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Future Urban Charging Solutions for Electric Vehicles

Dominic Villeneuve[1]
Centre de recherche en aménagement et développement (CRAD), Université Laval, Canada.

Yann Füllemann[2]
Energy Center, École polytechnique fédérale de Lausanne, Switzerland.

Guillaume Drevon[3]
Urban Sociology Lab, École polytechnique fédérale de Lausanne, Switzerland.

Vincent Moreau[4]
Laboratory of Environmental and Urban Economics, École polytechnique fédérale de Lausanne, Switzerland.

François Vuille[5]
Energy Center, École polytechnique fédérale de Lausanne, Switzerland.

Vincent Kaufmann[6]
Urban Sociology Lab, École polytechnique fédérale de Lausanne, Switzerland.

The numbers of electric vehicles (EV) will increase as many countries perceive EVs as a solution to reduce the emissions of transportation and therefore incentivize their adoption. However, the deployment of public charging infrastructure is lagging behind that of EVs, which represents a potential barrier to their wide-scale adoption. The objective of this paper is to develop a comprehensive overview of potential EV charging solutions to be deployed in urban areas. Using a micro-Delphi approach, experts from transport, energy and urban planning were consulted and identified 15 realistic options for charging electric vehicles in urban environments by 2035. The

[1] A: 2325, rue des Bibliothèques Québec (QC) G1V 0A6, Canada T: +1 418 656-2131 ext 403740 E: dominic.villeneuve@esad.ulaval.ca
[2] A: EPFL IV CEIF CEN, BAC 104, Station 5, CH–1015 Lausanne, Switzerland E: yann.fuellemann@hotmail.com
[3] A: EPFL-ENAC-IA-LASUR, Bâtiment BP, Station 16, CH-1015, Lausanne Switzerland T: +41 21 693 62 38 E: guillaume.drevon@epfl.ch
[4] A: EPFL LEURE, Station 16, CH–1015 Lausanne, Switzerland T: +41 21 693 93 98 E: vincent.moreau@epfl.ch
[5] A: EPFL IV CEIF CEN, BAC 104, Station 5, CH – 1015 Lausanne, Switzerland E: f.vuille@epfl.ch
[6] A: EPFL-ENAC-IA-LASUR, Bâtiment BP, Station 16, CH-1015, Lausanne, Switzerland T: +41 21 693 62 29 E: vincent.kaufmann@epfl.ch

solutions range from purely technical to more service oriented. Most of these solutions already exist today, although some remain at a very early stage of deployment. The five most likely options were on-street public charging points, charging at work, fast-charging stations, using building domestic plugs and semi-fast charging in public areas. When combined with the typical mobility and residential profiles, our results show that EV drivers will most likely rely on a mix of solutions, when they have no home chargers. As such, no breakthrough or major shift is expected in charging infrastructures, rather a scale-up of existing solutions. Our analysis concludes that urban charging options will be numerous and no single solution is expected to dominate as users with different EV user profiles will charge at different times and locations.

Keywords: *charging infrastructure, electric vehicles, Europe, urban areas.*

1. Introduction

Electric vehicles (EVs) are increasingly present on our roads (International Energy Agency and OECD, 2018). If their market shares remain small, their sales grow exponentially. Indeed, many perceive EVs as a solution to reduce carbon emissions from the transportation sector (Attias and Mira-Bonnardel, 2017; Kihm and Trommer, 2014). Multiple policies across regions and nations support their adoption to accelerate the transition from combustion engines to electric motors (Liu and Lin, 2017; Rezvani et al., 2015; Shepherd et al., 2012). More benefits from EVs potentially lie in providing grid services as the share of intermittent renewable energy sources increases in the generation of electricity (Hildermeier et al., 2019). The infrastructure requirements for such transition in both transportation and renewable electricity supply are considerable, partly because they are distributed rather than concentrated around replacing refineries and power plants. The deployment of public charging infrastructure is currently lagging behind that of EVs, which represents a potential barrier to the wide-scale adoption of electric mobility. This is particularly critical in urban environments, where a large share of vehicle owners park on street, and thus do not have access to private parking with dedicated chargers. In order to accommodate the expected influx of EVs, urban areas will need to plan and implement the deployment of urban EV charging solutions.

The objective of this paper is to provide a comprehensive overview of potential EV charging solutions that could be deployed in urban areas. We identify and evaluate, in a systematic approach, solutions for charging EVs in European cities in the short to midterm. The most probable and relevant EV charging solutions identified form a mix of options that would be suitable for a diversity of future EV users. Recent research shows that EVs and associated infrastructures should address the practices and routines of potential adopters instead of purely technical or environmental benefits (Friis, 2020). The time horizon is 2035, close enough to bring meaningful results, yet far enough to enable novel EV charging solutions to potentially emerge and give institutions time to prepare for them. The geographical scope is primarily Europe where the urban form differs between East, West, North and South, yet the typical urban centre and peri-urban areas can be found in most cities around the world. We focus on battery electric vehicles (BEV), which cannot charge without dedicated infrastructure, unlike some hybrid vehicles. For simplicity, we use the more common EV acronym for BEV in this paper.

The structure of the paper is as follows: Section 2 presents a state of the art on urban EV charging. Section 3 presents the methodology used in the three different phases of the research to build a list of potential urban charging solutions and to vet them with various experts. Section 4 presents the results of the research and section 5 concludes.

2. State-of-the-art in urban charging

With their potential to reduce CO_2 emissions and air pollution, especially in urban areas, electric vehicles captured the attention of both public and private decision makers. Many researchers point out that a transition from combustion engines to electric motors is required in order to achieve sustainable urban transportation (Kihm and Trommer, 2014; Nykvist and Nilsson, 2015). Predictions of market penetration of EVs by 2035 are high (Attias and Mira-Bonnardel, 2017; Nykvist and Nilsson, 2015; Orbach and Fruchter, 2011). A report by the International Energy Agency (2018) shows that many countries[7] plan to reach a 30% share of EV in sales of new vehicles by 2030. According to the same report, Ireland and Slovakia even forecast a 100% share in sales by that time. This growth outlook is not shared by all researchers (Fréry, 2000; Høyer, 2008; Liu and Lin, 2017) and practitioners (Servou, 2016) and some still express doubts that EVs will succeed in becoming an important component of our transportation system.

Among the many potential benefits of broad EV adoption, Yong et al. (2015) cite energy security through a diversification of energy sources since the electricity required to power the vehicles can come from nuclear or from local renewable energy sources such as solar, wind, and hydro. García-Villalobos et al. (2014) cite the same potential benefits, however they also make the link between reduced tail pipe emission and increased air quality which could conceivably lead to improved public health.

Infrastructure support is also growing. According to Attias & Mira-Bonnardel (2017), the French government has adopted measures to enforce the electric connection of all parking lots in new buildings and equip existing workplace parking spaces. The same government also invested in the creation of 1250 charging stations with plans to have a total of 9,9 million charging stations by 2025 (including 750 000 public charging stations and 150 000 fast-charging stations) (Leurent and Windisch, 2011). Like France, most EU countries have adopted policy schemes supporting the adoption of EVs and the deployment of charging infrastructure.

While broad adoption of EVs represents an opportunity for national electricity companies, the increasing number of EVs is also challenging for stability of the urban electric grid (Fairley, 2010; Shareef et al., 2016; Yong et al., 2015). Constraints range from the capacity of electricity distribution networks to meet the peaking power demand to the lack of space in city environment for installing public EV charging infrastructure. The deployment of EVs in urban areas presents multiple challenges that require considerable changes compared to conventional energy supply and vehicle manufacturing markets (Bohnsack et al., 2014). According to Madina, Zamora, & Zabala (2016), the broad adoption of EVs is also challenged by a number of consumer perceptions, such as long charging times, higher initial purchasing cost, shorter range and limited availability of charging stations. The issue of long-charging time is particularly important in urban environment, where parking spots are scarce and public, with little access to high-voltage. Other researchers also mention the important role that the availability of charging infrastructure plays in the consumer choice to purchase an EV (Glerum et al., 2014; Propfe et al., 2013).

As Wiederer & Philip (2010) state: "The availability of charging infrastructure is a barrier to large-scale deployment of EVs that is closely intertwined with range anxiety". A survey realized by the Norwegian EV association in 2016 shared the same conclusion as almost all EV owners were shown to have access to a private parking spot and can thus recharge their batteries mainly at home (Haugneland et al., 2016). Similar results were found in Germany in which current EV owners are mostly using their own charging station (84%), a standard electric outlet (11%) and public charging stations for only 5% (Franke and Krems, 2013). This charging pattern is likely to change depending on the urban environment and the evolution of EV urban charging solutions. For example, Lam, Leung, & Chu (2013) suggest that in extremely dense cities like Hong Kong, public type charging stations are essential to EV ownership. However, by combining and analyzing the American

[7] In Europe these are Finland, France, the Netherlands, Norway and Sweden.

Housing Survey and the Residential Energy Consumption Survey, Traut, et al. (2013) estimated that only half of US vehicles have a reliable access to a dedicated off-street parking space. The authors suggest that the limited availability of dedicated parking spaces, onto which chargers can be installed, remains a significant barrier to EV penetration. Several EV market forecasts suggest adoption rates that would require these parking limitations to be resolved (Balducci, 2008; BNEF, 2018). They also point out the logistical challenges as a result of competition for parking and charging. They conclude that significant economic, logistical, and consumer convenience barriers exist, on top of the issue of access to home charging.

Therefore, the availability of public charging infrastructure is paramount to the successful adoption of EV (Liu and Lin, 2017). Urban charging has specifically been identified as one major barrier to EV deployment by several authors (e.g. Haugneland et al., 2016; Transportation Research Board and National Research Council, 2015). However, these studies focus either on the technical feasibility of implementing novel charging solutions such as static/dynamic wireless charging (Lukic & Pantic, 2013; Miller et al. 2015) and battery swap (Zheng et al., 2014), or on the location optimization of conventional charging stations through linear programming models (Liu and Wang, 2017; Wagner et al., 2014). A frequent conclusion states that coordinated charging of EVs will be necessary to spread the electricity demand both spatially and temporally (Neaimeh et al., 2015). Papadopoulos et al. (2012) also highlighted the benefits of a combined penetration of EVs and distributed renewable electricity generation as this has the potential to reduce significantly the overload probability on the distribution grid.

Optimizing the charging infrastructure to cover the needs of thousands customers with different charging needs is also the realm of big data, for example through the usage statistics of the Amsterdam charging network (Wagner et al., 2014). They derive points of interest influencing the use of the charging infrastructure to map the best locations where such infrastructure has to be installed. Xu et al. (2018) did a similar analysis, with higher spatial and temporal resolution by integrating three unique datasets, mobile phone activity of 1.39 million residents of the San Francisco Bay Area, census data and plug-in electric vehicles drivers survey data. Considering driving patterns and time constraints, they recommended changes to EV charging times for commuters at their workplace. They estimated the monetary savings associated with shaving the evening peak in power demand. However, both studies considered only historical data and conventional charging points and thus cannot answer the question of further penetration of EVs since future customers are likely to be different from current early adopters.

Thus, to the best of our knowledge, no research to date considers and compares all possible charging solutions and how they might complement each other in order to meet the growing demand for urban charging. This is precisely the question we address in the article.

3. Methodology

We have developed an ad hoc methodological approach in order to appraise urban charging solutions with full considerations of their respective technological, societal and operational aspects. This methodological challenge requires the pooling of both scientific knowledge and the opinions of recognized experts in their field while evaluating concrete usage scenarios. This research perspective implies the implementation of a mixed methodology of data collection (Bergman, 2008; Teddlie and Tashakkori, 2009). The data collection methodology used in this research is based on the principle of triangulation between the three survey techniques used for the evaluation of urban charging solutions. Triangulation is commonly used in the social sciences to ensure complementarity between collected data and cross-fertilization (Czepkiewicz et al., 2020; Frias and Popovich, 2020). In the social sciences, this approach offers a multiple perspective in relation to the object of research, which can thus be observed from different angles. In the context of this article, this multi-perspective approach makes it possible to compare, on the one hand, the state of technical knowledge from the scientific literature (literature review), the opinion of experts (workshop) and the potential implementation of recharging devices (micro-Delphi approach).

From the triangulation technique perspective, a three-phased approach based on a combination of three methodologies was applied to ensure maximum relevance and inclusion of potential EV urban charging solutions:

1. Systematic identification of urban charging solution based on combined:
    - bottom-up design thinking.
    - Top-down structured problem solving.
2. Filtering the charging solutions identified based on expert collective thinking.
3. Identification of possible combinations of charging solutions based on micro-Delphi interviews with experts.

These three phases are briefly explained in this paragraph and further detailed in the next subsections. In the first phase (see Figure 1), bottom-up design thinking is combined with top-down analysis of these solutions to create a list of potential urban charging solutions for electric vehicles in 2035. The bottom-up design thinking took the form of a structured brainstorming session with researchers in technical and non-technical aspects of energy production and consumption. The evaluation of all potential solutions was performed returning to very basic exclusive alternatives to categorize them while remaining inclusive overall. The second phase consisted of filtering the solutions based on collective thinking. A workshop was held with researchers from several disciplines including urban planning, energy and transportation research. During this workshop the participants were placed in groups of three with complementary expertise and were asked to rate all the potential solutions identified in Phase 1 in order to filter down only those solutions that are considered realistic, i.e. that have a high potential of being implemented by the year 2035. Finally, the third phase was based on the micro-Delphi method (Skulmoski et al., 2007), which is a useful forecasting tool based on the cross-validation of expert judgments. We interviewed various experts from industry as well as start-ups to share the list of potential solutions coming from Phase 2 and got their opinion on the deployment of urban charging infrastructure. This combination of different phases and approach to forecasting the future is in line with the morphological Delphi research designs described by Mozuni & Jonas (2017). Furthermore, Melander (2018) in her literature review of transportation research trying to predict potential future scenarios has shown the potential of such combination of methods specifically for transport forecasting.

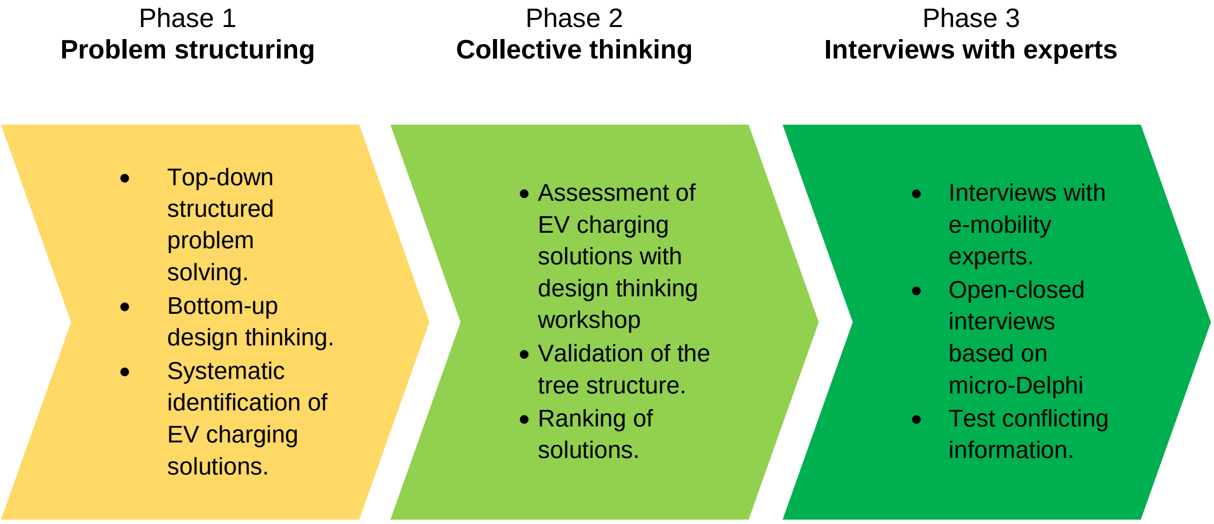

Figure 1. Phases of the project

3.1 Phase 1 - Experts brainstorm to envisage all potential solutions

In phase one, more than 10 researchers active in energy and transport at large were invited to a brainstorming session with the objective of identifying a complete list of potential urban charging solutions. This bottom-up based brainstorming session combined the two typical concepts of brainstorming: deferred judgment and stretching of imagination (Rickards, 1999, p. 220). This effort led to a list of 23 innovative and standard EV charging solutions, which we present in the result section.

In parallel, we developed a top-down approach inspired from structured problem solving to identify EV charging solutions in a systematic way. This approach is based on the systematic construction of a Boolean tree with mutually exclusive and collectively exhaustive branches (Parker, 1995). The beginning of the tree structure is presented in Figure 2, while the full tree is shown in the result section.

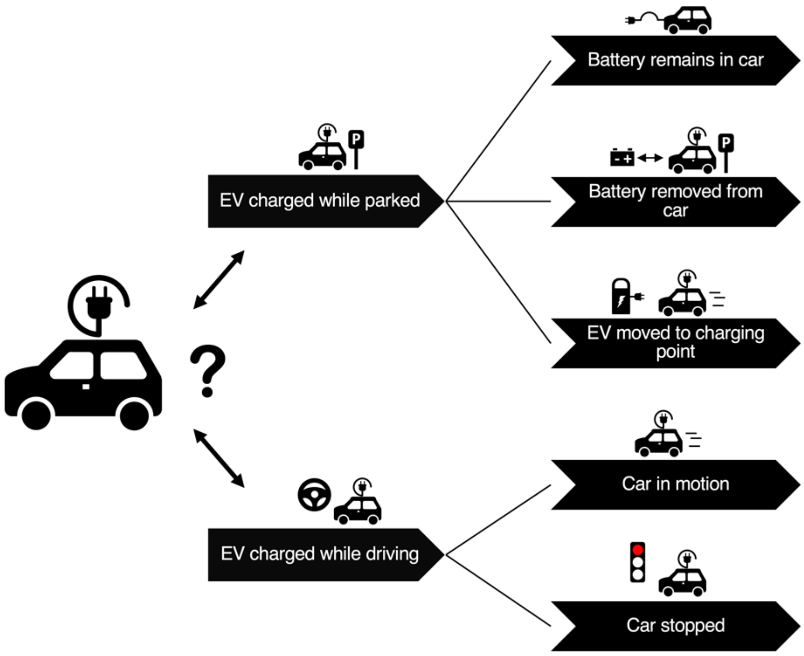

Figure 2. Lower tree structure of EV urban charging solutions. The full tree structure contains 2 additional branch levels (see Table 3).

3.2 Phase 2 - Expert workshop to identify the most likely solutions

Participant recruitment procedures are designed to limit bias by limiting the predominance of disciplines and positions. Indeed, the methodology for recruiting participants tends to mix expertise profiles in order to compare opinions and points of view. It is also a matter of avoiding the predominance of one discipline over the others.

From the list of EV charging solution produced in phase 1, the objective of phase 2 was to vet this list with a broader base of researchers. Specialists of both energy and urban disciplines were consulted during a workshop. Professors, professional researchers and PhD candidates from across disciplines (engineers, economists, architects-planners, transport specialists, sociologists and geographers) were invited to share their opinion and further complete the list by thinking of additional solutions. Table 1 shows the distribution of participants who attended the workshop.

Table 1. Details of the types of expert participating in the workshop

Type of experts	Number of experts who participated in the workshop
Energy Engineering	8
Urban Sociology and Planning	5
Transport Engineering and Planning	4

The two main objectives of this workshop were to:

- Assess and rank the relevance of the 23 EV charging solutions identified in phase 1.
- Identify solutions that might have been overlooked in phase 1.

Multiple groups of three to four researchers combining different research backgrounds were formed. The purpose of this configuration in small groups was to promote discussions and exchanges while facilitating the control of speaking time. A facilitator was assigned to each group to stimulate the discussion, control the timing and take notes. The workshop was divided into 6 steps as illustrated in Figure 3.

Figure 3. Workshop steps for phase 2

A brief overview of the tree produced in phase 1 was presented at the beginning of this half day workshop. Each solution was then presented individually by the moderator to the whole group and each small group had a couple of minutes to discuss its pertinence and assess its barriers to deployment. Following the discussion, the participants voted anonymously and electronically to rate each potential solution according to its probability of being available in the year 2035 on a scale of 1 to 4 (1, very improbable; 2, not very probable; 3, probable; 4, very probable). A second vote was requested to rate each solution according to its popularity by indicating to what extent EV user would rely on each solution in 2035. This was also performed on a scale of 1 to 4 (1, a small minority; 2, a minority; 3, a majority; 4, a large majority).

Once all the solutions in each branch of the tree had been discussed, a further discussion in small group was held to determine whether charging solutions might have been missed. When a new solution was brought up by a participant, the whole group also rated it on the same criteria as the original ones.

A score was then calculated for each solution by summing up all their individual scores. For example, a solution with 6 votes for "probable" with a value of 3 and 2 votes for "very probable" with a value of 4 would get a score of 26 (= 6 x 3 + 2 x 4).

After tallying the scores for each criterion, the results were then shared with the group and the participants' reactions were recorded. At the end of the workshop, a final wrap-up phase was conducted to get the participants' feedback on the overall process and results. This was in particular important to see if the participants felt comfortable with the results and with the solutions that emerged as the most or least probable ones.

3.3 Phase 3 - External expert interview to evaluate the combination of likely solutions

In phase 3, we interviewed e-mobility expert on the EV charging solutions that were identified as the most probable to be implemented in 2035 during phase 2. Several studies forecasting technological developments in 10 -15 years use various forms of Delphi research design. For example, studies on the future of international trade (Czinkota and Ronkainen, 1997), the future of Wi-Fi (Rossel and Finger, 2011), the forecast of mobile broadband internet use (Lee et al., 2016) or the future of fuel cells and the hydrogen economy (Hart et al., 2009). As pointed out by Zubaryeva et al. (2012, p. 1625), this method of gathering expert opinion is widely applied in research attempting to elicit a forecast of technological solution adoption and diffusion in the future[8]. In order to produce a forecast based on the cross-validated judgments of multiple experts, the interviews were based on a micro-Delphi approach[9]. As pointed by Czinkota & Ronkainen (1997, p. 829), the selection of a proper and diverse panel of experts is critical to the success of the process. Therefore, we selected interviewees with the broadest expertise possible: electricity distributors, car parts manufacturers, charging infrastructure developers, EV charging service companies, start-up companies, car/ride-sharing services, academics, user associations and urbanists. In total 12 experts were interviewed.

Each interview lasted around one hour. The interviews started with a general presentation of the research and the two previous phases. The interviewees were reminded about the possible impact on EV urban charging of the evolution of a) battery price and capacity, b) car-sharing, and c) autonomous vehicles. Then each of the top 15 solutions was presented individually. For each EV charging solution, the interviewee was invited to express her or his thoughts on:

- The probability of being deployed.
- The constraints to its implementation.
- The user profiles who might use the solution.
- The urban context in which they can be implemented.

At the end of this part, the experts were also asked for potentially missing charging solutions. The purpose was in particular to see if any of the discarded solution in phase 2 might rank better from another expert point of view.

In a second part of the interview, three typical user profiles were presented to the interviewees (see Table 2). The profiles were designed by a team of urban sociologists to ensure a varied range of usage types and residential locations while remaining simple to differentiate for the interviewees. The experts were invited to select which of the 15 EV charging solutions would be combined to fulfil the charging need of different predefined user profiles.

[8] See also (Baker et al., 2010; Buchholz et al., 2009; Wang et al., 2009)
[9] See Skulmoski, Hartman, & Krahn (2007)

Table 2. Three scenarios for interview external experts

Attributes:	Matthew	Jessica	Richard
Work status:	Works as a sales rep.	Working woman with children	Retired
Typical activities:	Customer tour	Travel for work, childcare and shopping	Travel for leisure and shopping
Parking:	On-street, neighbourhood zone	On-street, neighbourhood zone	Underground apartment parking without plug
Mobility configuration:	220 km/day over the entire urban region	60 km/day with access to downtown for work	20 km/day - downtown and suburbs
Housing:	Apartment in urban centre	Individual periurban house	Apartment in the suburbs

To be aligned with a Delphi approach, the interviewees were challenged throughout the interview with possible conflicting responses received from other experts in previous interviews. With this process, we expected to increase the chances to converge towards consensus amongst the experts. Some of the initial participants were contacted after their interview in order to share the feedback from the experts who were interviewed subsequently.

4. Results and Discussion

4.1 Phase 1 – Systematic identification of potential EV urban charging solutions

Phase 1 yielded a list of 23 potential urban charging solutions classified in a tree structure (Table 3)

Table 3. Tree of Energy Centre potential solutions

Situation	Status	Type of solution	Solutions
EV charged while parked	Battery remains in the EV	Fixed infrastructure	1) On-street public charging point 2) Public inductive parking spot 3) Using building domestic plugs 3a) Private charging station sharing via app *
		Mobile solution	4) Feeding from battery truck 5) Integrated solar panels
	Battery removed from EV	Battery swap	6) Battery swap truck
		Battery charged elsewhere	7) Valet battery charging service 8) Lego-type battery distributed home charging 9) Removable battery pack for home recharge
	EV moved to charging point	Autonomously	10) Autonomous charging 10a) Autonomous charging service – car-sharing fleet *
		By driver	11) Valet charging 12) Car & charge sharing
EV charged while driving	EV in motion	Fixed charging infrastructure	13) Inductive streets 14) Panthograph-cathener system 15) Plugging to electric rail
		Mobile solution	16) Tanker trucks
	EV stopped	Charging infrastructure at traffic light	17) Airborne feeding infrastructure 18) Inductive charging at the red light
		Smart charging in traffic jam	19) Feeding by autonomous vehicle in traffic jams 20) Inter-vehicle siphoning system 20a) Recharging while piggybacking (rail-road service)*
		Charging stations	21) Battery swap station 22) Fast charging station 23) Semi-fast charging (public areas) 23a) Charging at work*

* Solutions added by the academic experts during the phase 2 workshop

Note that some of the branches of the tree were developed further than what is presented in Table 3, but we decided to keep the discussion at the same hierarchical level for all branches not to bias the analysis by overweighting certain alternatives. This is for instance the case for solution #1 "on-street public charging points" which can take several physical forms, from individual fixed charging points at each parking spot to movable plug systems (e.g. along a rail) with a common charging station for a whole street.

The 23 solutions identified are presented in Appendix 1 together with some indication about their main pros and cons. The main limitation of this phase of the study is that the brainstorming involved a homogenous group of researchers, all within the field of energy research. Using such a group ensured deep knowledge of the topic but might have limited the extent of the range of innovative ideas generated. To alleviate this concern, phase 2 involved a heterogenous group of experts from various fields and involved steps to elicit new solutions we might have missed as well as confirming the solutions we had included. We also note that most solutions are related to already existing or attempted solutions that have failed commercially. A drawback of our approach is the lack of inclusion of new technological innovations not already in the work.

The following conclusions can be drawn from phase 1:

- EV charging options are many and varied. A total of 23 solutions could be identified, which range from purely technical to more service oriented.
- A systematic identification of charging solutions without considering their technical and economic feasibility yields to improbable solutions. These will be filtered out in phase 2 of the analysis.
- Most of these charging solutions already exist today though at various stages of development and deployment (Table 4).

Table 4. Development stages of the different EV charging solutions

EV charging solutions:	New Concept	Proof of Concept	Demon-stration	Early commercial	Fully commercial
1) On-street public charging point					■
2) Public inductive parking spot			■		
3) Using building domestic plugs		■			
3a) Private charging point sharing via app*				■	
4) Feeding from battery truck		■			
5) Integrated solar panels	■			■	
6) Battery swap truck	■				
7) Valet battery charging service	■				
8) Lego-type battery home charging	■				
9) Removable mini-battery pack	■				
10) Autonomous charging		■			
10a) Autonomous charging with car-sharing*		■			
11) Valet charging		■			
12) Car & charge sharing				■	
13) Inductive streets			■		
14) Pantograph - cathener system	■				
15) Plugging to electric rail	■				
16) Tanker trucks		■			
17) Airborne feeding infrastructure	■				
18) Inductive charging at the red light		■			
19) Autonomous vehicle feeder in traffic jams	■				
20) Mobile charging autonomous vehicle	■				
20a) Park & ride & charge*				■	
21) Battery swap station			■		
22) Fast charging station					■
23) Semi-fast charging (public areas)					■
23a) Charging at work*					■

* Solutions added by the academic experts during the phase 2 workshop

4.2 Phase 2 - A vetted list of most likely solutions

During phase 2, an additional 4 solutions were identified during the workshop as we polled the participants for solutions they thought were missing to avoid the limitations of phase 1. These solutions are presented in Table 3 and Table 4 and are marked by an asterisk in those tables. They are:

3a) Private charging station sharing via app

10a) Autonomous charging service – car-sharing fleet

20a) Recharging while piggybacking (rail-road service)

23a) Charging at work

The complete list of solutions was also rated by the expert workshop participants based on their likelihood of being fully commercial in Europe by the year 2035 (see Figure 4), irrespective of how much they would be used. The top five most likely charging solutions were identified by the participants as:

23) Semi-fast charging (in public areas)

22) Fast charging station

23a) Charging at work

1) On-street public charging point

3a) Private charging points sharing via app

Interestingly, the battery swap option has scored relatively high (51 points), in spite of the actual failure of this option in the past due to the challenge of standardisation. This can be explained by the fact that this phase 2 "collective thinking" has been carried out with a broad spectrum of specialists in engineering and social sciences, but not with experts of EV charging. The objective of this phase was more to eliminate the least relevant solutions in order to reduce the list of options to be discussed in depth with the experts in phase 3.

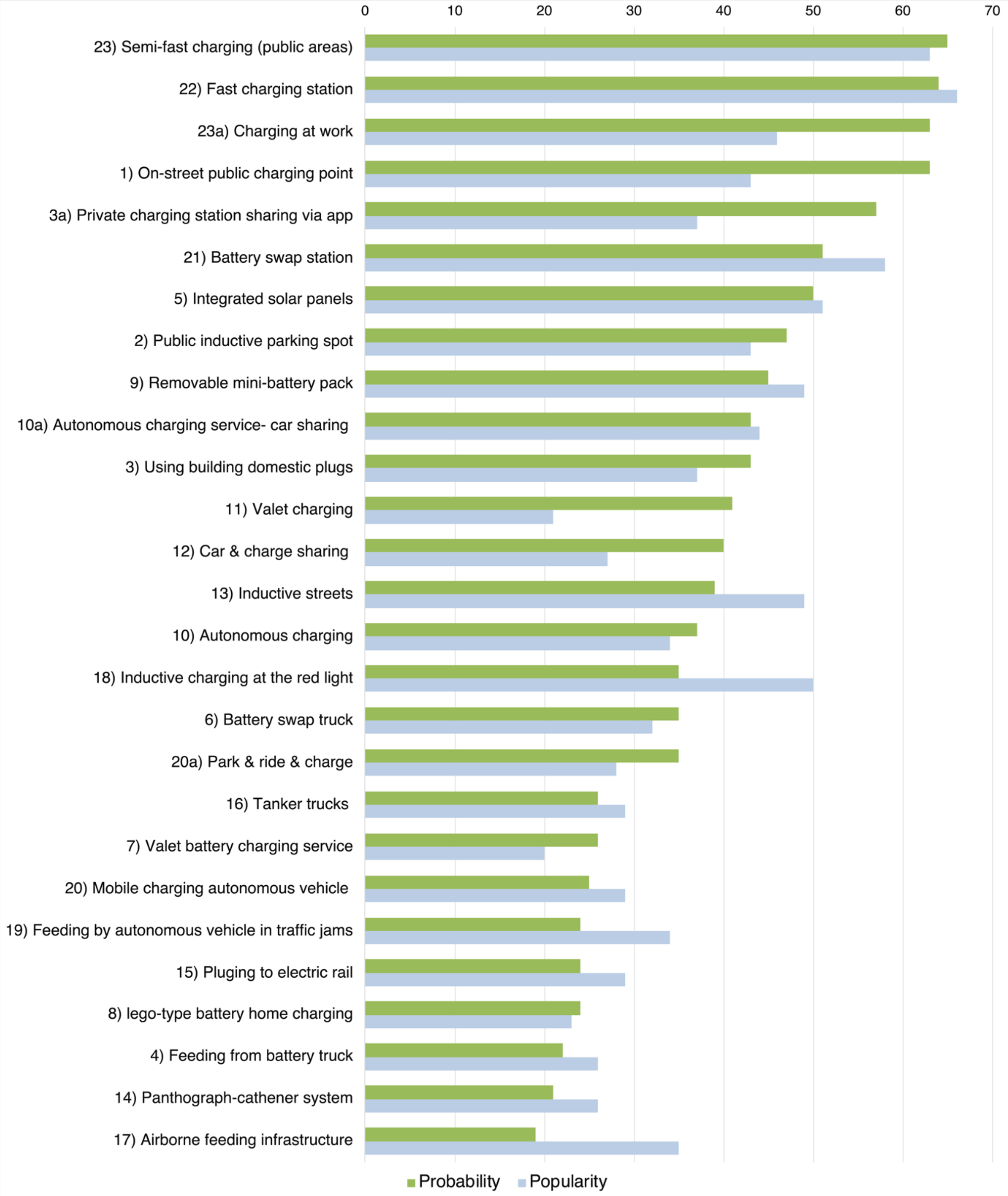

Figure 4. Probability and popularity rating of the expert panel for potential EV charging solutions

Each solution was also rated for its expected share of use amongst available solutions in 2035 (see second variable in Figure 4), assuming the solution would be deployed. In other words, the participants had to answer the question regarding the percentage of time each solution would be used to recharge the vehicles. The top five most popular solutions that emerged are

22) Fast charging station

23) Semi-fast charging (public areas)

21) Battery swap station

5) Integrated solar panels

18) Inductive charging at the red light

It should be noted that the popularity rating process did present an intrinsic bias, as it proved difficult for the participants to assess the popularity of solutions assuming these would be deployed if they had actually been considered very unlikely to be deployed. However, we considered that this did not affect the overall results as the main objective of this phase was to filter out the least likely options. As is often the criticism with Delphi workshops, the main limitation of this phase of the research was that we could run into "group think" or forced consensus where individual experts would exert influence on the overall group (Mullen, 2003). Our use of real-time polling clickers combined with secret individual voting allowed us to circumvent this problem. Of course, the results are only the opinions of the panel, but through a selective invitation process we gathered a range of 17 academic experts from various hierarchical levels, disciplines, age groups with a gender mix.

The following conclusions can be drawn from phase 2:

- Most charging solutions identified in phase 1 are considered likely to be commercially deployed by 2035.
- According to the panel of academic experts who participated in the workshop, one single "silver bullet" type solution will not exist for charging EVs in urban environment in 2035. Rather, EV owners will likely rely on several solutions in parallel, connecting at different locations each time the car is parked (at work, at shops, at park & rail lots, on street at night, etc.) or in use (fast-charging stations).
- Charging solutions that are expected by the panel to play a major role in 2035 are already the most widely deployed today. No major paradigm shift is expected, but a broadening of the offer.
- The most likely solutions indicated by the panel are also the most popular, or in any case that there is often a correlation between these two metrics for most cases. This is somewhat expected as technical solutions can reach fully commercial status only if they are popular enough as their implementation need to be economically viable.

4.3 Phase 3 – A panel of solutions to meet different users' profile

The 15 most promising solutions that arose from phase 2 were presented to 12 external experts from various horizons linked to the urban charging problematic. Figure 5 shows the perception of the interviewees regarding the use of each charging solution by the 3 user profiles defined in Table 2 (Richard, Jessica and Matthew). The X-axis shows the number of profiles likely to use a given solution[10], while the vertical axis represents the number of experts that included the solution in at least one user profile. The third dimension of the graph, given by the bubble sizes, corresponds to the number of interviewees having selected the given solution for each user profile.

[10] In order to avoid single expert bias, we have considered that a profile would use a given charging solution only if mentioned by at least 2 of the 12 interviewees.

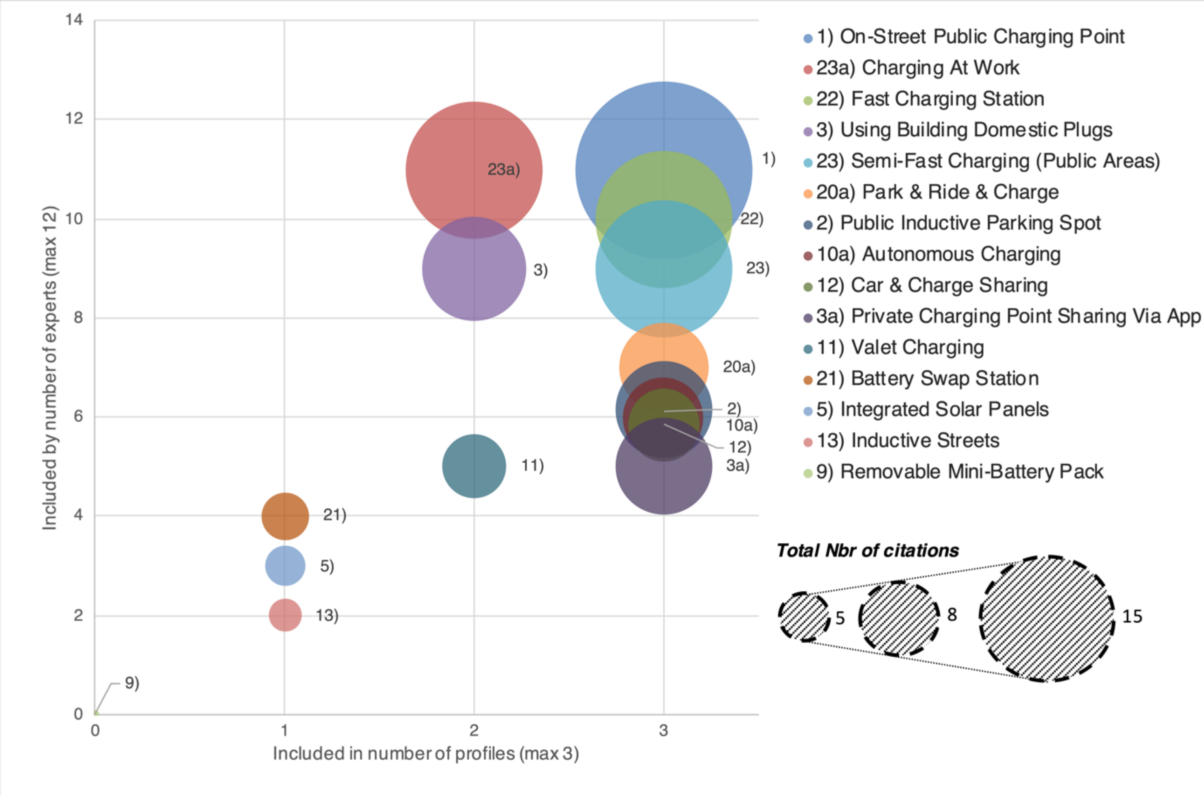

Figure 5. Popularity of charging infrastructure amongst experts

On the top right corner of Figure 5, "On-street public charging points" is the most popular urban charging solution, as it was mentioned by 11 out of 12 experts. All three user profiles are expected to use on-street public charging points at least for part of their charging needs, mostly at night. If one considers "public inductive charging spots" as an advanced option of "on-street charging", it shows that the on-street infrastructure is by far the option that, according to our panel will play the biggest role in urban charging by 2035 in Europe.

"Fast charging stations" and "semi-fast charging in public areas" stations come next, again used by all 3 user profiles. Charging at work is also cited by all but one expert. This solution would however suit only 2 of the 3 profiles defined as the retired person would of course not use it. This implies that companies are expected to incentivize e-mobility amongst their employees by installing EV plugs. This was, however, a case of disagreement between experts, as some indicated that companies, in particular those located in dense urban environment, are more likely in the medium term to incentivize exclusively reliance on public transport.

"Using building domestic plugs" for charging EVs has been highly rated by experts although they all agree that crossing the pavement with the charging cables from the building to the street would be challenging both from an urbanistic and regulatory point of view. It was considered to be a realistic option only in certain specific context particularly favourable, such as in new-built neighbourhoods.

Services represented by "private charging point sharing via app", "car & charge sharing" and "valet service" is forecasted by the expert panel to jointly play a significant role in urban charging. It is likely that the reliance on these services might appeal to a variety of user profiles. These services do already exist today in specific cities, but are expected to scale up by 2035.

Amongst the solution that were almost discarded by our panel of experts, we find: battery swap, inductive streets, integrated solar panels, removable mini battery pack. The following arguments against battery swap have been evoked by the experts: battery swap bears the disadvantage of requiring high level of standardization of battery pack and their vehicle integration. Also, it requires a complex logistics of balancing the stock between distribution points. Finally, it is likely to be an expensive solution as batteries represent a significant share of EV cost. Inductive streets have been considered more complex to implement that inductive parking lots and require cars to use specific routes. Integrated solar panels have been considered to deliver insufficient power in comparison to the vehicle needs, while removable battery pack has been considered a very user-unfriendly solution unlikely to meet customer acceptance. As a consequence, our analysis concludes that these solutions will only play a marginal role, most probably in very specific context.

Figure 6 shows the share of usage of each charging solution by the three user profiles. Overall this shows a relatively homogeneous use of each solution between the different types of users, although "fast charging stations", "battery swap" (though unlikely to be available) and "valet charging" are likely to be used more often by Matthew (commercial profile) who travels a significantly longer annual distance, while services such as "car & charge sharing" or "using domestic plugs" might be used mainly by people with more time available and smaller mileage. Overall, this indicates that our panel sees no single charging solution dedicated to each user profiles, but that every EV owner will likely use a combination of available charging options, whatever these will be.

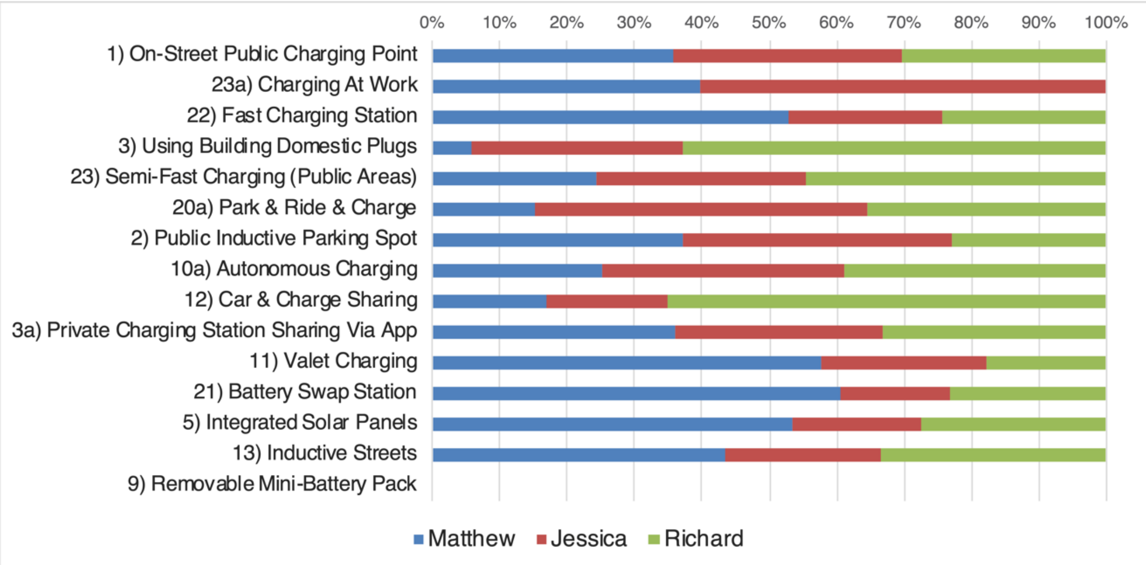

Figure 6. Share of profiles using each solution[11]

For each user profile, experts also mentioned the percentage of recharge they think will be covered with each solution retained. Figure 7 shows the average over all experts of the percentage of recharge done with each solution for each driver profile.

[11] As "removable mini-battery pack" was not mentioned by any expert the share of profiles using it could not be calculated.

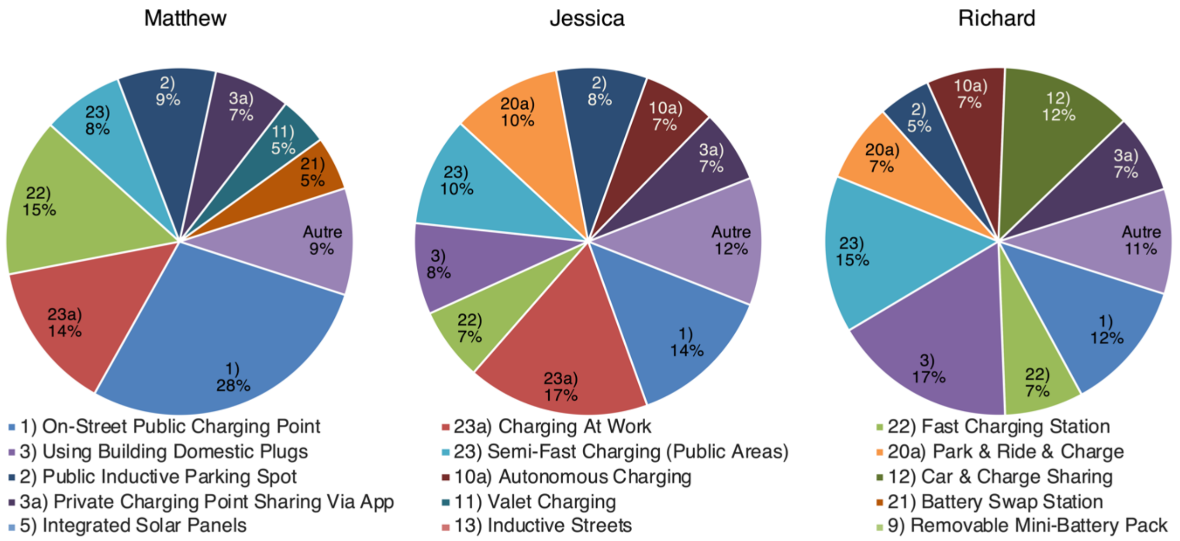

Figure 7. Preferred mix of recharge solution for each user profile

The main limitation of this phase was the limited number of experts consulted in this phase, however as Mullen (2003, p. 41) states, small panels are common in Delphi studies and the average panel size is between 8 to 12 participants. Nonetheless, our experts were selected to ensure a variety of backgrounds as is recommended for Delphi studies (Beretta, 1996).

Several key conclusions can be drawn from Phase 3

- No single urban charging solution will dominate in any of the user profile considered. Rather, each solution will play its share. It shows that the experts consulted foresee that the users will be opportunistic and use any solution available.
- Each user will still have his/her preferred mix of charging solutions, but overall each solution will probably be relatively homogeneously used.
- It is expected that over 70% of the EV charging needs of each category of users will be covered by a mix of 5 to 6 main solutions.
- The remaining 30% is anticipated to be covered mainly by those early adopters that will benefit from an autonomous car (10%) or who will rely on car-sharing services (10%).
- The only solutions expected to remain marginal are "integrated solar panels", "removable mini-battery pack" and "inductive streets" which accounts for less than 5% of the needs in any profile.

Finally, we need to emphasise that these results are very sensitive to the evolution of car-sharing and autonomous vehicles, as most experts pointed out. Some solutions, such as inductive charging, are well adapted for this new paradigm which might serve as a trigger for deployment. Hence, our conclusions need to be taken with full consideration for the uncertainty around these concepts.

5. Conclusion

This study identified 15 realistic options for charging electric vehicles in urban environments by 2035, which range from purely technical to more service oriented. Most of these solutions already exist today, although some remain at a very early stage of deployment. This shows that no major breakthrough or paradigm shift is expected in the charging ecosystem, but rather a scale-up of existing solutions.

Interestingly, apart from inductive streets that is expected to play a marginal role all the charging solutions retained by the expert panel are charging the vehicle while parked rather than in use. In a sense, this is consistent with the fact that vehicles are parked some 95% of the time (Guo, 2013, p. 19). However, with the increasing role of car-sharing which will increase the use factor of vehicles, one would expect to see more dynamic charging solutions emerge, such as inductive roads. Similarly, the expected development of autonomous vehicles might favour solutions such as electric rail on highways. However, these solutions have been considered technically too complex to implement and unable to cover the needs of all the user profiles. Further research might nonetheless be needed to investigate in more depth the arguments that condemned these dynamic solutions.

In any case, our analysis concludes that the urban charging options are numerous and no single solution is expected to emerge as a clearly preferred option. Rather, each EV user depending on his/her specific driving profile, will rely on a mix of 5 to 6 different solutions. With the increased penetration of EVs, there will be a need to diversify the solutions so that EV owners can charge whenever parked (at work, at shops, at park & rail lots, on street, etc.). An analogy can be made with charging points for cell phones, the supply diversified enormously over the past decade (trains, airports, cars, shopping malls, etc.), so that a cell phone can always be recharged partially and never go flat, with USB-pocket batteries as the ultimate back-up. We will most likely experience the same trend with EVs which will be plugged whenever possible to partially recharge, while fast-charging stations will offer the back-up solution or when longer distances are travelled. We expect that smart plugs and apps will be increasingly available to help the EV user optimize their charging (minimising waiting time while securing range).

There are three main disrupting evolution that will impact on the mix of solutions available in 2035 and on the extent to which these will be used. These are:

- The increasing EV range: the longer the range, the fewer the recharging constraints and the more the charging options available.
- The share of drivers who will rely on car-sharing solutions, as this will put the EV charging burden on the fleet operator and not any longer on the drivers. Also, this will increase the use factor of vehicles, thus increasing the range requirement while reducing the time available for charging.
- The state of deployment of autonomous vehicles: which level of autonomy will be available in 2035 and what penetration of these vehicles will be reached by then.

Several interviewed experts have indicated that there will be more EVs on the road than the number of public plugs available for recharging. In other words, it is an illusion to think in terms of "one plug, one car". This means that EV owners will often find all nearby charging points occupied. Hence, an increase of the battery range appears as an enabler for the mass market deployment of EV, as this will reduce the need to recharge every day, therefore reducing the pressure on the charging infrastructure and increasing the possibility to share charging points. Plug-in hybrids (PHEVs) might, however, complexify the situation as they might occupy charging locations more frequently and for longer time than they actually need, hence impacting negatively on the availability of the shared infrastructure. The same applies to EV owners that travel short distances everyday but want to nonetheless charge every day to avoid range anxiety. Optimising the use of infrastructure is a challenge that remains to be addressed.

What this study shows is that the future ecosystem of charging solutions is expected to be very varied, with numerous solutions emerging in parallel to address the needs of different user profiles. One key challenge will be to ensure that these various solutions are being deployed in a harmonious way so that they truly complement rather than compete against one another. The risk is high that some solutions, considered individually, will not find a business model, so there is a need for optimizing the deployment to ensure that the supply will adequately meet the demand both in space and time. This is a significant challenge ahead for cities, as well as for operators of charging infrastructure, in particular because there will not be a "one-solution-fits-all" but a mix of charging solutions. Rather, the optimal deployment will depend on cities themselves, in particular their urban density and typology, as well as the vehicle user profiles that differ significantly between countries. This is another topic that will attract more research in the coming years.

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Appendix 1

Table 5. The 23 charging solutions identified in phase 1

Solution	Advantages	Disadvantages
EV charged while parked >> Battery remains in the car >> Fixed infrastructure		
1) On-street public charging point • Conventional public charging points • Few places equipped • Driver plug manually the car	• Mature • Relatively easy deployment	• Obstruction of sideways • Competition between EV/ not dedicated parking spots • Slow charging speed
2) Public inductive parking spot • Automatic inductive charging on dedicated parking spot • Charge can be initiated from inside the car • Charging infrastructure is protected inside the ground and not occupy space	• Convenience of use • Small footprint	• Heavy construction work • Competition between EV/ not dedicated parking spots • Standardization of recharge system
3) Using building domestic plug • Wires coming from existing building plugs • Consumers pay to charge with private plugs	• Infrastructure partially existing • New income for residents	• Deployment not controllable • Wire bridge EV – building complicated and visually unpleasant • Slow charging speed
EV charged while driving >> Car in motion >> Mobile solution		
4) Feeding from battery truck • A battery truck charges the EVs while parked • Travel to charging infrastructure required only for the truck	• Less fixed infrastructures	• Street congestion • Additional traffic created by battery trucks
5) Battery swap truck • A truck brings and swaps batteries of EVs while parked • Depleted battery is exchanged with a fully charged one • Travel to charging infrastructure only for the truck	• Centralized charging infrastructure • Swap faster than conventional charging	• Necessity of easy access to batteries • Standardisation of batteries required • Additional traffic created by battery trucks

EV charged while parked >> Battery removed from car >> Battery swap		
6) Integrated solar panels • PV integrated into the EV to produce electricity • Recharge occurring any time the sun is shining	• Recharge occurring any time the sun is shining • "Free" and passive conversion of energy • No infrastructure required	• Useless in underground parking • Not very efficient with the shadows of buildings • Very slow charging speed
EV charged while parked >> Battery removed from car >> Battery charged elsewhere		
7) Valet battery charging service • The battery is removed from the EV by a valet and brought to the charging station • Battery is charged and brought back to the EV	• Centralized charging infrastructure • Autonomous from driver's perspective	• Additional traffic created • Cost of such valet service • Require the possibility to extract the battery
8) Extractible battery pack for home recharge • Small parts of the main battery can be removed and charged at home	• No fixed infrastructures • Solution well known for electric bicycles	• Weight of the batteries to be carry by drivers • Difficulties for customers to change their batteries alone • Security
9) Lego-type battery distributed home charging • Small parts of the main battery can be removed and replaced • The battery becomes modular • Each smaller partition can be replaced individually	• Less fixed infrastructures • EV autonomy is adaptable • Part of the battery can be used while the rest is charging	• Additional traffic created • Standardisation of batteries required • Complex logistics for battery deliveries
EV charged while parked >> EV moved to charging point >> Autonomously		
10) Autonomous charging • Autonomous car drive to the charging infrastructure • Come back once charged or upon demand • Reduces the needs of charging infrastructure in dense areas	• Less fixed infrastructures • Convenient (autonomous) • Lower the number of parking required	• Parking spots potentially not available when coming back • Necessity of autonomous vehicles • Traffic generated
EV charged while parked >> EV moved to charging point >> By driver		
11) Valet charging • EV brought by a valet to the charging station • Come back once charged or upon demand • Reduces the needs of charging infrastructure in dense areas	• Centralized charging infrastructure • Convenient (autonomous from driver's perspective)	• Car not available in case of unplanned needs • Price of the valet service • Traffic generated
12) Car & charge sharing • EV owner share his car in exchange for charging • The car is brought back charged by other driver • Reduces the needs of charging infrastructure in dense areas	• Less fixed infrastructures • Win-win situation for both drivers	• Car not available in case of unplanned needs • Dependence of one driver upon the other
EV charged while driving >> Car in motion >> Fixed charging infrastructure		
13) Inductive streets • EV charge while driving on inductive areas dedicated	• Convenience • Lower battery requirements	• Complex and costly infrastructure to deploy and maintain

• Lower battery requirements for journeys in urban settings	• No time dedicated for charging	• Require normalization and legislation of inductive system
14) Plugging to electric rail • EV connects to a rail while driving • Lower battery requirements for journeys in urban settings	• Lower battery requirements	• Costly infrastructure • Extra cost to equip cars • Insulation issues for pedestrians
15) Panthograph-cathener system • EV equipped with pantograph similarly to electric buses • Lower battery requirements for journeys in urban settings	• Technology already known • Lower battery requirements	• Costly infrastructure • Extra cost to equip cars • Security and complexity of use
EV charged while driving >> Car in motion >> Mobile solution		
16) Tanker trucks • A battery truck charge EVs while in motion • Similar to tanker planes	• Centralized infrastructure • No time dedicated for charging	• Access to the truck • Limited charging time • Complexity of the connecting procedure
EV charged while driving >> Car stopped >> Charging infrastructure at traffic light		
17) Airborne feeding infrastructure A drone fly to EVs with low battery to charge them Less infrastructures needed Quickly accessible anywhere	• Centralized infrastructure • Quickly accessible anywhere • No time dedicated for charging	• Security due to flying objects in cities • Weight of embarked batteries makes flight difficult
18) Inductive charging at the red light • An inductive area specially located at red lights • Less infrastructures needed than equivalent inductive streets • Lower battery requirements for journeys in urban settings	• Less fixed infrastructures • Lower battery requirements • No time dedicated for charging	• Maintenance is difficult • Recharge depending on the fluidity of the traffic • Require normalization and legislation of inductive system
EV charged while driving >> Car stopped >> Smart charging in traffic jam		
19) Feeding by autonomous vehicle in traffic jams • An autonomous vehicle potentially connected to the grid charge cars in traffic jam • The vehicle passes autonomously between stopped cars	• Optimization of the charging infrastructure	• Complexity of implementation • Possible discrimination for charging
20) Inter-vehicle siphoning system • EVs with enough charge distribute it to others	• Based on sharing economy • Indirect mutualisation of fixed infrastructure	• Not really a solution of "recharge by itself" • Protocol & plugging technically complicated • Deployment difficult to control
EV charged while driving >> Car stopped >> Charging stations		
21) Battery swap station • Current petrol stations are replaced by battery swap stations • The battery is replaced by a full one	• Similar to petrol stations • Swapping faster than charging	• Batteries need to be accessible and removable

• The battery is charged before being installed on another car		• High standardisation of the batteries required • Extra batteries required
22) Fast charging station • Charging stations similar to petrol stations • The battery is charged by the driver	• Infrastructure and behaviour already present	• Takes longer time than petrol refill • Charging time dependent of the number of EVs charging
23) Semi-fast charging (public areas) • Semi-fast charging points in public areas (supermarkets, sport centres, …) • The battery is charged while the driver does its conventional activity	• Infrastructure and behaviour already present	• Depend upon private willingness