									
	FASTINCHARGE									
	KAIST									
	VICTORIA									

Table 3: Working Matrix for interoperability analysis.

Each of the combinations will receive a score of interoperability:

- **1: Systems perfectly interoperable**
  - No structural changes are needed (systems fit as they are)
  - Only minor losses in efficiency (<10%)
  - No further comments are required
- **0.5: Systems partially interoperable**
  - Systems need some changes (software, hardware) in order to be interoperable
  - Major losses in efficiency may occur (>10%)
  - Comments on necessary changes or efficiency losses
- **0: Systems not interoperable**

- System parameters are not compatible and cannot be adjusted with reasonable effort
- Mismatch causes very large losses in efficiency (>50%)
- Comment on boundary conditions

- **Empty: Data not available**
  - One or two of the two parameters which have to be analysed are not available and therefore the field will stay empty

In addition to the numerical scores, a traffic light colour code is proposed according to the different scores:

- 1: green
- 0.5: yellow
- 0: red

The colour code will make it easier to see at a glance the compatibility of the different combinations in a table. The colours are defined in an Excel sheet with conditional formatting and thus will be created automatically, once the score is introduced.

At the end, a summary table will be created, in order to illustrate overall interoperability, including all studied parameters. The score for each combination will be the average score of all evaluated parameters. If just one of the scores was zero, the overall score will be zero also. The colouring will be done in the same way as for each parameter. Intermediate values between 0.5 and 1 will produce shades between yellow and green (according to default settings of the Excel sheet).
The equation which produces the final score is as follows:

=IF(PRODUCT(C22;C35;C48;…;D118)=0;0;AVERAGE(C22;C35;C48;…;D118))

Summary product Table		**Road system part**								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,00	0,75	0,00	0,00	0,00	0,00	0,00	0,00
	CWD	0,00		0,91	0,00	0,00	0,00	0,00	0,00	0,00
	IPV	0,00	0,82		0,00	0,00	0,00	0,00	0,00	0,00
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00
	UNPLUGGED 50 kW	0,00	0,00	0,00	0,00		0,00	0,00	0,72	0,78
	UNPLUGGED 3,7 kW	0,00	0,00	0,00	0,00	0,00		0,00	0,00	0,00
	FASTINCHARGE	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,00
	KAIST	0,00	0,00	0,00	0,00	0,78	0,00	0,00		0,00
	VICTORIA	0,00	0,00	0,00	0,00	0,78	0,00	0,00	0,00	

Table 4: Example of a possible summary table of interoperability for all solution combinations.

Comment:

At the moment, only 3 levels of interoperability are considered. Nevertheless, the simple method of scoring and averaging leaves open the possibility to assign intermediate scores. For example, if a solution is partially interoperable, but the required modification is easy to do, a higher score, such as 0.8 might be given. If in the opposite case, modifications are costly and even though, resulting efficiency will be rather low, a lower score, such as 0.3 might be considered.

Although the methodology offers that possibility, the alternative scores should be justified properly. As this may lead to confusion in a first approach, no intermediate scores are proposed here.

However, at the end an overall table will be created which summarizes all working tables and so gives a good overview on the degree of interoperability level between different systems. In this way, spots in the matrix can be identified where interoperability could be reached easily or possibly never will. Table 5 shows a possibly example of such an overview.

Addittion table		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		5,50	6,00	0,50	4,50	4,00	4,00	5,00	3,00
	CWD	6,00		10,00	1,50	6,50	5,50	5,00	5,00	5,00
	IPV	4,50	9,00		1,00	5,50	5,00	3,00	5,00	4,00
	PRIMOVE	0,00	1,50	1,00		2,50	1,00	3,00	2,50	1,50
	UNPLUGGED	4,00	6,00	6,00	2,50		6,50	4,50	6,50	7,00
	UNPLUGGED 3,7 kW	4,00	5,00	5,50	1,00	7,00		5,00	5,00	3,50
	FASTINCHARGE	4,50	5,50	4,00	3,00	5,00	4,50		6,50	4,50
	KAIST	5,50	6,00	6,00	2,50	7,00	5,00	7,00		5,00
	VICTORIA	4,00	5,50	4,00	1,50	7,00	3,50	6,00	5,00	

Table 5: Addition table to identify "possibilities for interoperability".

As a short example, Table 6 shows how the table should be analysed and which conclusion possibly could be drawn. Of course the overall conclusion is a result of the methodology shown in Table 4 as well as Table 6.

The ratings in the different tables are given by the experts working in this task of the project. All values and inputs are crosschecked by the different experts and discussed in detail. As a base for the input the comparison of the hard physical data was used and rated with the above mentioned value possibilities.

Addittion table		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		5,50	6,00	0,50	4,50	4,00	4,00	5,00	3,00
	CWD	6,0		10,00	1,50	6,50	5,50	5,00	5,00	5,00
	IPV	4,50	9,00		1,00	5,50	5,00	3,00	5,00	4,00
	PRIMOVE	0,00	1,50	[illegible]		2,50	1,00	3,00	2,50	1,50
	UNPLUGGED	4,00	6,00	6,00	2,50		6,50	4,50	[illegible]	7,00
	UNPLUGGED 3,7 kW	4,00	5,00	5,50	1,00	7,00		5,00	[illegible]	3,50
	FASTINCHARGE	4,50	5,50	4,00	3,00	5,00	4,50		[illegible]	4,50
	KAIST	5,50	6,00	6,00	2,50	7,00	5,00	7,00		5,00
	VICTORIA	4,00	5,50	4,00	1,50	7,00	3,50	6,00	[illegible]	

Although it is possible that the systems aren't 100% interoperable (possibly red or orange in the summary table above) these solutions provide good possibilities to become interoperable with only minor adjustments

Systems not interoperable and not possible to get to interoperability

Although it is possible that the systems aren't 100% interoperable for (possibly red or orange in the summary table above) these solutions provide possibilities to get interoperable (effort to be determined)

Table 6: Analysis of addition table.

To analyse every solution combination, in addition a more detailed analysis is performed and to point out the areas in which interoperability is critical or fulfilled for the solutions. Table 7 shows an example of a solution analysis table to have a quick overview of the incompatibilities between the different solutions.

The horizontal sums give the number of incompatibilities for each combination (similar to the information given by the previous table).

The vertical sums give an estimate of the complexity of achieving interoperability regarding each parameter.

	Communication method	Communication protocol	Position tracking	Coil geometry	lateral misalignment	Air gap and tolerance	Achievable velocity	Operational frequency	Magnetic field intensity	Sec. Voltage	Power rating	Effciency	Safety	Interperability cost	**Sum of incompatibilities**
WEVC & CWD			*						*						**2**
WEVC & IPV			*						*						**2**
WEVC & PRIMOVE	*	*	*	*	*	*	*	*	*	*			*	*	**12**
WEVC & Unplugged 50kW						*	*	*	*					*	**5**
WEVC & Unplugged 3,7kW							*	*	*					*	**4**
WEVC & FASTINCHARGE			*					*	*	*					**4**
WEVC & KAIST			*					*	*				*		**4**
WEVC & VICTORIA			*					*	*						**3**
CWD & WEVC			*						*						**2**
CWD & IPV												*			**1**
CWD & PRIMOVE	*	*	*	*	*	*	*	*	*	*			*	*	**12**
CWD & Unplugged 50kW						*	*	*	*				*	*	**6**
CWD & Unplugged 3,7kW							*	*	*					*	**4**
CWD & FASTINCHARGE			*					*		*					**3**
CWD & KAIST			*			*		*					*		**4**
CWD & VICTORIA			*					*		*					**3**
IPV & WEVC			*						*						**2**
IPV & CWD															**0**
IPV & PRIMPOVE	*	*	*		*	*	*	*	*	*			*	*	**11**
IPV & Unplugged 50kW							*	*	*				*	*	**5**
IPV & Unplugged 3,7kW							*	*	*		*			*	**5**
IPV & FASTINCHARGE						*		*		*					**3**
IPV & KAIST								*					*		**2**
IPV & VICTORIA								*		*					**2**
PRIMOVE & WECV	*	*	*		*	*	*	*	*	*	*			*	**11**
PRIMOVE & CWD	*	*	*		*	*	*	*	*	*	*			*	**11**
PRIMOVE& IPV	*	*	*		*	*	*	*	*	*				*	**10**
PRIMOVE & Unplugged 50kW	*	*			*	*	*		*	*				*	**8**
PRIMOVE & Unplugged 3,7kW	*	*			*	*	*	*	*	*	*			*	**10**
PRIMOVE & FASTINCHARGE	*				*	*	*		*						**5**
PRIMOVE & KAIST	*				*	*	*		*	*					**6**
PRIMOVE & VICTORIA	*					*	*		*	*					**5**
Unplugged 50kW & WECV						*	*	*	*					*	**5**
Unplugged 50kW & CWD							*	*	*					*	**4**
Unplugged 50kW & IPV							*	*	*					*	**4**
Unplugged 50kW & PRIMOVE	*	*			*	*	*		*	*			*	*	**9**
Unplugged 50kW & Unplugged 3,7kW							*	*							**2**
Unplugged 50kW & FASTINCHARGE						*	*		*	*				*	**5**
Unplugged 50kW & KAIST							*		*				*	*	**4**
Unplugged 50kW & VICTORIA							*		*					*	**3**
Unplugged 3,7kW & WECV							*	*	*					*	**4**
Unplugged 3,7kW & CWD							*	*	*					*	**4**
Unplugged 3,7kW & IPV						*	*	*	*					*	**5**
Unplugged 3,7kW & PRIMOVE	*	*		*	*	*	*	*	*	*			*	*	**11**
Unplugged 3,7kW & Unplugged 50kW							*	*							**2**
Unplugged 3,7kW & FASTINCHARGE							*	*	*	*				*	**5**
Unplugged 3,7kW & KAIST							*	*	*	*			*	*	**6**
Unplugged 3,7kW & VICTORIA							*	*	*	*	*			*	**6**
FASTINCHARGE & WECV			*					*	*	*					**4**
FASTINCHARGE & CWD								*		*					**2**
FASTINCHARGE & IPV						*		*		*					**3**
FASTINCHARGE & PRIMOVE	*		*		*	*	*		*				*		**7**
FASTINCHARGE & Unplugged 50kW						*	*		*	*				*	**5**
FASTINCHARGE & Unplugged 3,7kW							*	*	*	*				*	**5**
FASTINCHARGE & KAIST						*				*					**2**
FASTINCHARGE & VICTORIA			*			*				*					**3**
KAIST & WECV			*					*	*						**3**
KAIST & CWD						*	*	*							**3**
KAIST & IPV								*							**1**
KAIST & PRIMOVE	*		*		*	*	*		*	*			*		**8**
KAIST & Unplugged 50kW							*		*					*	**3**
KAIST & Unplugged 3,7kW							*	*	*	*	*			*	**6**
KAIST & FASTINCHARGE						*				*					**2**
KAIST & VICTORIA	*		*												**2**
VICTORIA & WECV			*					*	*						**3**
VICTORIA & CWD								*		*					**2**
VICTORIA & IPV								*		*					**2**
VICTORIA & PRIMOVE	*		*		*	*	*		*	*			*		**8**
VICTORIA & Unplugged 50kW							*		*					*	**3**
VICTORIA & Unplugged 3,7kW							*	*	*	*	*			*	**6**
VICTORIA & FASTINCHARGE			*							*					**2**
VICTORIA & KAIST	*		*												**2**
Sum of incompatibilities	**18**	**10**	**26**	**3**	**15**	**29**	**43**	**46**	**50**	**36**	**7**	**1**	**15**	**34**	

Table 7: Overview of the incompatibilities between the different solutions (Example).

2.4. Interoperability standards

2.4.1. Relevant Standardisation Bodies

There are an extensive number of standards focused on electric vehicles (EVs), their relationships to the infrastructure and to their users. These standards and regulations are developed at different levels (such as International, European and National) in a number of different organizations. At the international level, the standardization is mainly dealt with by two institutions: the International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO). IEC, founded in 1906, deals with all electrical technologies, while ISO, founded in 1948, deals with all other technologies. In the IEC committees, many of the delegated experts are electricians or component manufacturers, while in ISO committee there is a much stronger input from vehicle manufacturers.

In addition, the International Telecommunication Union (ITU) is a specialized agency for communications and information which develops the technical standards to ensure networks and technologies meet consistent standards. The main objective is to enable the growth, to sustain the development of telecommunications and information networks and to facilitate universal access so that people everywhere can participate in, and benefit from, the emerging information society and global economy.

Within Europe, CENELEC and CEN operate as the European counterparts of IEC and ISO. Both have been active in electric vehicle standardization in the 1990s, through their technical committees CENELEC TC69X and CEN TC301. However, much of this work was parallel to the global standardization work, with the European standards created superseded by international standards when these were available (such as EN50275 vs. IEC61851, and EN1987 vs. ISO6469). The CEN and CENELEC electric vehicle committees have been reactivated in 2010, aiming principally to expedite the European adoption of international standards rather than drafting own standards.

2.4.2. Addressed concerns of inductive EV charging

Certainly a wireless inductive charging standard is required for long term interoperability of all electric vehicles with all charging stations. But if the market has not yet developed, it is not known which requirements are important, and what the best route to eventual interoperability is. So the standards are developed along the way, with the first wireless electric vehicle charging systems leading the way.

The major concerns for EV inductive charging systems regarding their interoperability can be listed;

- Safety and Security
  - Electrical safety, supply-side
  - Electrical safety, vehicle-side
- Magnetic fields
- Electromagnetic compatibility (EMC)
- Communications
- Reliability
- Performance & efficiency

2.4.3. International standardisation work done by ISO/IEC and their current status

Currently, the following standard is under development by IEC-TC69:

IEC: 61980-1/Ed.1: Electric vehicle wireless power transfer systems (WPT) Part 1: General requirements (corresponding to 61851 for conductive charging). This standard is of interest for the ISO TC22 SC21. It was started one year ago with the objective to fulfil requirements related to inductive charging, while the development has brought to cover all the wireless charging technologies.

Two other ongoing standards are in the state of New Work Item (NWI) Proposal:

- Future IEC 61980-2: Electric vehicle wireless power transfer (WPT) systems - Part 2 specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to wireless power transfer (WPT) systems
- Future IEC 61980-3: Electric vehicle wireless power transfer (WPT) systems - Part 3 specific requirements for the magnetic field power transfer systems.

Both parts 2 and 3 of IEC 61980 will be developed in a Joint Working Group (JWG) between IEC-TC69 and ISO TC22/SC21. Pending publication of the international standard, they will be circulated as Technical Specification. Figure 2 presents the main parts of the IEC-TC69-PT61980 and its expected dates for publication.

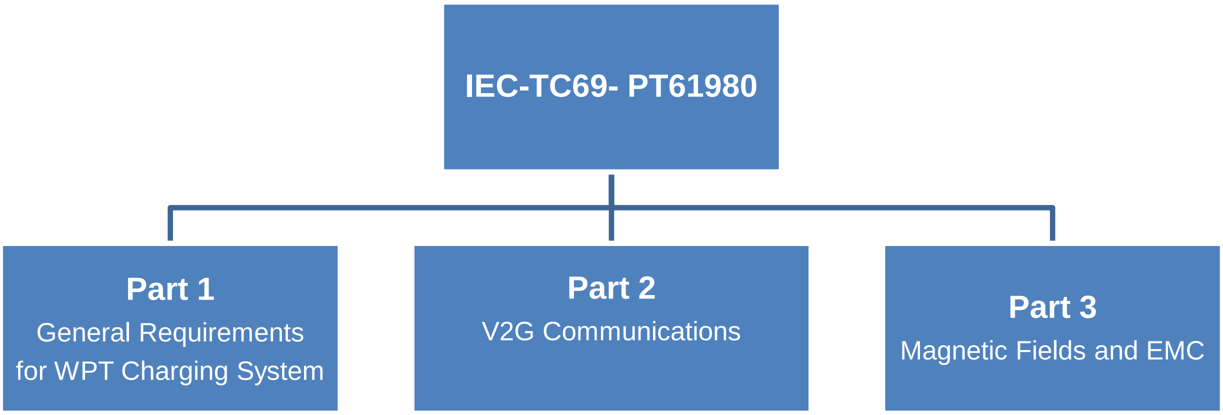

Figure 2: The main parts of the new IEC-TC69-PT61980 standard.

According to IEC 60038 standard, the standard AC supply voltage is up to 1000V (AC), while the DC supply voltage is up to 1.5 kV (DC). These supply voltage standards are considered in IEC-TC69-PT61980/1. Furthermore, the rated frequency of the AC supply is 50 Hz ± 1% or 60 Hz ± 1% (IEC60038, Ed. 6.2, July 2002). However, the internal voltages in the WPT charging system (such as the resonance voltages) are currently not available in this standard.

There is a joint working group drafting a family of standards called ISO/IEC 15118 to describe the communication, in terms of data format and message content, between the electric vehicle (this term refers to battery electric vehicles as well as plug-in hybrid electric vehicles) and the electric vehicle supply equipment (charging post). This also includes the message content and data structure to enable billing-related communication and grid management. Provisions for additional communication aspects (like vehicle charge status information and configuration) can be considered to allow for interoperability of all vehicles with all charging stations. The main communication-parts of the generic equipment are the Electric Vehicle Communication Controller (EVCC) and the Supply Equipment Communication Controller (SECC). Therefore, this standard describes the communication between these components. All connections beyond the EVCC and how the messages can be exchanged are considered to be out of the scope as specific use cases. ISO/IEC 15118 standard is oriented on the charging of electric road vehicles (ISO/IEC15118, DIS, 2011), dealing specifically with the communication link between vehicle and charging post. The major concerns of ISO/IEC 15118 are illustrated in Figure 3.

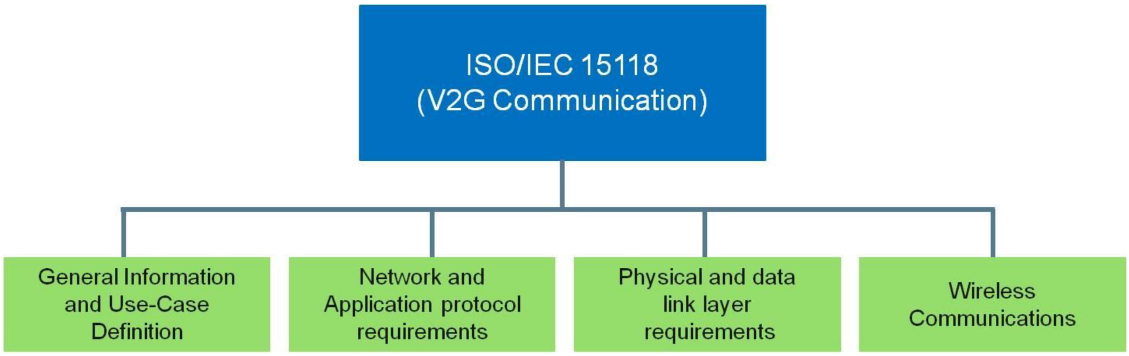

Figure 3: The main scope of ISO/IEC 15118.

It should be pointed out that SC3 has the responsibility for the charging communication aspects. At the moment, V2G communication interface has been developed for the conductive charging only. However, the wireless V2G interface is currently under development. Currently, the ISO/IEC 15118 standards family is composed of the three items applicable for the conductive electric vehicle charging process, two items describing conformance test for conductive charging and finally three items currently addressing wireless V2G charging

- ISO/DIS 15118-1: Road vehicles - Vehicle to grid communication interface - Part 1: General information and use-case definition. This standard can be used for WPT charging system.
- ISO/IEC DIS 15118-2: Road vehicles - Vehicle to grid communication interface - Part 2: Network and application protocol requirements
- ISO/DIS 15118-3: Road vehicles - Vehicle to grid Communication Interface - Part 3: Physical and data link layer requirements
- ISO/DIS 15118-4: Road vehicles - Vehicle to grid communication interface -Network and application protocol conformance test
- ISO/DIS 15118-5: Road vehicles - Vehicle to grid communication interface- Physical layer and data link layer conformance test
- ISO/DIS 15118-6: Road vehicles - Vehicle to grid communication interface- General information and use-case definition for wireless communication
- ISO/CD 15118-7: Road vehicles -- Vehicle to grid communication interface - Network and application protocol requirements for wireless communication
- ISO/DIS 15118-8: Road vehicles -- Vehicle to grid communication interface - Physical layer and data link layer requirements for wireless communication

2.4.4. Communication requirements for dynamic inductive charging

Dynamic inductive charging poses stringent communication requirements as vehicles traverse charging pads. In contrast to static or stationary charging, limited time for communication between EVs and the infrastructure is available per charging pad, thus low latency efficient information exchange is required to perform necessary charging management related operations. Such requirements must be taken into consideration by communication standards deployed within the charging infrastructure.

ISO/IEC 15118 parts 6-8 target wireless communication, so they are natural candidates for deployment in dynamic wireless charging installations. One outstanding aspect that differentiates dynamic charging from other types of charging addressed by current standardization is the limited timeframe for charging management communications. For

example, a communication protocol timing analysis has been performed in D2.5.3 “Prototype of ICT modules for the off-board charge planning system” for the specific case of demand side management. The basic outcome of the analysis is that the current information flow adopted by ISO/IEC 15118 in combination with emerging higher layer charging management protocols such as OCPP (Open Charge Point Protocol), fail to address demand side management operation in a timely manner due to excessive protocol latencies that exceed inductive power transfer timeframes over a single charging pad. Therefore, one generic conclusion that can be made is that wireless charging standardization and specifically ISO/IEC 15118 6-8 should review operations supported by the proposed protocol under the minimal per pad charging timeframe, in order to adjust or not the underlying physical, mac. network and application OSI layers.

A detailed analysis focusing on dynamic wireless charging communications standardization will be reported in D5.5.4 “Analysis of deployment scenarios, standardization and harmonization”.

3. DESCRIPTION OF THE COMPARED EXISTING SOLUTIONS

The inductive charging prototypes included in the FABRIC project and used for the interoperability analysis are described below. The first three systems are wireless inductive power transfer systems which are expected to be trialled on test tracks in Italy and France. The fourth system is a conductive power transfer system which will be studied in theory, but not subject to trial. As this is a conductive system, interoperability with the wireless power transfer systems which are the focus of FABRIC is not possible, so will not be considered. The fifth is another inductive power transfer system which will again be subject to a desk study, but will not be trialled. Four prototypes not included in the FABRIC project, however also used for the interoperability analysis are two UNPLUGGED project solutions, the FASTINCHARGE project solution as well as the OLEV system developed by KAIST. Finally, the solution from the VICTORIA project is described, which was included as a third FABRIC test site in September 2016 and will give additional data on dynamic wireless power transfer systems with power levels suitable for buses (50-kW coils).

The inductive charging solution system descriptions will provide a general description of the systems, and then provide more detail on the following four system parameters categories, as introduced in chapter 2.

Communication

It is crucial from an interoperability point of view that the vehicle to grid communications channel is standardised. However, it is not only this communications channel which requires interoperability, but also the entire back office and billing interface to ensure that users can be correctly recognised and billed for their usage of the charging equipment and to ensure that charging operations comply to grid constraints.

Construction and geometry

From an interoperability perspective, coil size, shape and spacing will have an influence on the efficiency of power transfer.

Electromagnetic

For any resonant power transfer, standardisation of the operating frequency is crucial as any deviation from the operating frequency will results in significant drop in efficiency. It is also important that the architecture of the system is understood by both the primary and secondary ends. For example, if the secondary operates in a constant current mode, power control will

have to happen at the primary side, while if the secondary operates in a constant voltage mode it can perform its own power control.

Other

While not strictly an issue for interoperability, safety features of any system must not affect the interoperability with systems from other suppliers. An important issue here is one of foreign object detection where systems may include a feature which disables the power transfer if a foreign object is detected within the power transfer area. Safety features like this must continue working when interfacing with equipment from other suppliers. Additionally, the charging efficiency and costs to accomplish interoperability are assessed.

3.1. Development basis of FABRIC 1

This system has been developed by Qualcomm and will be supplied to Vedecom under sub-contract. The system was trialled in London in 2011 as a static charging system. However, Qualcomm envisages a dynamic charging implementation of their system in the future.

At this point it is interesting to reference Joe Barrett, Senior Director, Marketing, Qualcomm Europe Inc. who, in September 2014 notes: "WEVC [Wireless Electric Vehicle Charging] charging equipment therefore needs to be interoperable to enable any EV to wirelessly charge with equipment from any manufacturer in the same way that any mobile phone works with any mobile network anywhere in the world." This system is developed as FABRIC solution 1 as shown in Figure 4. In common with the other wireless solutions in the FABRIC project, the Qualcomm Halo system is a resonant inductive charging system, utilising magnetic coupling between the primary coil(s) buried in the road, and the secondary coil(s) mounted under the vehicle as the means of power transfer.

Figure 4: FABRIC 1 solution.

3.1.1. Communication

At this stage of the project, no information is available on the communications used between the in-road equipment and the on-vehicle equipment. An analysis regarding this aspect is therefore not possible.

3.1.2. Construction and geometry

The in-road equipment consists of closely spaced charging coils (called pads in the Qualcomm literature). No information on the physical dimensions of the charging coils is available at time of writing. The air gap between the primary and secondary coils is between 125 mm and 175 mm.

3.1.3. Electromagnetic

The system transfers power at a frequency of 85 kHz. The architecture of the system has not been disclosed at this stage. Maximum power transfer rate is quoted as 20 kW. It is essential that the primary and secondary are in agreement as to the negotiated power transfer level.

3.1.4. Other

No specific other data, especially safety related information is available at this stage.

3.1.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	802.11p
Communication protocol (ISO 12118, IEC 61851 etc.)	ITS G5 plus proprietary implementation
Position tracking/tracing for primary coil activation	To be confirmed
Construction and Geometry	
Coil geometry	Ground module dimension: Segment:0.4 x 1.75 x 0.052 (W x L x H) Coil: 0.312 x 0.64 x 0.033 m
Lateral misalignment tolerance	Target Y tolerance of ± 20 cm
Air gap and tolerance	Coil to coil distance of 12.5 – 17.5 cm supported
Achievable vehicle velocity	Up to 100 km/h
Electromagnetic	
Operational frequency	85 kHz
Magnetic field intensity	Not available
Achievable secondary coil voltage	300-400 V DC (battery voltage) on vehicle request; Up to 67 A on vehicle request
Power rating and power	Target of up to 20 kW on vehicle request

Table 8: Available technical FABRIC 1 solution information for interoperability analysis.

3.2. Development basis of FABRIC 2

Politecnico di Torino (Polito) developed the Charge While Driving (CWD) solution in cooperation with Centro Ricerche Fiat (CRF). The solution is based on dynamic wireless resonant inductive coupling principle. It was developed as part of the FP7 project eCo-FEV (efficient Cooperative infrastructure for Fully Electric Vehicles). This system will be further developed and will result in the FABRIC solution 2 as shown in Figure 5.

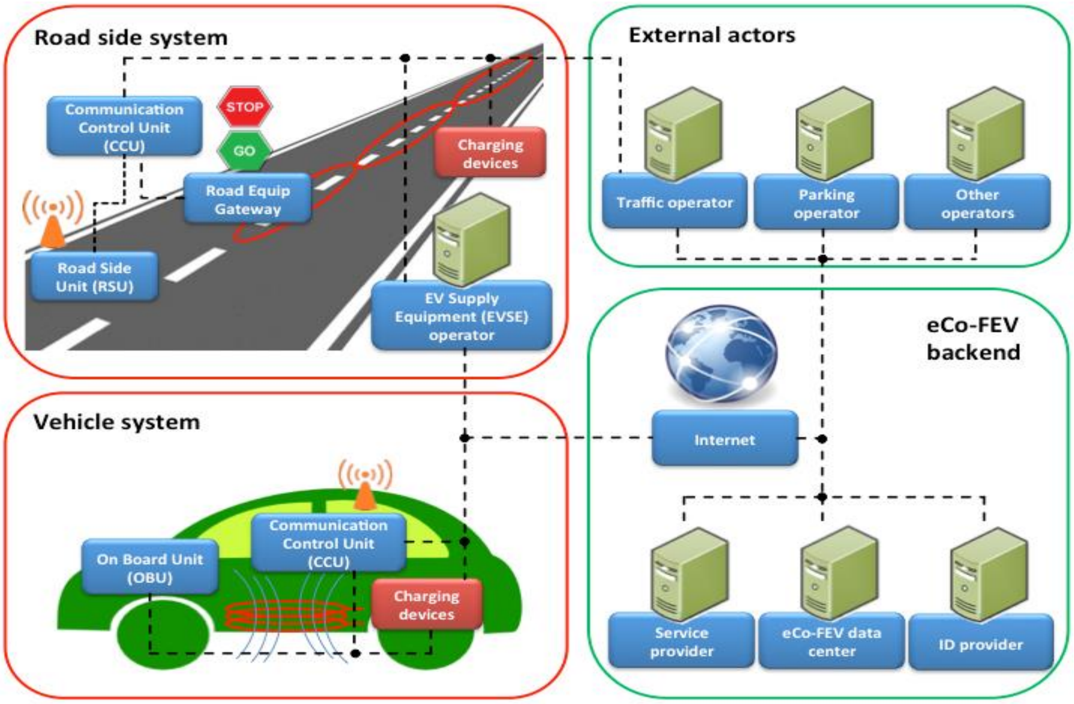

Figure 5: FABRIC 2 solution.

3.2.1. *Communication*

Regarding the vehicle-to-road side unit short range communications and V2V communications ITSG5 based on IEEE 802.11p (5.9GHz) is considered since it seems to be the most promising technology for low latency wireless communication.

Legacy communication networks such as cellular network and Internet are used for communication between FEVs to backend and between infrastructure systems.

3.2.2. *Construction and geometry*

The primary segment is 9 metres in length enclosed in a single plastic mould, each segment contains five 1.5 metre coils. However, the number of coils per segment can be varied depending on the development of the system and the final system is meant to work in a buried solution at 4 to 5 cm under the level of the road. The operational temperature within the primary

is maintained by natural air cooling. The primary coils collect the power from the low-voltage three- phase connection point, and the road-side control system converts the AC voltage to DC and then to a 600V 100kHz rectangular waveform in order to transfer the power through the air gap to the secondary coil. As this system is still under development, specifications are preliminary and subject to change.

3.2.3. Electromagnetic

The operating frequency of the power electronic can be anywhere in the 20-200 kHz range, although it is essential that the primary and secondary circuits operate at the same frequency, the 85kHz frequency reference will be adopted.

The CWD system operates as a constant current secondary, which means that power control can be done at the secondary side without any additional controller. This also means that it is easier to transfer power back to the network, however, in the developed solution no power back to the grid will be implemented.

The power transfer rate is quoted as 20 kW. Secondary voltage can span from 0 to 400V, for a full rate power transfer from 300 to 400V. Primary input voltage will be 600-700V dc.

3.2.4. Other

No specific other data, especially safety related information is available at this stage.

3.2.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	WLAN
Communication protocol (ISO 12118, IEC 61851 etc.)	CAN on Wi-Fi (CAN- BUS ISO 11898)
Position tracking/tracing for primary coil activation	Available
Construction and Geometry	
Coil geometry	Ground module dimension: Segment:0.5 x 25 x 0.024 m (W x L x H) Coil: 0.5 x 1.5 x 0.02m Note: Number of coils per segment can be varied. On-vehicle equipment Dimensions: 0.7 x 0.3m (WxL)
Lateral misalignment tolerance	20 cm (to be improved)
Air gap and tolerance	25 cm ± 10 cm
Achievable vehicle velocity	90 km/h TBC
Electromagnetic	
Operational frequency	80-90 kHz
Magnetic field intensity	1.5 mT ò 0.1 5cm from centre of transmitting coil Z direction at full power
Achievable secondary coil voltage	Secondary 450 V / 66 A
Power rating and power	20 kW

Table 9: Available technical FABRIC 2 solution information for interoperability analysis.

3.3. Development basis of FABRIC 3

The Induction Powered Vehicle (IPV) is based on wireless resonant inductive power transfer. It is currently under development by Inovalab, which is part of the SAET Group. The development is closely related to the CWD system used in the FABRIC 2 solution, in fact the SAET IPV solution and the CWD system (FABRIC solution 2) use the same secondary coil and vehicle. This system will be developed as FABRIC solution 3. Therefore, no secondary coils will be provided in this project.

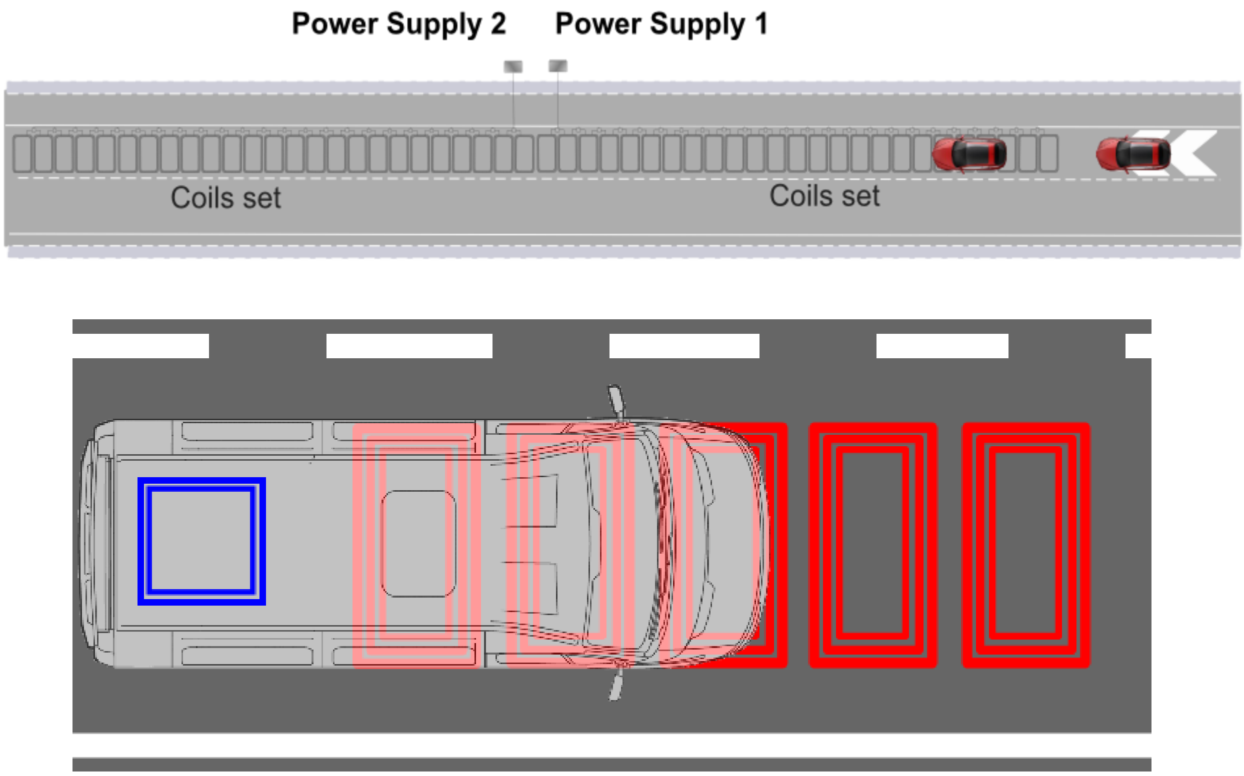

Figure 6: FABRIC 3 solution concept.

3.3.1. Communication

Because the IPV system is designed to be interoperable with the CWD system, it uses the same communications system as the CWD system.

3.3.2. Construction and geometry

The dimensions for the ground coils are still being finalised, but are currently designed to be installed 5 cm below the road surface.

The primary coil is 1.92 m long and 0.55 m large, single litz wire with double insulation versus ground the distance between coil will be 50 cm.

3.3.3. Electromagnetic

The system normally operates at 85 kHz, but can operate in the range 60-150 kHz for interoperability, the final solution is tuned to 85kHz but the primary resonator configuration allows modify manually the resonating frequency.

While designed to be interoperable with the CWD system, the IPV system has a different architecture to the CWD in that the primary is expected to operate in a constant current mode, with power transfer controlled by the primary itself. This means that the secondary will need to be able to switch between operating modes, making the communications before the power transfer a crucial element of the system for successful operation.

The maximum power transfer rate is quoted as 20 kW. Secondary voltage can span from 0 to 400 V, for a full rate power transfer from 300 to 400 V. Primary input voltage will be 600-700 V dc.

3.3.4. Other

No specific other data, especially safety related information is available at this stage.

3.3.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	WLAN
Communication protocol (ISO 12118, IEC 61851 etc.)	CAN on Wi-Fi (CAN- BUS ISO 11898)
Position tracking/tracing for primary coil activation	Available
Construction and Geometry	
Coil geometry	Primary Coil (W x L): 0.55 x 1.92 m
Lateral misalignment tolerance	X = Y = 20 cm
Air gap and tolerance	25cm ±10 cm
Achievable vehicle velocity	90km/h TBC
Electromagnetic	
Operational frequency	80-90 kHz
Magnetic field intensity	1.5 mT ò 0.15 cm from centre of transmitting coil Z direction at full power
Achievable secondary coil voltage	450 Vdc
Power rating and power	20 kW

Table 10: Available technical FABRIC 3 solution information for interoperability analysis.

3.4. Development basis of FABRIC 4 – ERS Conductive charging

The development basis of FABRIC solution 4 is Volvo's Slide-in Electric Road System (ERS). The ERS system is based on conductive energy transfer, the power is transferred from a rail embedded in the road, to an on-board pantograph. The system was developed in partnership with Alstom, who provided the ground systems such as conductive rails, control and protection electronics and connections to the grid. Volvo has developed on-board solutions with support from Swedish Universities and institutions and has tested the system on a 400 m test track in Sweden. As mentioned before, this is a conductive system, so there is no possibility for interoperability analysis, since all the other systems use resonant inductive power transfer. It should be noted that the system is still under development, so specifications are subject to change.

Figure 7: FABRIC 4 solution.

3.4.1. Communication

The speed of the vehicle is the key factor on determining the length of the live segments. For safety reasons the power from the ground module to the vehicle will only be activated between speeds of 60 km/h and 100 km/h, therefore the system uses speed detection loops to activate the power supply. The signal from the loops detects the direction of the vehicle with long pulse

first, then two short pulses indicating vehicle is moving from left to right, and speed is calculated by the time it has taken to drive over the detection loops.

3.4.2. Construction and geometry

The power is transferred from the rail to the vehicle via on-board pantograph. The ground module consists of positive rail and ground rail in parallel. The system also has an additional ground rail next to the positive rail to prevent creep current over long distances.

3.4.3. Electromagnetic

Substations are located every 968 m to collect power at 30 kV, then step this down to 800 VAC. The 800 VAC runs along the roadside and connected to the road-side equipment every 88 m, where there are manholes with two power boxes powering two 44 m segments. The power boxes convert 800 VAC to 750 VDC to power the 44 m segments. Each section consists of 22 sets of 44 m rails and each segment provides energy to one ERS vehicle at one time.

3.4.4. Other

The Power Supply presents no danger to persons or equipment. The solution develops voltage only in the section that is physically enclosed within the area occupied by the vehicle, however for the Volvo test system a more open setup is used right now.

3.5. Development basis of FABRIC 5

PRIMOVE is the e-mobility unit within Bombardier Transportation whose focus is on creating market-ready wireless charging solutions for all types of rail and road electric vehicles. The system has been tested as charging option for trams, buses and cars in both stationary and dynamic modes. The PRIMOVE system is brought to the FABRIC project by Scania in collaboration with Bombardier and will be assessed for its feasibility to be applied to other use cases in FABRIC solution 5. Note that the system will only be considered in a desk study and will not be subject to test track trials as is the case with FABRIC solutions 1 to 3.

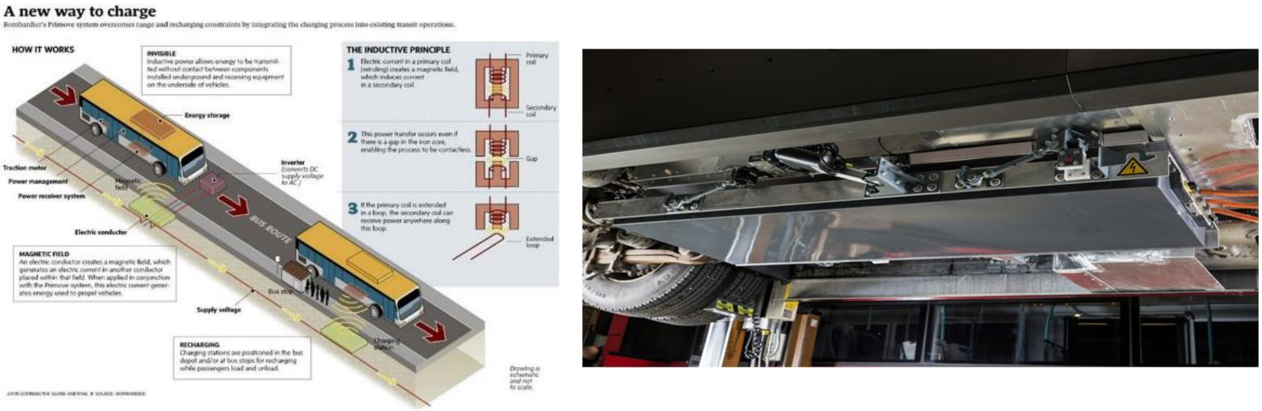

Figure 8: FABRIC 5 solution.

3.5.1. Communication

Details of the communication system have not been provided.

3.5.2. Construction and geometry

The PRIMOVE primary coils are installed in the road in 20 m long modules with a 40 mm asphalt covering. The size of individual coils is not quoted.

The secondary coils are 2m x 1m and are mounted on a moveable platform under the vehicle to maintain the correct air gap while charging (although the size of the air gap is not given).

3.5.3. Electromagnetic

The system operates at 20 kHz. This is low compared to other dynamic charging solutions.
The architecture of the system is not known.

3.5.4. Other

Under normal operation the magnetic field will be less than 6.25 uT in all public areas and in the driver cabin. This field level is lower than the recommended level for public exposure (ICNIRP, 2010) and is safe for all modern pacemakers (VIDE, 2002).

The PRIMOVE system has also been shown 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 TÜV SÜD has confirmed that the PRIMOVE system complies with the regulations and requirements regarding electromagnetic field emissions (EMF) and compatibility (EMC).

3.5.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	Antenna loop between the road and the vehicle
Communication protocol (ISO 12118, IEC 61851 etc.)	N/A
Position tracking/tracing for primary coil activation	N/A
Construction and Geometry	
Coil geometry	Ground Module Dimensions: 20 m length On-vehicle equipment Dimensions: 2 x 1 m
Lateral misalignment tolerance	N/A
Air gap and tolerance	N/A
Achievable vehicle velocity	N/A
Electromagnetic	
Operational frequency	20 kHz
Magnetic field intensity	N/A
Achievable secondary coil voltage	Input: 10 kV Output: 750 VDC Current: Up to 400 A per Phase
Power rating and power	Up to 200 kW

Table 11: Available technical FABRIC 5 solution information for interoperability analysis.

3.6. UNPLUGGED project-50 kW system

The UNPLUGGED project aims to investigate how the use of inductive charging of Electric Vehicles (EV) in urban environments improves the convenience and sustainability of car-based mobility. The system is developed as a static on-route charging system in two power versions; high power version with 50kW and a low power version with 3.7kW have been developed. This system is not part of the FABRIC project, but since some FABRIC project partners have been strongly involved in the UNPLUGGED project the data is available to include this system in this study.

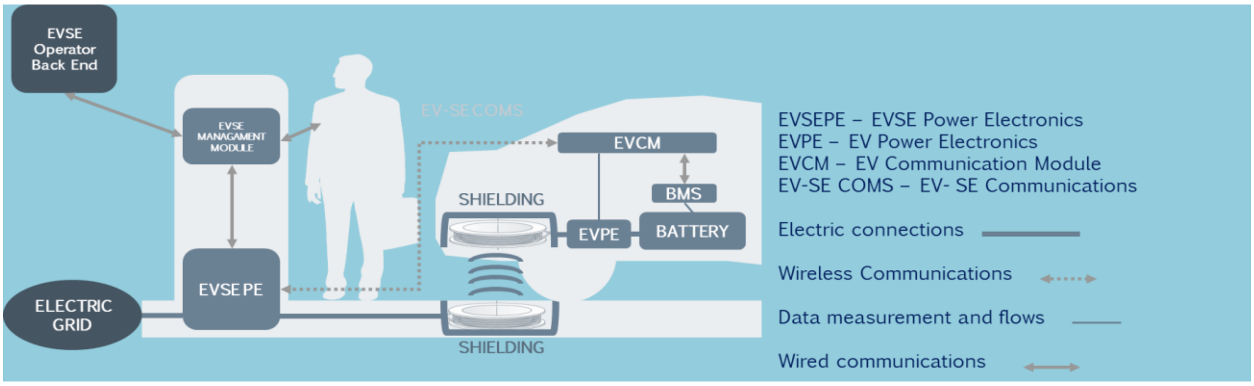

Figure 9: UNPLUGGED project solution overview.

3.6.1. Communication

Communications between the primary and secondary elements of the charging system makes use of WLAN technology compatible to IEEE 802.11b/g/n, with ISO 15118 protocol providing the messaging formats. ISO 15118 specifies the communication between Electric Vehicles (EV) and the Electric Vehicle Supply Equipment (EVSE). Note that significant elements of this standard are still under development.

3.6.2. Construction and geometry

The 50 kW system consists of two 25 kW coils mounted alongside each other. The high power level means that this system cannot be supplied from a domestic mains supply, requiring at least a 400 V 3-phase supply.

The 50 kW system is intended to operate with an air gap of 180-250 mm.

3.6.3. Electromagnetic

The 50 kW system operates at 20-30 kHz.

3.6.4. Other

No specific other data, especially safety related information is available at this stage.

3.6.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	WLAN
Communication protocol (ISO 12118, IEC 61851 etc.)	Protocol based on ISO 15118
Position tracking/tracing for primary coil activation	RFID and camera based
Construction and Geometry	
Coil geometry	On-Vehicle and ground Coil Dimensions: 0.3 x 0.4 m (WxL) Ground Module Dimensions: 1.8 x 1 m (WxL) (2 coils + shielding and housing)
Lateral misalignment tolerance	20 cm
Air gap and tolerance	18 to 25 cm
Achievable vehicle velocity	N/A
Electromagnetic	
Operational frequency	20-30 kHz
Magnetic field intensity	
Achievable secondary coil voltage	Primary: 400 V AC, three phase Secondary: up to 700 V DC, 350 V DC used for the demonstrator
Power rating and power	25kW or multiple of 25 kW possible

Table 12: Available technical UNPLUGGED solution information for interoperability analysis.

3.7. UNPLUGGED project 3.7 kW system

General information can be taken out of chapter 3.6

3.7.1. Communication

For the communication it can be stated that the same communication method is used as for the 50 kW system as described in chapter 3.6

3.7.2. Construction and geometry

The 3.7-kW-system consists of a primary coil being 700 x 500 mm and the secondary coil being 290 x 330 mm. The 3.7-kW system is intended to be able to be supplied from a domestic 230 V supply.

The 3.7-kW system is intended to operate with a typical air gap of 100-130 mm, although operation is possible up to an air gap of 170 mm.

3.7.3. Electromagnetic

The 3.7-kW system operates at 145 kHz.

3.7.4. Other

No specific other data, especially safety related information is available at this stage.

3.7.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	WLAN
Communication protocol (ISO 12118, IEC 61851 etc.)	Protocol based on ISO 15118
Position tracking/tracing for primary coil activation	RFID and camera based
Construction and Geometry	
Coil geometry	Ground Module Dimensions: 0.7 x 0.5 m (WxL) On-vehicle equipment Dimensions: 0.29 x 0.33 m (WxL)
Lateral misalignment tolerance	10 cm
Air gap and tolerance	up to 17 cm, typical 10 – 13 cm
Achievable vehicle velocity	N/A
Electromagnetic	
Operational frequency	145 kHz
Magnetic field intensity	
Achievable secondary coil voltage	Primary: 230 VAC, one phase Secondary: 250 V DC
Power rating and power	3.7 kW

Table 13: Available technical UNPLUGGED solution information for interoperability analysis.

3.8. FASTINCHARGE project solution

The aim of the solution developed within FASTINCHARGE is to implement a system that will charge at relatively high charging rates at adequate spacing limits with high efficiency. Within FASTINCHARGE, many diverse aspects of charging operations are taken into consideration. Focus is on the design of IPT circuitry aspects such as compensation and matching in order to meet requirements for efficient power transfer that reaches 92% at a 30 kW maximum power transfer rate for low vehicle speeds that can reach 20 km/h maximum.

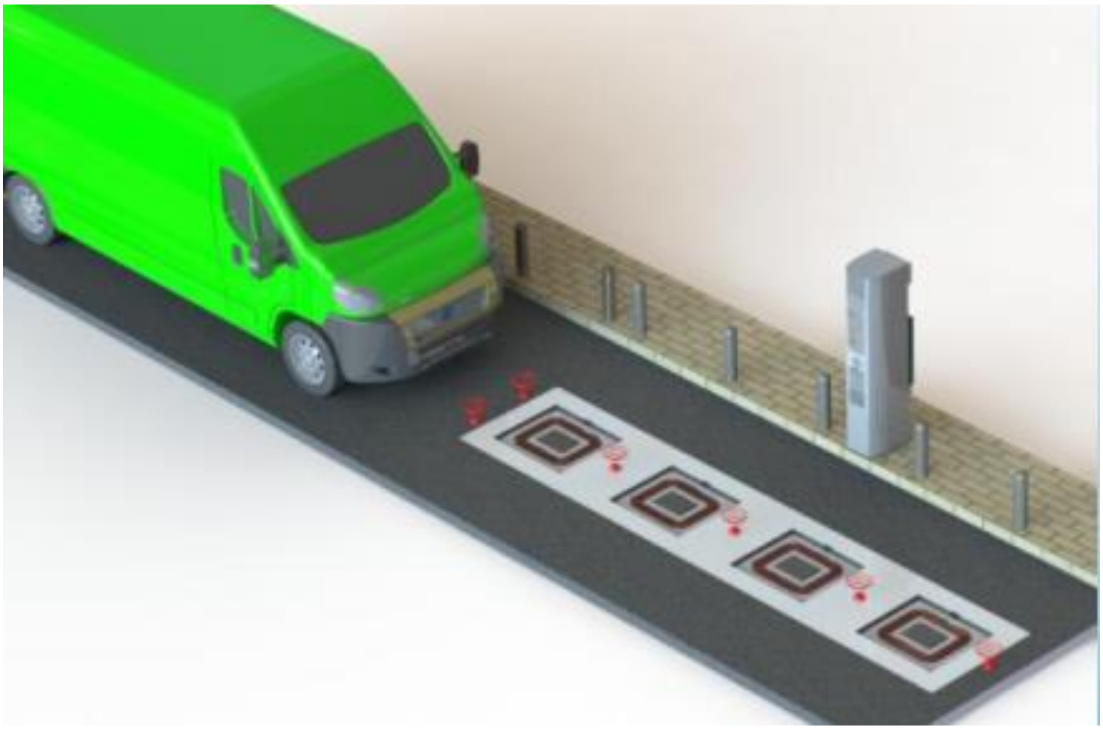

Figure 10: FASTINCHARGE concept.

3.8.1. Communication

The FASTINCHARGE solution proposes the use of 802.11p specification for wireless automotive communications between the primary and secondary coils. 802.11p defines enhancements and amendments to the 802.11 series of standards that target essential requirements for reliable low-latency communications in a hostile physical layer. Moreover, in order to support operations for authentication, power transfer process management, monitoring and billing, FASTINCHARGE proposes the use of the ISO/IEC 15118 standard as it could form a concrete basis for interoperability.

3.8.2. Construction and geometry

The solutions consist of a primary coil of 800 mm length and 700 mm width. The secondary coil also consists of a 800x700 coil installation supporting power transfers up to 30 kW. The primary system is interfaced to a 3-phase 400 V power supply and supports a maximum current of 60 A. The system operates efficiently at an air gap ranging from 70-90 mm.

3.8.3. Electromagnetic

The system operates at a frequency ranging from 10-50 kHz, whereas the magnetic field intensity ranges from 40-50 mT at the centre of the coil.

3.8.4. Other

In order to increase EMC and insulate the WPT system shielding of the primary coil has been considered. Moreover, thermal protective sensors have been installed in order to prevent over-heating.

3.8.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	Wi-Fi
Communication protocol (ISO 12118, IEC 61851 etc.)	proposal - Protocol based on ISO15118
Position tracking/tracing for primary coil activation	primary coil activation - sensor
Construction and Geometry	
Coil geometry	primary and secondary: 0.8x0.7x0.6 m (WxLxH)
Lateral misalignment tolerance	In direction X(L): ±15 cm In direction Y(W):± 10 cm
Air gap and tolerance	8 cm ± 1 cm
Achievable vehicle velocity	20 km/h
Electromagnetic	
Operational frequency	10-50 kHz
Magnetic field intensity	coil centre 40-50 mT
Achievable secondary coil voltage	600 V
Power rating and power	30 kW

Table 14: Available technical FASTINCHARGE solution information for interoperability analysis.

3.9. KAIST solution (OLEV)

OLEV is an electric bus that runs on electromagnetic induction. Developed by The Korea Advanced Institute of Science and Technology (KAIST), OLEV has installed an inductive charging system which can transfer up to 200 kW. A system overview is shown in Figure 11. The last generation is the third generation and used for this document.

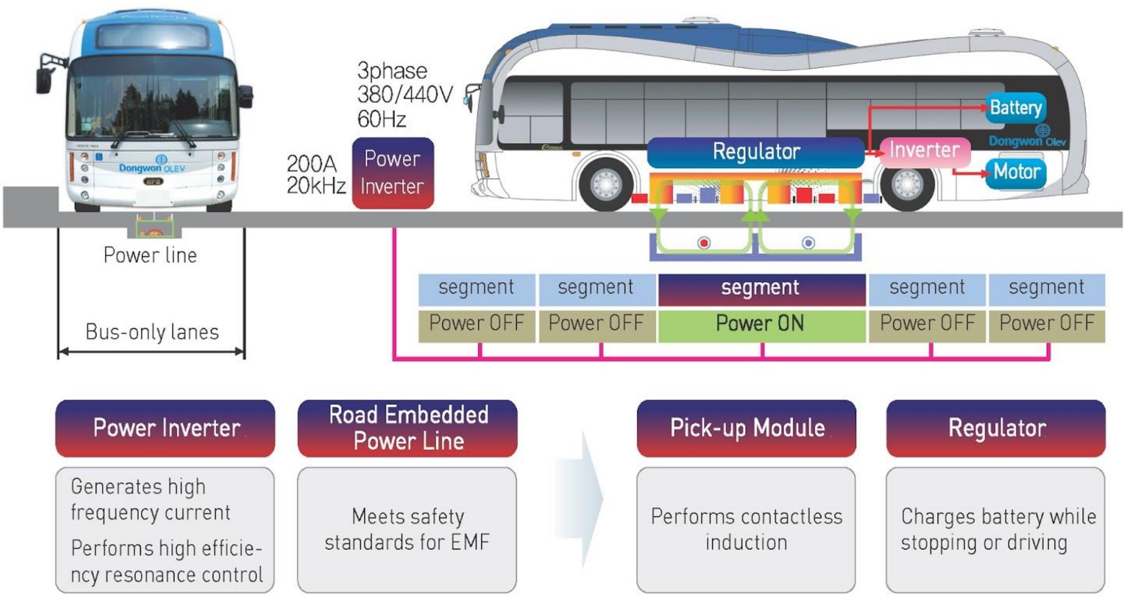

Figure 11: OLEV system overview.

3.9.1. Communication

The only information which is available for the communication is that the communication method is WLAN and the protocol is based on ISO 15118.

3.9.2. Construction and geometry

The 3rd generation so called ultra slim W-type structure is used for the system construction. As shown in Figure 12, the ultra slim W-type has narrow primary core pole width and wide pick-up core length. So the ultra slim W-type can transfer power with large air gap. The return path of magnetic flux in the ultra slim W-type is doubled. So the transferred power from primary core to pick-up can be increased. But the maximum allowable lateral misalignment (WD) is roughly a quarter of the length of primary coil. In the 3rd generation of OLEV, by adopting fish bone like core structure depicted in Figure 12, the amount of core is reduced to 1/5 compared to the 2nd generation of OLEV, whereas the output power is improved to 17kW per pick-up.

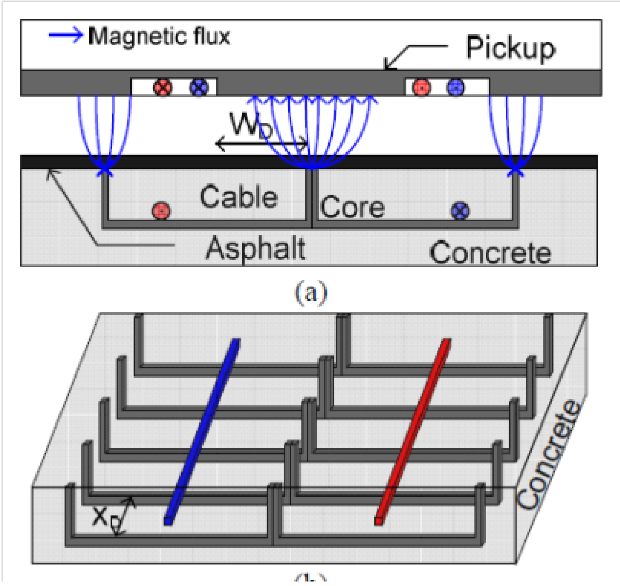

Figure 12: Primary and secondary side schematic.

3.9.3. Electromagnetic

The measured power efficiency for an OLEV system with the 3rd generation IPT system is 71% at 17 cm air gap. The nominal frequency of power supply is 20 kHz and primary rated current is 200 A. The rated load is 6kW per pick-up. Total output power of 52 kW with 10 pick-ups and 72% power efficiency is accomplished at 17 cm air gap. For efficiency calculation, all power losses between input power for inverters and battery stage at vehicles (inverter switching loss, rail & pick-up losses, regulator loss and so on) are considered. Power efficiency is very low when output power is small because of base power consumption, and is at maximum when output power is about 30 kW.

3.9.4. Other

To meet increasing anxiety about the safety of EMF the OLEV system is designed such that the EMF around the OLEV bus (5.1 μT @ 1.75 m from the centre of road) can satisfy the permitted guideline, 6.25 μT @20kHz.

3.9.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	Magnetic communication
Communication protocol (ISO 12118, IEC 61851 etc.)	Protocol based on ISO 15118
Position tracking/tracing for primary coil activation	Magnetic method
Construction and Geometry	
Coil geometry	2.5 m to 24 m long loop wires Effective 2x0.7 m units. On vehicle: 0.8x1.7x0.08 m (WxLxH)
Lateral misalignment tolerance	20 cm
Air gap and tolerance	24 cm ± 3 cm
Achievable vehicle velocity	
Electromagnetic	
Operational frequency	20 kHz
Magnetic field intensity	EMF level lower than 6.25 μT
Achievable secondary coil voltage	400 V
Power rating and power	Up to 200 kW
Other	
Charging efficiency	75%
Safety considerations (Shielding, EMC, Heating, etc.)	
Costs to accomplish interoperability	Ca. €800,000/km

Table 15: Available technical OLEV solution information for interoperability analysis.

3.10. VICTORIA solution

VICTORIA solution has been developed by CIRCE within a national project together with the Spanish electricity company Endesa and other partners. The objective was to showcase the viability of static, stationary and dynamic charging for a small city bus under real-world conditions.

Figure 13: VICTORIA Vehicle Initiative for Transport operation & road inductive applications.

The wireless power transfer system is based on the technology developed and proven within the European FP7 project UNPLUGGED, although all elements (coils, capacitors, etc.) were re-designed in order to obtain an improved 50-kW dynamic solution, while UNPLUGGED was a 2x25-kW static solution (see UNPLUGGED chapter in this document). A schematic view of the solution is shown in Figure 14.

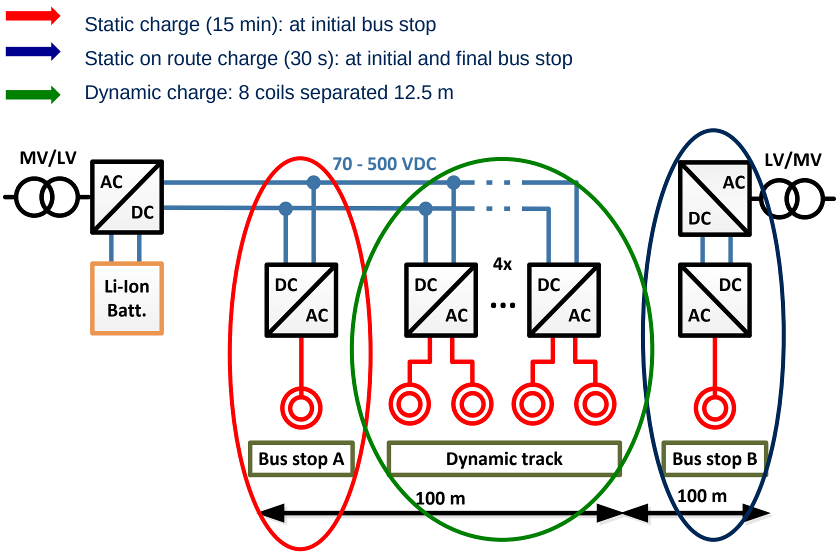

Figure 14: Schematic view of the power distribution of the VICTORIA test site in Malaga.

3.10.1. Communication

Similar to CIRCE's UNPLUGGED solution, communications between the primary and secondary elements of the charging system makes use of WLAN technology compatible to IEEE 802.11b/g/n, with ISO 15118 protocol providing the messaging formats. ISO 15118 specifies the communication between Electric Vehicles (EV) and the Electric Vehicle Supply Equipment (EVSE). Note that significant elements of this standard are still under development.
CAN BUS messages are exchanged via WLAN (Wi-Fi) between the ground equipment and the bus. In addition, there is a GPS-based positioning system which assists the vehicle for proper alignment.

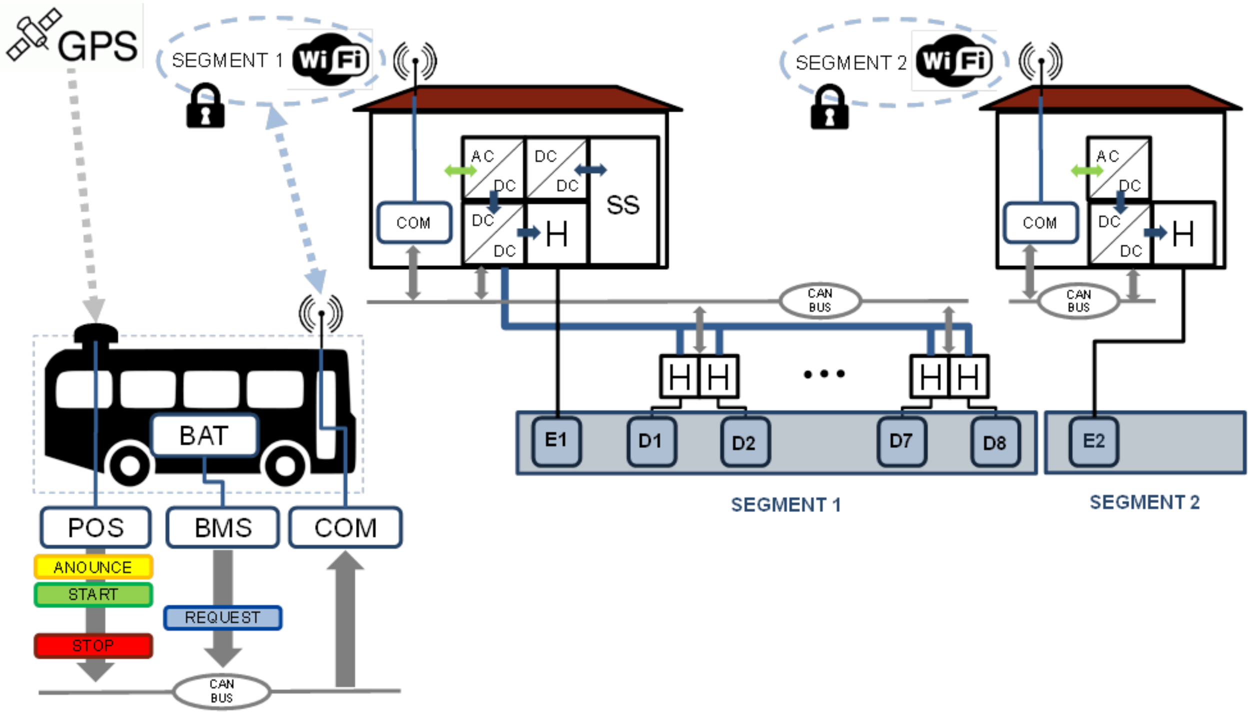

Figure 15: Communication of the VICTORIA test site in Malaga.

3.10.2. Construction and geometry

The ground coils of the VICTORIA systems are 0.8 m long and 0.6 m wide (2 windings) and the coil mounted on the vehicle is 2.5 m long and 0.6 m wide (4 windings). The configuration with a long on-board coil and a small ground coil has several advantages, but mainly it improves EMF shielding, as the field is always confined below the vehicle.
In the figure below, several views of the primary (ground, emitter) and secondary (vehicle, receiver) coils are shown.

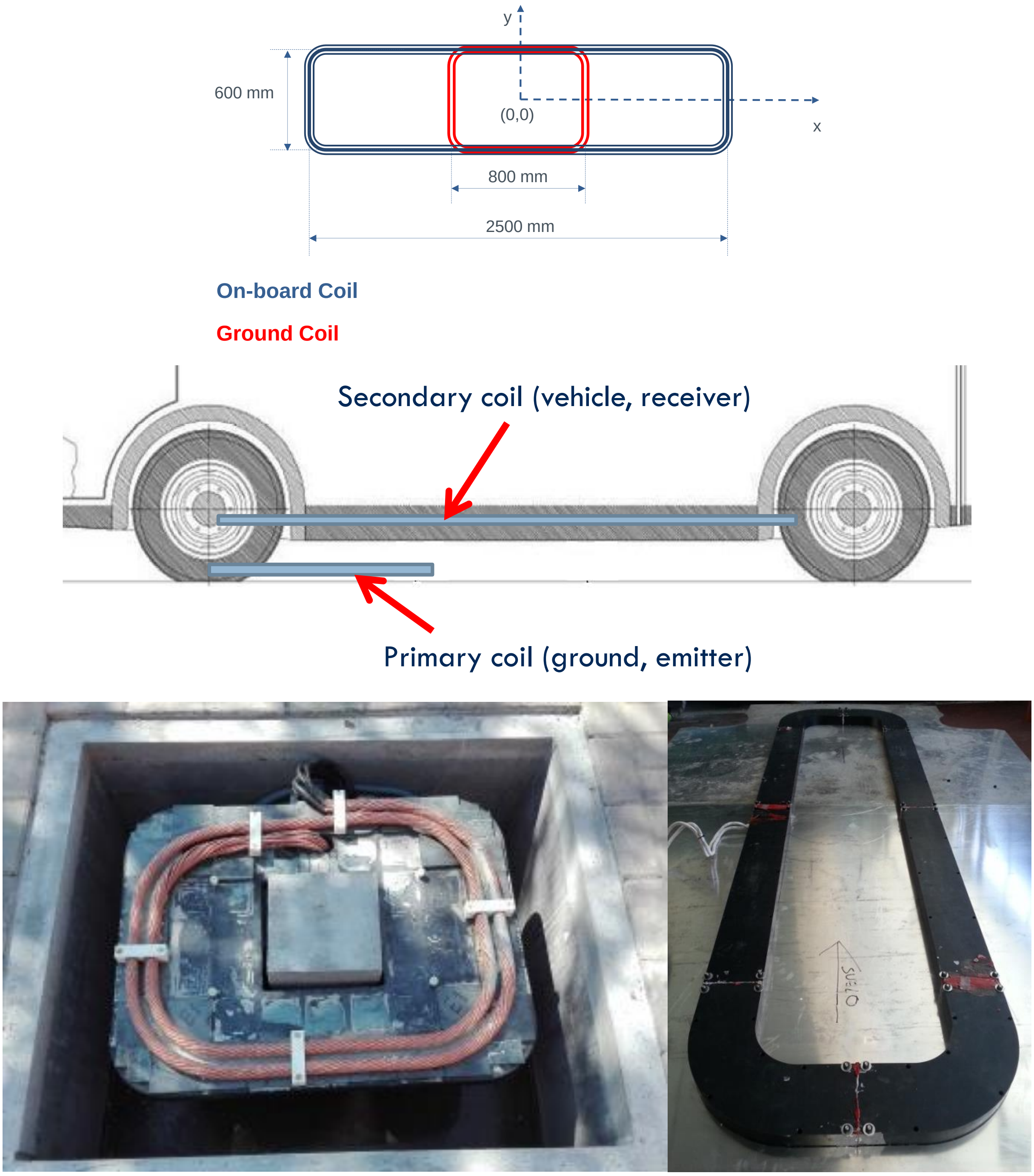

Figure 16: Different views of primary (ground, emitter) and secondary (vehicle, receiver) coils.

The following tables show main design parameters of the system which are also relevant for interoperability.

Coils	Turns	Conductor section	Width	Length
N1 (primary)	2	300 mm²	0.6 m	0.8 m
N2 (secondary)	4	45 mm²	0.6 m	2.5 m

Figure 17: Coil parameters.

3.10.3. Electromagnetic

The system operates at 20-30 kHz.

3.10.4. Other

EMF:
Under normal operation the magnetic field will be less 27 μT at 25 kHz (ICNIRP, 2010) in all public areas and in the driver cabin. Additional measurements will be carried out within the FABRIC project and reported in D4.7.2.

Protection switch at secondary side:

- Secondary side is current source → possible over-voltage in open circuit
- If battery disconnects (BMS emergency routine), secondary side must be protected
- BMS “open” signal is used to close protection switch (short-circuit secondary WPT coil)

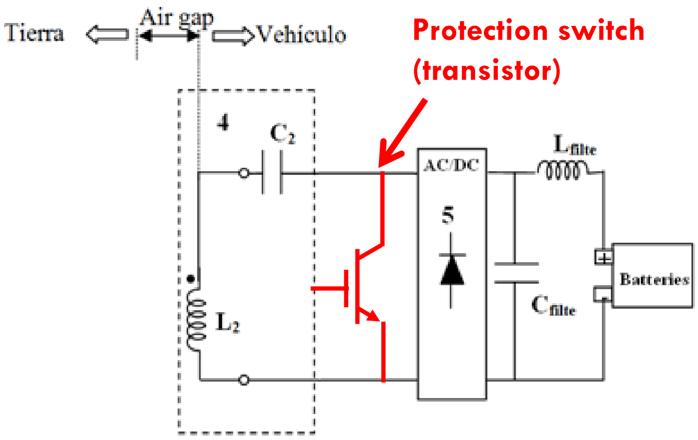

Figure 18: Different views of primary (ground, emitter) and secondary (vehicle, receiver) coils.

3.10.5. Summary

Communication	
Communication Method (wireless, Bluetooth, etc.)	WLAN
Communication protocol (ISO 12118, IEC 61851 etc.)	CAN / Wi-Fi
Position tracking/tracing for primary coil activation	GPS, WLAN, local detection at coil level
Construction and Geometry	
Coil geometry	Primary: 0.6x0.8 m, Secondary: 0.6x2.5 m (WxL)
Lateral misalignment tolerance	Target Y tolerance of ± 20 cm
Air gap and tolerance	Coil to coil distance of 15 – 25 cm supported
Achievable vehicle velocity	10 km/h
Electromagnetic	
Operational frequency	25 kHz
Magnetic field intensity	< 27 µT
Achievable secondary coil voltage	350 V (Battery voltage range: 285 … 410V)
Power rating and power	Up to 50 kW on vehicle request

Table 16: Available technical VICTORIA solution information for interoperability analysis.

4. INTEROPERABILITY CONSIDERATIONS

4.1. Introduction

After describing the methodology for the analysis and the existing solutions in the two proceeding sections, an analysis regarding the different solutions and their individual interoperability parameters can be carried out. Within this section every listed interoperability parameter is described in detail. Then an evaluation based on Excel sheets is presented, which displays a detailed picture of the opportunities and boundary conditions for interoperability regarding each parameter. The final objective of this exercise is to answer the question whether interoperability can be achieved and what effort will be required for this.

4.2. Communication

4.2.1. Communication interoperability general (out of standards)

In order to enable interoperability with the various actors of the charging ecosystem such as EVs on the client side, Electric Vehicle Supply Equipment Operators on the infrastructure side and finally Distribution System Operators (DSO) and Energy Retailers an interoperable communications stack is required. Conformance with the interoperability stack ensures that communications are compliant, starting from the physical layer up to the business context layer. ETSI/CE/CENELEC have adopted the following scheme as a model for the definition of categories of interoperability:

- Organizational
    - Economic/Regulatory
    - Business objectives
    - Business procedures
- Informational
    - Business context
    - Semantic understanding
- Technical
    - Syntactic interoperability
    - Network interoperability
    - Basic connectivity

The definition of the interoperability domain is initially categorized in technical, informational and finally organizational concepts. In this analysis the focus will be mostly on the technical and informational characteristics of various communication solutions.

The technical interoperability level consists of three layers, namely, basic connectivity, network interoperability and syntactic interoperability. Basic connectivity refers to the consideration of physical equipment and software for data encoding and transmission. Network interoperability, assesses various types of network protocols that enable the exchange of messages across multiple systems of the network. Syntactic interoperability emphasizes the common understanding of data structures of messages exchanged across the system.

In addition to the previous group of categories that mostly emphasize the basic functionality of communication systems, informational aspects will also be assessed. The interoperability stack defines two categories. The first one is semantic understanding which assesses the common understanding of the concepts container in a data structure and the second one is the business context which abstracts the overall interaction into a business case and assesses the coverage regarding the overall set of business cases.

In addition to the interoperability stack, CEN, CENELEC and ETSI have defined a common architectural framework for smart grid communications as shown in the following chart. Interoperability considerations will focus on the vehicle-to-grid interface and compatibility with generic smart-grid related applications that are applicable to the customer and service provider domains such as, authentication, billing, metering, demand side response, etc.

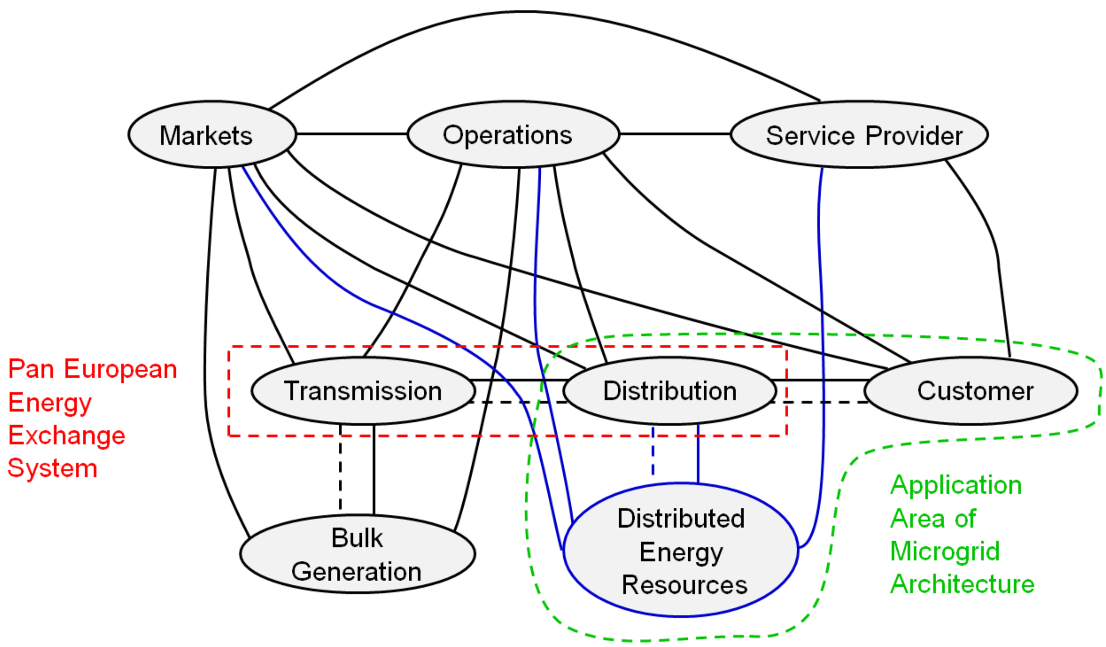

Figure 19: Pan European Energy Exchange System Reference Architecture.

4.2.2. Chart analysis: Communication method

For the communication method, the following chart presents the results of the analysis of the different FABRIC solutions and the non-FABRIC solutions. In the presented case interoperability targeting and basic connectivity of the communication link is investigated. (Physical, medium access control, OSI layers)

Communication Method (wireless, Bluetooth, etc)		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,50	0,50	0,00	0,50	0,50	1,00	1,00	0,50
	CWD	0,50		1,00	0,00	1,00	1,00	0,50	0,50	1,00
	IPV	0,50	1,00		0,00	1,00	1,00	0,50	0,50	1,00
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00
	UNPLUGGED 50 kW	0,50	1,00	1,00	0,00		1,00	0,50	0,50	1,00
	UNPLUGGED 3,7 kW	0,50	1,00	1,00	0,00	1,00		0,50	0,50	1,00
	FASTINCHARGE	1,00	0,50	0,50	0,00	0,50	0,50		1,00	1,00
	KAIST	1,00	0,50	0,50	0,00	1,00	1,00	1,00		0,00
	VICTORIA	0,50	1,00	1,00	0,00	1,00	1,00	1,00	0,00	

Table 17: Communication method interoperability chart.

Critical areas (lacking interoperability) which can be identified are:

- PRIMOVE Solution

All solutions, except PRIMOVE have identified WLAN and 802.11p as the wireless communication link covering Vehicle-to-Infrastructure communications related to the management of the charging process. The 802.11p specification targets vehicular communication systems with focus on the support of Intelligent Transportation Systems (ITS) applications covering both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. 802.11p enforces mechanisms for low latency in communications and minimization of errors due to the characteristics of the vehicular environment radio channel, thus it is a natural candidate for real-time wireless communications required to support dynamic charging operations.

Moreover 802.11p is a public standard supported by major standardization and legislative bodies. In 2008, the EU, reserved part of the 5.9 GHz band for use in ITS applications thus this frequency band can be used for communications associated with EV wireless charging.

The PRIMOVE system does not encompass a generic communications module for information exchange between the grid/road interface and the vehicle. In this case, communication methods are used to detect the speed of the vehicle and to authenticate the EV for charging procedure activation. Communications are based on a near field communication approach, therefore, the system is not interoperable with the 802.11p specification for physical layer and medium access control definition which has been adopted by CWD, IPV and UNPLUGGED charging systems.

4.2.3. Chart analysis: Communication protocol

In this section emphasis will be given to communication protocols that target the Vehicle-to-Grid interface. The overall coverage of information exchange that enables applications such as authentication, real-time charging control, metering and finally billing, is directly proportional to the interoperability of the interface with auxiliary yet essential actors of the charging eco-system such as, Electric Vehicle Supply Equipment Operators, DSOs, Energy retailers. Therefore it is important to note that a truly interoperable protocol is one that allows interoperability of the overall charging ecosystem.

Existing solutions will be compared with respect to communication protocols and the completeness of these protocols with respect to the overall requirements of charging operations.

The following chart presents the results of the analysis of the different FABRIC solutions and the non-FABRIC solutions, with respect to the Vehicle to Grid communication protocol

Communication protocol (ISO 12118, IEC 61851 etc)		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,50	0,50	0,00	0,50	0,50	0,50	0,50	0,50
	CWD	0,50		1,00	0,00	0,50	0,50	0,50	0,50	0,50
	IPV	0,50	1,00		0,00	0,50	0,50	0,50	0,50	0,50
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,50	0,50	0,50
	UNPLUGGED 50 kW	0,50	0,50	0,50	0,00		1,00	1,00	1,00	1,00
	UNPLUGGED 3,7 kW	0,50	0,50	0,50	0,00	1,00		1,00	1,00	1,00
	FASTINCHARGE	0,50	0,50	0,50	0,50	1,00	1,00		1,00	0,50
	KAIST	0,50	0,50	0,50	0,50	1,00	1,00	1,00		0,50
	VICTORIA	0,50	0,50	0,50	0,50	1,00	1,00	0,50	0,50	

Table 18: Communication protocol interoperability chart.

Critical areas for interoperability which can be identified are;

- PRIMOVE Solution
- Partially: FABRIC solutions interlinked and in comparison with the non-FABRIC solutions

As can be observed in the interoperability matrix, only IPV and CWD will be interoperable at the semantic and syntactic understanding level as the CAN over Wi-Fi interface defines the exchange of basic charging information in a raw binary format whereas the UNPLUGGED solution follows the definition of IEC 15118, which defines the use of the Efficient Mark-up Language Interexchange (EXI) at a syntactic level. These solutions are also interoperable with the FASTINCHARGE and KAIST solution. Moreover CAN over Wi-Fi supported by IPV, CWD supports the exchange of basic charging management variables in contrast to IEC/ISO 15118 which has a broader scope. Therefore the approaches are neither semantically interoperable. PRIMOVE's communication protocol is undefined, however given that the communication

system overall is oriented at implementing a specific functionality (vehicle detection and authorization), interoperability with IPV, CWD, WEVC, Unplugged which support data exchange targeting at charging management is not the case currently, overlapping functionalities however are available. Also the VICTORIA solution uses the CAN over Wi-Fi approach, minimizing the communication to the required signals, similar to IPV, CWF and WEVC. Being a proprietary development, no ad-hoc interoperability can be expected, but if CAN message definitions are shared between the providers, interoperability can be obtained easily.

ISO 15118 defines the data model and communication sequences that are required to perform essential charging operations such as authentication, authorization, charging parameter discovery, demand side management, charging session control, metering and charging session closure.

Additionally ISO/IEC 15118 parts 6-8 define the requirements and configuration on the OSI stack (PHY, MAC, NETWORK, TRANSPORT, APPLICATION) when considering wireless communications. Though the aforementioned parts of the standards are not publicly available it is expected that the development of this standard will lead to the definition of an interoperable standard under wireless environments.

In order to achieve interoperability IPV, CWD, WEVC and VICTORIA charging solutions could adopt ISO 15118 as the higher layer communications protocol for charging. The adoption of such a solution would enable the support of essential charging operations and auxiliary services such as demand-side management, thus enabling the support of related business cases (direct/ indirect load control) that exploits the elasticity of EV load in order to improve the electric grids efficiency. In this case the system would be "business wise" interoperable with DSOs and energy retailers supporting grid operation techniques such as demand side management. However current specifications target conductive charging requirements. Therefore standardization efforts are pre-requisite to obtain protocol interoperability for WPT.

4.2.4. Chart analysis: Position tracking /tracing for primary coil activation

Regarding the vehicle position tracking for the primary coil activation, no proper data for the analysis is available.

Position tracking/tracing for primary coil activation		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC					0,50	0,50			
	CWD			1,00		0,50	0,50			
	IPV		1,00			0,50	0,50	0,50	0,50	0,50
	PRIMOVE					0,50	0,50	0,50	0,50	0,50
	UNPLUGGED 50 kW	0,50	0,50	0,50	0,50		1,00	0,50	0,50	0,50
	UNPLUGGED 3,7 kW	0,50	0,50	0,50	0,50	1,00		0,50	0,50	0,50
	FASTINCHARGE		0,50	0,50		0,50	0,50		1,00	
	KAIST		0,50	0,50		0,50	0,50	1,00		
	VICTORIA		0,50	0,50		0,50	0,50			

Table 19: Position tracking/tracing interoperability chart.

Solutions presented in chapter 3 have designed position tracking/tracing systems for vehicle detection, the interoperability comparison is however hard to do without real interoperability tests on the road.

The PRIMOVE solution consists of a vehicle detection system that is installed on both primary and secondary sides of the WPT system. The vehicle detection system is based on near field communications, which are activated only when the vehicle in placed on top of a charging pad. Through the communication link that is established in this case, authentication credentials are transmitted to the charging pad, in order to initiate the power transfer process.

Given that the vehicle side of the detection system consists of a minor set of transmitter sensors, interoperability with other systems may be possible by installation and integration of this sensor system on EVs.

Due to the fact that the UNPLUGGED and FASTINCHARGE (under development) solutions are aligned to each other, a high level of interoperability can be identified. In addition to this, the UNPLUGGED solution with the camera as well as RFID based positioning is developed as a non-specific solution for this project and could probably, with minor modifications be used with the other systems, therefore already a partial interoperability is stated. On the other hand, these solutions are designed for static charging and might not be practical for the dynamic case.

In case of the VICTORIA solution, a GPRS positioning system (for long-range tracking) is combined with a laser system (for guiding). Here interoperability is attached especially to the vehicle and communications with the road-side installations. Being a specific development for this project, interoperability is very limited. A VICTORIA vehicle might be able to be guided and only communications with the non-VICTORIA road-side equipment must be adapted, which could be considered as a minor adaptation, as communication channels (Wi-Fi) are similar to other solutions. The other way round, a non-VICTORIA vehicle, if it depends on specific road-side equipment (such as RFID), might not be able to be guided on a VICTORIA track.

As a conclusion, it can be stated that current guiding solutions show low to medium interoperability levels. This is due to the experimental character (FABRIC, UNPLUGGED, FASTINCHARE) or proprietary solutions (VICTORIA, KAIST, PRIMOVE), But this is not a situation which can be extrapolated to the future. If all guiding ability is self-contained in the vehicle (similar to the VICTORIA solution), interoperability mainly is reduced to communication standards. Therefore, assuming the rise of autonomous driving, guiding WILL be solved independently of the road-side charging equipment, so guiding is not expected to be a rock on the road of dynamic wireless power transfer deployment.

4.3. Construction and geometry

4.3.1. Chart analysis: Coil geometry

For the coil geometry, the following chart presents the results of the analysis of the different FABRIC solutions and the non-FABRIC solutions;

Coil geomety		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		1,00	1,00	0,00	0,50	1,00	0,50	0,50	0,50
	CWD	1,00		1,00	0,00	0,50	1,00	0,50	0,50	0,50
	IPV	1,00	1,00		0,50	0,50	1,00	0,50	0,50	0,50
	PRIMOVE	0,50	0,50	0,50		0,50	0,50	0,50	0,50	1,00
	UNPLUGGED 50 kW	0,50	0,50	0,50	0,50		1,00	0,50	0,50	0,50
	UNPLUGGED 3,7 kW	0,50	0,50	0,50	0,00	1,00		0,50	0,50	0,50
	FASTINCHARGE	0,50	0,50	0,50	0,50	0,50	0,50		0,50	1,00
	KAIST	0,50	1,00	0,50	0,50	0,50	0,50	0,50		1,00
	VICTORIA	0,50	0,50	0,50	1,00	0,50	0,50	1,00	1,00	

Table 20: Coil geometry interoperability chart.

WEVC, CWD and IPV as well as UNPLUGGED 3.7 kW and 50 kW systems use secondary coils of similar sizes so good interoperability is expected.

Critical areas for interoperability which can be identified are:

- PRIMOVE road coil is larger than the other ones and thus some power transfer capability is expected, but quite different from the design value. Thus, a 0.5 assessment has been given. Due to safety issues an under designed coil geometry with a non-comparable primary coil geometry is assessed with 0.
- UNPLUGGED system uses a more complex coil configuration, since it includes two emitting and receiving coils. However, there is possibility of energy exchange between the UNPLUGGED system and the other systems, so a 0.5 rating has been given.
- The UNPLUGGED 3.7 kW solution has the smallest coil as road system part, thus energy always will reach the secondary coil. Reasonable similar coil geometries therefore are listed with 1.
- The implemented coils in the VICTORIA solution are relative big and therefore interoperable with PRIMOVE, FASTINCHARGE and KAIST solution.

4.3.2. Chart analysis: Lateral misalignment tolerance

For the lateral misalignment tolerance, the following chart presents the results from the analysis of the different solution. Wider coils improve misalignment tolerance. As a rule of thumb, it is considered a misalignment when the tolerance exceeds 30% of coil width. It has to be pointed out that for this assessment only coil dimensions are considered, and not the compensation topology used.

In the following chart, if interoperability does not reduce lateral misalignment tolerance, a “1” rating is assigned.

Lateral misalignment tolerance		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		1,00	1,00		1,00	0,50	0,50	0,50	1,00
	CWD	1,00		1,00		1,00	0,50	0,50	1,00	1,00
	IPV	0,50	1,00			0,50	0,50	0,50	1,00	1,00
	PRIMOVE									
	UNPLUGGED 50 kW	1,00	1,00	1,00			0,50	0,50	0,50	1,00
	UNPLUGGED 3,7 kW	0,50	0,50	1,00		0,50		1,00	1,00	0,50
	FASTINCHARGE	0,50	0,50	1,00		0,50	1,00		1,00	0,50
	KAIST	0,50	1,00	1,00		0,50	1,00	1,00		1,00
	VICTORIA	1,00	1,00	1,00		1,00	0,50	0,50	1,00	

Table 21: Lateral misalignment interoperability chart.

- WEVC, CWD, UNPLUGGED 50 kW and VICTORIA systems have a lateral misalignment tolerance of 0.2 m, so according to this parameter there is perfect interoperability between them.
- IPV system has a tolerance of 0.5 m. If the conditioning to the driver/vehicle is considered, an IPV vehicle should pay more attention when placing itself for charge in another road system (e.g. 0.2 m tolerance instead of 0.5 m) so a 0.5 rating has been given. On the other hand, if any other vehicle wants to charge in an IPV road system, it would find no change in misalignment restrictions, so a 1 rating has been given.
- There are no misalignment data for the PRIMOVE system
- The VICTORIA solution shows an acceptable lateral misalignment tolerance of 0.2 m and is therefore in the centre of all solutions regarding the interoperability aspect lateral misalignment
- The UNPLUGGED 3.7 kW, FASTINCHARGE as well as KAIST solution have a misalignment tolerance of 0.1 m and therefore interoperable

4.3.3. Chart analysis: Air gap and tolerance

For the air gap tolerance, the following chart presents the results from the analysis of the different solutions.

Air gap and tolerance		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,50	1,00		0,00	1,00	0,50	1,00	1,00
	CWD	0,50		0,50		0,00	0,50	0,50	0,00	1,00
	IPV	1,00	0,50			1,00	0,50	0,00	0,50	1,00
	PRIMOVE									
	UNPLUGGED 50 kW	0,00	0,50	1,00			0,50	0,00	1,00	1,00
	UNPLUGGED 3,7 kW	1,00	0,50	0,00		0,50		0,50	1,00	0,50
	FASTINCHARGE	0,50	0,50	0,00		0,00	0,50		0,00	0,00
	KAIST	1,00	0,00	0,50		1,00	1,00	0,00		1,00
	VICTORIA	1,00	1,00	1,00		1,00	0,50	1,00	1,00	

Table 22: Air gap and tolerance interoperability chart.

Critical areas for interoperability which can be identified are:

- PRIMOVE Solution
- Several single solution combinations

The analysis of the air gap and tolerance matrix, shows critical areas for the PRIMOVE solution. For the PRIMOVE solution no input on the air gap as well as the tolerance is available, therefore the conclusion is that the system is not interoperable, however an proper input could lead to a positive result regarding interoperability.

All other solution combinations are analysed in detail and the air gap tolerance can be defined as a very heterogeneous physical parameter as can be concluded out of the matrix. This parameter, as a result out of the matrix, could be identified as an important physical parameter to improve/adjust towards interoperability of the different systems.

4.3.4. Chart analysis: Achievable vehicle velocity

For the achievable vehicle velocity, the following chart presents the results from the analysis of the different solutions.

Achievable vehicle velocity		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		1,00	1,00				0,50	0,50	0,50
	CWD	1,00		1,00				0,50	0,50	0,50
	IPV	1,00	1,00					0,50	0,50	0,50
	PRIMOVE									
	UNPLUGGED 50 kW									
	UNPLUGGED 3,7 kW									
	FASTINCHARGE	1,00	1,00	1,00					0,50	0,50
	KAIST	1,00	1,00	1,00				1,00		0,50
	VICTORIA	1,00	1,00	1,00				1,00	0,50	

Table 23: Achievable vehicle velocity interoperability chart.

- There is no achievable vehicle velocity data for the PRIMOVE system.
- UNPLUGGED solutions are conceived for stationary charge, so no velocity data is provided.
- CWD and IPV systems have a maximum velocity of 90 km/h, although both are still to be confirmed during tests. WEVC system has proven during tests at Satory test site a maximum velocity of 100 km/h. With this information it is concluded that the vehicles probably could charge combined with other road side systems, so a 1 rating has been given
- Similar analysis is done for FASTINCHARGE, VICTORIA and KAIST system
- The VICTORIA solution has the lowest velocity with 10 km/h, therefore the vehicle side will probably be interoperable with other solutions, however for the road side interoperability with vehicles out of other solutions cannot be guaranteed.

4.4. Electromagnetic

4.4.1. Chart analysis: Operational frequency

For the inductive charging process operational frequency, the following chart presents the results from the analysis of the different solutions.

	Operational frequency	Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		1,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00
	CWD	1,00		1,00	0,00	0,00	0,00	0,00	0,00	0,00
	IPV	1,00	1,00		0,00	0,00	0,00	0,00	0,00	0,00
	PRIMOVE	0,00	0,00	0,00		1,00	0,00	1,00	1,00	1,00
	UNPLUGGED 50 kW	0,00	0,00	0,00	1,00		0,00	1,00	1,00	1,00
	UNPLUGGED 3,7 kW	0,00	0,00	0,00	0,00	0,00		0,00	0,00	0,00
	FASTINCHARGE	0,00	0,00	0,00	1,00	1,00	0,00		1,00	1,00
	KAIST	0,00	0,00	0,00	1,00	1,00	0,00	1,00		1,00
	VICTORIA	0,00	0,00	0,00	1,00	1,00	0,00	1,00	1,00	

Table 24: Operational frequency interoperability chart.

Regarding the operational frequency, the analysis is divided in 2 sections, due to the specific operating frequency of WEVC, IPV and CWD on the one hand as well as all other solutions on the other hand.

In general it can be observed that systems with higher power, such as PRIMOVE, UNPLUGGED (50 kW), FASTINCHARGE, VICTORIA and KAIST use similar frequencies of 20 – 30 kHz, while the 85-kHz standard is adopted for solutions with lower power. The 3.7-kW system from UNPLUGGED which operates at 145 kHz is an exception and is actually already overcome, as for these static low-power applications the 85-kHz standard is already adopted in the industry. Therefore, this outlier can be disregarded for the conclusions to be drawn in the context of the FABRIC project.

The reason behind the two observed frequency levels is a technological one, as losses in power electronics increase with switching frequency and with switching current. Even with soft switching schemes (switching when current is near zero) it is not likely that in a foreseeable future the 85-kHz standard might be adopted for power levels of 100 kW and beyond. Therefore, two standard frequencies can be extracted from the technology survey above: 85 kHz (current standard for static charging up to 20 kW) and 20 – 30 kHz (for higher power).

As an overall conclusion it can be stated that the operational frequency is in line with the standards. Nevertheless, there are two frequencies which are not interoperable and divide basically low to medium-power systems and high-power systems in two non-interoperable applications. In the UNPLUGGED project a dual frequency operation with two different resonance capacitor banks has been proven feasible, but from a technological point of view it is not clear if the achieved interoperability compensates for additional complexity and cost.

Future developments in power electronics will foreseeably move the power level for 85-kHz systems gradually upwards. In fact, today, 50-kW systems are conceivable at 85 kHz. If in addition a multi-coil solution is adopted (several pick-up coils in the same vehicle, as done in FABRIC solution 1), even higher power levels can be considered with the 85-kHz standard. Therefore, with time the definition of “high power” will change, although the basic conclusion that high-power and lower-power systems might not be interoperable remains in place.

4.4.2. Chart analysis: Magnetic field intensity

For the magnetic field intensity, there are not much data available yet. In general terms, EMF issues may appear if ground coil width is similar to (or larger than) vehicle width.

Magnetic field intensity		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC									
	CWD			1,00				0,50	0,50	0,50
	IPV		1,00					0,50	0,50	0,50
	PRIMOVE									
	UNPLUGGED 50 kW						0,50			
	UNPLUGGED 3,7 kW					0,50				
	FASTINCHARGE		0,50	0,50					0,50	0,50
	KAIST		0,50	0,50				0,50		0,50
	VICTORIA		0,50	0,50				0,50	0,50	

Table 25: Magnetic field intensity interoperability chart.

Magnetic field intensity is an important design parameter, as it is directly related to safety issues (see section 4.5.2 of this document). Due to the fact that a defined statement on magnetic field intensity is hard to give, no data is available from WEVC as well as UNPLUGGED and PRIMOVE, therefore, the table is rather empty. In general terms, EMF issues may appear if ground coil width is similar to (or larger than) vehicle width.

4.4.3. Chart analysis: Achievable secondary coil voltage

For the achievable secondary coil voltage, the following chart presents the results from the analysis of the different solutions.

Achievable secundary coil voltage		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		1,00	1,00	0,00	1,00	0,50	0,00	1,00	0,50
	CWD	1,00		1,00	0,00	1,00	0,50	0,00	1,00	0,00
	IPV	1,00	1,00		0,00	1,00	0,50	0,00	1,00	0,00
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,50	0,00	0,00
	UNPLUGGED 50 kW	1,00	1,00	1,00	0,00		0,50	0,00	1,00	0,50
	UNPLUGGED 3,7 kW	0,50	0,50	0,50	0,00	0,50		0,00	0,00	0,00
	FASTINCHARGE	0,00	0,00	0,00	0,50	0,00	0,00		0,00	0,00
	KAIST	1,00	1,00	1,00	0,00	1,00	0,00	0,00		1,00
	VICTORIA	0,50	0,00	0,00	0,00	0,50	0,00	0,00	1,00	

Table 26: Achievable secondary coil voltage interoperability chart.

Critical areas for interoperability can be identified between high-voltage systems (PRIMOVE: 750 V and FASTINCHARGE: 600 V) and low-voltage systems (all the others: 250 – 400 V). A special case is UNPLUGGED 3.7 kW with only 250 V, which further reduces its interoperability with other systems. However, this is not a typical case and can be disregarded for further analysis. Different design voltages for the secondary coil are a consequence of the vehicle power train topologies (including battery voltage). Thus, 2 typical on-board DC voltage ranges can be identified:

- Light vehicles: 300 – 400 V (passenger vehicles, light vans, small buses)
- Heavy vehicles: 600 – 800 V (buses, heavy vans, trucks)

Lower voltages are related to lower power levels (except for the KAIST and VICTORIA system) and higher voltages are typical for high-power applications on heavy vehicles. Up to 50 kW, on-board voltages of 300-400 V can be expected, with the exception of KAIST which is a 100-kW system with 400 V secondary voltage. PRIMOVE – the other high-power system with up to 200 kW – works with 750 V. FASTINCHARGE with 600 V and only 30 kW is also not typical.

At the light of these observations, interoperability is possible if the primary side is capable of modifying voltages in the ranges mentioned above: 300 – 400 V or 600 – 800 V. From the experience of the FABRIC consortium, this can be considered a minor technical issue, easy to achieve or it is even already part of existing system designs. But still, two different systems will remain: high and low-voltage. To overcome this and to agree on a common, standardised voltage range, a major effort is needed.

Different voltage levels might be overcome with on-board DC/DC converters, although this solution adds weight and complexity to the vehicle which is not in line with the requirements from the OEMs which are seeking to reduce both.

Here it becomes apparent again, that interoperability between light and heavy vehicles is not easily achievable. This is a similar observation as already obtained from operational frequency (see section 4.4.1).

Remarks:

The 50-kW system of the UNPLUGGED solution could be adapted for two different voltages. It consists of two 25-kW coils which can be connected either in parallel or serial. In serial, 700 V can be reached. However, this system is very complex and although feasible for static charging, it is not a viable solution for dynamic charging, as physical switching is needed to change from one configuration to the other. For dynamic charging, it might be necessary to change the configuration each second (or even faster) which would result in thousands of switching events each hour.

In addition, there is a clear trend for increased fast charging (conductive) with announcements of 350 kW chargers in medium term, to be installed at highway gas stations. These high power ratings for fast charging imply the need for higher battery voltages on board. Therefore, the 600 – 800 V range for on-board DC bus might be the choice also for passenger cars. In this sense, it is likely that interoperability will be achieved here. Of course, this trend is considering ever larger battery packs and consequently more autonomy for the vehicles, which in turn is contrary to the assumption that DWPT might reduce battery size. This aspect will be treated in SP5 of this project and is not part of the interoperability study.

4.4.4. Chart analysis: Power rating and power

For the analysis of the power rating and transferred power, the following chart presents the results from of the analysis of the different solutions.

Power rating and power		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		1,00	1,00	0,50	1,00	0,50	1,00	0,50	1,00
	CWD	1,00		1,00	0,50	1,00	0,50	1,00	0,50	1,00
	IPV	1,00	1,00		0,50	0,50	0,00	0,50	1,00	1,00
	PRIMOVE	0,00	0,00	0,50		0,50	0,00	0,50	0,50	0,50
	UNPLUGGED 50 kW	0,50	0,50	0,50	0,50		0,50	0,50	0,50	1,00
	UNPLUGGED 3,7 kW	0,50	0,50	0,50	0,50	1,00		1,00	0,50	0,00
	FASTINCHARGE	1,00	1,00	0,50	0,50	1,00	0,50		0,50	0,50
	KAIST	0,50	0,50	1,00	0,50	0,50	0,00	0,50		0,50
	VICTORIA	1,00	1,00	1,00	0,50	1,00	0,00	0,50	0,50	

Table 27: Power rating and power interoperability chart.

For the power rating and interoperability regarding the transferred power, a very positive result of the analysis chart can be displayed. The red cells are configuration where the possible transferred power is very low (UNPLUGGED 3.7 kW) or very high (PRIMOVE). These spots are

the upper and lower boundary conditions for the chart and results in a certain amount of interoperability.

The explanation of this result is the fact that the systems do not require a minimum power rating, but only define a maximum allowed power. In addition it has to be stated that the fact that all systems could theoretically be interoperable, certainly, the efficiency is a limiting factor. This physical factor however is considered in another chart. At the end the results will be combined and an overall statement can be made on the quality of the interoperability regarding these factors.

4.5. Other

4.5.1. Charging efficiency

Charging efficiencies are not available for any of the studied solutions. Moreover, it is a very complex task to estimate the efficiency of one system operating with another. Available data does not permit the establishment of any qualitative or quantitative metrics of efficiency for any given combination.

Even if systems are interoperable, they may not work at their optimum. Therefore, in general it can be expected that efficiency will be reduced due to interoperability of different solutions. How efficiency is affected will be explained below with examples for each parameter.

Communication:
If communication works properly, power transfer efficiency is not affected. If it does not work properly, probably there will be no power transfer at all.

Coil geometry:
In order to obtain highest efficiencies, primary and secondary coils should have identical geometry. Any deviations from this optimum will result in efficiency reductions. Although important for efficiency, geometry is one of the least critical parameters for interoperability. This means that due to the geometry systems may be less efficient but will still be able to transfer power.

Lateral misalignment tolerance:
In general, lateral misalignment reduces efficiency. The tolerance is directly related to the coil geometry. As a rule of thumb, a misalignment of 30% of the coil width can be tolerated (assuming equal primary and secondary coil width). If one coil is wider than the other, additional tolerance is gained, losing by default maximum efficiency, as described before.

Finally, it should be mentioned here that only inductive circuit topologies are considered here which inherently tolerate some misalignment.

Air gap:
Different air gaps can be compensated by frequency variation. As all systems are working with resonant topologies, a variation of the frequency will move the system out of resonance and less power will be transferred.

It should be noted here that in this case a reduction in transferrable power does not always mean less efficiency. It is possible that the efficiency even increases slightly.

Vehicle velocity:
Vehicle velocity is limited mainly by the speed of the implemented control and the ramp-up capability of the system. If the vehicle moves faster than the maximum specified, less power will be transferred. Also in this case this does not mean necessarily that power transfer efficiency is lower. The system is just not able to react fast enough in order to supply nominal power.

Operational frequency:
As mentioned before, frequency is directly related to resonance. The inductive circuit is optimized for a certain frequency, and only small variations are possible without significantly losing performance. Nevertheless, if the system moves away from resonance, also less power is demanded from the primary circuit. Therefore, power reduction not necessarily means efficiency reduction.

Achievable secondary coil voltage:
Assuming that voltage deviations are small, the impact on overall system efficiency is small. Nevertheless, if voltages are not compatible, this system will not transfer any power.

Power rating:
In general, system efficiency is optimised for nominal power conditions. If power transfer must be reduced, part load conditions typically increase losses and reduce efficiency. The reduction of cable losses due to reduced power can be neglected here, as its contribution is much less than that of power electronic elements.

4.5.2. Chart analysis: Safety considerations

Regarding safety considerations and measures the solution providers delivered several solutions, however the effectiveness regarding interoperable operation is hard to analyse from data only, real testing should be performed here. Therefore, no comparable study can be presented. Similar to efficiency, this leads to the need that this will be a central topic to be analysed in the tests which will be conducted within WP4 of the project.

Safety issues related with the electromagnetic field are mainly related to coil geometries and shielding.

In general terms, the electromagnetic field must be oriented in such a way that passengers inside the vehicle and persons outside cannot be affected. In this case, coil geometry is the most important parameter to be considered. Although power transfer can be established for virtually any combination of coil geometries, safety is not always fulfilled. Especially, if primary coils are too large, the field may extend beyond the vehicle (lateral or longitudinal). In this case, it is preferable that the secondary coil (on the vehicle) is larger than the primary coil. This way, the primary coil will always be covered by the vehicle. As a result out of these considerations, the following analysis chart can be displayed;

Safety considerations (Shielding, EMC, Heating, etc)		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,50	0,50	0,00	0,50	0,50	0,50	0,00	0,50
	CWD	0,50		1,00	0,00	0,00	0,50	0,50	0,00	0,50
	IPV	0,50	1,00		0,00	0,00	0,50	0,50	0,00	0,50
	PRIMOVE	0,50	1,00	1,00		0,50	0,50	1,00	1,00	1,00
	UNPLUGGED 50 kW	0,50	0,50	0,50	0,00		0,50	0,50	0,00	1,00
	UNPLUGGED 3,7 kW	0,50	0,50	0,50	0,00	0,50		0,50	0,00	0,50
	FASTINCHARGE	0,50	0,50	0,50	0,00	0,50	1,00		0,50	1,00
	KAIST	1,00	1,00	1,00	0,00	1,00	1,00	1,00		1,00
	VICTORIA	1,00	1,00	1,00	0,00	1,00	1,00	1,00	0,50	

Table 28: Safety considerations interoperability chart.

4.5.3. *Chart analysis: Costs to accomplish interoperability*

Regarding the costs to accomplish interoperable systems, the following chart presents the results from the analysis of the different solutions.

Costs to accomplish interoperability		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,50	0,50	0,00	0,00	0,00	0,50	0,50	0,50
	CWD	1,00		1,00	0,00	0,00	0,00	0,50	0,50	0,50
	IPV	0,50	1,00		0,00		0,00	0,50	0,50	0,50
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,50	0,50	0,50
	UNPLUGGED 50 kW	0,00	0,00	0,00	0,00		0,50	0,00	0,00	0,00
	UNPLUGGED 3,7 kW	0,00	0,00	0,00	0,00	0,50		0,00	0,00	0,00
	FASTINCHARGE	0,50	0,50	0,50	0,50	0,00	0,00		0,50	0,50
	KAIST	0,50	0,50	0,50	0,50	0,00	0,00	0,50		0,50
	VICTORIA	0,50	0,50	0,50	0,50	0,00	0,00	0,50	0,50	

Table 29: Costs to accomplish interoperability chart.

Critical areas regarding the possible costs which can be identified are;

The PRIMOVE solution would incur the biggest cost point of all solutions in order to accomplish interoperability. Major issues here would be the technical equipment adjustments which would have to be made regarding voltage levels and operating frequency.

The UNPLUGGED solution, due to the solution's static character (no dynamic charging) is regarding the costs the second critical, most cost intensive solution towards accomplishing interoperability. Making changes to accomplish a dynamic charging requires high costs especially regarding positioning and communication.

The other developed FABRIC Solutions, WEVC, CWD and IPV show a rather good interoperability and the costs to make these systems 100% interoperable will be the lowest due to only minor adjustments.

FASTINCHARGE, KAIST as well as VICTORIA show a rather good interoperability in majority of analysis aspects and thus can be rated with “intermediate costs”.

5. CONCLUSIONS

The overall conclusions which result out of this document can be divided into two sections:

- Methodology
- Interoperability analysis results

Regarding the developed methodology to analyse the interoperability of inductive EV charging systems as described in section 2, it can be stated that all (possible) critical areas can be identified using this methodology. A proper combination of the assessed matrices for all characteristics, the summarized matrices by hard interoperability scores, 0, 0.5 and 1, as well as summarized values (to define the level of interoperability and the specific interoperability topics) result in a comprehensive representation of interoperability of the investigated systems.

From section 3 it can be concluded that not every solution is currently fully specified and thus some information is not available. Nevertheless, the overall analysis methodology allows us to abstract this unavailability and develop a fundamental conclusion on interoperability of the different systems.

For the analysis of the overall charts the following results can be presented at an overall data availability of almost 82.5% (17.5% of the requested data is not available, including vehicle speed for static solutions from UNPLUGGED, for example):

- Interoperability analysis with only the available data
- Interoperability analysis with a positive scenario; the unavailable data which will be available in the future will be interoperable with the current data.
- Interoperability analysis with a negative scenario; the unavailable data which will be available in the future will be not interoperable with the current data.
- Interoperability gap analysis; which technical areas are critical regarding interoperability

5.1. Interoperability analysis with only the available data

Analysing and considering only the available data out of the project, the following analysis table can be presented:

Summary product Table		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,83	0,89	0,00	0,00	0,00	0,00	0,00	0,00
	CWD	0,83		0,95	0,00	0,00	0,00	0,00	0,00	0,00
	IPV	0,83	0,95		0,00	0,00	0,00	0,00	0,00	0,00
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00
	UNPLUGGED 50 kW	0,00	0,00	0,00	0,00		0,00	0,00	0,72	0,83
	UNPLUGGED 3,7 kW	0,00	0,00	0,00	0,00	0,00		0,00	0,00	0,00
	FASTINCHARGE	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,00
	KAIST	0,00	0,00	0,00	0,00	0,78	0,00	0,00		0,00
	VICTORIA	0,00	0,00	0,00	0,00	0,83	0,00	0,00	0,00	

Table 30: Interoperability analysis out of available data.

This summary/product table, Table 30, shows interoperability regarding the available data for the 9 solution combinations. All other interoperability analysis combinations show at least one physical area in which interoperability does not exist. Analysing the level of interoperability in order to make a proper conclusion towards the process (costs, effort etc.) for achieving interoperability, the following chart can be presented:

Addittion table		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		7,50	8,00	0,50	5,00	5,00	4,50	5,50	5,50
	CWD	7,50		10,50	0,50	5,50	5,00	4,50	5,00	6,00
	IPV	7,50	10,50		1,00	5,50	4,50	4,00	6,50	6,50
	PRIMOVE	0,50	0,50	1,00		2,50	1,00	3,50	3,00	3,50
	UNPLUGGED	4,50	5,50	6,00	2,50		6,50	4,50	6,50	7,50
	UNPLUGGED 3,7 kW	4,50	4,50	4,50	1,00	7,00		5,00	5,00	4,00
	FASTINCHARGE	5,00	5,50	5,00	3,00	5,00	4,50		7,00	5,50
	KAIST	6,00	6,50	7,00	2,50	7,00	5,00	7,50		7,00
	VICTORIA	6,00	7,00	7,00	3,00	7,50	4,00	7,00	7,00	

Table 31: Interoperability level analysis out of available data.

Table 31 shows clearly by which degree interoperability (out of 14 interoperability topics) is given. As a result it can be stated that 3 levels of interoperability can be identified;

0-4: Low level of possible interoperability, significant effort has to be invested to reach interoperability (12 combinations).
4-8: Medium level of possible interoperability, some effort has to be invested to reach interoperability (6 combinations).
9-14: High level of possible interoperability, little or no effort has to be invested to reach interoperability (2 combinations).

5.2. Interoperability analysis with a positive scenario; the unavailable data which will be available in the future will be interoperable with the current data.

For defining the interoperability possible boundaries for the different system a positive scenario regarding interoperability will be investigated.
The positive scenario emerges from the assumption that all missing data will exist in the future in a way that interoperability is guaranteed. For this scenario the following analysis charts can be represented;

Summary Table		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		0,86	0,91	0,00	0,00	0,00	0,00	0,00	0,00
	CWD	0,86		0,95	0,00	0,00	0,00	0,00	0,00	0,00
	IPV	0,86	0,95		0,00	0,00	0,00	0,00	0,00	0,00
	PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00
	UNPLUGGED 50 kW	0,00	0,00	0,00	0,00		0,00	0,00	0,77	0,86
	UNPLUGGED 3,7 kW	0,00	0,00	0,00	0,00	0,00		0,00	0,00	0,00
	FASTINCHARGE	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,00
	KAIST	0,00	0,00	0,00	0,00	0,82	0,00	0,00		0,00
	VICTORIA	0,00	0,00	0,00	0,00	0,86	0,00	0,00	0,00	

Table 32: Interoperability analysis out of a positive scenario regarding missing data.

As a conclusion out of Table 32, it can be stated that in the current situation, 10 solution combinations could lead to an overall interoperability.

As equivalent to Table 31, Table 33 shows the degree of interoperability in a positive development scenario regarding the missing data considering that 15 is the maximum achievable interoperability value.

Addittion table		Road system part								
		WEVC	CWD	IPV	PRIMOVE	UNPLUGGED	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
EV system part	WEVC		9,50	10,00	5,50	7,00	7,00	6,50	7,50	7,50
	CWD	9,50		10,50	5,50	7,50	7,00	5,50	6,00	7,00
	IPV	9,50	10,50		6,00	7,50	6,50	4,00	6,50	6,50
	PRIMOVE	5,50	5,50	6,00		6,50	5,00	7,50	7,00	7,50
	UNPLUGGED	6,50	7,50	8,00	6,50		7,50	6,50	8,50	9,50
	UNPLUGGED 3,7 kW	6,50	6,50	6,50	5,00	8,00		7,00	7,00	6,00
	FASTINCHARGE	7,00	5,50	5,00	8,00	7,00	6,50		7,00	6,50
	KAIST	8,00	6,50	7,00	7,50	9,00	7,00	7,50		8,00
	VICTORIA	8,00	7,00	7,00	8,00	9,50	6,00	8,00	8,00	

Table 33: Interoperability level analysis with a positive development scenario.

Only medium and high levels of possible interoperability can be concluded out of the overview.

5.3. Interoperability analysis with a negative scenario; the unavailable data which will be available in the future will be not interoperable with the current data.

For defining the interoperability possible boundaries for the different system also a negative scenario regarding interoperability will be investigated.

The negative scenario emerges from the assumption that all missing data will exist in the future in a way that interoperability isn't possible for that specific data. For this scenario the following analysis charts can be represented;

Summary product Table	Road system part								
EV system part	WEVC	CWD	IPV	PRIMOVE	UNPLUGGED 50 kW	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
WEVC		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
CWD	0,00		0,95	0,00	0,00	0,00	0,00	0,00	0,00
IPV	0,00	0,95		0,00	0,00	0,00	0,00	0,00	0,00
PRIMOVE	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00
UNPLUGGED 50 kW	0,00	0,00	0,00	0,00		0,00	0,00	0,00	0,00
UNPLUGGED 3,7 kW	0,00	0,00	0,00	0,00	0,00		0,00	0,00	0,00
FASTINCHARGE	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,00
KAIST	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00
VICTORIA	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	

Table 34: Interoperability analysis out of a negative scenario regarding missing data.

As a conclusion out of Table 34 it can be stated that in the current situation, any development, which would result in getting all data, however not interoperable to each other, would lead to an interoperability of only CWD and IPV solution.

As equivalent to Table 31 and Table 33, Table 35 shows the degree of interoperability in a negative development scenario regarding the missing data.

Addittion table	Road system part								
EV system part	WEVC	CWD	IPV	PRIMOVE	UNPLUGGED	UNPLUGGED 3,7 kW	FASTINCHARGE	KAIST	VICTORIA
WEVC		7,50	8,00	0,50	5,00	5,00	4,50	5,50	5,50
CWD	7,50		10,50	0,50	5,50	5,00	4,50	5,00	6,00
IPV	7,50	10,50		1,00	5,50	4,50	4,00	6,50	6,50
PRIMOVE	0,50	0,50	1,00		2,50	1,00	3,50	3,00	3,50
UNPLUGGED	4,50	5,50	6,00	2,50		6,50	4,50	6,50	7,50
UNPLUGGED 3,7 kW	4,50	4,50	4,50	1,00	7,00		5,00	5,00	4,00
FASTINCHARGE	5,00	5,50	5,00	3,00	5,00	4,50		7,00	5,50
KAIST	6,00	6,50	7,00	2,50	7,00	5,00	7,50		7,00
VICTORIA	6,00	7,00	7,00	3,00	7,50	4,00	7,00	7,00	

Table 35: Interoperability level analysis with a positive development scenario.

Of course, this figure is the same as Table 30, due to the fact that in this analysis (addition) no available data is handled in the same way -as a negative rating for each area.

5.4. Interoperability gap analysis; which technical areas are critical regarding interoperability

Finally, a short gap analysis for the data should be done, to make clear in which development areas the most energy/effort is needed regarding interoperability issues. Therefore Table 35 was developed and shows the relevant gaps.

The stars (*) show the areas where no data is available (and thus the systems first have to be contemplated as not interoperable), or the considered available data shows no interoperability.

In order to get also a proper overview of the differentiation of the (*) fields, Table 36 shows a colour differentiation of the data;

152	No data available
190	Data available no interoperability
508	Data available interoperable

A summary of the analysed 850 combinations of interoperability shown in Figure 20. The detailed analysis is shown in Table 36 and Table 37.

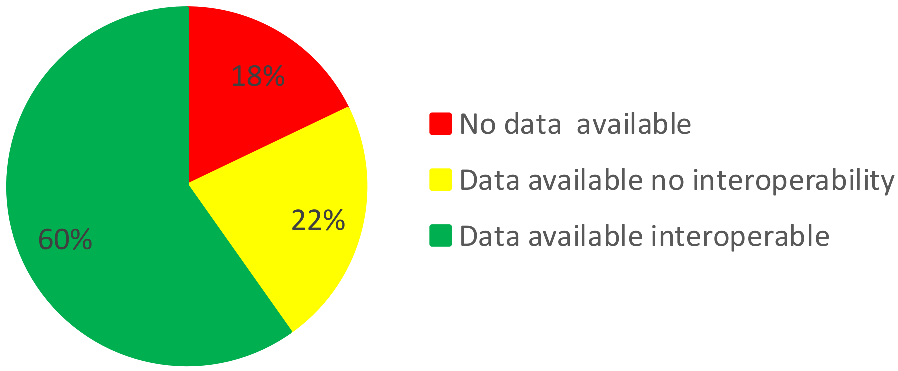

Figure 20: Analysis of the data out of Table 36.

	Communication method	Communication protocol	Position tracking	Coil geometry	lateral misalignment	Air gap and tolerance	Achievable velocity	Operational frequency	Magnetic field intensity	Sec. Voltage	Power rating	Effciency	Safety	Interperability cost	**Sum of incompatibilities**
WEVC & CWD			*						*						**2**
WEVC & IPV			*						*						**2**
WEVC & PRIMOVE	*	*	*	*	*	*	*	*	*	*			*	*	**12**
WEVC & Unplugged 50kW						*	*	*	*					*	**5**
WEVC & Unplugged 3,7kW							*	*	*					*	**4**
WEVC & FASTINCHARGE			*					*	*	*					**4**
WEVC & KAIST			*					*	*				*		**4**
WEVC & VICTORIA			*					*	*						**3**
CWD & WEVC			*						*						**2**
CWD & IPV												*			**1**
CWD & PRIMOVE	*	*	*	*	*	*	*	*	*	*			*	*	**12**
CWD & Unplugged 50kW						*	*	*	*				*	*	**6**
CWD & Unplugged 3,7kW							*	*	*					*	**4**
CWD & FASTINCHARGE			*					*		*					**3**
CWD & KAIST			*			*		*					*		**4**
CWD & VICTORIA			*					*		*					**3**
IPV & WEVC			*						*						**2**
IPV & CWD															**0**
IPV & PRIMPOVE	*	*	*		*	*	*	*	*	*			*	*	**11**
IPV & Unplugged 50kW							*	*	*				*	*	**5**
IPV & Unplugged 3,7kW							*	*	*		*			*	**5**
IPV & FASTINCHARGE						*		*		*					**3**
IPV & KAIST								*					*		**2**
IPV & VICTORIA								*		*					**2**
PRIMOVE & WECV	*	*	*		*	*	*	*	*	*	*			*	**11**
PRIMOVE & CWD	*	*	*		*	*	*	*	*	*	*			*	**11**
PRIMOVE& IPV	*	*	*		*	*	*	*	*	*				*	**10**
PRIMOVE & Unplugged 50kW	*	*			*	*	*		*	*				*	**8**
PRIMOVE & Unplugged 3,7kW	*	*			*	*	*	*	*	*	*			*	**10**
PRIMOVE & FASTINCHARGE	*				*	*	*		*						**5**
PRIMOVE & KAIST	*				*	*	*		*	*					**6**
PRIMOVE & VICTORIA	*					*	*		*	*					**5**
Unplugged 50kW & WECV						*	*	*	*					*	**5**
Unplugged 50kW & CWD							*	*	*					*	**4**
Unplugged 50kW & IPV							*	*	*					*	**4**
Unplugged 50kW & PRIMOVE	*	*			*	*	*		*	*			*	*	**9**
Unplugged 50kW & Unplugged 3,7kW							*	*							**2**
Unplugged 50kW & FASTINCHARGE						*	*		*	*				*	**5**
Unplugged 50kW & KAIST							*		*				*	*	**4**
Unplugged 50kW & VICTORIA							*		*					*	**3**
Unplugged 3,7kW & WECV							*	*	*					*	**4**
Unplugged 3,7kW & CWD							*	*	*					*	**4**
Unplugged 3,7kW & IPV						*	*	*	*					*	**5**
Unplugged 3,7kW & PRIMOVE	*	*		*	*	*	*	*	*	*			*	*	**11**
Unplugged 3,7kW & Unplugged 50kW							*	*							**2**
Unplugged 3,7kW & FASTINCHARGE							*	*	*	*				*	**5**
Unplugged 3,7kW & KAIST							*	*	*	*			*	*	**6**
Unplugged 3,7kW & VICTORIA							*	*	*	*	*			*	**6**
FASTINCHARGE & WECV			*					*	*	*					**4**
FASTINCHARGE & CWD								*		*					**2**
FASTINCHARGE & IPV						*		*		*					**3**
FASTINCHARGE & PRIMOVE	*		*		*	*	*		*				*		**7**
FASTINCHARGE & Unplugged 50kW						*	*		*	*				*	**5**
FASTINCHARGE & Unplugged 3,7kW							*	*	*	*				*	**5**
FASTINCHARGE & KAIST						*				*					**2**
FASTINCHARGE & VICTORIA			*			*				*					**3**
KAIST & WECV			*					*	*						**3**
KAIST & CWD						*	*	*							**3**
KAIST & IPV								*							**1**
KAIST & PRIMOVE	*		*		*	*	*		*	*			*		**8**
KAIST & Unplugged 50kW							*		*					*	**3**
KAIST & Unplugged 3,7kW							*	*	*	*	*			*	**6**
KAIST & FASTINCHARGE						*				*					**2**
KAIST & VICTORIA	*		*												**2**
VICTORIA & WECV			*					*	*						**3**
VICTORIA & CWD								*		*					**2**
VICTORIA & IPV								*		*					**2**
VICTORIA & PRIMOVE	*		*		*	*	*		*	*			*		**8**
VICTORIA & Unplugged 50kW							*		*					*	**3**
VICTORIA & Unplugged 3,7kW							*	*	*	*	*			*	**6**
VICTORIA & FASTINCHARGE			*							*					**2**
VICTORIA & KAIST	*		*												**2**
Sum of incompatibilities	**18**	**10**	**26**	**3**	**15**	**29**	**43**	**46**	**50**	**36**	**7**	**1**	**15**	**34**	

Table 36: Overview on actual gaps regarding missing data as well as not interoperable data.

	Communication method	Communication protocol	Position tracking	Coil geometry	lateral misalignment	Air gap and tolerance	Achievable velocity	Operational frequency	Magnetic field intensity	Sec. Voltage	Power rating	Effciency	Safety	Interoperability cost
WEVC & CWD	0	0	2	0	0	0	0	0	2	0	0	0	0	0
WEVC & IPV	0	0	2	0	0	0	0	0	2	0	0	0	0	0
WEVC & PRIMOVE	1	1	2	1	2	2	2	1	2	1	0	0	1	1
WEVC & Unplugged 50kW	0	0	0	0	0	1	2	1	2	0	0	0	0	1
WEVC & Unplugged 3,7kW	0	0	0	0	0	0	2	1	2	0	0	0	0	1
WEVC & FASTINCHARGE	0	0	2	0	0	0	0	1	2	1	0	0	0	0
WEVC & KAIST	0	0	2	0	0	0	0	1	2	0	0	0	1	0
WEVC & VICTORIA	0	0	2	0	0	0	0	1	2	0	0	0	0	0
CWD & WEVC	0	0	2	0	0	0	0	0	2	0	0	0	0	0
CWD & IPV	0	0	0	0	0	0	0	0	0	0	0	2	0	0
CWD & PRIMOVE	1	1	2	1	2	2	2	1	2	1	0	0	1	1
CWD & Unplugged 50kW	0	0	0	0	0	1	2	1	2	0	0	0	1	1
CWD & Unplugged 3,7kW	0	0	0	0	0	0	2	1	2	0	0	0	0	1
CWD & FASTINCHARGE	0	0	2	0	0	0	0	1	0	1	0	0	0	0
CWD & KAIST	0	0	2	0	0	1	0	1	0	0	0	0	1	0
CWD & VICTORIA	0	0	2	0	0	0	0	1	0	1	0	0	0	0
IPV & WEVC	0	0	2	0	0	0	0	0	2	0	0	1	0	0
IPV & CWD	0	0	0	0	0	0	0	0	0	0	0	1	0	0
IPV & PRIMPOVE	1	1	2	0	2	2	2	1	2	1	0	1	1	1
IPV & Unplugged 50kW	0	0	0	0	0	0	2	1	2	0	0	1	1	2
IPV & Unplugged 3,7kW	0	0	0	0	0	0	2	1	2	0	1	1	0	1
IPV & FASTINCHARGE	0	0	0	0	0	1	0	1	0	1	0	1	0	0
IPV & KAIST	0	0	0	0	0	0	0	1	0	0	0	1	1	0
IPV & VICTORIA	0	0	0	0	0	0	0	1	0	1	0	1	0	0
PRIMOVE & WECV	1	1	2	0	2	2	2	1	2	1	1	0	0	1
PRIMOVE & CWD	1	1	2	0	2	2	2	1	2	1	1	0	0	1
PRIMOVE& IPV	1	1	2	0	2	2	2	1	2	1	0	0	0	1
PRIMOVE & Unplugged 50kW	1	1	0	0	2	2	2	0	2	1	0	0	0	1
PRIMOVE & Unplugged 3,7kW	1	1	0	0	2	2	2	1	2	1	1	0	0	1
PRIMOVE & FASTINCHARGE	1	0	0	0	2	2	2	0	2	0	0	0	0	0
PRIMOVE & KAIST	1	0	0	0	2	2	2	0	2	1	0	0	0	0
PRIMOVE & VICTORIA	1	0	0	0	2	2	2	0	2	1	0	0	0	0
Unplugged 50kW & WECV	0	0	0	0	0	1	2	1	2	0	0	0	0	1
Unplugged 50kW & CWD	0	0	0	0	0	0	2	1	2	0	0	0	0	1
Unplugged 50kW & IPV	0	0	0	0	0	0	2	1	2	0	0	0	0	1
Unplugged 50kW & PRIMOVE	1	1	0	0	2	2	2	0	2	1	0	0	1	1
Unplugged 50kW & Unplugged 3,7kW	0	0	0	0	0	0	2	1	0	0	0	0	0	0
Unplugged 50kW & FASTINCHARGE	0	0	0	0	0	1	2	0	2	1	0	0	0	1
Unplugged 50kW & KAIST	0	0	0	0	0	0	2	0	2	0	0	0	1	1
Unplugged 50kW & VICTORIA	0	0	0	0	0	0	2	0	2	0	0	0	0	1
Unplugged 3,7kW & WECV	0	0	0	0	0	0	2	1	2	0	0	0	0	1
Unplugged 3,7kW & CWD	0	0	0	0	0	0	2	1	2	0	0	0	0	1
Unplugged 3,7kW & IPV	0	0	0	0	0	1	2	1	2	0	0	0	0	1
Unplugged 3,7kW & PRIMOVE	1	1	0	1	2	2	2	1	2	1	0	0	1	1
Unplugged 3,7kW & Unplugged 50kW	0	0	0	0	0	0	2	1	0	0	0	0	0	0
Unplugged 3,7kW & FASTINCHARGE	0	0	0	0	0	0	2	1	2	1	0	0	0	1
Unplugged 3,7kW & KAIST	0	0	0	0	0	0	2	1	2	1	0	0	1	1
Unplugged 3,7kW & VICTORIA	0	0	0	0	0	0	2	1	2	1	1	0	0	1
FASTINCHARGE & WECV	0	0	2	0	0	0	0	1	2	1	0	0	0	0
FASTINCHARGE & CWD	0	0	0	0	0	0	0	1	0	1	0	0	0	0
FASTINCHARGE & IPV	0	0	0	0	0	1	0	1	0	1	0	0	0	0
FASTINCHARGE & PRIMOVE	1	0	2	0	2	2	2	0	2	0	0	0	1	0
FASTINCHARGE & Unplugged 50kW	0	0	0	0	0	1	2	0	2	1	0	0	0	1
FASTINCHARGE & Unplugged 3,7kW	0	0	0	0	0	0	2	1	2	1	0	0	0	1
FASTINCHARGE & KAIST	0	0	0	0	0	1	0	0	0	1	0	0	0	0
FASTINCHARGE & VICTORIA	0	0	2	0	0	1	0	0	0	1	0	0	0	0
KAIST & WECV	0	0	2	0	0	0	0	1	2	0	0	0	0	0
KAIST & CWD	0	0	0	0	0	1	1	1	0	0	0	0	0	0
KAIST & IPV	0	0	0	0	0	0	0	1	0	0	0	0	0	0
KAIST & PRIMOVE	1	0	2	0	2	2	2	0	2	1	0	0	1	0
KAIST & Unplugged 50kW	0	0	0	0	0	0	2	0	2	0	0	0	0	1
KAIST & Unplugged 3,7kW	0	0	0	0	0	0	2	1	2	1	1	0	0	1
KAIST & FASTINCHARGE	0	0	0	0	0	1	0	0	0	1	0	0	0	0
KAIST & VICTORIA	1	0	2	0	0	0	0	0	0	0	0	0	0	0
VICTORIA & WECV	0	0	2	0	0	0	0	1	2	0	0	0	0	0
VICTORIA & CWD	0	0	0	0	0	0	0	1	0	1	0	0	0	0
VICTORIA & IPV	0	0	0	0	0	0	0	1	0	1	0	0	0	0
VICTORIA & PRIMOVE	1	0	2	0	2	2	2	0	2	1	0	0	1	0
VICTORIA & Unplugged 50kW	0	0	0	0	0	0	2	0	2	0	0	0	0	1
VICTORIA & Unplugged 3,7kW	0	0	0	0	0	0	2	1	2	1	1	0	0	1
VICTORIA & FASTINCHARGE	0	0	2	0	0	0	0	0	0	1	0	0	0	0
VICTORIA & KAIST	1	0	2	0	0	0	0	0	0	0	0	0	0	0

Table 37: Differentiation of (*) into N/A and not interoperable.

As an overall conclusion out of this table it can be stated;

- Position tracking: Existing solutions are not interoperable or only show low levels of interoperability. This is due to the experimental character (FABRIC, UNPLUGGED, FASTINCHARGE) or to proprietary solutions (VICTORIA, PRIMOVE, KAIST). Current solutions such as PRIMOVE require on-vehicle transmitters for detection. Such an assumption leads to the fact that interoperability requires coordination and adoption of standardized on-board and off-board components for vehicle detection. However, current low interoperability cannot be extrapolated for a large-scale deployment, as autonomous driving technology will solve this issue according to common consensus of involved experts of the FABRIC project.

- Achievable velocity actually does not represent a real issue for interoperability, as there is no minimum speed, but only maximum speed. As every vehicle can move slowly, interoperability is always achievable. Aspects such as loss of comfort are not considered here. Also, experimental results are not showing principal issues regarding velocity. This is an issue for control loop and communication which can be solved, rather than technologically unsolved problems.

- Regarding power rating, communication method, communication protocol and coil geometry it can be concluded that already a proper degree of interoperability is reached. Intermediate ratings are identified here.

- Regarding air gap and tolerance, secondary coil voltage and operation frequency a rather high degree of non-interoperability is identified. Here, only standardization agreements can lead to high interoperability, aiming for standard voltages and frequencies. The already agreed 85 kHz for systems up to 20 kW are a good start and will gradually be applicable for higher power levels, as power electronics are improving. But it may be expected that for very high power applications (MW, such as railway) different standard will be established than for lower-power road applications.

- Although the UNPLUGGED project solution is a static solution, the technical boundary conditions fit relatively well to some dynamic solutions out of the FABRIC project. Also lessons learned from interoperability efforts are valuable for FABRIC too.

- As described the interoperability analysis document is a living document which grows hand in hand with the specifications and developments. Assuming the missing data can be provided, an interoperability level of over 80% is possible and thus can be rated as good.

- The majority of the approaches (IPV, CWD, UNPLUGGED) use similar methods for communications which are based on the 802.11p (DSRC) specification. However ambiguity regarding the higher-level communication protocols and data models exists, thus increased efforts for interoperability must focus on the definition of protocols that address the requirements of WPT. However, interoperability in communication is a minor issue, as is mainly depends on an agreement on a common standard to be implemented, rather than physical system parameters, which have a large impact of system designs.

- KAIST as a “series production readiness” solution shows a high graded interoperability level (or positive interoperability level possibility) with the other solutions. As a conclusion it can be stated that the FABRIC solutions are aligned to already market-ready systems.

- FASTINCHARGE, as a prototype solution under development and a follow-up out of the UNPLUGGED project is at the moment at a stage in which several technical degrees of freedom are used not only to develop an inductive charging system, but additionally to develop an interoperable system.

- VICTORIA is a prototype solution with almost the same interoperability level as the KAIST solution. Also here it can be concluded that the VICTORIA solution is aligned to market-ready systems and the interoperability level is at a rather high level.