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The role of charging technologies in upscaling the use of electric buses in public transport: Experiences from demonstration projects

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ABSTRACT

Electrification of public bus transport services is currently being explored in various demonstration projects around the world. The objective of this paper is to (i) gather insights from electric bus demonstration projects with a focus on charging technologies (conductive, inductive) and strategies (slow, fast); and explore the role these factors may play as upscaling of electric bus deployment is considered. The focus is on the Nordic region. A survey with stakeholders involved with electric bus demonstration projects is performed for understanding the benefits and drawbacks of each solution, and identifying the main themes emerging from project implementation and upscaling. Advantages of the conductive charging include the maturity of the technology and its higher maximum charging power compared to currently available inductive alternatives. On the other hand, inductive technology entails other benefits, such as the lack of moving parts which could reduce the maintenance costs for infrastructure, as well as minimal visibility of the equipment. The main issues likely to impact the upscaling of electric bus use are related to the maturity, cost-effectiveness, compatibility, and charging efficiency of the available technologies.

1. Introduction

Public transport is crucial for the functionality of urban systems. Globally, much attention is presently given to reducing the environmental impacts of transport by shifting to clean fuels, while also improving service availability. In this context, electrification of bus transport is gaining popularity because of the high energy efficiency improvements that can be accrued, together with low emissions and noise reduction compared to conventional buses.

Although several studies focus on engine performance optimization and powertrain characteristics of electric buses for individual demonstration projects, only few studies analyze charging technologies in more detail (e.g. Millo et al. (2015), Kontou and Miles (2015), Bi et al. (2017), Bi et al. (2015)). Charging is one of the most important challenges to address when it comes to electric buses, not only from the purely technological perspective. Charging infrastructure requirements and implementation prospects are greatly affected by conditions in the specific location considered (Xylia et al., 2017b). The challenge is further exacerbated as cities plan for incorporation of electric bus technologies in everyday public transport services in order to lead a more widespread adoption of electric vehicles (IEA, 2017). A recent report published by the International Organization on Public Transport (UITP) lists more than 60 cases of electric bus demonstration projects around Europe (UITP, 2017).

The objective of this paper is to (i) gather insights from electric bus demonstration projects with a focus on charging technologies (conductive, inductive) and strategies (slow, fast); and explore the role these factors may play as upscaling of electric bus deployment

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is considered. The charging technologies studied are conductive and inductive charging. The charging strategies studied are slow (otherwise known as overnight) and fast charging. The expected results shall help understand the benefits and drawbacks of each solution, and map the charging-related challenges faced when upscaling the use of electric buses in public transport.

The main questions sought to be answered here are the following: *What are the characteristics of the various charging technologies and strategies at hand, and what are the main themes emerging when it comes to implementation? How can the various "lessons learnt" from demonstration projects facilitate planning for upscaling electrification of public bus fleets?* The first question addresses the first part of the aforementioned objective, while the second question addresses the latter part. The analysis draws from experiences around the world, reviewing existing literature and complementing it with expert knowledge from selected stakeholders. Particular attention is given to the Nordic region, where several initiatives are already in place.

Following the present introduction, Section 2 presents background on charging technologies while Section 3 presents the analytical approach, as well as the methods chosen for each part of the study. Section 4 presents the results of the literature review, where the available technologies and strategies for charging are discussed. Section 5 focuses on the experiences from demonstration projects for electric buses. The results from the aforementioned sections are discussed further in Section 6 where emerging themes are defined, followed by the conclusions of the study which are presented in Section 7.

2. Background

Electric powertrain types can be differentiated in battery electric and electric hybrid, see Fig. 2. Battery electric buses have only an electric motor, while electric hybrid buses have an additional internal combustion engine (ICE) which is usually deployed for supplying energy to auxiliaries. Electric hybrids are considered to be an intermediate solution between ICE and battery electric buses (Tzeng et al., 2005). The energy storage systems available include ultracapacitors, batteries and fuel cells. In the Nordic region, only battery and fuel cells are currently used as energy storage for buses, therefore ultracapacitors are excluded from the analysis. The main focus of the study is on batteries for energy storage, since it is the most common option provided by all major electric bus manufacturers.

The main technologies currently available for battery charging are depicted in Fig. 1, and can be aggregated in conductive (plug-in) and inductive (wireless). For conductive charging, direct contact is used between the connector and the charge inlet (Yilmaz and Krein, 2012). For inductive charging, the power is transferred through magnetic fields and no cables are needed (Yilmaz and Krein, 2012). The inductive system is built based on the bottom coil system topology, where a primary coil system is placed underground, and a secondary coil system is installed on board of the vehicle. This topology offers flexibility in the coil geometry design, but can be a source of inefficiencies due to the air gap between the primary and secondary coil (Lempidis et al., 2014).

Charging can take place either in stationary mode (when the vehicle is stopped) or dynamically (when the vehicle is moving). Conductive charging technologies can additionally be differentiated in overhead or ground/underground solutions. As mentioned earlier, inductive charging is an underground solution and can be either stationary or dynamic. In this paper, we are interested in the comparison between stationary conductive and inductive charging technologies. Dynamic inductive charging technologies are excluded from the analysis as the technology is yet at a very early stage of development, and is not yet being tested for buses in the Nordic region. Also trolleybuses are excluded. The latter is a dynamic conductive charging technology, but well-established technology since the 1970s, and thus considered to be mature. It is therefore not in the scope of the analysis, which is focused on emerging charging technologies.

The choice of charging strategy is linked to the powertrain technology, as well as the battery size and the available budget for infrastructure investments. The slow charging strategy is also known as overnight charging. With this technology, the charging happens in AC in the depot or parking space allocated for the vehicle over longer time periods. Fast charging, otherwise known as opportunity charging, requires the installation of a charging station that transforms AC to DC. Table 1 provides examples of fast-chargers for buses that are currently available in the European market.

The costs for charging systems can vary significantly. In fact, when comparing the costs of conductive vs. inductive fast charging systems for buses, we should assume that costs are affected by the conditions around each specific case, e.g. space availability and local electricity grid conditions.

Lindgren (2015) has collected information for a Swedish case study showing that conductive fast charging systems are cheaper than inductive (1.5 million SEK (150000 €[1]) and 2 million SEK (200000 €) respectively). In addition, the inductive charging system requires the installation of a pickup system that is estimated to cost 1 MSEK (100000 €) (Lindgren, 2015). This gives an indication of the cost difference between the two charging technologies.

Another study indicates a cost of 1 222 $/kW (ca. 9 750 SEK/kW or 975 €/kW)) for a stationary inductive fast charging system such as the Bombardier PRIMOVE, and 405 $/kW (ca. 3 250 SEK/kW or 325 €/kW) for a stationary conductive fast charging station, such as the Siemens and ABB models, including both the charger itself as well as the necessary grid connection costs (Bängtsson and Alaküla, 2015). Nevertheless, the costs of both charging systems are uncertain at this early stage of technology deployment, and are expected to decrease as higher commercialization rates for fast charging technologies are achieved.

Currently, there is lack of comparative studies for charging technologies and strategies to guide choices. A possible reason for this is that conductive overnight charging is currently the most established charging option. Reasons for this include the ease of installation, the maturity of the technology, and the lower overall cost of the infrastructure. For example, the costs for a simple

[1] *SEK is the Swedish currency (Swedish Krona). The average exchange rate for 2016 is 1SEK = 0.10€ (Oanda, 2016).*

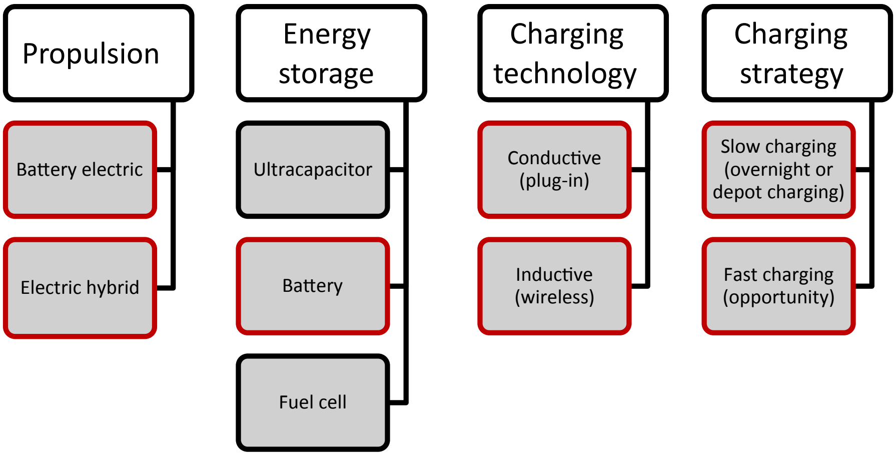

Fig. 1. Powertrain, storage, charging technologies and strategies for electric buses (the charging technologies and strategies included in the analysis are in red boxes). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Characteristics of selected fast-charging infrastructure options.

Supplier	System	Charging technology	Charging power	Reference demonstrations	Source
ABB	TOSA	Conductive	150, 300, 450 kW, 600 kW	Charleroi, Harrogate, Östersund	ABB (2017)
Bombardier	PRIMOVE	Inductive	200 kW	Södertälje, Bruges, Berlin	Bombardier (2016)
Conductix-Wampfler	IPT charger	Inductive	60/120/180 kW	Genoa, Turin, Milton Keynes	Conductix Wampfler (2017)
Endesa	Fast DC Charger	Conductive	400 kW	Barcelona	Endesa (2017)
Heliox	Fast DC Charger	Conductive	120/200/500 kW	Gothenburg, Eindhoven	Heliox (2017)
Siemens	Offboard High-Power Charger	Conductive	150/300/450 kW	Stockholm, Gothenburg, Hamburg	Siemens (2017)

overnight charging installation are considered to vary between 20 000 and 23 000 SEK (2000 and 2300 €) in a study by Karlsson (2016). From this and the cost estimations for fast chargers discussed earlier, one can observe that the cost of overnight charging is lower than both conductive and inductive fast-charging infrastructure by an order of magnitude.

Despite the higher costs, fast charging is an option worth consideration, as it offers other benefits such as the use of smaller batteries. The latter can significantly reduce the vehicles' cost and lifecycle environmental impact. In addition, simultaneous overnight charging of large electric bus fleets in the future would place concentrated, high power requirements on the grid, which capacity might not be able to cover the charging needs. Therefore, dispersing the charging occasions spatially and temporally would be required for scaling-up electric bus adoption (and electric vehicle adoption overall).

3. Methodological approach

An electronic database search was performed using keywords related to charging technologies (see Fig. 2). The analysis included studies published in top-tier (Q1) journals. Q1 journals represent the top 25% of the impact factor distribution of journals in the subject category of search. Then, a one-by-one quality assessment was done in order to exclude duplicates and/or publications that are outside of the scope of this paper. As a result, 12 peer-reviewed articles in Q1 journals were identified and used for the literature review (see Fig. 2). This initial list is complemented with articles found in the reference lists of the originally selected articles, as well as international reports on the historical development of electric buses. The results of the literature review are presented in Section 3 of the paper.

After the literature review, we draw knowledge from existing expertise through a qualitative survey with stakeholders active in electric bus demonstration projects, with a particular focus on the Nordic region. The survey was carried out in May 2016 using an anonymous electronic questionnaire. The questionnaire was sent to 62 persons. In total, 25 persons responded the survey, thus the response rate was 40%. The respondents were asked to specify the stakeholder group they belong to, such as transport operators and planners, bus and charger manufacturers, and researchers. The stakeholder groups are defined based on the structure of constellations collaborating in various demonstration projects in the Nordic region. The project coverage for the Nordic region is extensive, as stakeholder from all major electric bus demonstration projects were contacted. We included some actors outside the Nordic region in the original survey sample, mainly to gain more information about the wireless charging technology, but their participation in the survey was limited, as shown later in Section 4.

The aim of the survey was to investigate experiences in planning for implementation of demonstration projects, and scaling-up of

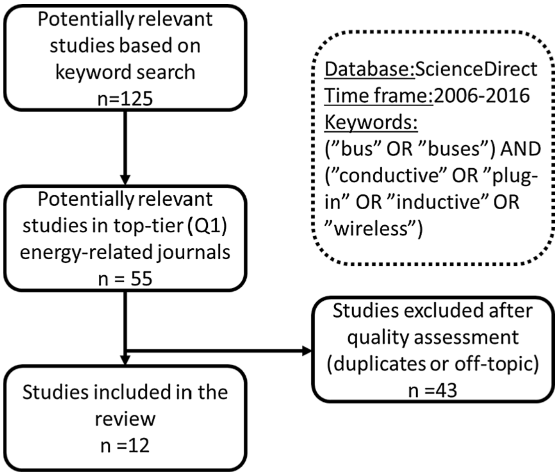

Fig. 2. Literature review inclusion/exclusion process (n indicates the number of articles selected for each step of the process) (process . adapted from Carlsen et al. (2007))

electric bus deployment in public transport. The questions were divided into four categories: (i) *General information*; (ii) *Technology choices*; (iii) *Experiences from the implementation process*; and (iv) *Plans for continuation*. The same categorization is basically followed for the presentation of the survey results in later sections of the paper. The survey was anonymous, unless the respondent specified otherwise at the end of the questionnaire. From 17 questions in total, 8 of them were closed format questions, and the rest were open format questions for elaboration. We chose to use a mix where open questions dominate in order to give freedom to the respondents to more freely formulate their responses based on their experiences. In this way, the open questions provide a broad collection of insights. The use of the electronic method facilitated reaching out to more stakeholders in different countries than what would be possible with personal interviews. It also facilitated the coding and result interpretation process. The design of the questionnaire was discussed and tested with stakeholders of the sector before distribution.

A simplified application of the thematic analysis method is used for further analyzing the results. When applying thematic analysis, important recurrent themes within the data are identified, and the findings are summarized under descriptive thematic headings (Ring et al., 2011; Thomas and Harden, 2008). Defining a theme is subject to the researcher's judgment, and does not necessarily depend on quantifiable aspects such as the number of observations of a specific pattern, but rather on the importance of the observed pattern in relation to the research questions (Braun and Clarke, 2006). The thematic analysis used in this paper is inductive, i.e. bottom-up and data-driven, and moves from description to interpretation.

The survey allows us to identify the recurrent themes related to the selection of fast charging technologies in demonstration projects, as well as the main challenges that need to be tackled in order to effectively expand the use of electric buses in public transport. The results are also useful to enrich the knowledge basis on the topic of electrification of transport, shifting from individual empirical findings in individual projects to a generalized framework for evaluation of technology choices when it comes to charging infrastructure. Such frameworks may be valuable in assisting decision makers when contemplating large-scale electrification of urban bus transport in the future. The methodological framework designed for this paper is illustrated in Fig. 3.

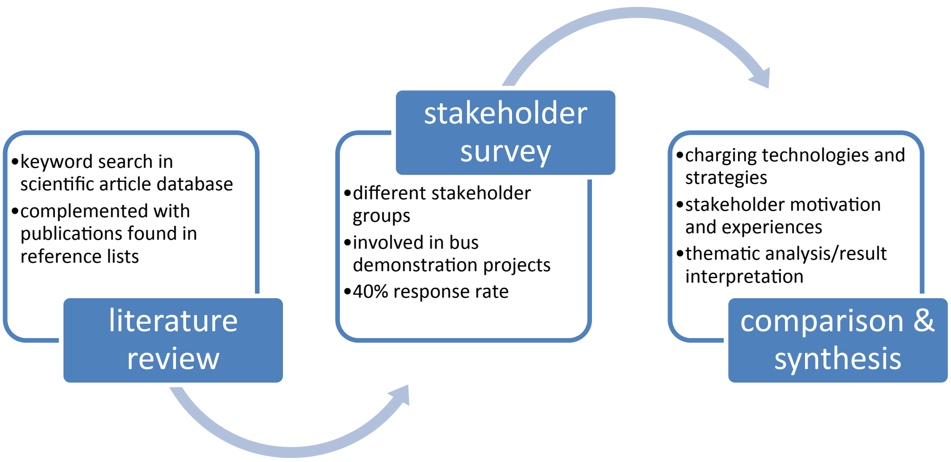

Fig. 3. Methodological framework of the study.

4. Literature review

4.1. Historical development of electric buses in Europe

The fast deployment of electric buses around the world can be largely accredited to stricter environmental requirements for public transport rather than commercial drivers (UITP, 2017). Stricter environmental requirements in public transport has given a strong push to the introduction of renewable fuels in Swedish buses, for example. An ambitious goal for 90% renewable fuels in Swedish public transport by 2020 was set in 2007, and the share of renewable fuels in bus fleets rose from 8% in 2007 to approximately 60% in 2014 (Xylia and Silveira, 2017). Requirements for further energy efficiency improvements in the bus fleets are expected to push the shift to hybrid and fully electric buses in various regions (e.g. Stockholm).

Deployment of electric buses has accelerated quickly in the past five to ten years, with an estimated global battery electric bus fleet of 345 000 vehicles in 2016 (double the number in 2015), with China holding the largest share (close to 90%) (IEA, 2017). Europe accounts for 1 273 vehicles of the global stock, and the USA for only 200 (IEA, 2017). Although the European share in the global electric bus fleet is small, European industries play a significant role in research and development of new solutions for transport electrification which can also be exported (UITP, 2017).

Electric vehicle deployment is supported by legally binding legislation in the European Union (Benz, 2015). A 10% target for renewable fuels in the transport sector by 2020 is set in the Renewable Energy Directive 2009/18/EC (RED) (European Commission, 2009). EU sustainable transport policies are guided by the European Commission's White Paper "Roadmap to a Single European Transport Area — Towards a Competitive and Resource Efficient Transport System", which includes a target to reduce greenhouse gas emissions from transport by 60% by 2050 compared to 1990 levels. The White Paper also calls for a mix of policy instruments to promote the development of sustainable alternative fuel strategies and related infrastructure.

In line with the above, the Directive 2014/94/EU on the deployment of alternative fuels infrastructure addresses common standards and consumer initiatives for the promotion of alternative fuels in transport. Electrification receives significant attention, and an interoperability standard for electro mobility is suggested (European Commission, 2014). In addition to these, the EU has one of the world's strictest greenhouse gas emission standards for vehicles, the EURO VI standard (Benz, 2015), and guidelines for reduction of noise levels in urban areas in the Directive 2002/49/EC (European Parliament and Council of the European Union, 2002).

Although there are no specific targets for electric bus deployment in the European Union, there is a clear support for clean public transport solutions. Member States are free to set their own level of ambition in national strategies. Nevertheless, the EU subsidizes demonstration projects for electric buses under the FP7 and Horizon 2020 programs. Under the FP7, the ZeEUS (Zero Emission Urban Bus System) initiative was launched, with over 40 consortium participants and a budget of 22 million Euros (Benz, 2015; UITP, 2017). Many countries, including France, Germany, Italy and the UK, are setting national legal frameworks which shall further encourage the deployment of electric buses for public transport (UITP, 2017). In Sweden, 80% of inner city buses could be electric by 2030. The share is indicatively set to be 100% by 2050 (Regeringskansliet, 2013).

The future seems promising for electric buses in the Nordic region. Lately, authorities are shifting from individual demonstration projects to single orders of a larger number of buses which are placed in normal traffic rather than special "demo" routes. For example, the city of Trondheim in Norway shall have a fleet of 35 fully electric buses by August 2019, the largest in the Nordic region (Volvo, 2017). The city of Malmö in Sweden plans to put 10 electric buses in operation, starting in December 2018 (Nobina, 2017). For the case of Trondheim, as well as the majority of the projects shown in Fig. 4, the responsibility for implementation lies with the local Public Transport Administration Authorities (PTAs). It has been nevertheless observed that in Europe the PTAs, municipal and regional authorities have been the most active in pushing forward for electric bus demonstrations (Aldenius et al., 2016). Malmö's case is exceptional, as the operator of the public bus transport services is responsible for the purchase of the electric buses, after a special agreement with the regional PTA.

4.2. Charging technologies' role in electric bus evaluation studies

A first observation when reviewing the existing literature regarding charging technologies is that inductive charging is not as established as conductive charging. Only one project with inductive charging is presently being implemented in the Nordic region (see Table 1 and Fig. 4). As a result, the standardization and normalization of inductive technologies is at a very early stage. There are, however, a few ongoing projects in Europe, with prominent examples found in Berlin and Braunschweig in Germany, as well as London and Milton Keynes in the UK. Outside Europe, the city of Gumi in South Korea is also testing inductive charging for public buses.

For most of the studies reviewed, the focus has been on the evaluation of requirements and performance of various EV powertrains and battery configurations. Several studies focus on Tank-to-Wheel (TTW) or Well-to-Wheel (WTW) analyses of energy consumption, emissions and costs for various powertrain configurations. Hu et al. (2013) study tank-to-wheel (TTW) energy efficiencies under two optimization-based energy management strategies for a series of plug-in hybrid electric bus operated in Gothenburg, Sweden. Lajunen and Lipman (2016) analyze lifecycle costs and emissions of various powertrain types and compare them with the case of Finland and California. Lajunen 2014 performs a cost-benefit analysis (CBA) under various energy performance scenarios for electric and hybrid electric buses in Finland. Ribau et al. (2014) highlight the effect of the driving conditions on cost, efficiency and life cycle impact of fuel cell and plug-in hybrid buses. Ribau et al. (2015) address the differences in lifecycle emissions for fuel cell and plug-in hybrid buses. Zhou et al. 2016 investigate energy and emission savings from the use of electric buses in a case study for

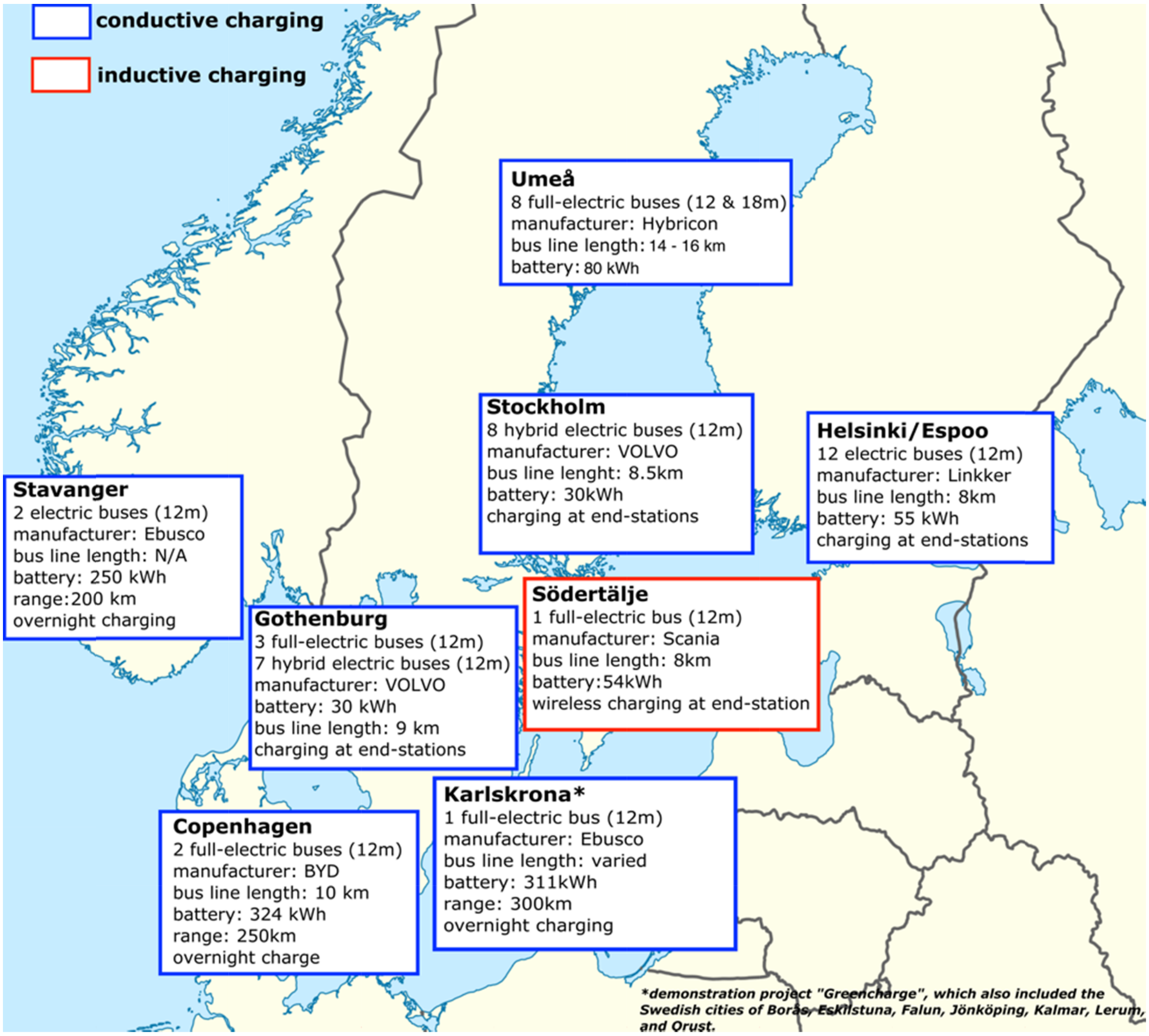

Fig. 4. Map of electric bus demonstration projects in the Nordic countries 2016 (information compiled by the authors).

Macao in China. Millo et al. (2015) and Kontou and Miles (2015) review the performance of electric buses in demonstration projects, discussing powertrain and charging systems for Genoa, Italy and Milton Keynes, UK, respectively. However, these studies do not compare various alternatives, but rather focus on the specific cases presented.

In contrast, only a few studies with comparisons of charging alternatives were identified. Bi et al. (2015), for example, discuss grid-related aspects, comparing the differences for lifecycle energy and emissions of a plug-in and a wireless charging system for electric buses in Michigan, USA. The plug-in chargers are located at the bus depots only, while the wireless chargers are located at major transit hubs. The authors conclude that the wireless charging system consumes 0.3% less energy and emits 0.5% less greenhouse gas emissions than the plug-in system in its total lifecycle. The assumed charging efficiencies are 90% and 85% for the plug-in and wireless system, respectively. The authors identify the carbon intensity of the electricity mix and the wireless charging efficiency as key parameters for further improvement.

A study by Bi et al. (2017) compares the lifecycle costs (LCC) for the same conductive and inductive bus charging systems analyzed in Bi et al. (2015). The results indicate that, although the wireless system entails an overall lower LCC compared to the plug-in alternative, there are still significant uncertainties when it comes to the impact of the battery unit price, wireless charging efficiency, and procurement, installation, and maintenance costs of the wireless charging systems.

An advantage identified in the literature for inductive charging is the convenience it offers for extending the invisible infrastructure for dynamic charging on the roads, which could potentially reduce the need for fast charging stationary infrastructure (Lukic and Pantic, 2013; Yilmaz and Krein, 2012). Although conductive technologies have also been used for dynamic charging, with a prominent example being trolleybuses, the impact of visible infrastructure on urban environment is a factor that needs to be considered.

Corazza et al. (2014) uses survey methods to evaluate a set of Key Performance Indicators (KPIs) for three major EU-funded electric bus demonstration projects, i.e. EBSF, 3iBS, and ZeEUS. The main KPI categories include customer satisfaction, urban environment and integration, system productivity, and quality of the bus services, which are evaluated by stakeholders and passengers. It would be beneficial to also include in such evaluation the impact of choosing different charging technologies. In fact, as later discussed in this paper, the choice of charging technology can affect perceptions on safety, punctuality, and dwell times which were among the KPIs tested.

Finally, it is worth noting that, apart from charging technology comparisons, there are also examples in the literature in which the characteristics of various charging strategies are compared. Li (2014) discussed battery-electric bus developments since the 1990s at an international scale. The most suitable charging strategies for addressing the shorter operational ranges of electric buses are proposed. The author identifies the impact of energy consumption from air-conditioning, driving behavior, and battery health issues as the main factors influencing the operational range of battery electric buses. Comparing these strategies, the authors conclude that fast-charging is advantageous in terms of spatial requirements in the dense urban contexts, but requires significantly higher investments and power capacity than slow-charging strategies. Slow charging is also more advantageous in terms of electricity pricing, as it happens mostly at off-peak hours. One option that is not discussed is fast-charging combined with on-site energy storage solutions which includes particular off-peak pricing benefits.

To summarize, most existing studies mainly focus on the impact of specific powertrains on costs, energy, and emissions. Charging technologies are not compared or investigated in depth in previous literature, and this study aims to fill this gap. As suggested earlier, the lack of previous literature on this topic could be due to the fact that these alternatives have only been available in the market for a short time, and only few projects have been implemented. In Sweden, for example, only 0.3% of the buses operated in public transport services were fully electric or hybrid electric in 2017 (31 out of 9970 (Svensk Kollektivtrafik, 2017)).

Another gap we observe in the literature is the lack of analysis on the various stakeholders' opinions and motivations when it comes to charging technology choices. In the following sections, this gap is addressed by evaluating the experiences of representatives from various stakeholder groups with the introduction of electric buses mostly in the Nordic region.

5. Stakeholder survey results

5.1. The respondents of the survey

As mentioned earlier, 25 persons responded the survey (out of 62 invited). The majority of the respondents come from Nordic countries and only a few (8%) are from other (European) countries (see Fig. 5). Actors outside of the Nordic region were contacted mainly to gain insights about the inductive charging technology, which is presently only tested in one project in the Nordic region. The respondents belong to a wide range of stakeholder groups, with the Public Transport Authorities (PTAs hereafter) and academia representing the majority of respondents, 28% and 20% respectively. Stakeholders from municipalities and bus manufacturers represent 12%, while charger manufacturers and transport operators represent 8% of the respondents. Respondents from other groups of stakeholders amount to 12% and include, for example, the engineering industry and research centers outside academia (see Fig. 6).

The majority of respondents (68%) indicated that their organizations have more than 3 years of experience in electric bus demonstration projects. In most cases (56%), a fleet of 5 to 15 electric buses has been tested by their respective organizations (see Fig. 7). A 36% of the respondents indicated that their organizations have tested less than 5 electric buses, while 8% tested more than 15 electric buses, as Fig. 7 shows.

5.2. Charging technologies and strategies

As shown in Fig. 8, the majority (56%) of the survey respondents have participated in projects in which battery electric buses have been used. A share of 24% has experience from both hybrid and battery electric buses, while options such as trolleybuses and buses

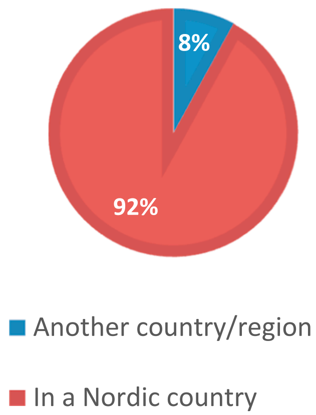

Fig. 5. Country of origin of survey respondents.

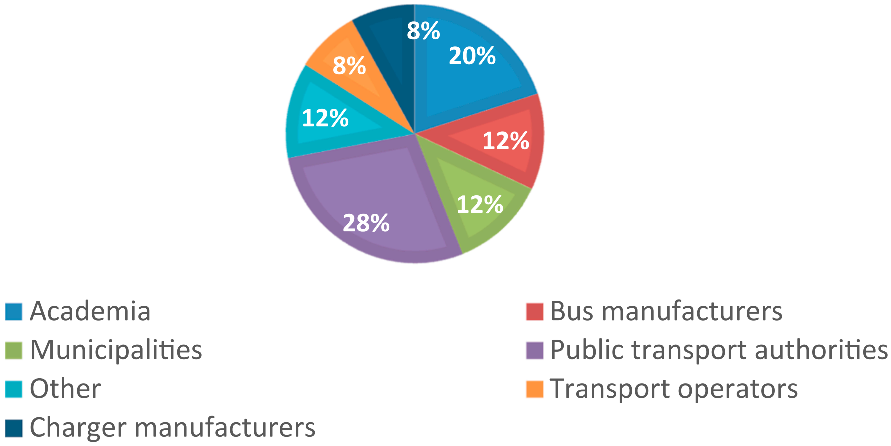

Fig. 6. Stakeholder group of survey respondents.

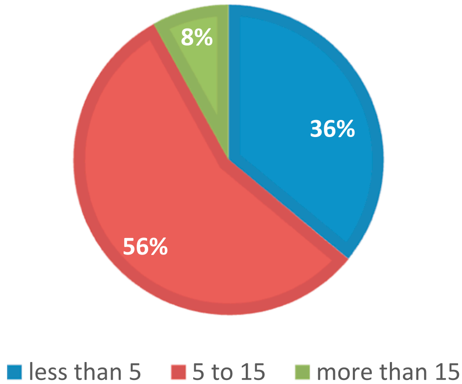

Fig. 7. Size of the electric bus fleet tested in demonstration project(s) implemented by the respondents' organization.

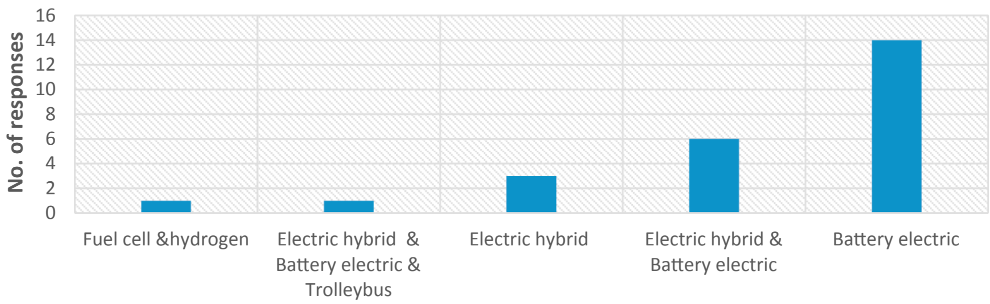

Fig. 8. Type of electric bus used in the demonstration project(s) in which the survey respondents are involved.

using fuel cells come last in the number of responses. For the case of fuel cells, one respondent mentions that the decision to test a fuel cell bus was made before the rapid development and expansion of battery electric buses.

When it comes to charging technologies, the vast majority of respondents indicated experience with conductive technology (80%), compared to 16% that indicated experience with the inductive technology and 4% with fuel cells (see Fig. 9). Obviously, the dominance of conductive technology coincides with the electric bus demo projects being implemented in the Nordic region (see Fig. 4). As mentioned earlier, the technology choices happened prior to the commercial availability of some of the technologies, as well as the linkage between the choice of charging technology and the choice of vehicle. Therefore, when certain vehicle manufacturers partner with charger providers, "lock-ins" for the charging technology choices may occur.

Previous studies have noted that it is more common that full electric buses are used in these demonstrations. For the case of Sweden, depot and conductive charging are the most common solutions. However, for the case of Europe, there is a wider variety of technological options, and more applications of inductive as well as opportunity charging (Aldenius et al., 2016).

Separating the survey responses per charging technology, the most important advantages of the conductive charging technology,

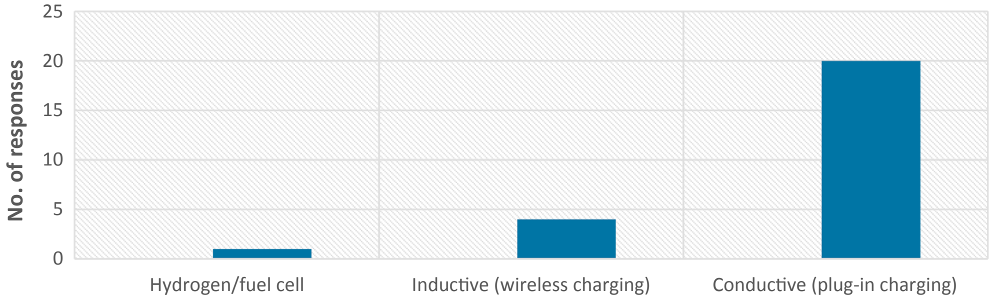

Fig. 9. Charging technology used for the demonstration project(s) in which the survey respondents are involved.

as perceived by the survey respondents, are the reliability and maturity of the technology compared to other charging alternatives. Other advantages listed in the responses are the bus dwell time (perceived as short due to the fast charging mode), the lower TCO (Total Cost of Operation) in comparison to other charging technologies, and the ability to use the bus in winter time, as well as adaptability to various urban contexts. The main disadvantages are the bus dwell time, the charging reliability (usually measured in number of missed charges), the limited driving range per charge, and the fact that the charging points are fixed.

Interestingly, bus dwell time is perceived as both an advantage and a disadvantage by the survey respondents (see Fig. 10). This characteristically illustrates the different perceptions and disposition of the respondents when it comes to the charging concepts tested. It actually depends whether the charging technology is compared with other available charging technologies, or if it is compared to buses with internal combustion engines. In fact, the bus dwell time increases in the case of electric buses with fast charging if compared to non-electric technologies. In general, at least 5 to 6 min are needed for a full charging at end stops with technologies commercially available at the moment (Siemens, 2016). Thus, a full-scale shift to electric buses would require significant changes in schedules. Additionally, this can be explained by the fact that the technology performed differently among different projects, depending on the design, charging strategies and surrounding prerequisites.

The insights on advantages and disadvantages of charging technologies in this study fit well with previous studies on KPIs for evaluating electric bus demonstration projects. For example, in Corazza et al. (2014), KPIs such as operating costs, bus dwell time, punctuality, frequency etc. are included, though the evaluation does not explicitly include charging systems. The analysis made here does not aim at development of such KPIs, but rather on understanding of stakeholders' perceptions about charging technologies. Still, one can notice the strong influence that the performance of a chosen charging technology may have on KPIs for the bus service overall.

There were less responses related to inductive charging than to conductive charging. This was not surprising given that the majority of electric bus demonstration projects in the Nordic regions use conductive charging. However, the main advantage of inductive charging identified in the survey is the lack of cables and moving parts, as the infrastructure is generally much less visible than any other charging solution (see Fig. 11). The main disadvantage of the technology, as indicated by the respondents, is the high

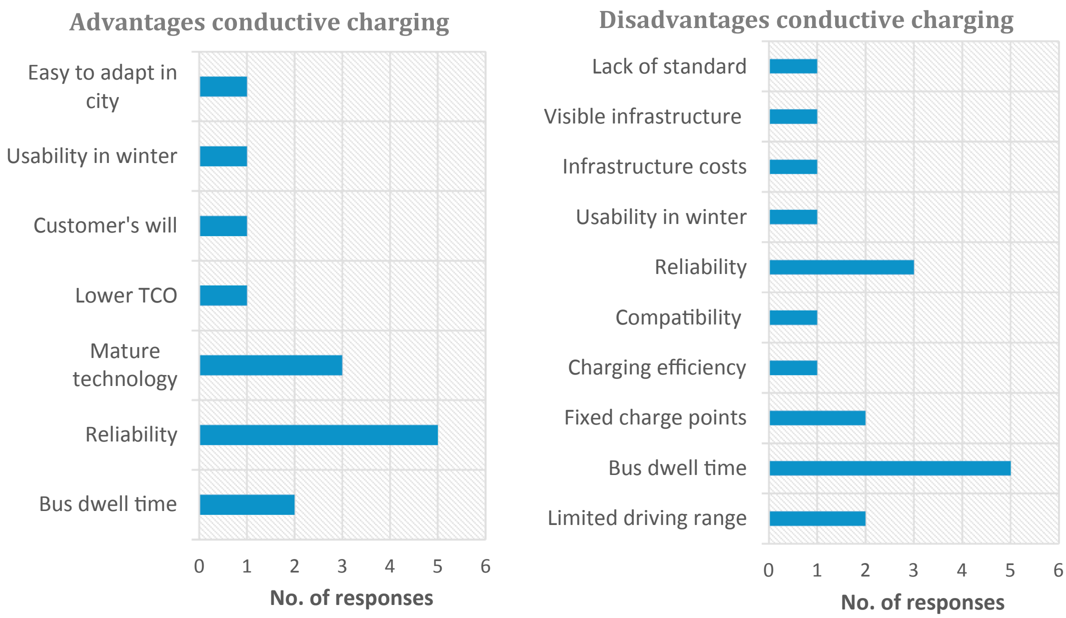

Fig. 10. Advantages (left) and disadvantages (right) of the conductive charging technology as perceived by the survey respondents.

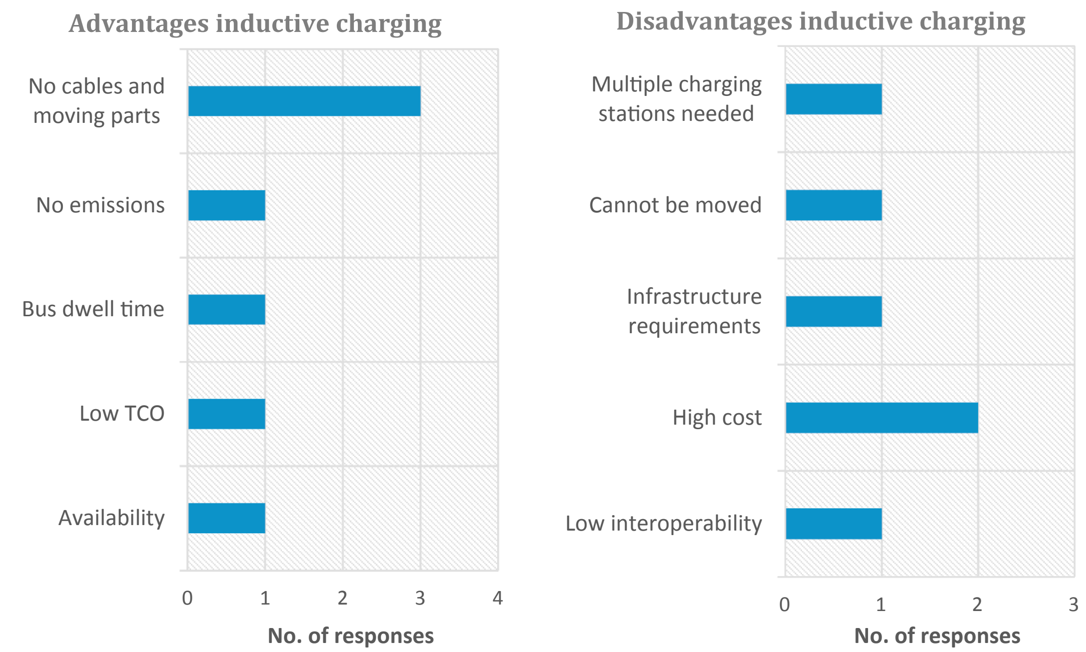

Fig. 11. Advantages (left) and disadvantages (right) of the inductive charging technology, as perceived by the survey respondents.

cost in comparison with other charging technologies (see Section 3) and conventional non-electric bus operation (see Fig. 11).

The survey respondents indicate that a variety of charging strategies has been applied in the different demonstration projects they participate in. The most common charging strategy (with almost 35% of the responses) is fast charging at the bus stop, in most of the cases referring to end stops along the route (see Fig. 12). Then combinations of overnight and fast charging follow (24% of responses), and 10% of responses referred to dynamic opportunity charging as the sole option or in combination with overnight and fast charging. Hydrogen fuel cells are also included in the responses (one case reported in the survey).

5.3. Experiences from implementation

The last part of the survey analysis focuses on the general experiences that the respondents have gained from the demonstration projects. Since the chargers are a central component of the electric bus systems, the technologies earlier discussed should not be seen in a vacuum, but in relation to the surrounding components of the system. We were interested in understanding what motivated the different stakeholder groups to participate in the implementation of projects, and the key issues of concern identified during the operation phase. Such information is relevant in order to understand how different charging technologies and strategies address the specific expectations and interests of the various stakeholder groups.

As Fig. 13 shows, the main motivation for participating in the demonstration projects among all stakeholder groups was to gain experience with the new technologies. Secondly, stakeholders were motivated by the possibility to improve environmental sustainability, and third, they want to lead in the development of new transport concepts. Other motivations were also mentioned in some of the responses. From this survey, we can see that stakeholders testing the electrification of bus transport aim to be part of a

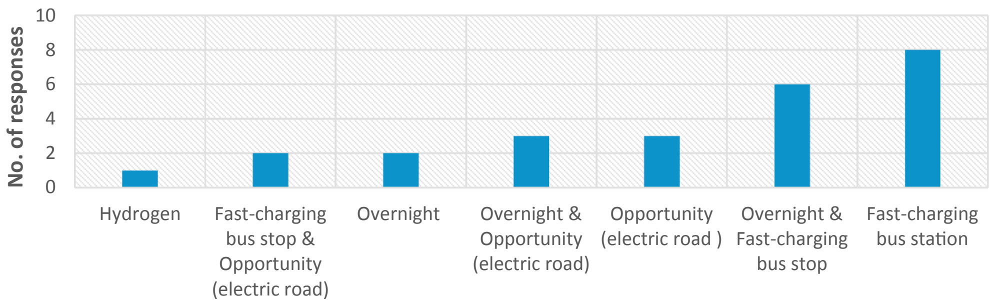

Fig. 12. Charging strategy used in demonstration project(s) in which the respondents are involved.

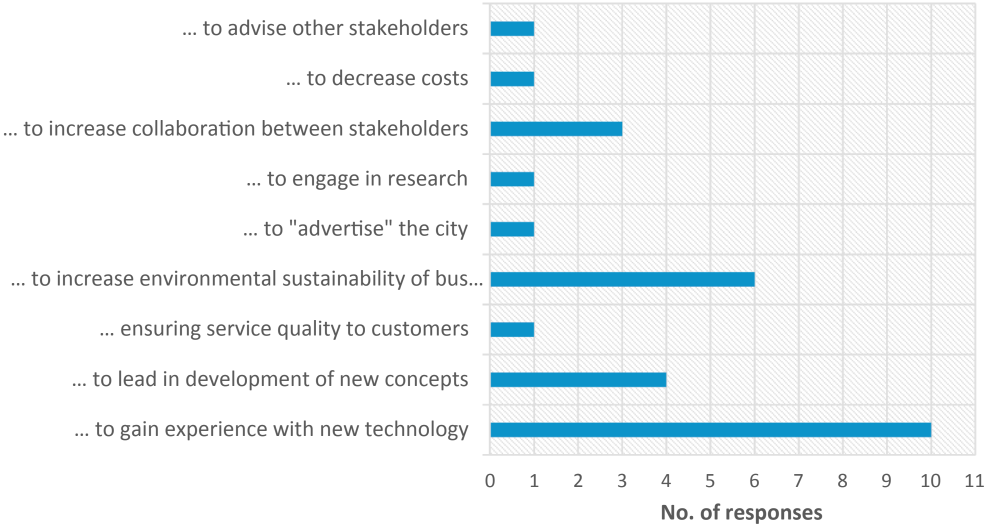

Fig. 13. What motivated participation in the electric bus demonstration project(s) (axis indicates number of responses).

technological innovation process that can generate major environmental benefits such as energy savings, emissions and noise reductions. Through participation in this kind of projects, stakeholders are partakers but also influencers of future development and planning choices.

Analyzing the responses per stakeholder group, respondents from the academia are mainly motivated by the need to gain experience with the new technology, while bus manufacturers are motivated by both the experience and the enhanced collaboration with stakeholders in the sector. Municipality stakeholders that responded to the survey are firstly motivated by the increased environmental benefits, while PTA respondents are mostly interested in gaining experience. Political motivation (e.g. environmentally-motivated strategical decisions) may have some role in motivating participation in such projects as well. Finally, transport operators indicate the will to lead in the development of new concepts as their main motivation.

The difficulties found in compromising on the different perspectives of the stakeholders came first among unexpected issues related to project implementation. Another unexpected issue is related to increase in costs mainly related to the installation of the charger, followed by the drivers' behavior and commitment not to miss any charging occasion. Also reliability and battery performance issues, as well as long project implementation time are mentioned (see Fig. 14). This shows that, although concerns related to the technology costs are important and still require attention, collaboration within the project and alignment of stakeholder

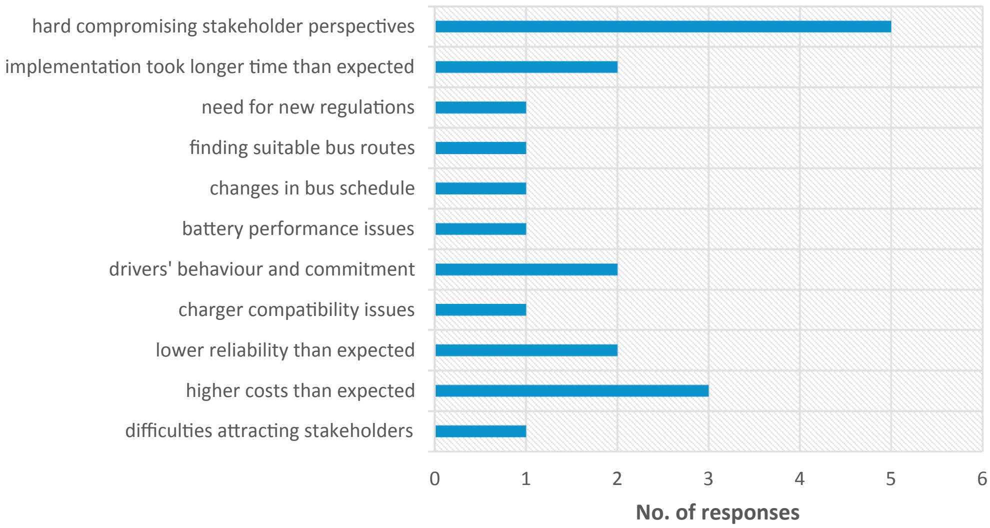

Fig. 14. Main unexpected issues faced by stakeholders during project implementation (axis indicates number of responses).

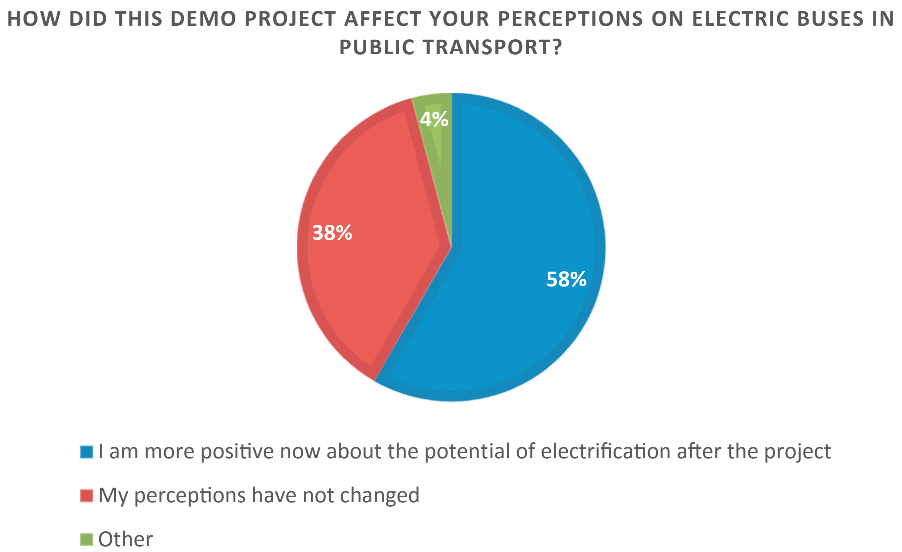

Fig. 15. Perceptions from implementation of electric bus demonstration project(s) as understood by the survey respondents.

perspectives and expectations is of greater importance given the complexity involved in the electrification of public transport.

Though difficulties to find common ground were considered "unexpected" by the respondents, they should not come as a surprise. Since the implementation of these technologies is in demonstration phase and all involved parties are still in the process of acquiring expertise, the frameworks for collaboration are still unclear, and general implementation guidelines do not exist. Therefore, synthesis of experiences, and knowledge sharing are of utmost importance at this stage. Another issue mentioned from the survey respondents is the lack of appropriate regulations for addressing electrification of transport (see Fig. 14). This could cause a variety of problems, such as delays in the charging station construction where building permit regulations for chargers are unclear or non-existent, or difficulties in the formulation of partnerships in case there are no precedents of such collaborations. Such issues could cause unexpected problems to the implementation of the demonstration project, but do not directly relate to the charging technologies or the operation of the electric bus.

Other unexpected issues include compatibility issues for the chargers, identifying suitable bus routes for the demonstration project, the required changes in the bus schedule, potential impact on other bus routes than the one electrified, and difficulties in attracting partners. Aggregating all the responses, we can observe that setbacks in the operation of electric buses in urban

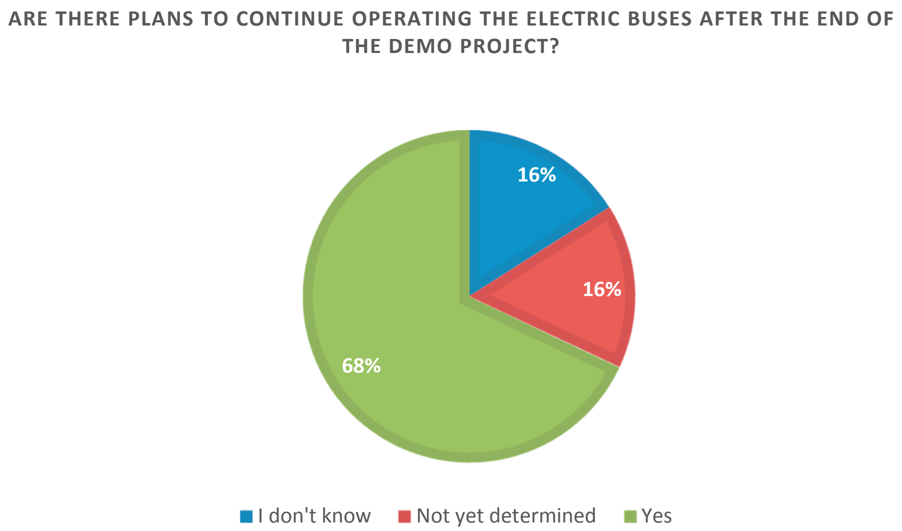

Fig. 16. Plans for continuation of electric bus demonstration project(s) as understood by the survey respondents.

environments occur due to issues related to: (i) *the technologies* (e.g. reliability, compatibility, performance of the bus and charger); (ii) the *project planning* (e.g. costs, time, regulations, bus route and schedule adjustments); and (iii) the *project management* which highly depend on the commitment of the involved parties (e.g. compromising perspectives, attracting stakeholders, drivers' behavior).

Despite the challenges regarding implementation of such projects, the majority of the respondents (58%) has developed a more positive opinion about the potential of electric buses in public transport after being part of a demonstration project (see Fig. 15). A share of 38% of the respondents have retained the same perception as initially, although it was not clarified in the survey whether that prior perception was positive or negative. Most of the respondents (84%) think that the solution tested in the project could be scaled-up. It should be noted that none of the respondents mentions a negative effect from the demonstration project on their perception about electric buses.

In most cases (68% of the responses), there are plans to continue operating the electric buses even after the demonstration project is finished (see Fig. 16). It is interesting to notice that no respondent indicated decisions against continuing the electric bus operation, although the rest of the respondents indicate that they are not aware of future plans.

Fourteen of the respondents offered some indication of which organization they found appropriate to take responsibility for the expansion of an electrified system. Three of the respondents indicated that the PTAs should be responsible for the continuation. Another three of the respondents answered that the PTAs and municipalities should be together responsible for continuation and expansion of electric buses in the fleet. Thus, the majority of responses placed the responsibility for continuation upon public stakeholders. Two respondents indicated that the public transport operators should be responsible for continuing the operation of electric buses after the demonstration project is finished. One respondent indicates that the PTAs in collaboration with the operators should be responsible. Another respondent indicates that it requires a collaboration between several parties for securing continuation including *"[…]municipalities, traffic operators, government, etc"*.

Furthermore, one respondent indicates that the continuation will be the responsibility of the same constellation as the one responsible for the demonstration project (although "the current arrangement" is not specified), while a respondent from the bus manufacturer sector responded that continuation depends upon the customers. Finally, two respondents indicated that they are not certain about who should be responsible. As one respondent puts it, the responsibility of continuation is "[…] *one of the big questions…"*. As mentioned earlier, the PTAs are responsible for most demonstration projects for electric buses in the Nordic region. However, the diverse set of responses obtained in the survey, as well as the uncertainty indicated by a few respondents, shows that the arrangements for continuation of electric bus operation in Nordic cities are still unclear and shall be subject to discussion. In the efforts to expand electric bus adoption rates, the system governance, partnerships and business models for supporting the new system shall be subject to further development.

6. Thematic analysis results

One of the themes emerging, according to the survey responses, is the impact of *technology maturity* on the charging technology choice. Conductive solutions are dominating in the Nordic region so far, and their market-ready status is an advantage against competition. Most of the survey respondents that have indicated conductive charging as the chosen technology for their project mention technology maturity in various wordings. According to one survey respondent: *"[conductive chargers] were chosen before the project started, and because these solutions could be bought in an open market*".

Thus, the stakeholders that responded to the survey seem to be more inclined to use the conductive technology. As one of the survey respondents puts it: "*As we are evaluating the use of electric vehicles in public transportation, we needed something that has been previously tried and tested to be able to focus on the vehicles and traffic instead of pioneering new technologies"*. In other words, there is already high risk associated with these investments, thus the inclination would be to avoid the additional risk of choosing the technology that is less mature. Moreover, this could be an indication of a proximity bias, as conductive technology is the one that is more widespread in the Nordic region.

Several survey respondents touch upon issues of *cost-effectiveness*, and more specifically, the priority given to decreasing the *Total Cost of Ownership (TCO)*, i.e. the vehicle's lifecycle costs. Here, both conductive and inductive charging are discussed, and the reasoning for choosing any of these two technologies was the low TCO. With the exception of one respondent, TCOs are not directly compared between different electric bus configurations, but the comparison seems to occur in relation to conventional buses with internal combustion engines. It should be noted that the main target when making investments, according to one respondent, should be *"optimized total cost of ownership at system level"*.

System approach is necessary for upscaling the use of electric buses in public transport, as a technology that is cost-competitive at demo level might not be so at systems level. For example, depot charging for one bus is not economically challenging, as it requires quite cheap infrastructure to be installed. However, when discussing upscaling, the investment costs might increase significantly, as higher number of vehicles would be needed for replacing buses that charge for longer times at the depot during the day. Additional costs for upgrading the local grid should also be considered.

Another theme that is identified is that of *compatibility*. A respondent explains that they chose conductive chargers because *"The buses had this technology"*. A link between powertrain and charging technology can be observed which, under the current lack of standards for compatibility, enhances lock-ins to specific technologies and manufacturers. Additionally, compatibility should be ensured between the systems for fast and overnight charging at the depot. One of the respondents highlighted the need of a CENELEC (European Committee for Electro-technical Standardization) standard for electric bus chargers.

The last theme we identified is that of *charging efficiency*. Punctuality and high frequency of bus services are two indicators that are critical for evaluating performance. The concept of charging efficiency in this context does not only include the efficiency of the charging equipment, i.e. minimized losses during the power transfer from the charger to the battery and the conversion from AC to DC. Also the optimal combination of charging power capacity (the higher, the better) with the battery size (the smaller, the better) is important as it would reduce charging time. Efficiency was often mentioned in combination with technology maturity and cost-effectiveness, when explaining the rationale for choosing a charging technology for the demonstration project.

A general observation is that charging technology and charging strategy are often treated jointly by the respondents, namely when it comes to the advantages and disadvantages and reasons why specific choices were made. This implies that charging technologies are (and should be) chosen in relation to the preferred charging strategies. From an investment cost perspective, the choice of charging strategy is a balance between the costs of (i) *infrastructure (fixed cost)*; (ii) *batteries (semi-variable cost)*; and (iii) *operation (variable cost)*. For the first aspect, i.e. infrastructure costs, overnight charging is most probably the best option, while from the battery cost perspective stationary and/or dynamic fast charging are better options, as the batteries required are smaller. Opportunity charging also entails lower operation costs, as the drivers are not required to spend more time in the bus while charging, neither an additional number of replacement vehicles is required.

The issues above are illustrated in Table 2. The relationship between the costs is qualitative. For example, operation costs are significantly larger than both the infrastructure and vehicle costs, as previous studies have shown (SKL, 2014; Xylia et al., 2017a). Thus, a small change in operation costs can have a more significant impact on the total costs of a bus network than a larger change in infrastructure costs. Such synergies should be taken into account when deciding the charging technologies and strategies. Eventually costs should be evaluated at systems level and in relation to each other. An example for the case of Stockholm is provided in Xylia et al. (2017a, 2017b), where a cost optimization model is applied to an extensive bus network. The results show that the savings in fuel costs from the switch to electricity could balance the investment costs for charging infrastructure and new electric buses.

However, more aspects affect the strategy choices than just costs. These aspects include the operating range, the flexibility of using the buses in different routes without adjustments, the time schedules, operation requirements under special weather conditions (such as snow, for example), the requirement of adequate space and power capacity, as well as the lifecycle and visual impact of selected alternatives.

Additionally, we may think of themes that were not included in the survey responses, but should have probably been mentioned, as they could also affect upscaling of electric buses in public transport. Issues such as the grid capacity and the battery lifetime, were not mentioned by the survey respondents but should be taken into account when selecting and sizing the charging system, as they can affect both operation and investment costs to a great extent. Another issue not mentioned is the additional energy consumption of auxiliaries. For the case of the Nordic countries, auxiliary consumption for heating during the cold winter months could affect the design requirements (i.e. the battery capacity if the heating is electric), or lead to additional greenhouse gas emissions in case diesel heaters are used.

The fact that these issues are not mentioned in the survey indicates that stakeholders still think small-scale when it comes to bus electrification, despite the expressed intentions to continue and upscale. The duration and scale of the demonstration projects in Nordic countries confirms this. With the exception of a Danish report showing battery lifetime estimations based on demonstration project data (Norregaard et al., 2016), battery degradation has not been studied in detail in the existing literature. Additionally, the scale of demonstrations, i.e. the number of buses tested, is quite small, therefore grid capacity has not been a real issue this far. There should be additional efforts targeted towards developing projects of larger scale and longer duration, i.e. electrification projects for several (interconnected) routes sharing charging infrastructure. Such initiatives would give better opportunities for studying the aforementioned system effects and plan further for upscaling. Stakeholder networks for knowledge dissemination could assist in this process.

Table 2
Qualitative comparison of charging strategies in terms of associated costs and other planning considerations.

Charging strategy	Costs			Other planning considerations
	Infrastructure	Vehicle battery	Operation	
overnight charging (at depot)	decrease	increase	increase	longer range higher flexibility affects battery health
Stationary fast charging (bus stop)	increase	decrease	increase	larger passenger capacity lower flexibility increased drivers' costs
Dynamic fast charging (electric road)	increase	decrease	decrease	benefits from synergies low environmental impact from battery higher flexibility

7. Conclusions

Despite many studies dealing with electric bus performance, little attention has been given to charging infrastructure. In this paper, we gathered insights from electric bus demonstration projects with focus on charging technologies in order to understand the benefits and drawbacks of each solution, and the challenges related to charging as the use of electric buses in public transport is up scaled.

A first observation is that commercially available options, as well as the variety of local contexts and service requirements tend to guide the technological choices. The most plausible course of development entails a mix of technologies and strategies for charging, which relates to more factors than just economic considerations. Future upscaling should be evaluated at systems level, where demonstration projects serve to provide an indication of potential synergies, though they cannot provide answers to all challenges involved.

Conductive charging is the technology which is most tested in the Nordic countries so far. The survey respondents consider the technology to be mature, and the maximum charging power of conductive chargers is considerably higher than inductive chargers. High charging power capacities are key to reducing charging time, and thus also bus dwell time and operational costs of electric bus solutions in public transport.

On the other hand, the survey respondents recognize benefits of the inductive technology as well, such as the lack of moving parts which could reduce the maintenance costs for infrastructure and the minimal visibility of the equipment. Such attributes can be advantageous, especially in dense urban environments, where space availability for building infrastructure can be challenging and costly. However, these issues are not so evident in our analysis since most projects are based on conductive technology.

Using thematic analysis on the material from the stakeholder survey, the main charging-related themes affecting future electrification of public bus transport include market-readiness, cost-effectiveness, total costs of ownership (TCO), and charging efficiency of the technologies in place. It should be noted that the survey responses show that the selection of charging technologies and consequent charging strategies is not only based on costs. Other aspects, such as reliability, dwell times, visual impact, and performance during winter time have been identified as additional factors that come into play. Furthermore, we observe that it is difficult – and perhaps not necessary - to separate the choice of technology from the choice of charging strategy. This indicates that exploring the options of charging technologies (e.g. conductive, inductive) and charging strategies (e.g. overnight, fast-charging) is integrated from the stakeholders' perspective in the same decision-making process.

It is interesting to note that survey respondents identified the difficulty of compromising on the different stakeholders' perspectives was the most common unexpected issue when it comes to project implementation. In summary, the unexpected issues identified by the survey respondents are related to the following categories: (i) *the technologies* (e.g. reliability, compatibility, performance of the bus and charger); (ii) *the project planning* (e.g. costs, time, regulations, bus route and schedule adjustments); and (iii) *the project management* and involved parties' *commitment* (e.g. compromising perspectives, attracting stakeholders, drivers' behavior). The lessons learnt from the demonstration projects offer valuable experience in tackling unexpected issues that have been addressed and solved. Meanwhile, lack of clear institutional frameworks and continuation plans poses a risk that the knowledge acquired from the demonstrations might be lost.

In relation to the above, the still open issue of infrastructure ownership is key to developing and regulating the market. The survey respondents indicate that, although the general perception of electric bus demonstrations is largely positive, the continuation and upscaling of these initiatives is quite unclear. Hence it is recommended that the selection of charging locations and technologies, as well as stakeholder constellations to participate in such demonstration projects is made early and in such way that continuation after the demonstration period is not an obligation, but a reasonable and cost-effective next step.

A final note should be given to the challenge of compiling information about charging technologies and strategies applied for electric bus demonstration projects. Project results are not always reported publicly or regularly updated. Stakeholder networks and other knowledge dissemination activities should be encouraged in order to make more informed choices and accelerate implementation.

With the exception of factors related to weather conditions (i.e. usability in winter), the survey responses on advantages and disadvantages of different charging solutions could be relevant to other European cities, where dense traffic and extensive public transport networks with high costs are common issues. An interesting future case to investigate is how charging technologies and upscaling of electric bus services has been realized in contexts other than the European. An interesting case is China, where there are examples of cities relying almost exclusively on electric buses for public transport services.

Finally, the role of charging technologies, with the insights provided in this paper, could also be taken into account for updating existing and/or developing new KPIs for more detailed evaluation of public transport services where electric buses are used. The perspectives on charging technologies of drivers and users could also be incorporated into the evaluation.

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