UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

DETAILED ANALYSIS OF THE IMPLICATIONS OF THE URBAN PUBLIC TRANSPORT TRANSITIONING TO A FULLY ELECTRIFIED MODEL

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COMPANY: IBERDROLA S.A.
Madrid, 21st July 2019

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SUMMARY

The transition from conventionally fuelled urban buses towards electric buses seems inevitable given the demands of civil society and public authorities and the increasing ecological requirements of EU policies. However, the global bus fleet is still predominantly powered by diesel and CNG, and, with the exception of China, the share of electric buses in the total fleet is minimal. Therefore, there is still much work to do in this matter.

Momentum for eBuses is building globally even if the large-scale adoption of electric mobility solutions for urban public transport is accompanied by a large number of technical and economic barriers. The key actors for this transition will be municipalities. Since local conditions are critical for the choice of the eBus solution variation, local authorities will need to promote the implementation of this technology and find the optimal solution design for their municipality.

To find suitable technological, economic and ecological solutions in such complex processes, it is necessary to follow appropriate decision-making tools, which should be able to consider each relevant variable (internal and external) of the eBus solution.

Also, for municipalities to be successful, their ability to pool and look after the interests of all stakeholders involved in the process will be key.

When adequate solutions are found considering all the relevant input data, the eBus is a viable alternative to diesel and CNG buses in technical, economic and environmental terms. In fact, if the environmental costs were internalized, the eBus would be much more competitive than the rest of the current alternatives.

Municipalities still have many barriers of different nature to overcome so that the adoption of eBuses reaches or exceeds China's penetration levels. However, everything seems to indicate that if the process is carried out in a gradual, reasonable manner and with the collaboration of all the actors involved, the result will be beneficial for all and it will be a great industrial opportunity for Europe.

TABLE OF CONTENTS

List of Acronyms

BEV	Battery Electric Vehicle
CNG	Compressed Natural Gas
DSO	Distribution System Operator
eBus	Electric bus
EMT	Empresa Municipal de Transportes de Madrid, S.A.
EV	Electric Vehicle
HDV	Heavy Duty Vehicles
ICE	Internal Combustion Engine
M€	Million Euros
O&M	Operation and Maintenance
RES	Renewable Energy Sources
TCO	Total Cost of Ownership
TSO	Transmission System Operator

List of Figures

List of Tables

1. INTRODUCTION

In recent times, public attention is focusing on urban areas, as there is a growing concern with the large number of problems that are emerging and that must be addressed in the short term in these environments. Gentrification, air quality, human footprint, lack of coexistence and ghettoization, optimizing resources, traffic and road safety, and noise are some that can be mentioned. In addition, the urbanization of the population means that any problem that occurs in cities affects a large part of the world population due to the fact that more than half of the world population lives in cities with more than 300,000 inhabitants and that figure will increase to 70% by 2050 [1]. Some of those problems depend on the level of development of the area. However, some of them could apply to every urban area in general.

In this scenario, air pollution and public health stand out among the other issues. Public authorities and the public eye are increasingly focused on both these subjects. In fact, the EU has set the medium-term goal of reducing GHG emissions by at least 40% by 2030 when compared to 1990 levels with the aim of limiting global warming to 2 ºC. The transport sector has a key contribution to make to the total reduction since it accounts for about a quarter of total GHG emissions in the EU, mainly in urban areas.

Public authorities are setting their focus on options to decarbonize urban environments. In this respect, the electrification of the transport is essential to meet the decarbonisation and energy security goals of the EU. Electrification of transport combines an energy efficient power train system with the opportunity of using any source of energy other than fossil fuels including those from renewable sources. In brief, electric vehicles are much more environmentally friendly, as their engines consume less energy, have greater efficiency as well as use the phenomenon of energy recovery.

In fact, urban buses are the first road transport mode where electrification is having a significant impact today and it is expected to be the first road transport mode to reach zero emission. This trend is driven primarily by the rising awareness of toxic air pollution in the cities from internal combustion engines.

At the end of 2017 there were 3 million city buses in operation worldwide; of these, 385.000 belong to the category of electric bus, but this figure is expected to widely increase. Electric vehicle skeptics often say that the cost of switching is prohibitive. However, battery costs have come down dramatically and electrification of urban public transport seems closer than ever.

Beyond cost considerations, e-buses offer many advantages: air quality, customer experience, load balancing, GHG emission reduction, possibility of supply from renewable energies, oil displacement and energy security, among others.

However, there is no doubt that the impact of eBuses, with different modes of recharge, in the management of fleets will be considerable when coexisting with diesel and CNG buses. What is more, electrifying the entire fleet of the EMT, for instance, would cost close to 1,000 M€ (calculated applying the costs of eBuses of recent tenders in Spain [2]) and would probably require more depots than the current ones.

Taking into account that the transition to electricity is highly probable, assuming this complexity, being able to try different recharging schemes and financing methods with a certain margin, has several advantages:

- Fleet management logistics can be adapted with time and with a minor impact on the quality of service.
- The acquisition strategy of the future fleet could be improved with possible cost savings, valuing options such as partial or total leasing of the vehicle or other emerging financing alternatives.
- Many different business models could be tested, such as selling part of the energy of the unoccupied fleet to the electric grid or solar panels in depots.

As stated, the rollout of eBus solutions is accompanied by substantial challenges as well as opportunities. The main issue remains in how to design the technology switching plan of fleets in municipalities with the maximum optimality possible. The implementation process is complex, and many factors of different nature need to be considered simultaneously.

On the one hand, environmental policies, passenger expectations an EU Transport Policy call for the transition to bus fleets based on electric technology, but when trying to switch technologies is when socio-economic and technological strategy issues arise, that to solve require great efforts in R&D (see Figure 1).

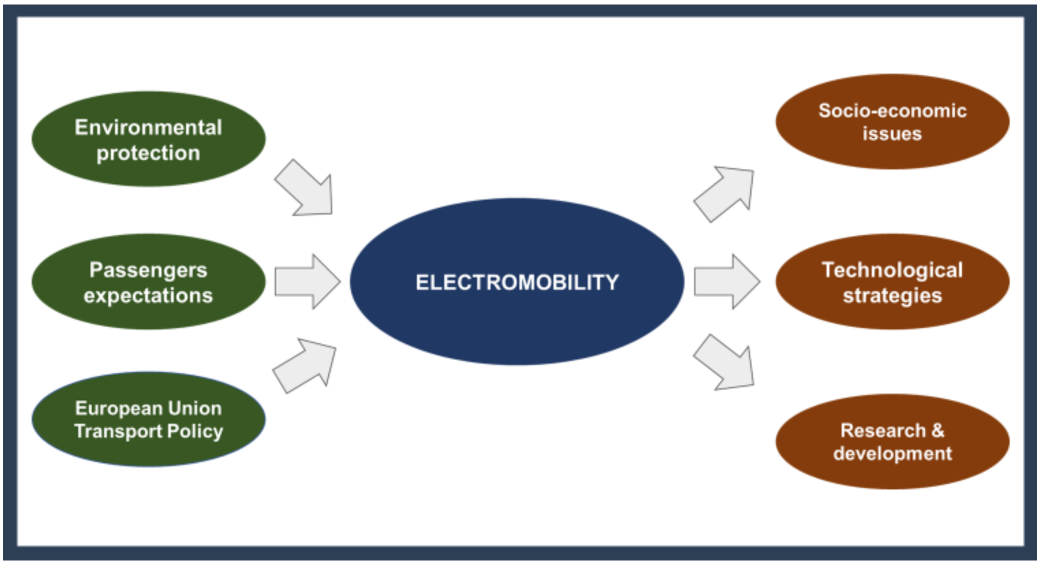


Figure 1. Factors affecting the development of electromobility

Therefore, electrification of transport in cities requires to take into consideration a range of strategies based on a mix of policy, technology and behavioural changes. Being a recent trend, there is a need to demonstrate the economic, environmental and societal feasibility of electric urban bus systems. The ambition of this Master Thesis is to contribute to the clarification of these issues and to help in the promotion of the electric bus.

1.1. OBJECTIVE

As explained, it seems that the transition from conventionally fuelled urban buses towards electric buses is inevitable given the demands of civil society and public authorities and the increasing ecological requirements of EU policies.

This change, however, presents the challenge of how to enable large-scale adoption of the electric bus optimally. The implementation of the electric bus is really complex, with a wide variety of factors to consider in technical, transport, economic and ecological issues, which have a significant influence on the choice of the scenario of the bus fleet for each application. The local conditions considered in the technological, human and economic sense are important to select the optimal variant and scenario of the fleet exchange process. Each opportunity of implementation should be carefully analysed since local conditions considered are essential when trying to define the optimal deployment.

The aim of this Master Thesis is to shed some light on the factors, considerations and requirements that should be taken into account when trying to define this optimal implementation model, mainly from the point of view of adopting municipalities and bus operators but also mentioning the generalities that all interested parties should bear in mind.

1.2. METHODOLOGY

As explained in Figure 1, the electromobility has several reasons to be and in turn several work lines to develop. In order to work on those investigating lines, the following procedure has been defined to arrive at the final results:

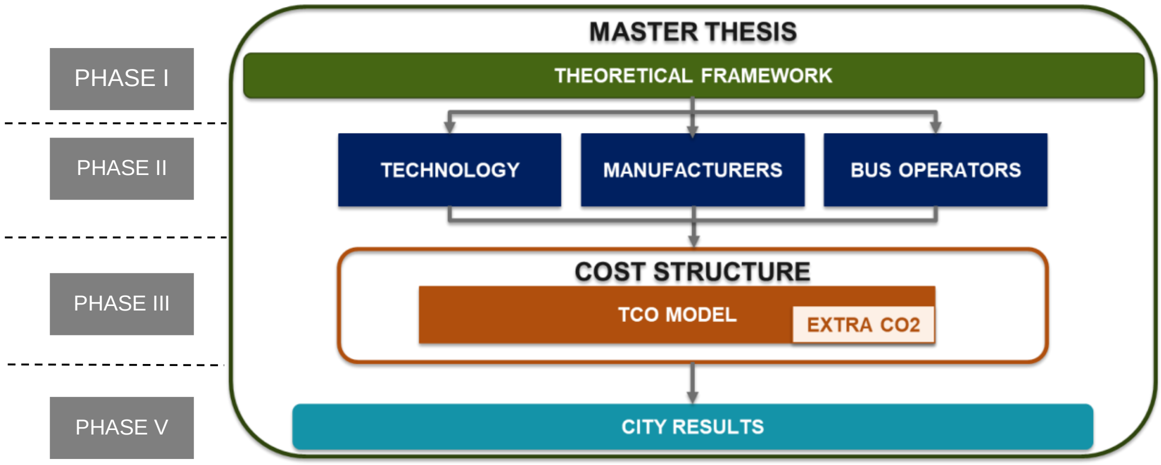


Figure 2. Summary of the methodology

As Figure 2 shows the methodology is divided in four different phases. Each phase is structured as follows:

- Phase I: THEORETICAL FRAMEWORK

  Data collection on environmental policies in force, technology, market figures and current regulation.

- Phase II: DATA ANALYSIS

  Analysis on the technical solutions available for eBus implementation. Contrast of information with eBus manufacturers and other relevant agents of the process.

Draw conclusion about relevant technical factors that most affect the eBus operation.

- Phase III: DEVELOPMENT OF THE TCO MODEL

  Analysis of the economical aspect of the implementation of the eBus.

  Development of a TCO model to compare costs of bus technologies, including the analysis of real eBus deployment cases in Spain.

  Brief environmental cost analysis comparing bus technologies.

- Phase IV: RESULTS

  Definition of barriers, possible solutions and guidelines for municipalities in terms of large-scale eBus adoption.

2. STATE OF THE ART

The objective of this section is to try to give the reader few guidelines of the current situation so that the rationale of the project and the statements and assumptions that have been done in the following sections are understandable.

2.1.1. Scope on mobility and public transport

Electromobility is usually considered as one of the technologies that would contribute to European Union decarbonisation and environmental targets. Often times focus is set on electric vehicles, yet by the end of 2019 the displacement of diesel barrels a day caused by electric buses will be more than three times the displacement by all the world's passenger electric vehicles [3]. In fact, urban buses are the first road transport mode where electrification is having a significant impact today and it is expected to be the first transport mode to reach zero emission.

In this context, public transport shall play a key role in road towards decarbonization. Currently, the vast majority of the bus fleet operated by public transport companies are conventional fuel diesel buses, which are emitters of polluting substances. However, one efficient way to achieve that is shifting towards clean fuels and modern electric buses, an option that is already under implementation in several cities around the world. In fact, as shown by the data presented in [4], any significant reduction in the impact of urban public transport on the environment can only be achieved through the substitution of diesel buses for alternative drive systems.

It is important to consider the eBus from a systemic perspective to assess whether it is an economically viable option that reduces greenhouse gas (GHG) emissions in the transport sector. The change seems inevitable, what is yet to define is when and how it will be done in order to follow the steps already taken to make the transition cost-efficiently.

The main drivers of the deployment of urban public transport are the regulatory policies and political commitments of governments concerned with air quality and climate change. In the starting steps of this transition, authorities focused on limiting the emissions of conventional technology modes of transport, for instance through standards in Europe. A European standard on polluting emissions is a set of requirements that regulate the acceptable limits for the emission of internal combustion gases from new vehicles sold in the Member States of the European Union. The emission standards are defined in a series of directives of the European Union with progressive implementation that are increasingly restrictive (see Figure 3).

Currently, the emissions of nitrogen oxides (NOX), hydrocarbons (HC), carbon monoxide (CO) and particles are regulated for most types of vehicles, nonetheless different rules apply for each type of vehicle. In this matter, the last standard in force is EURO6 since 2014, which is a standard that substantially reduces local pollutant emissions of HDV [5].

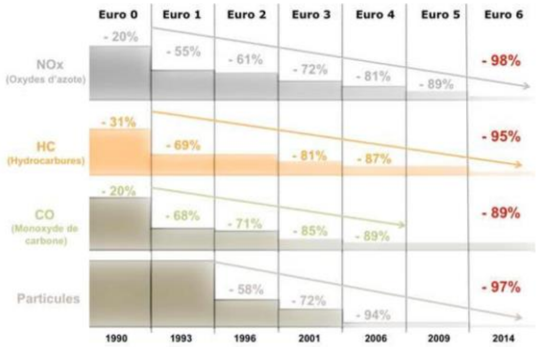


Figure 3. Evolution of the EURO standard [2]

However, with the increasing worry about environmental issues, as previously mentioned, any significant reduction in the impact of urban public transport on the environment can only be achieved through the substitution of diesel buses for alternative drive systems [4], therefore, focus is now set in transitioning to bus fleets based on alternative fuels. These technologies improve by far what is forced by the EURO standard.

In this sense, many cities started taking local initiatives to reduce emissions form urban buses. In a survey carried out by the European Commission several years ago (2012) to 70 authorities, operators and municipalities with 68.500 buses in their fleets more than 40% of them stated the willingness to transition towards electric buses [2], and since then the will in European cities has only grown.

For instance, 22 cities have signed the C40 Clean Bus Declaration (London, Paris, Los Angeles, Copenhagen, Barcelona…), pledging to adopt innovative clean bus technologies such as electric, hybrid and hydrogen buses. They are committed to increasingly procure zero-emission buses to end up only purchasing them from 2025 onwards [6], what will suppose the switching of 42.000 buses to low emission incorporation out of 160.000 buses in their fleet by 2020.

At European level, the Netherlands leads demanding 100% of the sales of public transport buses with zero emissions (ZEV) by 2025, followed by the fleet of 100% of ZEV by 2030. At regional level, cities, regions, manufacturers and transport organizations supported the common ambition to accelerate the deployment of clean buses, formalized by the signing of the European Clean Bus Deployment Initiative.

The issue is that, up until now, those initiatives were not coordinated, with different restrictions in each city that depend on the environmental case of each city. Hence, there is a need for a set of clear rules of common application in the cities that need to take measures. It is the role of the EU to provide the municipalities with global and clear guidelines.

Recently, the EU has intended to send a clear message by modifying the Directive 2009/33/EC (or the Clean Vehicles Directive) to establish binding targets for the public procurement of clean vehicles according to the economic capacity and exposure to pollution of each MS. Applies to transport vehicle contracts by public road, by road and passenger transport, by public entities or private operators that execute a public service. They have to take into account the energy consumption and emissions of CO2, NOX, non-metallic hydrocarbons and particles since 2010. In the case of buses, the objectives range from 28% to 45% until 2025 and from 33% to 65% until 2030. With respect to Spain, the required objectives are set in the 45% until 2025 and 65% until 2030. It should be noted that the new modification includes all types of contracts and not just those of direct purchase [7].

2.1.2. Expected benefits of transport electrification

The reason of being behind the modification of the Directive 2009/33/EC is the willingness of the EU in creating a sustainable, competitive, secure and decarbonised energy system, considering that achieving a sustainable transport is a key objective of the common transport policy. Also, beyond environmental considerations (air quality, GHG emission reduction), eBuses offer many advantages, such as customer experience, load balancing, possibility of supply from renewable energies, oil displacement and energy security, among others. Hereafter, the many benefices of eBuses will be mentioned:

- Improvement of the air quality: one of the main reasons to electrify the public transport is the negative impact on health of conventional buses. Every year, nitrogen oxide from transportation emissions contributes to about 38,000 premature deaths worldwide. Electric buses help on the reduction of those noxious gas emissions [8], in addition to particulate matters (PM). In fact, buses run close to people where noise and emissions have the most severe impact on their lives.
- Reduction of GHG emissions [9]: in Spain, transport emissions account for 25% of the total GHG emissions. Also 1/3 of road traffic emissions are concentrated in urban agglomerations and 30% of road traffic emissions are due to heavy vehicles. Taking all these data into account, one can see the great potential for reducing GHG emissions of the urban public transport.

  The actual reduction that ultimately becomes effective will depend above all on the generation mix with which the recharge is made. For instance, with the current generation mix in Spain each electric bus pollutes 0,246 kg/kWh against the 2,68 kg/sm3 of diesel buses.

  For additional information on these two bullets, Figure 4 shows the average unit emissions of the Spanish HDV fleet.

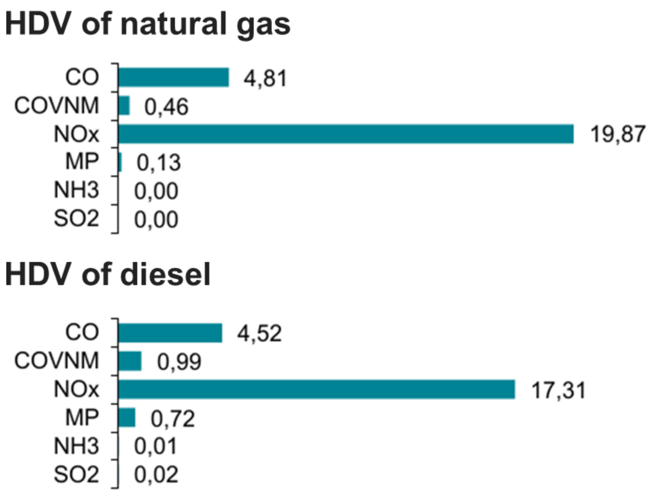


Figure 4. Average unit emissions of the Spanish heavy vehicles fleet (g/kg of consumed fuel) [10]

- Greater technology efficiency: it is well-known that the efficiency of electric motors is higher than in the case of combustion motors. The electric vehicle with electricity supplied by the Spanish electric mix of 2016 has an efficiency between 1,8-3,1 times higher than the diesel vehicles (almost the same with 100% CCGT). Besides, the EV with electricity supplied exclusively by renewables would have an efficiency between 3-5 times higher than that of diesel vehicles.

		ICE		BEV		
		CNG	Petrol/Diesel	100% Renewables	Spanish mix 2016	100% CCGT
Well to tank	*Fuel refine, Transport, storage and distribution*		85-88%			
	NG Drilling, Processing and Transportation	93%			93%	93%
	Electricity production: NG Power Plant				64%	54%
	Electricity Transport & Distribution			94%	94%	94%
	NG Distribution	99%				
	NG Compression	98%				
Tank to wheel	*Charging Efficiency*			84-95%	84-95%	84-95%
	Parasitic losses (control system, motor cooling, steering power...)			97,5%	97,5%	97,5%
	Auxiliary Losses (fans, headlights, navegation systems...)	16%	16-25%	98%	98%	98%
	Engine efficiency (motor + trasnmision)			84%	84%	84%
	Overall Energy efficiency	14%	14-21%	63-72%	38-43%	32-36%

Figure 5. Efficiency comparison between ICE and BEV technologies [2]

- Reduction of noise: in urban areas buses are HDV that have great potential to reduce high noise emissions. The study in [11] shows that:
  - With increasing speeds, the reduction of noise of the electric bus decreases. Their isolated comparison of the buses revealed large sound level differences of up to 14 dB(A) at low speeds.
  - On roads with heavy traffic they found almost no noise reduction using the electric buses.
  - On the contrary, the use of electric buses in a quiet residential area averages a noise reduction of 5 dB (A).

  Therefore, results on [11] prove that is a great potential for noise reduction when using electric buses on routes with a high bus share of total traffic and low average travel speeds.

- Reduction of energy dependence: energy dependence is defined as the amount of primary energy that must be imported into a country for its supply in the form of heat, electricity or transport. A high energy dependence causes a deficit in the trade balance of the countries and can be the cause of instabilities and shortages of energy costs. Spain has an external dependence on energy sources of 73% according to [12] (Figure 6), being one of the most dependant countries of the European Union.

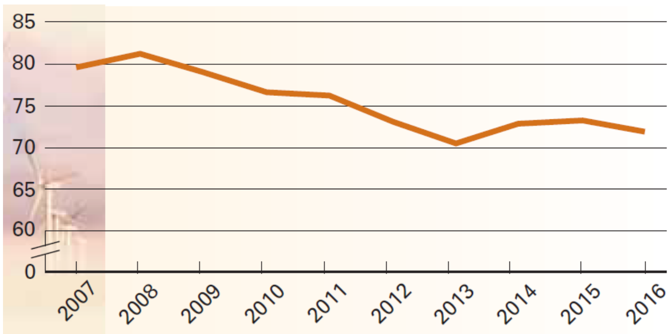


Figure 6. Spanish energy dependency (%) [12]

To combat this problem, it is necessary to look for own resources within the national territory that can supply all or most of the country's energy consumption. In this context, Electric buses arise as a partial solution that reduces this dependence associated with the use of conventional fuels.

- Improvement of the competitiveness of the European industry: a last benefit of alternative fuels is the opportunity to improve competitiveness of the European economy. With cities all over the world facing similar challenges, markets for clean, smart mobility and transport solutions are expected to strongly grow. Therefore, alternative fuels technologies are huge opportunity for European industry if it takes advantage of the market niche available.

However, there is need to balance benefits and barriers form the electrification of the transport. For instance, the economic impact of the National Integrated Energy and Climate Plan (PNIEC) presented by the Council of Ministers estimates that in order to fulfil the plans of the electrification of transport, between 2021 and 2030 an economic over-effort of more than 2.500M€ will need to be done. The document breaks down how investment should be delivered: 712 M€ for passenger cars, 23 M€ for motorcycles and 1.808M€ for buses and other electric mobility vehicles (vans, bicycles, trucks...) [13].

Electrification of transport in cities requires to take into consideration a range of strategies based on costs, policy, technology and behavioural changes. In brief, Europe wants a sustainable, silent, safe and secure transport, a transport mode that is attractive for passengers and delivers reliable services to cities.

2.2. CURRENT SITUATION OF THE EBUS

At the end of 2018 there were about 3 million city buses in operation worldwide; of these, 425.000 belong to the category of electric bus, but this figure is expected to widely increase (already a 32% increase in 2018) [14].

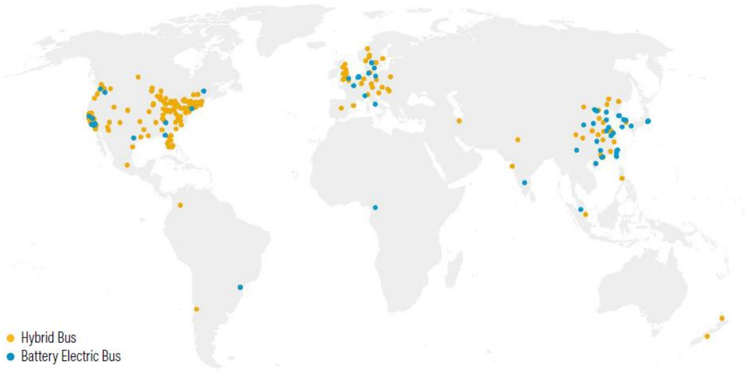


Figure 7. Electric bus and hybrid electric bus adoption worldwide [15]

China has been pushing in this area for several years, while in Europe, public awareness of urban air quality issues has increased in recent years. Cities and local governments have more and more freedom to step up their efforts in changing over their municipal bus fleets. At the same time, falling battery prices are making electric buses more economically attractive.

Nonetheless, it should be noted that the global bus fleet is still predominantly powered by diesel and CNG, and, with the exception of China, the share of electric buses in the total fleet is minimal. Around 13% of the total global municipal bus fleet was electric in 2017 (99% in China).

Momentum for eBuses is building globally and it seems that urban public transport will be the first segment of road transport to be fully electrifies. The rate of electrification to be followed is still uncertain, especially in Europe and the US which are starting to make relevant investment efforts.

2.2.1. Current demand of eBuses

Given that it has a significant unequal distribution among the different regions of the world, information on demand will be detailed with geographical distinction.

2.2.1.1. China

China is by far the largest producer, buyer and user of electric buses. Domestic demand in China has grown exponentially since its inception due to national sales targets, support subsidies and municipal air quality objectives. In fact, until the end of 2016, the combined national and regional subsidies in China brought the initial capital cost of eBuses below that of a diesel bus, which is usually the main barrier when purchasing eBuses.

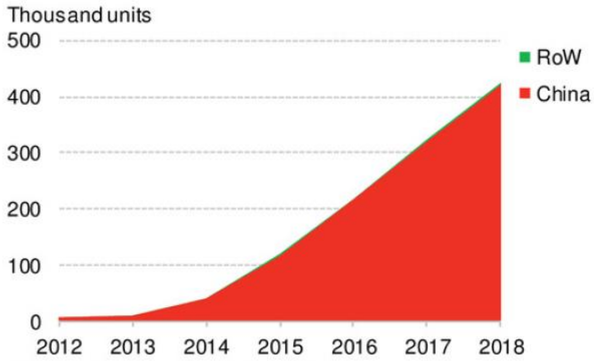


Figure 8. Global eBus fleet (RoW: Rest of the World) [14]

Figure 8 shows the units of eBuses that currently road worldwide. It is obvious the vast difference in situation present in the current market. One of the main boosters of this situation is that major cities like Shanghai and Shenzhen have stopped purchasing new internal combustion engine (ICE) municipal buses and are only buying electric. As a result, 99% of the cumulative number of e-buses sold globally at the end of 2017 were in China.

However, in 2017, eBus sales in China were slightly lower than in the previous year, an exception to the pattern of recent years that was a result of the suspension of subsidies. The share of e-buses in total bus sales in China increased to 22% in 2017, up from just 0.6% in 2011. E-buses now make up around 17% of the total Chinese bus fleet and pure electric buses clearly dominate over plug-in hybrid buses.
More than 30 Chinese cities have plans to reach 100% electric fleets by 2020. Pure electric buses have not only become commonplace in major Chinese cities like Beijing, Guangzhou, Shenzhen, Tianjin, Hangzhou, Nanjing, Changsha and Xian, but also spread to other medium- to small-sized cities in the country.

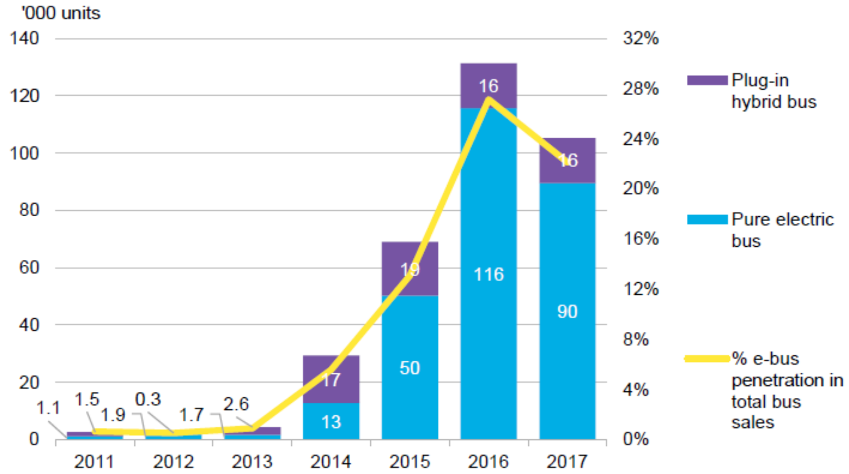


Figure 9. China electric bus sales and share of total bus sales [16]

It is highly important to understand why China is leading the transition to fully electric public transport, in order to be able to replicate successful actions and be able to keep pace with electrification.

- Funding: as mentioned, in China, since the implementation of eBuses began, national and regional authorities focused their efforts on breaking down the main barrier of eBuses: high upfront costs. Therefore, until the end of 2016, combined national and regional subsidies were able to bring the initial capital cost of an eBus below that of a similar diesel bus.

- Urban pollution and reduced oil imports: being the largest urban population in the world, the local air pollution issues due to the transport demand are a major political and health issue. In addition, China also aims to reduce its dependence on imported oil.

- Blank slate: China is a country with a late development compared to the US and the USA, thus many Chinese cities are building completely new public transport networks. Meanwhile, in the other two regions, bus operators need to find new ways to incorporate new electrical technology in a well-established existing infrastructure, which turns out to be much more problematic.

- Industrial policy: the Asian country is committed to electric vehicles, in large part, for reasons of industrial policy given the whole industry that has been generated around this technology. The government is committed to developing local brands that will be competitive outside the national market, in fact it has been one of the reasons for the subsidies.

- Great commitment to innovation: China is known as one of the leading countries in innovation matter of new technologies. Concerning eBuses, 58% of the patents relating to electric mass transportation technologies originate from the Asia-Pacific region, primarily dominated by China, Japan and South Korea (Figure 10). The region's motivation to innovate in the sector is driven by climate concerns and population density in urban areas. Europe is a recent entrant in the domain, with 20% share of all patents [2].

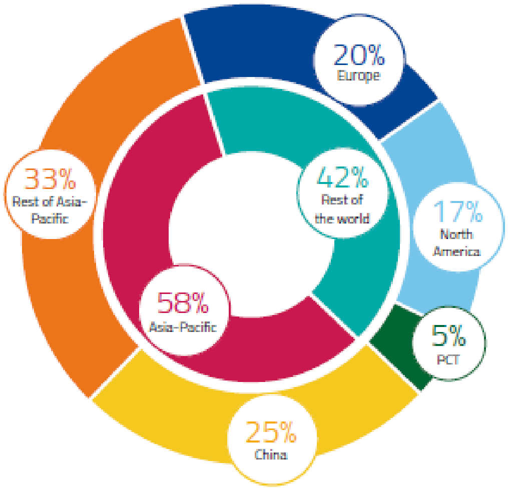


Figure 10. Geographical presence of patents

Over the long-term China will continue to have the largest municipal fleet worldwide and it seems that a great portion of non-municipal buses will also be electrified in the future. The estimation is that China will reach the 80% of penetration by 2040.

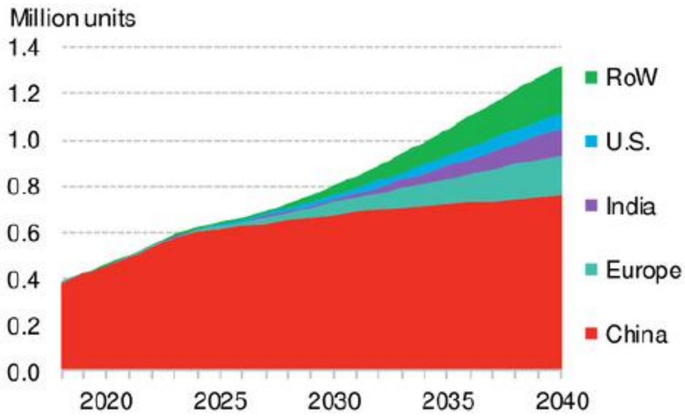


Figure 11. Global municipal eBus fleet

2.2.1.2. Europe

The European market is far from being what is Chinese, although interest and sales are beginning to take off. The main drivers of the deployment of urban public transport at this stage are the regulatory policies and political commitments of governments concerned with air quality and climate change. With the new policies and political commitments taken in European countries, widescale adoption of electric buses is near.

At the end of 2018, European roads accounted for 2.250 electric buses [14], with about 1.600 pure electric buses. The eBus market focuses mainly on metropolitan areas, where major cities are under pressure to find ways to improve air quality and cut CO_2 emissions. Although European cities initially focused on pilot projects, commercial roll-out is now underway [17].

Concerning adopting countries, the U.K. has the largest electric bus fleet in Europe in absolute terms, but the share of electric buses in the total municipal bus fleet in the country was still below 1% in 2017. In total, share of electric buses in the municipal bus fleet in the whole region was around 1.6% in 2017 [16]. Figure 12 shows the electric bus figures per European country and even if it is not completely actualised (2017), it shows the order of magnitude. It can be seen, that only considering pure electric buses or eBuses Netherlands is by far leading in Europe.

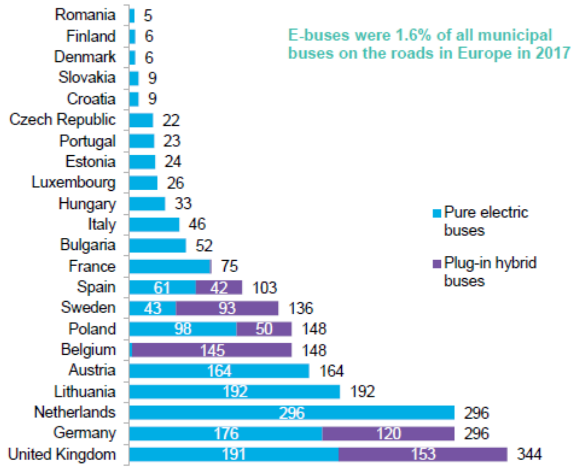


Figure 12. Electric bus fleets in Europe (2017) [16]

Europe will remain as the second biggest market for municipal eBuses over the medium-term. Due to the modification of the Clean Vehicle Directive, over 6% of Europe's municipal bus fleet (around 12.000 buses) are expected to be electric by the end of 2025.

After 2025, the economics of eBuses will dramatically improve and policy targets will no longer be the primary driver of eBus adoption. Due to falling lithium-ion battery costs, eBuses are expected to be cheaper on an upfront basis than comparable diesel buses in most countries form 2030 on. Therefore, Europe is expected to achieve 80% of fleet penetration.

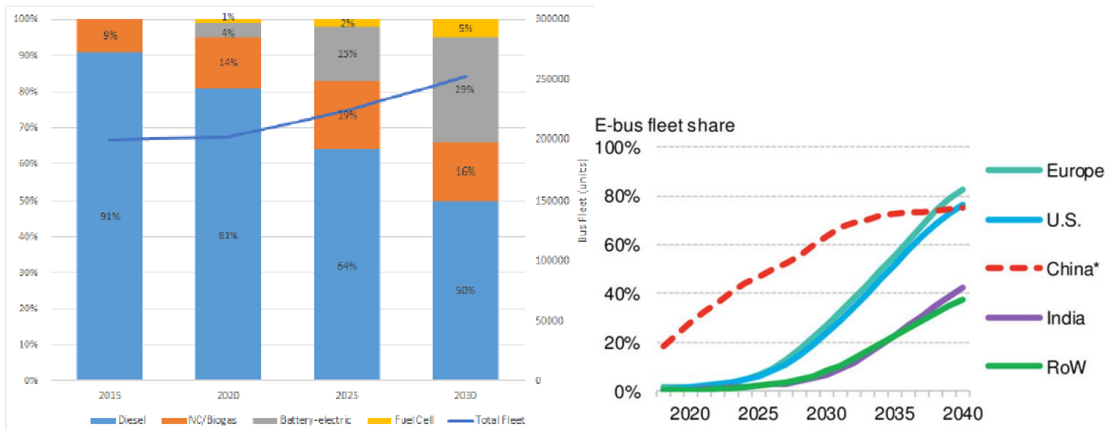


Figure 13. European urban bus fleet evolution [2] and [14][1]

Figure 13 shows different estimates on bus fleet penetration by technologies, although it can be seen that figures do not differ as much. What seems clear is that battery-electric buses will be the main technology to replace diesel buses.

Concerning Spain, many cities have tested eBuses in their fleets and have ended up buying them, namely Madrid, Barcelona, Bilbao, San Sebastian, Vitoria, Badajoz…Figure 14 gathers the details of certain Spanish bus fleets, as an example.

[1] Data of China includes all road eBuses.

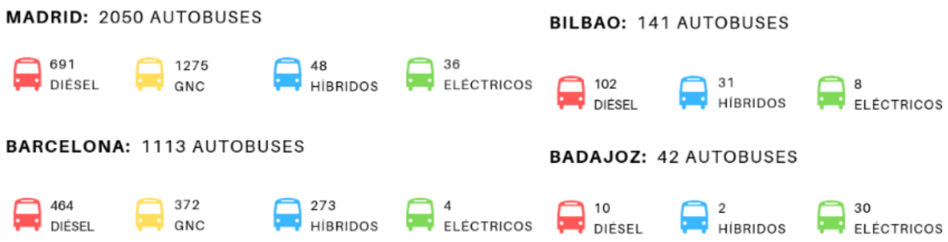


Figure 14. Example of Spanish bus fleets [2]

2.2.1.3. The rest of the world

In the rest of the world, municipal eBuses are expected to achieve around 80% fleet penetration in the US and around 40% fleet penetration elsewhere (Figure 13). Countries such as Brazil, India, Mexico and Thailand will lag China, the US and Europe due to charging-infrastructure and grid-capacity investment hurdles.

In Asia, India and, to a lesser extent, Japan will be the main drivers of eBus growth through 2025. In India, the government's FAME program aims for the country to deploy 7.000 eBuses. While there is no year associated with this target, India is expected to be over halfway toward this level of eBus adoption by the end of 2025. In Japan, the municipal eBus fleet will pass 1.000 units in 2025.

In emerging economies, upfront cost premiums and charging infrastructure investment requirements will remain barriers to eBus adoption over the medium-term. While there have been some promising eBus contracts announced recently in Latin America, collective municipal eBus sales in Brazil, Mexico and Thailand are expected to be less than 1.500 units by 2025. The municipal eBus fleet in these countries will be around 7.500 units in the same year. Innovative financing mechanisms for eBuses could accelerate growth in these regions.

Despite the competitive economy of eBuses, an array of other bus technologies is expected to continue to play a role in municipal bus fleets. Some jurisdictions will incentivize the adoption of other zero-emission drivetrains (like fuel cells) and others will choose to keep some diesel, compressed natural gas, biogas and biodiesel buses in their existing fleets due to local suppliers and other factors. However, the promotion of these types of technologies is usually very linked to the raw material available in the country, for instance, NGV vehicles have been promoted in countries with gas reserves or under economic and technological development (Figure 15).

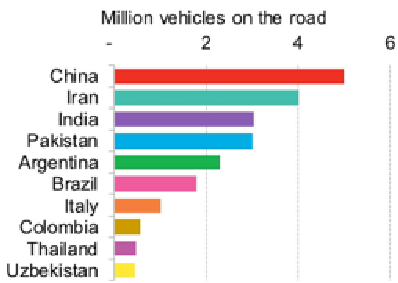


Figure 15. Main Natural Gas Vehicles (NGV) markets in 2017[2]

[2] Includes all types of vehicles whose fuel is compressed or liquefied natural gas.

3. FACTORS THAT AFFECT THE IMPLEMENTATION OF EBUSES IN URBAN AREAS

The latest movements of the European Union determine the direction of the development of transport systems in cities and other municipalities. The aim of these actions is to transform public transport into an ecologically clean and sustainable transport system. Assuming that public transport significantly reduces the use of buses powered by combustion, urban logistics studies are needed to enable finding the best way to deploy new infrastructure since there is still a lot of uncertainty around eBus battery charging strategies and the optimal type of charging hardware, mainly related to costs and operational flexibility.

Therefore, one of the main issues in the pathway towards full electrification of public transport is the complexity related to implementation strategies, based on given variants and possible scenarios of every case under analysis. A possible solution to this difficulty could be the application of a decision support algorithm, such as the one presented in Figure 16, in order to reduce the uncertainty faced by every agent involved in the decision making.

Input Data: it is crucial to highlight that there is no unique solution suitable for every municipality, thus a precise definition of local conditions is extremely relevant when selecting the input data to be analysed.

Transportation Model: there should be a profound analysis made around the bus route defined for the municipality, considering topography, bus stops, bus depot locations, bus schedules…Most municipalities should already have one in place, although it could need adapting to optimally manage electric bus fleets.

Technical Model: the data collected in the transportation model feeds the technical model, which is focused to the characteristics of the electric buses (e.g. driving unit, energy consumption, driving style and charging strategy). Additionally, it is also important that the model considers and processes the optimal allocation of buses to routes.

The output should be the optimal distribution of charging and switching stations, optimal strategy for battery recharging and the optimal strategy of replacement of the bus fleet.

Economic and Ecological Model: once the optimal output of both the transportation and subsequently the technical model is processed and fed to the environmental and economic model, those two branches run in parallel and the result should be a compromise between both aspects.

- The goal of the economic model is to evaluate acquisition, infrastructure, operational and external costs.
- The goal of the ecological environment is to estimate the local and global impact on the environment of the solution under analysis, considering the limits the municipality in question is dealing with, such as specific legislation or air quality level related to public transport.

After all the mentioned considerations the results should be sufficiently clear to make a decision on whether the electrification of a certain share of the bus fleet or even the electrification of some routes is beneficial for the municipality. If the outcome is unsatisfactory different initial data could be proposed.

Thus, the process shown in Figure 16 is a decision-making tool that could considerably reduce uncertainty in a process with that many steps and variables. In fact, due to the level of complexity of the complete algorithm, this Master Thesis covers those steps but without covering every detail and developing the models.

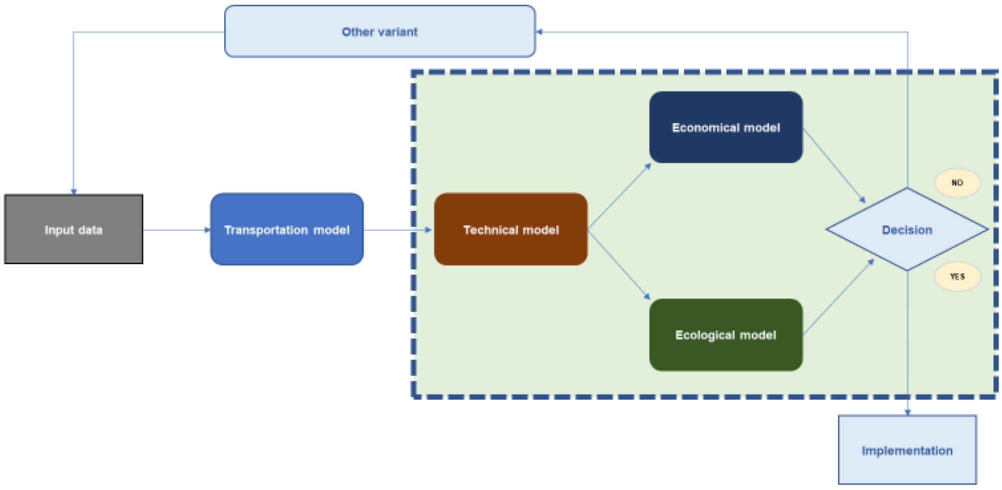


Figure 16. The decision algorithm to support electric bus implementation

The focus has been set on what is marked by the green square. Mainly the literature that currently exists has been analysed in addition to collecting real data thanks to the access that has been had to information of real cases that are underway. In addition, in the economic field, a model has been developed that allows knowing the economic viability of the selected deployment.

On the other hand, the transportation model has been left out of analysis due to the fact that most municipalities have been managing fleets for some time and know how to operate them. On top of that, most of bus fleets have a bus management system to respond adequately to the transport needs of the municipality. It involves regular monitoring and constant management of the entire transport system which is possible thanks to communications with the control centre. It is very common, for instance, to use the CAB bus communications protocol (could be another one). It seems that enough information should be available in this matter.

Having the limitations mentioned in mind, the scope of this report focuses on giving municipalities a tool for facilitating their decision-making process by disaggregating barriers and drivers for them. Hence, the contributions of the Master Thesis are focused on the following segments explained in the methodology section (Section 1.2):

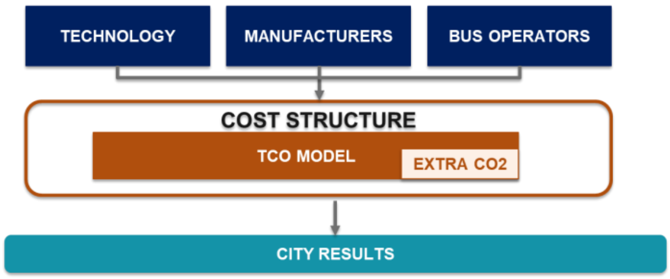


Figure 17. Major contributions of the Master Thesis

3.1. ANALYSIS OF CURRENT TECHNOLOGIES

There is a wide range of possible technological combinations when speaking about electric buses (see Figure 18). This section will try to give a brief glimpse on the offer available while trying to come to a compromise with the best combination considering the current status, advantages and limits of every option.

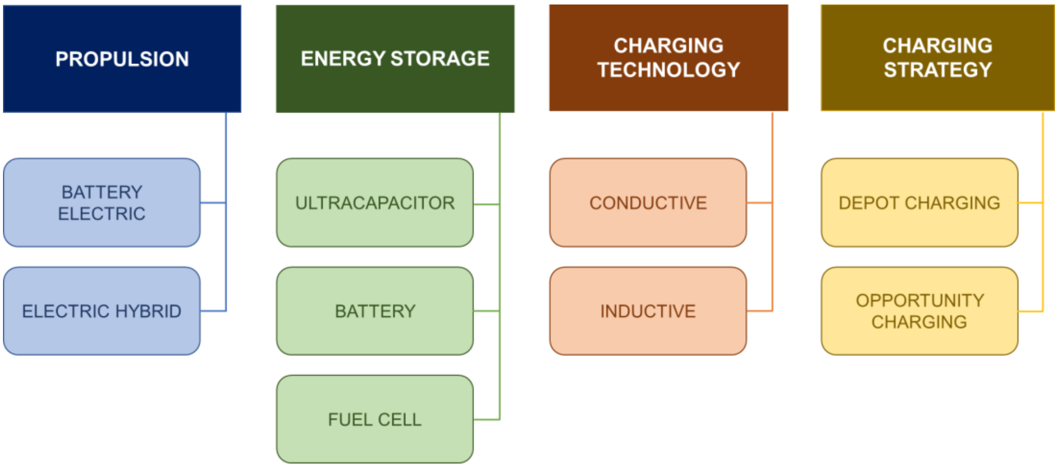


Figure 18. Powertrain, storage, charging technologies and strategies for electric buses

However, it is important to bear in mind that there is no system that offers the best possible starting position for all applications. It is only possible to make recommendations oriented towards the respective line characteristics and the specific use.

3.1.1. Definition and eBus types

Nowadays there is no consensus in literature around the specifics of what is an electric bus. There are many types of technology that are often times mentioned under the name of the electric bus. Figure 19 below tries to gather some of them.

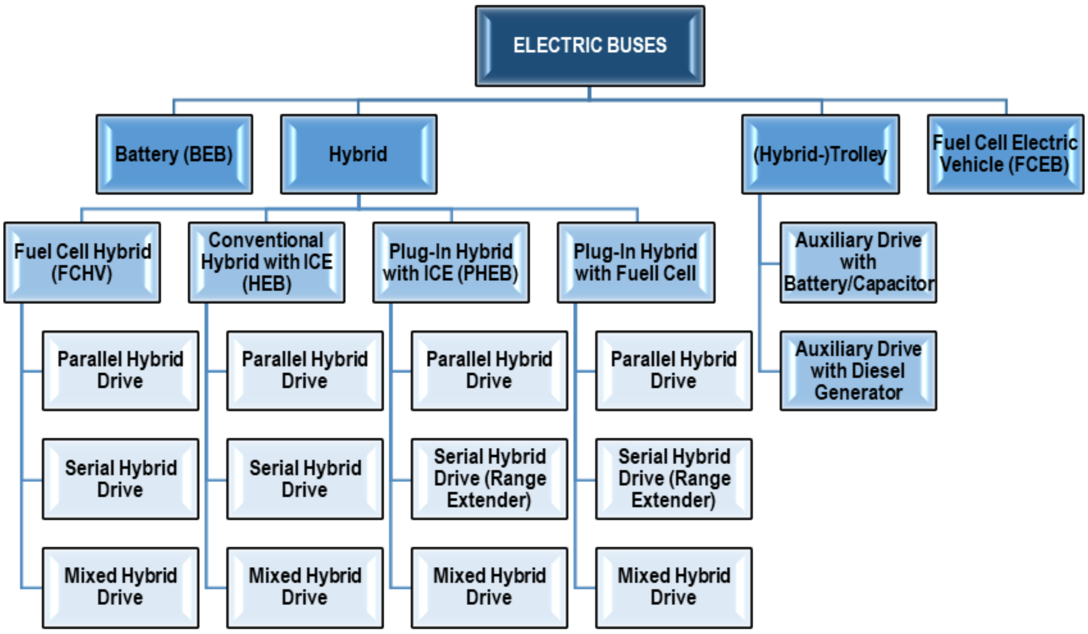


Figure 19. Classification of different types of electric bus technology

As the figure itself explains, most of the technologies shown are either hybrid or fuelled by hydrogen even if the powertrain is electric (FCEB). It should be noted that in this report, when referring to electric buses or eBuses, the technology related to is that of Battery Electric Bus (BEB), which are buses that have an all-electric motor as a means of propulsion and as a power source use electricity. When speaking about BEB, it is important to highlight that in comparison to hybrid vehicles the battery needed is larger and the charging infrastructure is critical (not optional).

Up to recent years plug-in hybrids were a very attractive option since they can run several kilometres (in fully electric mode in certain zones) without losing flexibility. Additionally, their technological maturity and commercial readiness is one step ahead of purely electric buses. However, since many of the kilometres they run are in diesel-mode it is considered that their improvement toward the environment is not sufficient.

In terms of maturity, eBuses can currently be classified as technologies of medium maturity level. Even if the technology has been completely proven there is still need for infrastructure deployment and years of experience to prove real feasibility. There are many elements of the whole solution that have a high maturity level, electric motors, for instance, have been present since the XVIII century and the bus structure (chassis, breaks, axes…) has been well-known for years. On the contrary, the charging system and the batteries are far from long-term maturity levels, as well as the combination of every element that results in the whole solution is what needs to be proven.

Key risks involving the maturity of eBuses could be summarised as:

- Low infrastructure maturity and further standardization required.
- No significant operational experience with opportunity charging. Also, current workers involved in fleet management are not familiar with the eBus operation or the plug-in charging.
- Battery capacity remains the key most important development area. Bus battery performance lifetime could be shorter than expected. Since the technology is recent, there is still no real data around battery replacement need.
- EBuses have limited commercial testing and the risk for early phase implementation issues is high.
- Varying uptime and service need of eBuses might impact total cost of ownership.

Consequently, as in the case of any other non-mature technology, there are many risks when you choose to electrify a fleet, risks and uncertainties that will dissolve with years of experience. For now, in these early stages, it is crucial to succeed and avoid directing investments to bad solutions that could generate an "unjustified" risk aversion towards the technology.

In order to get as close as possible to the cost-effective and technically feasible solution, it is very important to know the implications of all the technologies and strategies presented in Figure 18 in order to make a decision based on technical knowledge and economic viability and avoid investing only driven by environmental demands or political agenda.

3.1.2. Charging infrastructure

EBuses have generally a shorter range than diesel buses, hence, one critical question that municipalities, transport operators, and manufacturers are still facing is where and when to charge them.

Therefore, charging is one of the key issues involving the implementation of electric buses since it is really sensitive to many factors, such as the distance travelled, the topology of the road, the driving behaviour, the prevailing traffic conditions and the outdoors temperature. In addition, the physical layout and utilization of the charging infrastructure are elementary parts of the charging. In general, these factors can have a significant influence to allow operational implementations without dramatically changing the public transport panorama comparing to the existing one with conventional vehicles.

In the following subsections the main elements related to charging and the implications that are concluded with respect to them will be detailed.

3.1.2.1. Batteries

As previously mentioned, the battery is the key limiting factor of electric buses mostly in the case of autonomy and economic viability.

Currently, batteries for electric vehicles are based on lithium ion technology. In lithium ion batteries both the cathode, the anode and the electrolyte can consist of different materials that result in different properties (Figure 20). The anode is usually composed of graphite, which can be combined with carbon or graphene. Common types of lithium ion battery are NMC, NCA, LFP, LTO, being the most common the NMC combined with NCA.

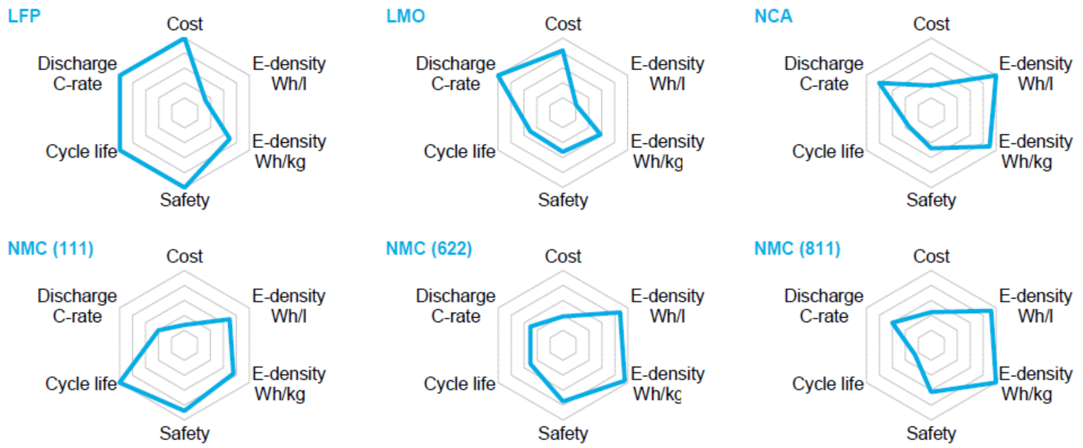


Figure 20. Characteristics of lithium-ion battery cathode chemistries [16]

The election of the chemistry of the batteries, in other words, the type of battery should be based on the application that this battery will have. For instance, the choice of battery will greatly differ if the charging technology is plug-in of (slow) or through pantograph (fast) since each of them have different needs[3]. The decision is usually based on whether there is need for high energy density batteries (e.g. LCO) or on the contrary high rated power batteries (e.g. LFP).

[3] Charging technologies are analysed in detail in the following subsection (3.1.2.2)

It should be kept in mind that there are many other factors to consider when considering the most suitable chemistry for the battery. Anyway, it is not the objective of this Master Thesis to analyse them in detail. For now, the following should be noted:

- Slow charging (usually plug-in): the eBus needs to transit from 14 to 18h per day (depending on the municipality), thus a single stop to charge should be able to provide enough energy for the day. The battery must have a high energy density, while the power is not so relevant, since there are many hours to charge (usually around 4h if cleaning time is taken into account).

- Fast charging (usually pantograph): the batteries carried onboard are much smaller than in the previous case given that they only need to cover short distances (10-20km) until they reach the next charging station. In about 5 minutes 80% of the battery is charged at these stops through a charging infrastructure of high rated power with a huge energy peak, which requires having a battery that endures that kind of charging curve, hence, a battery with high power capabilities.

In the near future, improvements of the battery cells are expected, mainly due to small modifications in the chemistry and the adjustments that allow to store more energy in the same cell. It is predicted that the cost per cell will increase slowly, but the greater storage of energy will lead to a decrease in the cost per unit of energy.

Besides, other technology options may be used shortly. In fact, Mercedes-Benz has already equipped its electric buses with solid-state batteries which according to the manufacturer have higher energy density and are able to maintain good properties facing adverse weather [18]. Nonetheless, some manufacturers are reluctant to use this type of technology due to the fact that it complicates the already laborious manufacturing process.

Besides battery chemistry, another relevant limiting factor that affects the autonomy is the limit set on the so-called depth of discharge (DoD), which determines the percentage of the battery that can be discharged relative to the overall capacity of the battery. It is not a physical limit, but a maximum value established by means of software. The choice of this value is an issue that highly affects the autonomy of the vehicle because it sets the maximum amount of the energy stored in the battery that could be spent per cycle of discharge.

The reasoning behind this limit is to try to extend the life of the battery as much as possible. The ideal is to keep the charge of the lithium ion batteries between 30 and 70% of charge so as not to affect the useful life. Therefore, it should be reached a compromise between increasing the autonomy of the vehicle and reducing the useful life of the battery, which can mean that it has to be replaced sooner than expected and can jeopardize the business model and its cost structure.

Currently manufacturers are establishing the limit between 70-90%, depending on the strategy followed by each [2].

3.1.2.2. Charging technologies

Nowadays there are two charging technologies with very different levels of maturity: conductive charging and inductive charging (pre-commercial level). With respect to conductive technology there are three ways of charging: plug-in, overhead wires and thorough a pantograph (see Figure 21).

Figure 21. Overview of charging technologies [19]

In this section, certain characteristics of each technology will be detailed, mainly of the most used technologies, which are the plug-in and the pantograph.

<u>Conductive charging technologies</u>

- **Plug-in technology:** it needs a charging point usually located at the fleet depot. The eBus is connected to the infrastructure through a industry-standard connector, which is currently the CCS Combo 2 (see Figure 10).

Figure 22. CCS Combo 2 connector

Plug-in enables slow (15-22 kW) or fast charging (22-50 kW or 50-120 kW), which is chosen depending on the time slot available for charging and the characteristics of the electric network surrounding the area. Depending on the power installed the charging point will be able to feed a certain number of eBuses simultaneously (it is common to dimension it to feed two different eBuses).

The plug-in technology, if considered individually (without evaluating the combination of elements composing the eBus solution), is the cheapest infrastructure among charging technologies.

As an additional advantage, with this solution, often the eBuses, utility vehicles and cars can share the same standardized chargers.

- **Pantograph technology:** it enables an automatic fast-charging technology solution. The pantograph is a widely proven mechanical concept for connecting trains, trams and buses to the power supply. When a bus arrives at the charging station, a wireless communication between the bus and the charger establishes, after which a special inverted pantograph automatically lowers. Once the safety checks have been carried out, the system supplies the bus with a powerful quick recharge (see Figure 23).

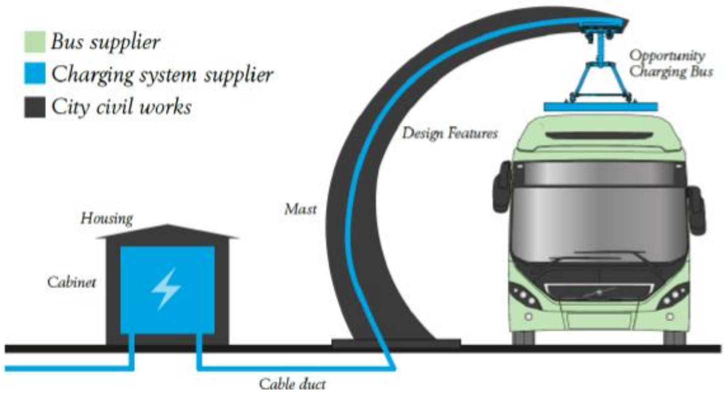


Figure 23. Overview of the pantograph infrastructure details [2]

With its automatic connection from the roof the system can be easily integrated into existing bus lines, by installing fast chargers at certain stops of the bus route. This enables the bus operation 24/7 with low maintenance costs and high availability.

Usually, to ensure fast and efficient loading, two types of sensors are installed in the eBus, which are: the approach sensor, located in the front, it warns the system that the vehicle is approaching the charging point ; and the position sensor, on the back, that prepares the pantograph arm to be attached to the bus ceiling and begin charging.

In this way, with this ultra-fast charger, it would take 5 to 8 minutes to fill the battery up to 80%.

- **Overhead wires** [20]**:** the eBus that uses this type of technology is called the trolleybus and it is fed from overhead wires installed all along the bus route using spring-loaded trolley poles. The power is usually supplied as 600V DC. Around 300 trolleybus systems have been and are in operation[4], in cities and towns in 43 countries, however it is considered an obsolete technology and not much future deployment is expected.

<u>Inductive charging technology</u>

Resonant wireless charging is another quite promising and practical technology with efficiency around 90% from the mains to the battery (plate to plate efficiency can reach 98%). The limitations on the maximum power transmissible and more specifically the limit on power density are likely to restrict the use of wireless charging to daily normal/medium power charging. Ongoing standardization issues on inductive charging are part of the European Commission mandate (M533) approved by the CEN/CENELEC in 2015 [21].

In the case of urban areas, it is considered an aesthetically more attractive option and also occupies less public space. There is a general consensus to consider wireless charging a promising optional

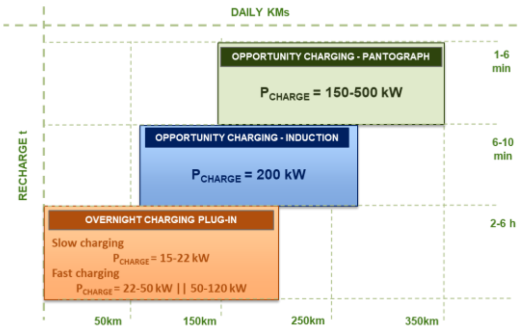
[4] Outdated information

charge solution to be added to the conventional conductive one and likely to spread as a basic element of the city infrastructure, especially for bus station/stop applications and plug-in hybrids.

However, it is still in a pre-commercial stage and first pilot projects are being carried out. It seems to be more expensive than conductive technologies but sometimes could be a viable alternative at least theoretically as in the case of Berlin [22]. However, practical application could be more complex. Allegedly, inductive technology is not properly working in real life [2].

Final considerations

It is concluded that the themes governing charging infrastructure deployment are the technology maturity, cost-effectiveness, compatibility and charging efficiency. It is a key factor to optimise the election of the charging technology. In order to do that, it is important to bear in mind the following scheme (Figure 24) as first approach to technology selection:



Criteria	Conduction	Induction
Required infrastructure complexity	converter, charging station	converter, inductive charging system
Cityscape	charging stations	invisible roadside integration of charging stations
Maintenance	negligible	negligible
Total charging efficiency	ca. 95%	ca. 90%
Vandalism	few accessible components	no accessible components

Figure 24. Overview of the main characteristics of charging technologies [2] and [22]

In addition, if mass deployment of charging infrastructure is intended, every charging technology should include a standardised electric interface with open architecture.

3.1.2.3. Charging strategies

In line with the charging technology, the municipality/bus operator must choose the charging strategy accordingly. When selecting a charging strategy for a particular bus or set of buses the operator has the option to follow two strategies or a combination of both (overview in Figure 27):

- Slow charging (overnight charging): typically associated with a **lower cost charging infrastructure and larger battery packs**. The charging technology associated is the plug-in charging at it is usually located in the fleet depot.

  The more eBuses there are, the more installed capacity will be needed at the depot.

  Figure 25 schematically shows an activity diagram of possible operation processes when plug-in technology is used at bus depots. As can be derived, it could be of great impact to have an intelligent management system that operates the processes wisely, mainly when the eBus fleets reach a certain size.

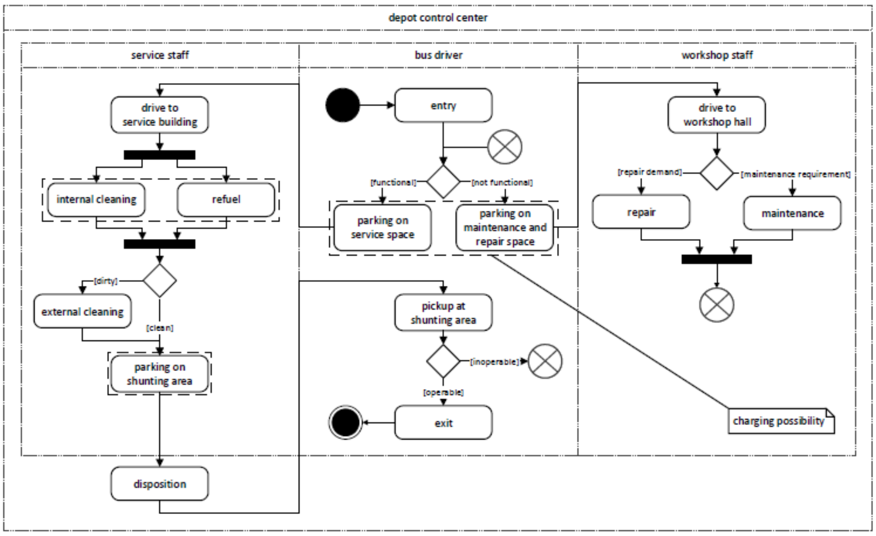


Figure 25. Operation processes at the depot [23]

- Opportunity charging at central points or along the routes: **opportunity charging** requires **a more expensive charging infrastructure but smaller battery packs**. The installation of chargers along the routes then typically depends on the existing infrastructure and associated complexity of placing an extra charger in terms of land ownership, permits and grid connection.

The opportunity charging concept allows 15% more passengers [2]. Additionally, it could be ideal to combine with electric supply of solar or wind (see Figure 26).

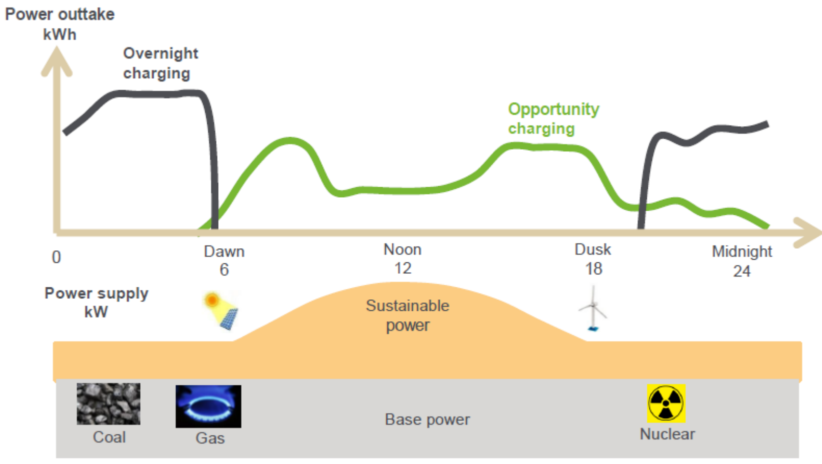


Figure 26. Suitability of combining wind and solar power with opportunity charging [2]

The positive aspect to take into account when trying to define the physical layout of the charging infrastructure network is that the predictability of bus routes is almost complete, which reduces the complexity of deployment compared to the case of EVs.

Depending on the route length there is need for certain number of intermediate charging stations, knowing that each charging stop gives the eBus autonomy for 10-20 km. The charger is always installed coinciding with a bus stop.

Depending on the length of the route, a number of intermediate loading stations are needed, since each loading stop grants eBus autonomy from 10 to 20 km. The exact range of autonomy will be determined by the size of the battery that carries the eBus on board. The charger is always installed coinciding with a bus stop.

Bearing in mind that the larger the size of the battery, the higher the price and the higher the number of stops with the pantograph the higher the price, the greater compromise between the two factors must be sought.

- A combination of overnight charging and opportunity charging is also possible given the availability of the large infrastructure. This setup can be used to allow buses to begin their operation fully charged making them able to operate continuously during morning rush hours. In some situations, the overnight chargers are over-dimensioned creating the possibility to delay the charging of some buses to smoothen the charging profile for the entire fleet.

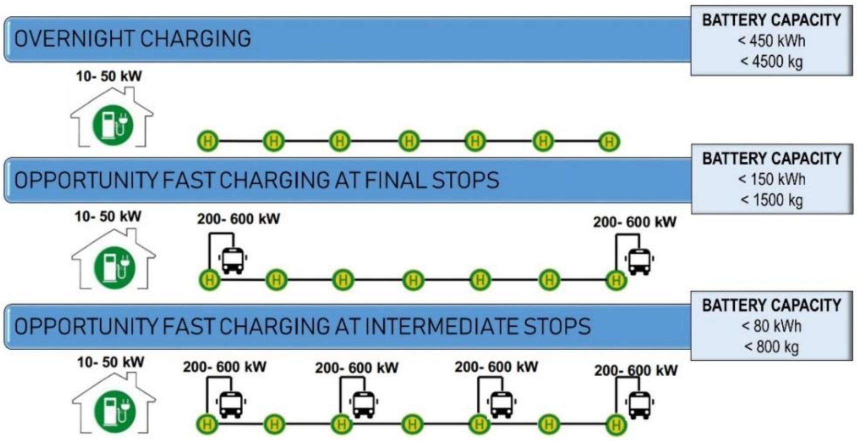


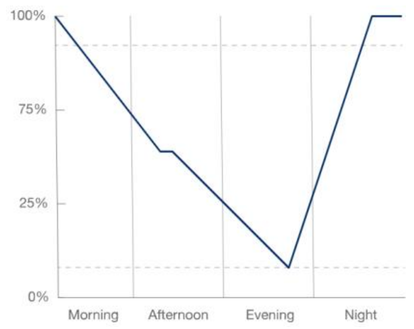
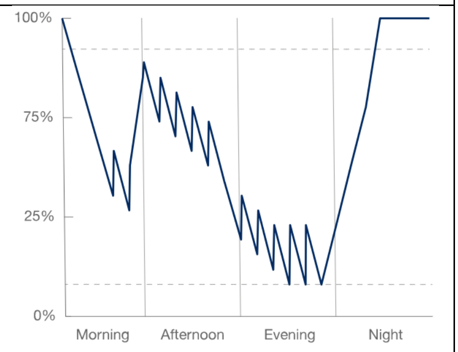
Figure 27. Overview of charging strategies [19]

Final considerations

There is no single optimal solution to implement without a sense of proportion, each municipality should consider in depth its starting point and evaluate the optimal solution that takes into account the long term and not only the initial investments and initial technical effort. Overnight charging at depot has been the most followed strategy up to now, however when fleets of certain size are considered it seems that opportunity charging could be a great alternative. Albeit infrastructure costs and the occupation of public space are sometimes arising as insurmountable barriers.

The following scheme could be helpful as first approach to strategy selection (Table 1):

Table 1. Comparison of battery-system-strategies [2], [22] and [17]

Criteria		Depot charging (overnight)	Opportunity charging
Required battery capacity		>150 kWh	ca. 60 kWh
Charger type		30-150 kW (for buses with high range)	150/300/450/600 kW
Charging technology		Mostly plug-in	Mostly pantograph Plug-in (less common) Induction (less common)
Load profile (illustrative)			
Range	**Company specification**	100-300km/day	ca. 10-20km per recharge 200-500 km/day
	Realistic operation	significantly lower	unlimited by fast-charging
Battery wearing characteristics		deep discharge	low discharge, many cycles
Battery costs		large, but relatively low-priced batteries	few, but relatively expensive batteries
Required space for infrastructure		one charging station for each bus in depot required	charging stations at final stops and depots
Infrastructure costs		charging station in depots	charging stations at final stops and depots
Route management flexibility		range dependent	between charging stations only
Additional Expenditures		possibly more buses required due to limited range	interruption possibly required for charging

3.1.2.4. Additional requirements and considerations

In brief, conductive and inductive charging systems accompanied by different charging strategies are used worldwide. Focusing on the operation of eBus fleets, comprehensive analysis for the determination of network capacities and appropriate solutions for the power supply are required are also required when considering the charging infrastructure layout. In that sense, , several optimization techniques for smart charging strategies can be adopted to lower the overall energy cost and avoid grid congestion and peak loads caused by charging processes [[24], [25], [26], [27], [28]].

Also, concerning overnight charging applying a smart charging management system should be beneficial for the optimal charging of the eBus fleet. Going a step further, charging strategies with energy procurements in joint market operation could be examined as in [23], were they propose the idea of supplying the energy demand for the operation of the electric bus fleet can be efficiently supplied within a multi-period optimization process, through optimally-determining and adjusting the charging schedules in day-ahead and intraday operations. The results in [23] show that it is possible to integrate eBus fleets in the operation of a power plant portfolio and have benefits.

An additional consideration that needs to be made is the assessment of the connection point to the network that will depend on the charging technology applied. Concerning opportunity charging (150-500 kW), network reinforcement will be needed at charging station, with a level of investment that will depend on the level of development of the network in that area. On the other hand, overnight charging will also require network reinforcements and what is more, the installation of a dedicated secondary substation in some cases. This fact, many times supposes an initial barrier for the municipality considering the electrification of the urban public transport fleet. However, what should be weighed up is also the fact that it is a punctual action needed for just the first units. Anyway, at the beginning of the 20th century, the internal combustion vehicles faced a similar infrastructure problem.

3.2. MAJOR EBUS MANUFACTURERS

The EC stated in the report called *Electrification of the Transport System* that if there were appropriate battery manufacturing capabilities for safe, long-lasting and affordable cells in Europe, 100% of buses could be electrified within the next 10 years [21]. European production capacity indeed is one of the main concerns when discussing the transition to fully electrified fleets.

If current production capacity is to be broke down, Chinese eBus manufacturers are clearly ahead as well as they are dominating the global market in terms of units sold. With regard to the European market there is uncertainty in whether reaching Chinese leadership is possible. Chinese eBuses usually have lower upfront costs and competitive advantages. However, European manufacturers are starting to position themselves in local markets and trying to move from pilot projects to massive sales.

3.2.1. Market share of the main eBus manufacturers

As mentioned, China is leading the eBus market by far. The global eBus fleet grew 32% in 2018, reaching 425.000 units with 99% of them in China. A key aspect that took part on China's success was that up to 2016, Chinese subsidies (national, regional and combinations) enabled bus operators to purchase eBuses for a similar initial capital cost of a diesel bus, removing the main barrier to eBus adoption: high upfront costs.

However, if the Chinese government completely phases out the subsidies as planned in 2020, manufacturers will be put on a level playing field in worldwide competition.

Figure 28 shows the fragmentation of the Chinese eBus industry, where sales are rather distributed and many agents take part, such as ANKAI, BYD Company, Higer Bus, Yinlong Energy, Yutong and Zhongtong Bus Holding [29]. Two of those manufacturers are worth highlighting: Yutong and BYD (19% and 13% of share in 2016 respectively), which are the biggest producers.

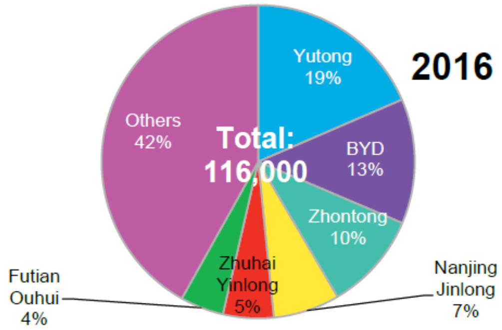


Figure 28. Chinese pure eBus producers [16]

Besides their leading position in Chinese sales, what makes these two manufactures to stand out is that both are delivering eBuses to municipalities in Europe and the US.

On the other hand, Europe and the U.S. have several domestic bus manufacturers with proven track records and growing expertise in eBus production. Bus producers like Irizar, Solaris, Optare, VDL, Volvo or Proterra were quick to recognize the opportunities for electric buses and offer models for sale.

Even if the expected rate of growth in sales for the following years is relatively moderate (see Figure 29), allegedly the next period will see a much higher share of eBuses in fleets (up to 80%) and it is a moderate estimation to suppose that most of the sales will come from European manufacturers. Their existing relationships with European municipalities and bus operators, as well as their expertise in the structure of the European public transport market, gives them an advantage over Chinese manufacturers.

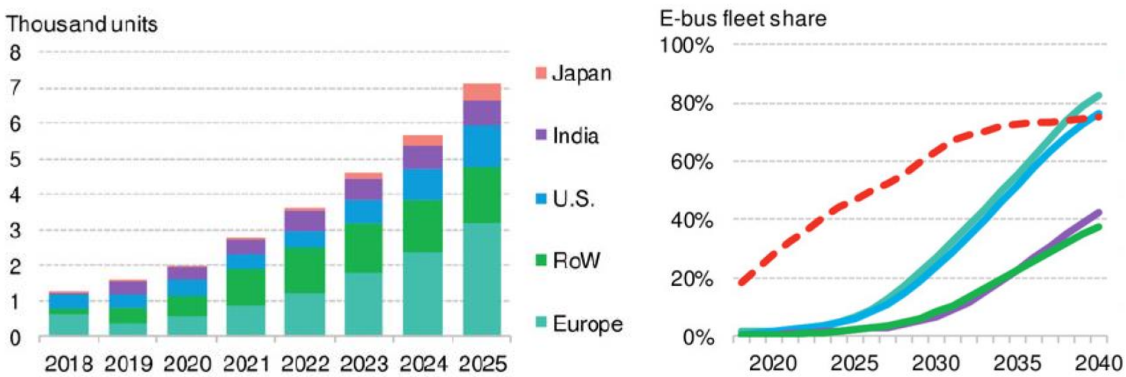


Figure 29. Municipal eBus sales (excluding China) and expected eBus share of global bus fleet

In the U.S. the two biggest competitors for BYD and Yutong are Proterra and New Flyer. Proterra seems to be the one leading thanks to big investments and the design of innovative business models such as battery leasing (see Section 4.1.2.3).

3.2.2. Focus on main manufacturers

The aim of this section is to focus the scope in looking into detail certain eBus manufacturers in order to better understand their possibilities of offers. The selection of those manufacturers have been made with relation to the Spanish market.

In 2018, there were 22 new eBus registrations in Spain, namely: one AYATS bus in Girona, one BYD bus in Valencia, 8 CAR BUS minibuses in Madrid, 9 IRIZAR buses (4 in Barcelona, 2 in Guipúzcoa, Valencia and 2 Vizcaya and 3 SOLARIS buses in Barcelona [30]. Among those, BYD, Irizar and Solaris are especially relevant agents in the Spanish scenario (see Section 3.3).

Hereafter, BYD and Irizar will be more closely discussed.

3.2.2.1. BYD

BYD started in China as a battery manufacturer, later moving in automotive business, taking advantage to the fact that the battery is the core part of electric vehicles. In fact, BYD was the first EV vehicles manufacturer in the world, including cars and commercial vehicles. Today, BYD has four core business areas: electronics. automotive, energy, rail transit.

BYD is one of the two world's largest producer of electric buses with BYD an enormous production network distributed among China, Hungary, California and Toronto.

However, it appears that if the government completely phases out the subsidies as planned in 2020, Chinese EV makers will be put on a level playing field with their Western and Japanese rivals, whose brands make up a minority of the Chinese market.

In fact, BYD temporarily halted operations at its electric bus factory in Guangzhou, Guangdong province, the latest knock-on effect that began when the government earlier this year decreased electric vehicle subsidies by up to 50% [31].

In spite of this fact, the company declared that it would not affect their sales and production rate. For that matter, they recently, January 2019, reached the milestone of producing 50.000 units [32] after nine years of production. Currently, the level of production is allegedly 50-100u/day [2] at their highly automated facilities.

Figure 30. BYD factory in China

They announce having the world's largest offer of battery electric buses and a clientele that spans across 300 cities around the world, with electric bus contracts in South America, North America, Europe, South Asia, North East Asia, and of course, China. BYD have also announced 650 electric buses delivered to a total of 44 European cities in 12 countries [33].

3.2.2.2. Irizar

The Irizar Group is a business group founded in 1889, leader in the design and manufacturing of buses in Spain and one of the references worldwide. Currently, Irizar is integrated into Mondragón Corporación Cooperativa (MCC).

With a workforce of over 2,600 workers and its headquarters in Ormaiztegi (Gipuzkoa), it has production plants in five countries (Spain, Morocco, Brazil, Mexico and South Africa) and commercial presence in 90 countries.

The radical transformation in its management began in 1991, at which time the cooperative was in a situation of deep crisis. Since then, sales have continued to grow, exceeding in 2018 the barrier of 700 M€ in turnover, a figure never before reached and that far exceeds € 620 million in sales that closed 2017 (€ 40 million more than the preceding exercise). The group's parent company, the headquarters of Ormaiztegi, continues to be the one that contributes most to the result, since just over 50% of the total turnover comes from that centre.

Irizar e-mobility: in 2016, the Irizar e-mobility branch was created, whose activity is centralized in the Aduna factory, inaugurated in May 2018. This branch of the Irizar Group was born with the aim of providing comprehensive electromobility solutions customized for cities, both in terms of the manufacture of 100% electric buses, and the manufacture and installation of the main infrastructure systems needed for charging and energy storage. All of them designed and manufactured with 100% technology of the Group and with the guarantee and quality of service of Irizar.

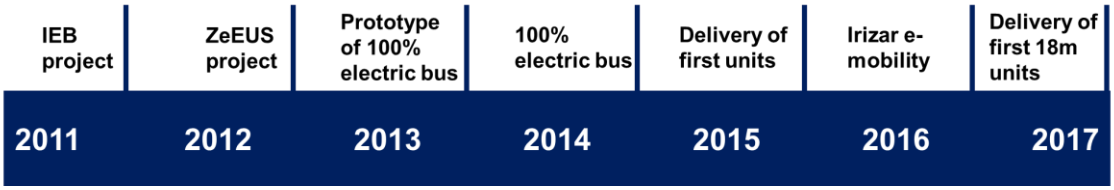


Figure 31. Major milestones of Irizar e-mobility (2017)

Having all the parts developed by the same group, provides the operator with the additional advantage of having a single interlocutor in all phases of the project, including after-sales service, maintenance and repair that are tailor-made and include comprehensive vehicle care.

The range of products of Irizar includes urban buses of 10,8m, 12m, 15m and 18m that circulate since 2014 in different European cities, articulated or biarticulated buses of 12m and 18m, as well as other electric vehicles directed to services of a city (e.g. garbage truck).

Regarding the charging systems, Irizar offers three:

- <u>Fast charging in each terminal:</u> the lithium-ion batteries of the buses are charged in each terminal through dedicated infrastructures (in 5 minutes) also provided by Irizar. A pantograph connects the bus to the loading system.
- <u>Braking recovery system:</u> the system of regenerative energy consumption by braking for the use of energy without the need for storage.
- <u>Slow recharging at night:</u> a slow recharge is also provided at night, in the depot where electric buses are parked.

Figure 32. Irizar ie tram and Jema charging system

Irizar ie bus: this model of 12-meter bus (also 10,8m, 15m and 18m available) circulates with a range between 200 and 220 km at an average speed of 15-17 km/h, guaranteeing between 14 and 16 hours of driving in dense, urban and interurban traffic conditions and different weather conditions.

In addition, it has great possibilities of adaptation to the operators both in the product as in the integral service and maintenance for the entire useful life of the vehicle.

Table 2. Specifications of the Irizar ie bus

Irizar ie bus (10,8m and 12m)		
Dimensions	Standard: 12m. Also available a 10,8m version. Possibility of articulated bus.	
Rated power/energy	180 kW Synchronous power train, with nominal torque 1.400 Nm and traction capacity with slopes of up to 18%.	
Autonomy	200-250 km. Estimated need for a single load at the end of the day.	
Charging system	Slow charging	E=350 kWh / P=100 kW/ t=3-4h
	Fast charging	Pantograph: E=185 kWh / P=450 kW/ t=5 min
		Combo2[5]: E=185 kWh / P=150 kW/ t=2h
	Ultra-fast charging	E=90 kWh / P=450 kW/ t=5 min (pantograph)
Irizar ie bus (15m and 18m)[6]		
Rated power/energy	235 kW Nominal torque 2.300 Nm	
Charging system	Slow charging	E=525 kWh / P=150 kW/ t=4h
	Fast charging	Pantograph: E=260 kWh / P=500 kW/ t=5 min
		Combo2: E=260 kWh / P=200 kW/ t=2h
	Ultra-fast charging	E=150 kWh / P=600 kW/ t=5 min (pantograph)

Irizar ie tram: it is a bus with tram aesthetic attributes that combines the great capacity, the ease of access and the inner circulation of a tram with the flexibility of an urban bus. It is presented as an alternative to the conventional tram.

[5] Combo 2 is the standardised connector.
[6] Only mentioned what differs from the 12m model.

Table 3. Specifications of the Irizar ie tram

Irizar ie tram 12m		
Rated power/energy	180 kW Synchronous power train, with nominal torque 1.500 Nm and traction capacity with slopes of up to 18%.	
Charging system	Slow charging	E=350 kWh / P=100 kW/ t=3-4h
	Fast charging	Pantograph: E=185 kWh / P=450 kW/ t=5 min
		Combo2: E=185 kWh / P=150 kW/ t=2h
	Ultra-fast charging	E=90 kWh / P=450 kW/ t=5 min (pantograph)
Irizar ie tram 18m		
Rated power/energy	235 kW Nominal torque 2.300 Nm	
Charging system	Slow charging	E=525 kWh / P=150 kW/ t=4h
	Fast charging	Pantograph: E=260 kWh / P=500 kW/ t=5 min
		Combo2: E=260 kWh / P=200 kW/ t=2h
	Ultra-fast charging	E=150 kWh / P=600 kW/ t=5 min (pantograph)

Focusing on the battery, Irizar offers different modular solutions, based on Lithium-Ion technology, namely:

- Slow charging (Energy Pack): designed so that the vehicle can circulate the maximum number of km and complete the operation, with only one charging per day. Its design allows the balance between autonomy and number of passengers.
- Fast charging (Nano Pack): tries to combine autonomy and charging power. Its use is directed to mixed operations, where the vehicle has sufficient autonomy to operate during peak hours.
- Ultra-fast charging (Power Pack): is the solution for a 24/7 operation with loads of up to 600kW.

Irizar battery packs are modular and incorporate liquid cooling systems that allow an optimization of the useful life of the batteries and the possibility that of operation under extreme weather conditions. Besides, it is highly recyclable.

Table 4. Overview of Irizar's battery pack offer

	Slow charging (Energy Pack)	*Fast charging (Nano Pack)*	*Ultra-fast charging (Power Pack)*
Energy	280-525 kWh	185-260 kWh	90-150 kWh
Range per charge	220-250 km	100-120 km	50-60 km

The energy storage management system, developed by Jema Energy (Irizar Group), manages the relationship between battery and super capacitors to maintain the state of charge of the two components in an optimum range and, thus, extend the life cycle of the components, resulting in an improvement of the operational cost.

Irizar e-mobility, as well as the other manufacturers, offers a wide flexibility when adapting to the needs of the operator, making available the possibility of ad hoc adapting several of the fundamental characteristics of buses, such as, for example, the number of batteries or the recharging strategy.

The place for manufacturing of Irizar e-mobility is located in Aduna (Gipuzkoa). Inaugurated in May 2018, it is the first plant in Europe dedicated solely to electromobility. It has 18,000 m^2 built for the construction of which 75 M€ of investment have been allocated.

Currently and since the end of 2018, Aduna produces one bus per day. This number is adjusted to the current demand that Irizar receives, since, in fact, the factory has a production capacity of four buses per day.

In addition, they generate all energy consumed by the factory, what makes it the first completely sustainable European electromobility factory.

3.2.3. Production capacity

Assuming that the transition from diesel urban buses towards electric buses is inevitable, it remains uncertain if European manufacturing capacities will be able to follow the fleet replacement pace.

Based on information displayed in the previous section, it could be seen that there is a remarkably high difference in terms of production capability between Chinese and European manufacturers, being China's at least an order of magnitude greater.

The reasoning behind that can be explained by many factors:

- China bet in favour of electric buses long before anyone else. Thus, the level of development of each business segment is far ahead that in the EU and the US. UU.
- China's manufacturing costs are remarkably low in any industry compared to other regions. This enables an environment of investment in emerging technologies and the appearance of new agents with enormous economic capacity to invest, for example, in manufacturing processes.
- The Chinese government has tried and is trying to develop a local industry capable of being competitive all over the world. Its positioning is nowadays optimal since its manufacturing is low not only for eBuses but also for batteries, besides having a considerable number of agents which increases competitiveness and facilitates diversity in the offer. In addition, many eBus manufacturers already had experience in EVs, which can really make a difference in such emerging technologies.

It is practically impossible to assess the real production capacities of any region, since manufacturers keep this type of information with extreme caution to avoid revealing information that could suppose a risk for the competitive advantage. China is supposedly able to cope with the expectations of future orders, although the uncertainty created by subsidy cuts is latent.

On the other hand, in Europe the concern is of a higher level. The manufacturers are complying with the deliveries with the current order level and it seems that, if the right path is followed, Europe will be able to generate enough industry around the eBus that will allow to meet the future demand. Naturally, this will depend to a large extent on the industrial and investment environment present in the region and the level of convergence between policies, manufacturers' wishes and municipal and social support, among others. What is clear is that Europe has to move forward with a decisive step to avoid losing this new market niche (as it seems that it has lost in the case of EVs), giving its entire order backlog to China and regional bottleneck could occur.

3.2.4. Turnkey projects: alliances

A key issue in cost-effectiveness of the different turnkey offers is the value chain of the complete system offering (bus manufacturing, charging infrastructure, energy storage system and services).

In general, two different models are usually followed:

- A single provider offers the turnkey solution: this is the model followed, for instance, by BYD and Irizar, even if there is a slight difference between both since BYD manufactures its own battery packs while Irizar buys the cells and only does the assembling.

  In principle, it should the most cost-effective solution due to synergies in the processes and the savings in concepts such as transportation or provider margins. It is as well the most followed model with emerging technologies or industries.

- A group of allied providers offers a solution: whenever the bus manufacturer decides not to be in charge of the complete value-chain either due to lack of capabilities or based on strategic decisions, usually alliances are formed. Municipalities looking for an eBus solution tend to ask for turnkey solutions and does not wish to process and purchase each element of the solution separately (higher transactions costs).

  An example of alliance could be the one formed by VinFast, Siemens Vietnam and LG Chem in Vietnam. VinFast will manufacture buses with the supply of components from Siemens Vietnam and batteries of LG Chem (VinFast and LG Chem have formed a joint venture) [12]. There is also, for instance, a long-term partnership formed between ABB and Volvo [34], which have worked side by side for many years on co-developing electric bus solutions and open standards.

  Of course there are exceptions to purchasing the turnkey solution, as in the case of the agreement between Hamburger Hochbahn AG (bus operator) and ABB (charging infrastructure provider) to provide just charging infrastructure to the city of Hamburg [35], but is not frequent.

In both cases, municipalities demanding the solution are setting the obligation of open interfaces which enables to exchange the bus or the infrastructure provider. Interoperability is a key issue in the competitiveness of a solution that relies on so many elements (even if no clear standards).

The problem is that the interoperability without standardisation is complicated which is still under development in the eBus industry in terms of communication protocols and interfaces for charging infrastructures. It is currently a work in process that every agent is setting as priority. In fact, some public tenders set the obligation to the provider to offer a solution with open interface.

3.2.5. Barriers

Bearing in mind what has been mentioned throughout the section, the following barriers have been identified with respect to the manufacturing of eBuses:

- Production capabilities are partially uncertain.
- Standardisation is yet to be developed.
- Complexity on the technology: apart from electric buses being a new technology in bus fleets, there are more issues to consider in their operation (charging, sensitivity in

operation…). That also requires trained workers that need an adaptation period to managing a new asset.

- Entry barriers: all relevant manufacturer in this sector were conventional bus manufacturer prior to opening the eBus production line. This gives them a great starting advantage with respect to newcomers by having previous experience in product manufacturing, the network of suppliers and after-sales service, among others.

  Certain Chinese manufacturers are the exception to this rule, since they arose from the diversification of their battery and/or EV manufacturing businesses, which also represents a competitive advantage over newcomers since the electrical expertise is a very important asset when speaking about eBuses.

  Another issue to consider for small market entrants is that the eBus industry is an asset-based industry with high capital costs that requires significant economic strength to face investments.

- Void auctions: since the complete bus system is recent there have been many issues with public tenders. Up to date, main difficulties in this area have been related either with bad designing of the public tenders or with difficulties of manufacturers to meet the imposed requirements.
  - *Example of bad designing of tenders:* ESWE had to extend the deadline of the Europe-wide tender to put 50 electric buses on the road in Wiesbaden which was already the second major delay in the tender. The reasoning behind the delay was that the ESWE determined that the bids received were not comparable, which is why it first had to compile a detailed catalogue of requirements [36].
  - *Example of manufacturers not meeting requirements:* Bogota's public transport operator, TransMilenio, called an auction last November. The winners of the process were two operators of diesel buses and three of gas, while the segment announced for electric buses was declared deserted (BYD was the only offeree company). TransMilenio stated that BYD did not meet the financial requirements of the public tender [37].

3.3. BUS OPERATORS

This section is specifically focused in the urban public transport system of Spain, which is a service of municipal ownership, although its operation depends on each municipality, with the following options:

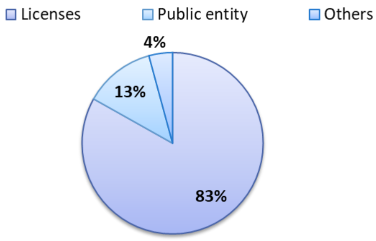


Figure 33. Bus management models in Spain

- It is operated directly by the Municipality.
- It is managed indirectly through licenses to private operators (83%).
- Transport Consortiums have been established in metropolitan areas, grouping the main administrations and, occasionally, the operators. They are entities that assume the powers of the public bodies that make up the consortium. Some Consortiums cover the entire territory of the Autonomous Community (such as Madrid and Asturias), while in others they are limited to metropolitan areas (such as the Andalusian Consortiums), so that routes that surpass the metropolitan area are autonomic competence.

3.3.1. General context of fleet operation

Addressing the complexity of the system for possible implementation schemes for electric bus fleets is the responsibility of the bus operator. Considering each of the possible variants with great care involves a huge impact when it comes to finding the solution that will eventually result to be the optimal.

The framework of conditions that an eBus operator needs to merge is shown in Figure 34. As it could be seen, it is not easy to consider the combination of every factor which requires to have either a great expertise in every key aspect of the eBus fleet management (which nowadays seems impossible) or a reliable network of collaborators and providers that factually help to assess the best pathway to follow.

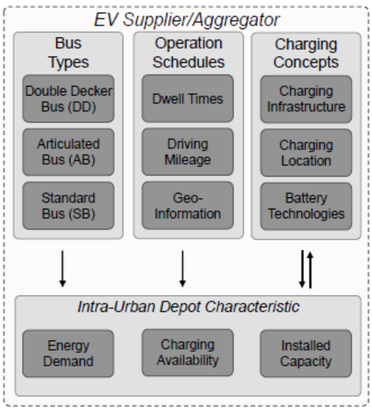


Figure 34. Framework conditions for the integration of the eBus [23]

As the figure shows, there are many problems and challenges associated with the implementation of eBuses in the urban public transport (location of charging infrastructure, decision on which routes to electrify…). Envisioning the complexity of the matter, it is key that decisions regarding the conduct of the process of implementation of electric buses to urban public transport are taken or are accompanied by the entities that provide public transport services.

A company could adopt several fleet exchange scenarios, taking into account the financial capabilities and date limits described in the recent modification of the Directive 2009/33/EC or Clean Vehicles Directive.

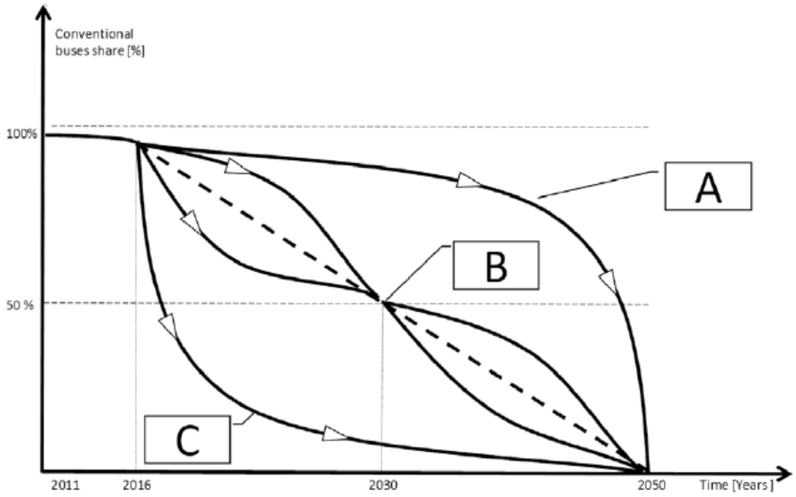


Figure 35. Bus fleet exchange variants to be conducted by public transport companies [38]

Figure 35 shows three variants of eBus penetration on public transport fleets' share having into consideration minimum milestones required by the Directive 2009/33/EC:

A. **Passive scenario**. While waiting for the technological maturity of the electric buses, the operator postpones the fleet replacement process. The effort to be made in final years is huge.

   In the case of delaying the incorporation of eBuses, given the fact that the change is imposed with certain penetration requirements, it could imply an important economic impact for the amortization of the CNG and diesel fleets due to the need for the abrupt adjustments in fleet management (adaptation of the facilities for recharging, increase of fleet and garages, etc.) as the deadline approaches. Ultimately, the quality of service would also be affected.

B. **Normative scenario**. Normative scenarios. Scenarios in which the rate of fleet replacement remains relatively constant over the years until reaching the 50% in 2030.

C. **Active scenario.** The fleet is replaced at the earliest, assuming that a grant or an economic boost of some kind is obtained for an innovative activity that respects the environment. The main effort is made in the first steps, that is, in the first years.

There are implicit advantages and disadvantages for every one of those variants. These include perspectives to obtain financing (could highly impact the TCO), the level of homogeneity with respect of bus manufacturers and models and the technological challenge linked to the complexity of fleet replacement.

3.3.2. Bus operation models in Spain

In order to delve the urban public transportation in Spain it is important to know management models inside out.

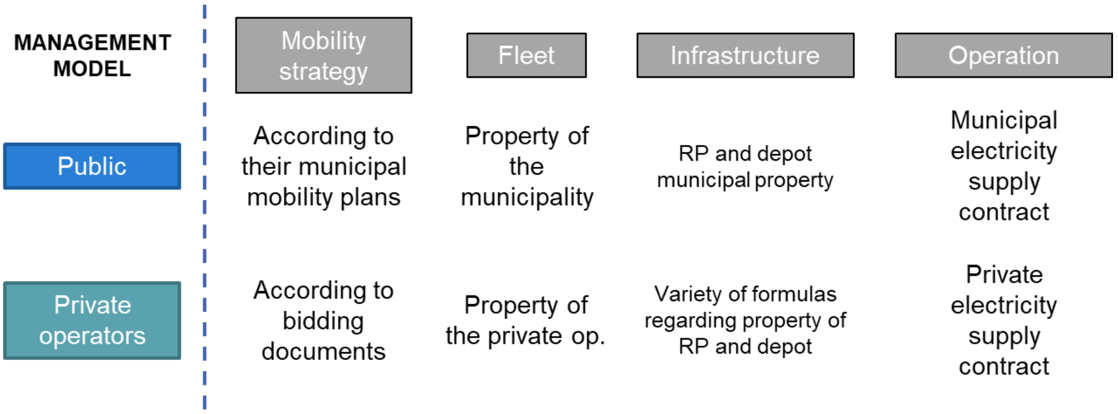


Figure 36. Spanish bus management model details

As previously mentioned, the bus fleet operation can be in hands of either a private operator or the municipality through a public company.

Figure 37 gathers the management model of the bus fleets of every Spanish capital.

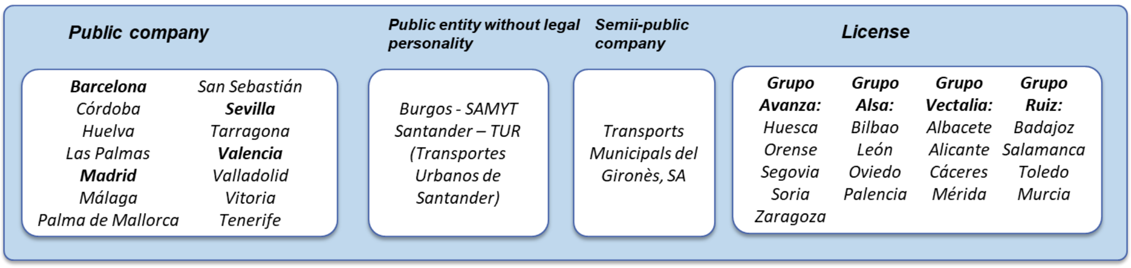


Figure 37. Management models of Spanish capitals

3.3.3. Detail of public tenders

During the development of the Master Thesis, it has been found that the tender is a key element that directly affects the route variant (Figure 35) that the municipality will apply in the following years until 2030 and 2050 afterwards.

If the existing management model is a license allowed by the municipality to a certain private operator, it is compulsory on the one hand, the municipality to publish a public tender on the matter and on the other hand, the private operator to win it with the highest evaluation and to fulfil every requirement of the same.

On the contrary, if the management model is the direct operation through public companies, the municipality is obligated to call for a public tender whenever they wish to purchase buses.

Given that urban public transport has been present for many years, municipalities are usually accustomed to both processes, although the electric component complicates it. In this matter, many municipalities worldwide follow the instructions of the UITP (Union Internationale des Transports Publics), which is the International Association of Public Transport and the only worldwide network to bring together all public transport stakeholder and all sustainable transport modes (more than 1600 member companies distributed in 99 countries).

This association publishes documents giving guidelines on how to structure tenders in both tender documents related to bus operators and tender documents for bus manufacturers. Additionally, they have designed an eBus deployment strategy within the ZeEUS project to support stakeholders in getting ready to deploy eBuses which is divided in four steps (Figure 38). The guidelines given for tender structuring match with the third step.

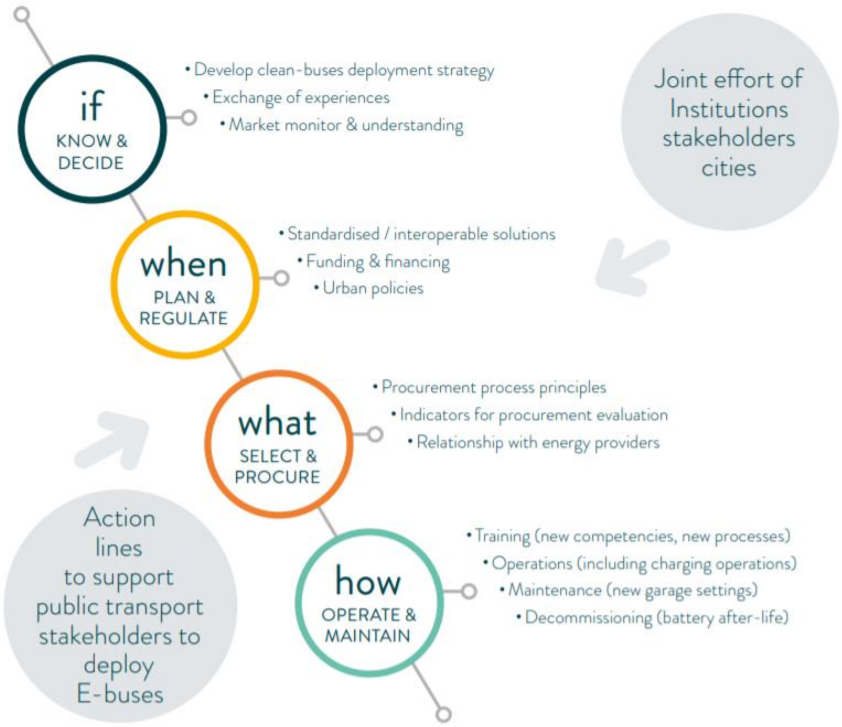


Figure 38. The phased approach of the UITP for eBus deployment

3.4. IDENTIFICATION OF TECHNICAL VARIABLES

With the available data, it is important to identify the key technical variables from the point of view of the municipalities that should serve as input for economic and ecological units of the decision-making tool designed in the following section.

A literature review and an enquiry among bus operator stakeholders identified some main influencing factors on the energy use of an electric bus, which are topography, number of bus stops and other traffic related stops, urban/rural traffic, average speed, passenger load, driver's experiences, climate, and outdoor temperature (as the batteries where not stored in a temperature controlled environment inside the bus).

Depending on the capability to optimally manage those factors (assuming efficiency ratios between 0.8-3 kWh/km, see Section 3.4.1), the fleet size and the annual distances traveled, the resulting consumption ranges of the fleet are shown in Figure 39:

	45.000 km	70.000 km	90.000 km
30 eBuses	1,1 – 4,05 GWh	1,7 – 6,3 GWh	2,2 – 8,1 GWh
50 eBuses	1,8 – 6,75 GWh	2,8 – 10,5 GWh	3,6 – 13,5 GWh
100 eBuses	3,6 – 13,5 GWh	5,6 – 21 GWh	7,2 – 27 GWh

Figure 39. Energy consumption ranges of eBus fleets

These wide ranges of consumption could be reduced when there is more real data derived from a greater number of electrified fleets.

3.4.1. Variables that affect energy consumption of the eBus

The energy consumption in electric mobility is very sensitive to different variables which considerably condition the autonomy of the vehicle. Factors such as the weight of the rolling stock, the speed limit and the acceleration of the bus notably vary the kWh/km ratio, which completely affects the operation of the bus. The higher the energy efficiency is, the greater the autonomy of the vehicle.

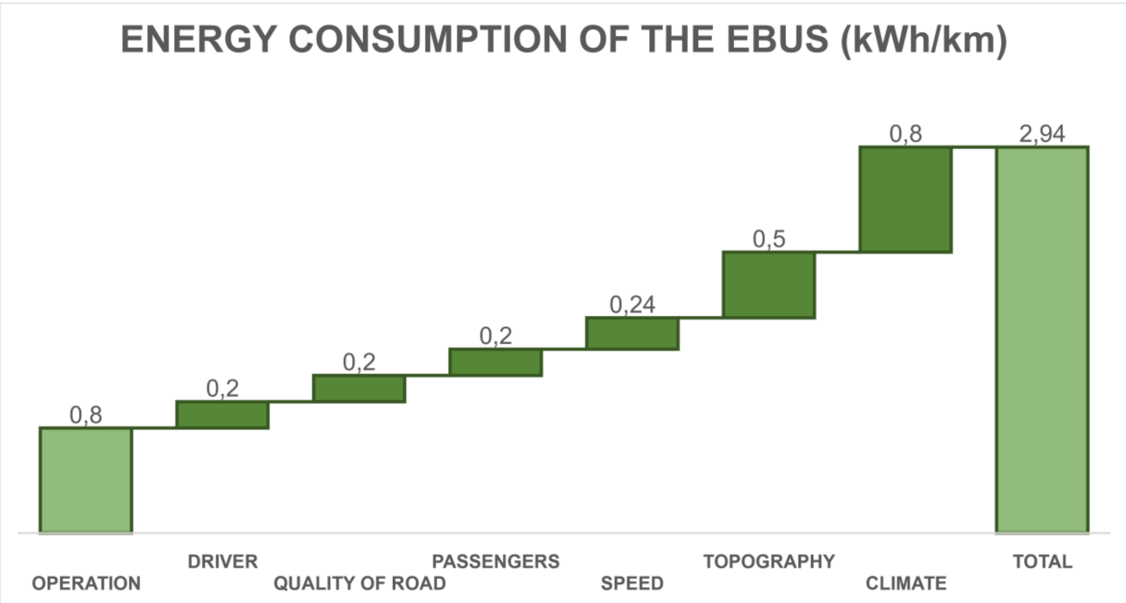


Figure 40. Key factors affecting efficiency of eBuses [2]

As shown in [22], heating requires a significant part of energy. There should be energy from the battery reserved for auxiliary systems (air conditioning, heating…) of the bus. In some countries, when heating represents 50% of consumption during winter, alternative systems such as heat pumps are used to avoid affecting the operation of the electric bus.

3.4.2. Identification of grid requirements

In addition to the efficiency of the bus and the design of the charging system, there is another critical element that limits the implementation of the eBus and that is often neglected: the electricity grid. It is important to know the status of this network to know if it is ready for new connections, to find the optimal connection point and to know if network reinforcements will be needed. To know all these details, a local network analysis must be performed.

Concerning general information related to the electricity network, based on the expected size of the eBus fleet in EU, its energy and power consumption can be estimated. To do this, the following hypotheses are made (based on available data, [2]):

- EBuses are supposed to do 150km/day in average and have an average consumption of 200kWh/100km [39]. The average energy consumption is thus 300kWh/day.
- The relative consumption is based on the annual European consumption, which is expected to increase.
- For the required power capacity estimation, all buses are supposed to be fully charged overnight during 8 hours with equal repartition. This does not correspond to the reality as many e-buses use opportunity charging but the aim is to simply give an order of magnitude.
- The relative power capacity is based on the total European capacity of 982 GW in 2015 (reference year for calculations) and is supposed to keep increasing at an average rate of 20GW/year as it did between 2010 and 2015 [40].

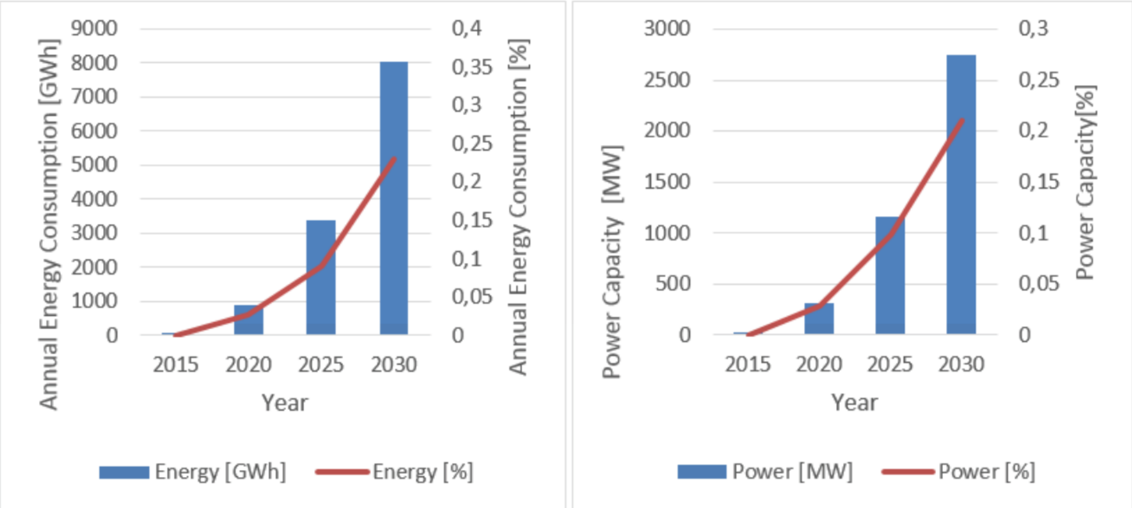


Figure 41. Increase of energy consumption and required power capacity (assuming overnight charging) for the expected e-bus fleet

Seeing Figure 41, the global impact of bus electrification in terms of consumption and power capacity seems relatively low. The required power capacity might however not be exact, as considering only overnight charging is a strong assumption. This approach also does not take the local effect on the grid into account.

Having ruled out a relevant impact on global energy demand growth, it is still important to determine specific grid technical requirements. In order to evaluate the impact on the grid of electrifying public urban transport it is crucial to determine the consumption profile of an eBus.

By all means, the consumption profile of a fleet of eBuses is different from the profile of EVs as they are likely to have more operating hours and often charged multiple times per day.

In Figure 42 the average consumption profile of a fleet of eBuses is given over the weekdays of August to November on 15-minute intervals. The bounds are defined as the average plus or minus two standard deviations. The y-axis is normalized and a value of 1 indicates the theoretical maximum energy consumption, defined as the combined rated power of the chargers installed.

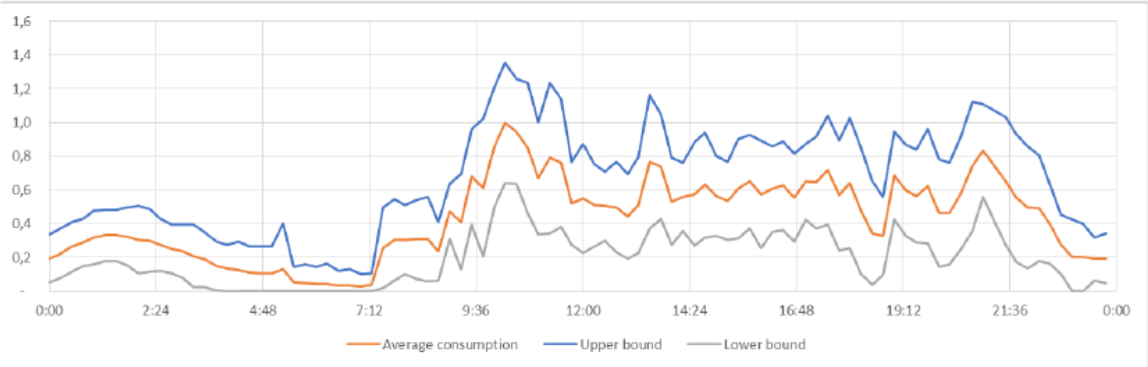


Figure 42. Average consumption profile of a fleet of eBuses [41]

The figure indicates that there is a significant amount of energy consumption between 9AM and 10PM with peak consumption around 10AM after morning rush hour. The space between the bounds indicates that there are significant differences in the energy consumption when comparing multiple days making it more difficult to accurately forecast the energy consumption on a given day. There is significant room to increase the full load hours of the installation.

Finally, it should be taken into account that when evaluating the implementation of the eBus requirements from the TSO and DSO need to be fulfilled, for instance, to avoid problems with security of supply.

4. DEVELOPMENT OF THE DECISION-MAKING TOOL

In the previous section it becomes evident that the possibilities when electrifying the urban public transport are immense. In principle, cities that choose to design their path towards electric mobility transformation from scratch will have an advantage over those seeking an adaptation of existing infrastructure that are more limited. Also, another lesson learnt is that there is no single solution or the same starting point for each municipality. Even if certain solutions can be scalable at some level and have a common ground, it is necessary to focus attention on each municipality case one at a time.

What is clear is that, in any case, a decision-making process similar to the one explained in Figure 31 should be followed in order to fulfil the most optimal deployment, which depending on the availability of data, the know-how of the agents involved and the limiting factors of each city will be a more or less laborious process.

Following what is explained in Figure 16, any municipality that has a decision-making tool could have a more manageable decision-making process. As mentioned above, the objective of this Master Thesis is to put the first bricks of that tool, focusing on the last steps of the process (Figure 43), including the technical model, the economic model and the ecological model.

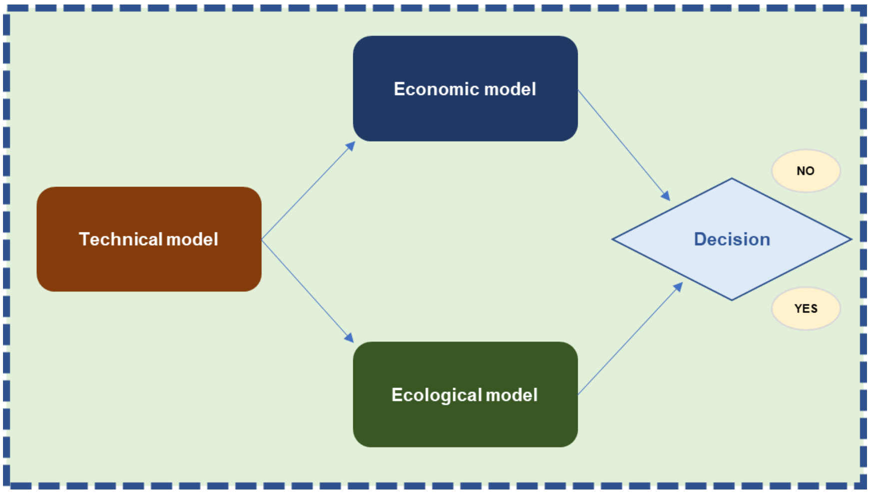


Figure 43. Elements of the decision tool that are under the scope of the Master Thesis

Working along these lines, Section 0 has tried to analyse and extract decisive inputs emulating the results that would come out of the technical model. Once that input is defined, the economic and ecological evaluation of the eBus solution should be done to have a detailed output and be able to take the most adequate decision possible. There are many variables that should be taken into account in both evaluations, as it is shown in Figure 44.

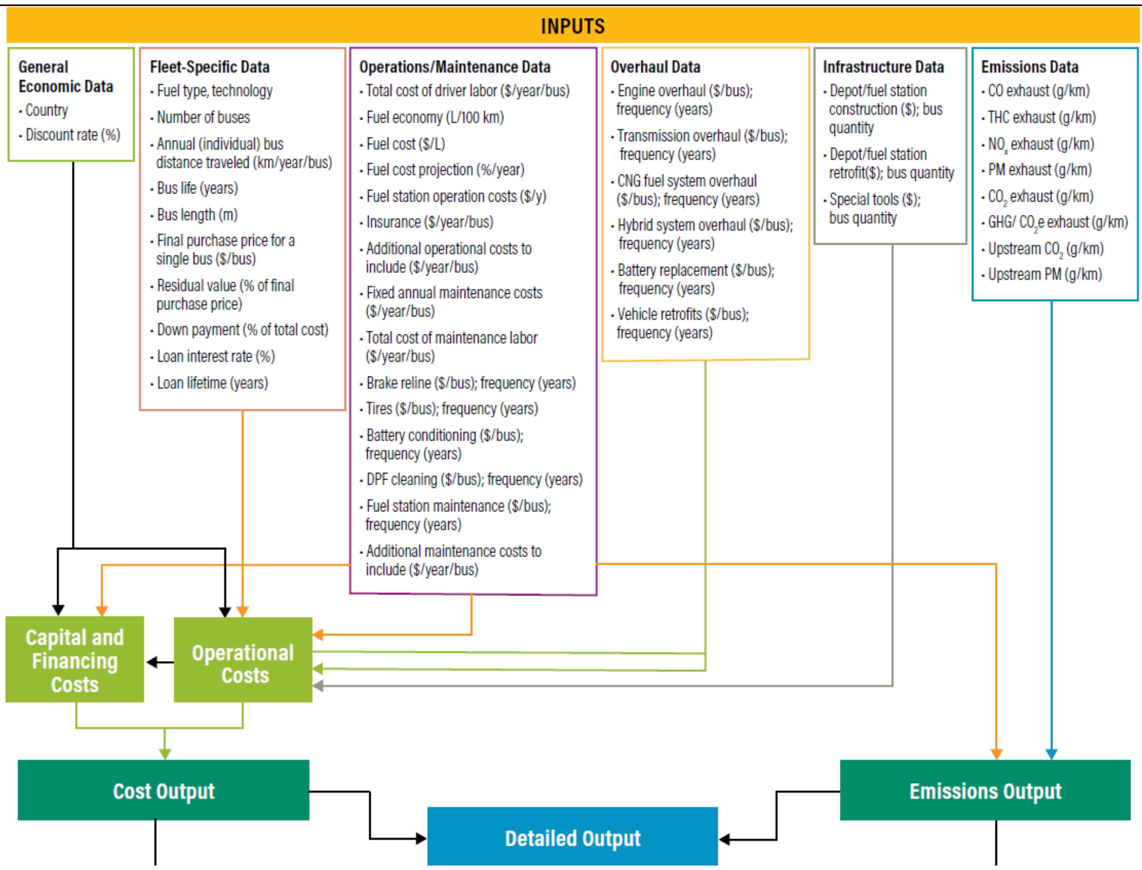


Figure 44. Input variables for costs and emission appraisal tool

In this section, a simplified version of this process has been carried out, developing a version of the economic model and assessing ecological issues. The work has been divided in four different blocks, namely:

- Cost structure analysis: to understand inputs that most affect the economic viability of a solution.
- TCO model development: to understand the economic competitiveness of eBuses in comparison to diesel buses and CNG buses.
- Analysis of economic results: that alongside the technical conclusions previously extracted will allow to draw some general result for municipalities.
- Environmental cost assessment: brief intuitive analysis on internalization of environmental costs.

4.1. CURRENT COST STRUCTURE AND EXPECTED EVOLUTION

Following the methodology established, the structure of costs is another key aspect on the way of implementing the electric bus. It is important to understand how costs are distributed along the useful life of the assets in order to be able to evaluate the economic competitiveness of the electric bus compared to other technologies. Even the most efficient technology could not be largely deployed if it is not cost-competitive with its alternative. However, it should be noted that any solution will only be valid if it meets the economic, but also technical and environmental requirements.

It is worth mentioning that most of the economic data that will be mentioned in this chapter relates to values found in Spanish and European markets [2].

4.1.1. Overview on cost structures of different bus technologies

The costs are considerably differently structured depending on the technology. Electric buses have remarkably high upfront costs but much lower variable costs, while diesel buses are in principle more affordable at first but with significant recurrent expenses. Additionally, CNG buses are in the middle of the way of the other both technologies as it is reflected in Figure 45.

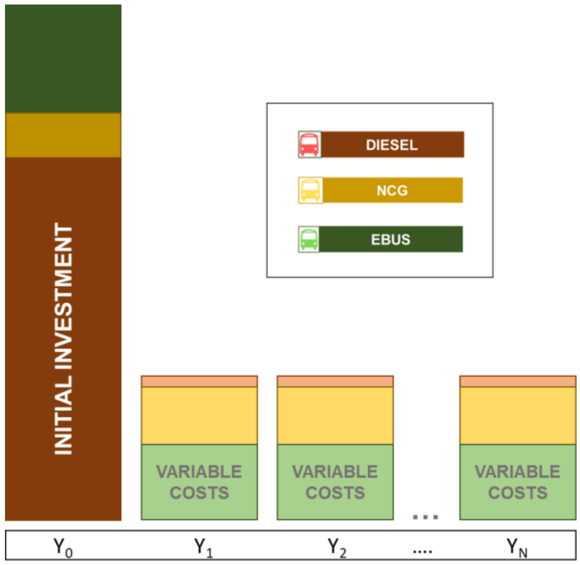


Figure 45. Comparative of the cost structure between different bus technologies

Even if the figure shows lower variable costs (mainly fuel costs plus O & M costs) for CNG buses than for diesel buses, that fact will depend to a large extent on the cost of fuel, thus depending on the country the variable costs of one or the other may differ.

For instance, Grupo Ruiz operates numerous urban and interurban transportation concessions in Spain and was the first private operator in the Spanish market to test CNG buses. Today, it has the largest private CNG fleet in Spain, with 60% of penetration share of the fleet. In their Corporate Social Responsibility Report of 2015, they justified this bet by claiming emission reductions, but also economic profitability. According to their operating data, CNG buses have the following cost differences compared to diesel:

Table 5. Difference in operating costs of CNG buses vs. diesel buses [42]

COST	€/100 km
Fuel cost	-14,05
Cost of compressing	+1,74
Maintenance cost	+3,27
Amortization extra cost of the bus[7]	+3,56
Amortization investment filling plant[8]	+1,88
Total	-3,60

[7] Calculated for a useful life of a 12-years and 80,000 km average trips per year.
[8] Calculated for a fleet of 20 buses and a repayment term of the plant for 15 years.

As can be seen, the cost of fuel is the key element for the Grupo Ruiz to find it more economical to operate CNG vehicles than diesel. However, it must be taken into account that this group has an extended CNG bus fleet and also has 4 CNG plants, so any other operator can get a completely different economic balance if they obtain the fuel at a different cost. Depending on fuel costs, it could also happen that diesel buses are more profitable than CNG buses, as in the case of [16].

H_2 buses

Another alternative to diesel buses could be the H_2. Being H_2 buses a recent tendency as they are, it is currently difficult to disaggregate their costs. In principle, the cost structure is similar to the cost structure of electric buses, although at a higher cost scale. The costs that are worth mentioning are: initial investment, infrastructure costs, fuel costs and O&M costs. Due to current market situation, H_2 buses will not be considered in the comparison between technologies.

4.1.2. Focus on the cost structure of the eBus

Bearing in mind the information in section 4.1.1, in this section the detail of the cost structure of the eBus as an alternative for bus fleets is presented. Electric vehicle skeptics often say that the cost of switching is prohibitive. The aim of this whole section is to demonstrate the lack of veracity of that affirmation and to really try to determine the cost for society of the switching.

4.1.2.1. Initial investment costs

The high upfront cost is the largest barrier that is slowing the pace of mass adoption of electric buses. Many municipalities lack the economic strength to face the initial investment and even if the willingness of transitioning is present, economic implications result impossible to face. Due to this fact, many actors are focusing in proposing new business models in order to facilitate the overcoming of this issue (see Section 4.1.2.3).

Nowadays, most projects are still paid for upfront in Europe and the US, either by the municipality or the bus operator, thanks to a combination of self-funding and grants provided at regional, national or EU level.

China is far ahead of the rest of these regions in this matter and since 2016 began to operate without public support. Nonetheless, their situation is exceptional, as detailed in previous chapters, and it seems that the rest of the regions still need some kind of public support (in the form of subsidies or policy design) to promote massive deployment. In this matter, it is interesting for the regions to extract the lessons learned from the Asian country to replicate successes and avoid failures.

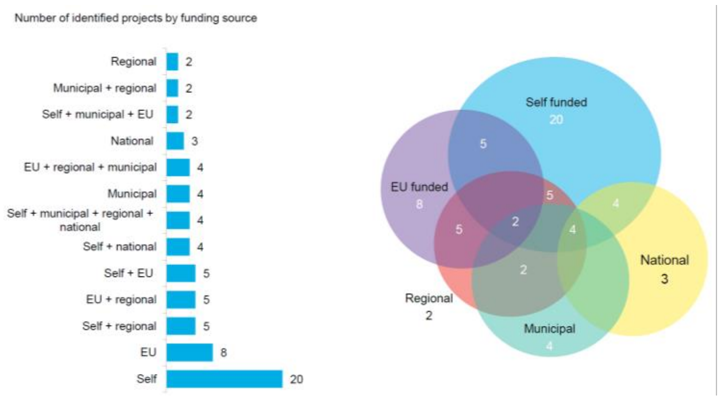


Figure 46. Electric bus funding sources for selected European eBus projects [16]

Figure 46 shows a gathering made by BNEF of the different paying structures that have been followed in several European projects. As mentioned, in most projects different funding sources are combined where a part is always self-funded, and that part is accompanied by some sort of grants. Even if it is not included in the figure, some municipalities occasionally cover the cost with operating budgets or debt.

Initial investment cost of switching to eBuses are divided in the following items:

- Capital cost of eBuses: current market prices are around 200k€ diesel buses, 300k€ CNG buses and 500-600k€ eBuses [2]. Typically, the Chinese government subsidized more than half the cost of the bus [43].

- Infrastructure: it is another of the elements that greatly affect the initial cost. It should be borne in mind that most of the time, network reinforcements are required regardless of the chosen charging solution. This entails the need for civil works and often the need to have a dedicated secondary substation. Anyway, it is important to consider that, if the municipality's strategy seeks a great penetration of eBuses, those initial costs only fall on the first units and the TCO of the following will be much cost-efficient. It is important for the municipality to have a clear final objective in mind in terms of fleet structure, in order to make the initial modifications of the network considering the future scalability of the solution and be the most cost-efficient possible.

  It should be noted that there are charging infrastructure deployment solutions that will never be cost-effective for some municipalities, depending on their fleet size, characteristics of the municipality, etc. It is important to find the solution that best applies to the initial situation and future expectations of each municipality.

Many cities lack funds to justify a higher initial cost to replace the fleet, but some are deliberately delaying the purchase decision because they expect eBuses to be cheaper in the future due to lower battery prices. In those cases, new formulas should be tried to avoid the stagnation of sales.

4.1.2.2. Variable costs

Variable costs of buses comprise fuel expenses as well as O&M expenses. In the case of the eBus, the fuel cost is the cost of electricity supply.

Electricity supply

The contract for the supply of electricity of the eBuses may be in the name of the municipality or the private operator. If this cost of electricity supply is down to the municipality, the supply contract should be assigned through a public tender.

The electricity cost depends on the negotiated price, although some studies estimate electric buses are 40% cheaper to maintain than traditional buses, allowing savings of more than $360,000 in fuel costs over their lifetimes [17]. As an orientation, while operating a diesel bus costs around 100-140€/day, the eBus costs between 16-20€/day [2].

Additionally, electricity is a commodity and can be produced locally and with RES.

O&M expenses

Concerning the O&M, the electric powertrain fewer moving parts than ICEs, resulting in a significantly lower need for O&M.

Variable costs could also be subsidised as in the case of initial capital costs. For instance, in the city of Shenzen the local government complemented the national grant with £58,000 if the eBus exceeded 60,000 km per year [43].

Technology comparison

Clearly, variable cost is the term of expenses were the eBuses notably reduces costs with respect to diesel and CNG technologies. EMT operates the three types of buses and sets the tractions cost of each one of them in: 20€/100km for eBuses, 34€/100km in the case of NGC and 54€/km for diesel buses [44].

4.1.2.3. Emerging business models

As mentioned in Section 4.1.2.1, the combination of self-funding and grants is the usual approach whenever a new technology is emerging and trying to reach mass sales in the market. The key issue is that there is a huge distance between being a technically proven technology and having a successful implementation. Often times between technology creation and early commercialization many projects are never able to surpass the so-called "Valley of Death" (Figure 47).

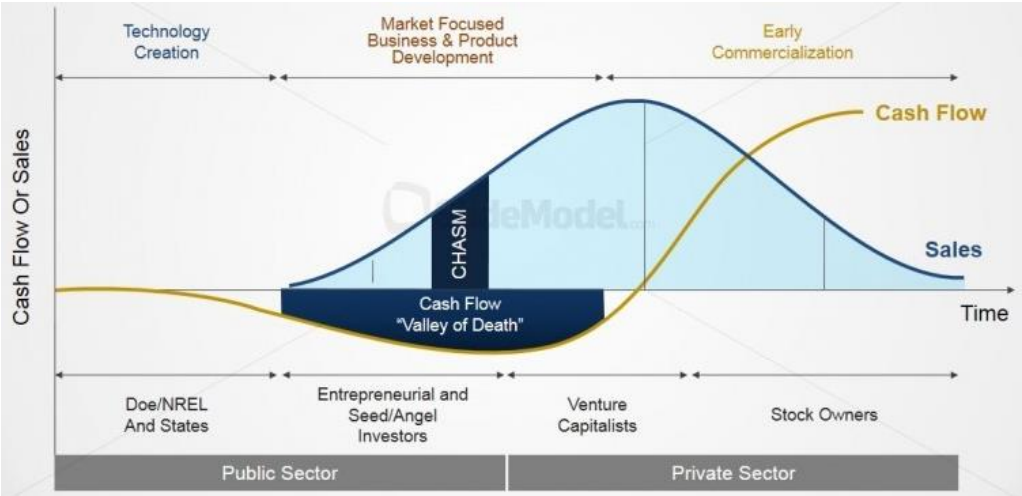


Figure 47. Market stages of high technology products [45]

It could be said that eBus technology is distributed along the entire time axis, depending on the element of the value chain that is being considered. On the one hand, there are charging solutions such as the inductive one or the design of new battery types that are still between the stages of technology creation and product development.

Several eBus solutions were also tested through subsidised pilots (ZeEUS project) in Europe and although they are already commercialised, in some cases the economic barrier is insurmountable, so certain public aid has been maintained until the technology is completely competitive. Such aid only makes sense if, at the moment when the technology can compete in the market, the aid is withdrawn, as has been done in the case of China and it is expected to be done soon in Europe. In China, since the sales have reached certain level the government announced a cut on subsidies, with the intention of encouraging manufacturers to rely on innovation instead of aid. If the main goal is to support environmentally friendly technologies, then there are other instruments such as environmental policies that should be enough to internalise externalities associated to GEI emissions.

Another figure that appears in these initial stages is that of risky investors. Focusing on the segment just before the early commercialization, many industry players who have low risk aversion are trying to discover new business models to overcome the barrier of the high initial cost of eBuses. Today, the business models that have had some kind of success are battery leasing, joint purchasing, capital leasing and operating leasing, explained below in detail.

Battery leasing

The core element of an electric bus is the battery, a key element in the viability of purchasing this type of technology. Through battery leasing, the buyer owns the bus but rents the battery so that the gap between the capital costs of the eBus and a diesel bus is closer.

Other benefits of this business model are:

- Payments for the battery are included in fixed service payments over the life of the asset which reduces uncertainty.
- All battery maintenance and repair costs are the responsibility of the leasing company; hence the buyer's balance sheet is considerably improved.
- It reduces the risk around battery life for the buyer.

Usually battery leasing is applied with the aim of giving a secondary live to the battery, which could also lead to an improvement of their life cycle.

However, it is a limited option for smaller manufacturers since the scalability could be complicated without certain level of economic and technical capabilities.

As a real-life example, Proterra recently teamed up with Mitsui & Co. of Japan to create a new credit facility. The scheme helps to offset the battery price of eBuses for transit operators, decoupling the batteries from the sale of the bus. The contract includes a 12-year warranty and maintenance as well [46].

Joint purchase

It consists on taking advantage of economies of scale. Two or more municipalities or bus operators join forces and try to get a better deal from the provider given that the contract is bigger, therefore the purchasing power of the combined buyers is increased.

The main barrier for this business model to be more common is that the agreement between buying parties can be significantly complicated due to the fact that cities have different technical requirements for their eBuses, delivery times may not coincide, and drafting contracts can take a long time.

As real-life example, San Francisco Municipal Transportation Agency (SFMTA) and King Country Metro in Washington collaborated in a joint contract to procure 60 articulated trolley buses for SFMTA and 33 for King County with the aim of reducing costs and time to purchase and receive eBuses [47].

Capital lease

Capital leasing is a renting contract that enables the temporary use of the electric bus by the renter. However, given the different accounting treatment for capital leasing with respect to operating leasing (that will be detailed in the following section) it is considered a purchase, while an operating lease is handled as a true lease.

With respect to benefits associated capital leasing:

- It offers flexibility to the fleet operator in case of technological change
- It can be cheaper than debt financing.
- Once the lease is finalized, the operator may not become the owner of the asset and transfer the bus to another city.

Nevertheless, it is still a relatively new model, so it has a certain level of associated uncertainty.

<u>Operating lease</u>

As mentioned previously, an operating lease results in the renting of the electric bus by the municipality or the bus operator. Its main driver is that it offers flexibility in case of technological change or if problems in operating a new technology are insurmountable, for instance.

Additionally, it can be cheaper than debt financing and the provider maintains all the risks and advantages of having the bus owned.

The problem is that it usually lasts for a short period of time, during which the rental payments do not cover the total cost of the asset. Therefore, they usually have maintenance contracts associated.

Real life examples of capital or operating leasing[9] business model are:

- BYD is running a leasing programme in the States as well, together with Generate Capital from San Francisco. In the case of the Chinese provider, the offer includes a leasing option for the entire bus and the JV partner effectively buys the electric buses from BYD [48].
- Alliance between BYD and Enel for the purchase of 100 eBuses for Santiago de Chile. Investment of some US $ 30 million to finance the purchase of the Chinese company BYD from this new fleet that will be operated by Metbus. The strategy that Enel will implement in Chile contemplates a figure of leasing for the bus operator that contemplates the purchase of the machines and the necessary infrastructure for the recharge of electricity. To this is added an advisory in maintenance and optimal management of the recharge [49].

4.1.3. Future cost evolution

As of 2025, a dramatic improvement in the economic competitiveness of eBuses is expected due to the drop in the cost of batteries. Approximately, the battery accounts for 35-40% of the total eBus cost [2], therefore, if those predictions prove true, the capital cost of eBuses will notably decrease.

[9] There is no detailed information on which of the two types applies to each example.

Figure 48 shows the price forecast of the lithium ion battery pack ($/kWh) depending on its demand (GWh/year). The estimate shows that the increase in demand results in a price decrease. BNEF expects the price to decrease by 65% by 2030 to reach $ 70/kWh.

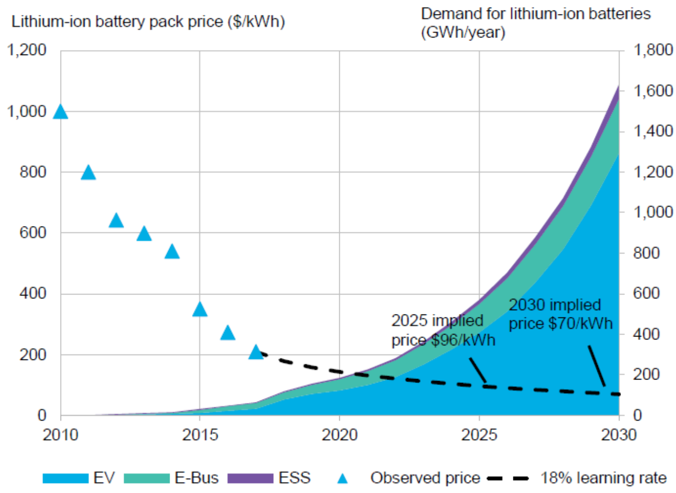


Figure 48. Lithium-ion battery pack price forecast [16]

Many experts agree that the price of the battery will continue to decrease significantly in the coming years, which as mentioned above would greatly help the reduction of eBus costs. However, there is some uncertainty in this forecast and some actors have expressed doubts about this claim. The main determining factors of these doubts are the continuous growth of the lithium-ion battery pack demand and the possible shortage of raw material.

Demand growth

Lithium-ion batteries have reduced costs continuously over the past few years. Still, it seems that there is room for reduction until 2030. However, some sceptics believe that if the demand forecasts are also met the expected price reductions will not occur and will no longer reflect the actual costs of the product. This has already happened with other emerging technologies such as solar and wind. Both technologies suffered a hiatus in the reduction of prices due to the effect of the demand, but after a certain time, when the increase in demand calmed down, they arrived at the prices that reflected the real costs, as shown in Figure 49. For this reason, it is expected that something similar could happen with lithium-ion batteries.

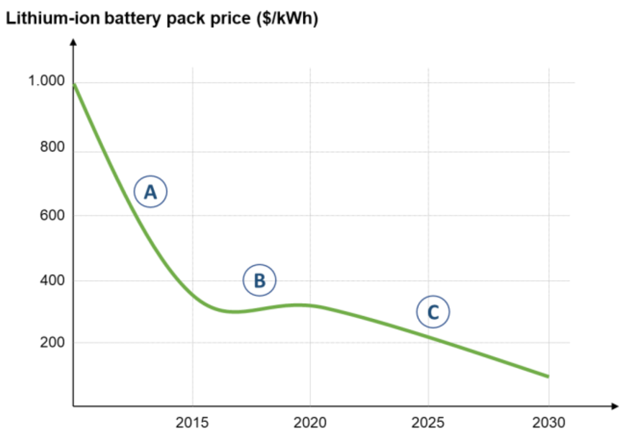


Figure 49. Possible scenario of lithium-ion battery pack prices

The different price segments in this possible scenario would be:

A. The **dramatic decrease in prices** that has already occurred in recent years. In the first years of commercialization of an emerging technology, the potential for price reduction is enormous and, in the case of batteries, expectations have been fulfilled by far.

B. **The price stabilisation** due to the phenomena afore explained, in other words, cost reduction is compensated by demand growth.

C. **The final price decreasing** to the minimum possible.

Shortage of raw material

Currently there is capacity to manufacture batteries above the need of demand (Figure 50). However, the possibility of shortages in lithium reserves is one of the main concerns of the stakeholders in this sector. These reserves are very localized in certain locations of the planet and are limited. If this happened, the immediate effect would be terribly high prices, which would make the eBus' economic viability impossible.

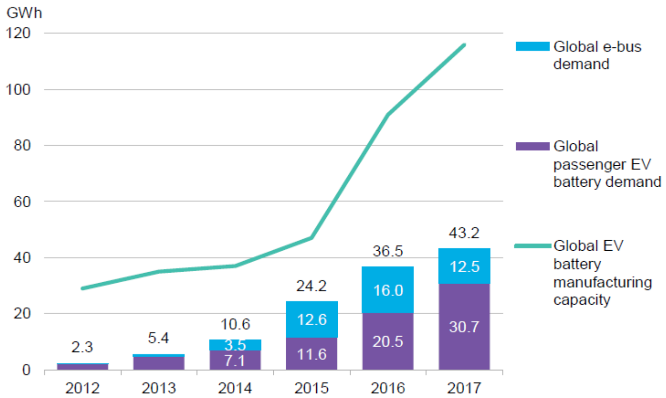


Figure 50. Global eBus lithium-ion battery demand and global EV lithium-ion battery manufacturing capacity

Even so, it seems that this negative scenario is far from happening. In addition, many experts say that future battery technology will not have to be based on lithium or other scarce materials.

Another factor that can make a difference when speaking about costs but with a lower potential to impact comparing to batteries are the economies of scale in the electric part of the bus. The rest of the bus is well-known by the industry.

4.2. DEVELOPMENT OF THE EBUS TCO MODEL

Although equality in the initial investment cost with respect to the diesel bus is expected by 2030 (Figure 51), each specific case of eBus fleet implementation results in very different Total Cost of Ownership (TCO), depending on the initial cost of the bus, infrastructure costs, other variable costs, the annual distance travelled by the buses and their useful life. In some of these cases, the TCO of the eBus has positive results.

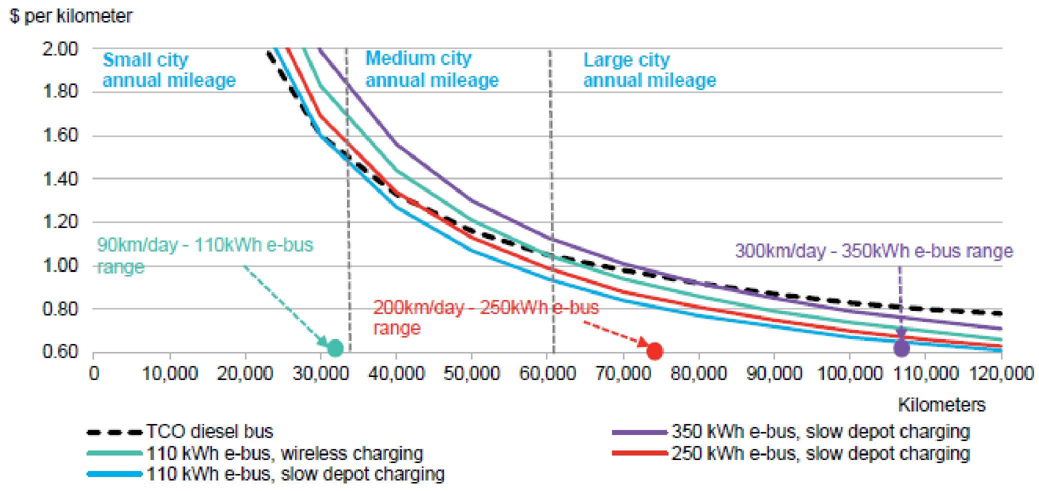


Figure 51. TCO comparison for eBuses and diesel buses with different annual distance travelled [16]

The objective of developing a model is to be able to evaluate the TCO of the different eBus cases in order to draw some conclusions on factors that affect economic viability of these projects. The cases presented are real Spanish cases to see whether these cities are cost-effectively deploying eBus solutions.

To verify the performance of the model, the development has been carried out in two very different blocks. First, after developing the TCO model, input data and assumptions made in [16] have been used in order to ensure comparable results between the own development and results of BNEF. Once this has been achieved, data from the European and Spanish markets have been used to perform the analysis of local results.

It should be noted that the model has been developed from the point of view of the fleet operator which directly or indirectly is the municipality.

4.2.1. Definition of input variables for the TCO model

Based on the cost structure discussed previously, the TCO model developed in Excel is made up of the cost of the vehicle (CAPEX and OPEX), the cost of infrastructure (CAPEX and OPEX) and the cost of financing capital. The input parameters of the TCO model are listed in Table 6. The final value of TCO is expressed in EUR/km and results from the sum of all mentioned costs, considering also the total mileage during the useful life of the bus considered. That is, the mileage and the useful life are also modifiable variables.

Table 6. Input parameters of the TCO model

DATA ON COSTS	Vehicle cost	CAPEX (€)	eBus cost
		OPEX (€/km)	Electricity cost (€/kWh)
			Efficiency (kWh/km)
			Maintenance
	Infrastructure cost	CAPEX	Cost of charging point including civil work and secondary substation (if necessary)
		OPEX	Maintenance costs (have been considered negligible)
	Financing cost	Interest expenditures	
OTHER RELEVANT DATA	Bus	Useful life	
		Average annual covered distance (km)	
	Battery	Useful life	
		Future expected costs (see Figure 52)	

To calculate the cost of electricity, the average energy consumption is multiplied (calculated using data provided by manufacturers and private operators), taking into account the charging efficiency, by the average price of electricity during the period of useful life considered.

Maintenance costs for the vehicle include spare parts and labor costs, but since eBuses are vehicles that have been in circulation for a short time, fleet operators do not have reliable data on this matter. Therefore, the theoretical data of [16] have been used. On the other hand, the maintenance expenses of the charging station have been considered negligible.

The investment cost of the vehicle also includes the replacement cost of the battery after the useful life (it is a modifiable variable, normally it is a value between 4 to 8 years, depending on the strategy of the operator) taking into account the estimated future prices of the battery according to the source [16] and showed in Figure 52.

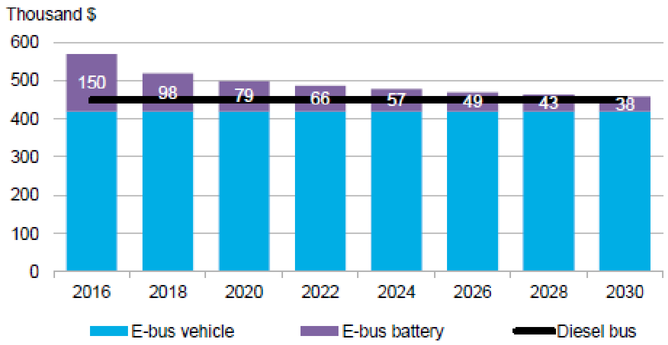


Figure 52. European eBus upfront price forecast considering future battery prices (250kWh) [16]

With the many considerations mentioned above, the TCO model includes a user interface where certain input data must be provided, and the model directly calculates the TCO of that case.

ANALYSIS CASE			BEV	GNC	Diésel
External inputs	Bus	Bus Lifetime (years)			
		Average annual distance (km)			
	Battery	Battery Size (kWh)			
		Battery Lifetime (years)			
		Annual Discount Rate (%)			
Specific inputs	CAPEX	Unit Purchase Cost (EUR)			
		Infrastructure cost (EUR)			
	OPEX	Fuel cost	€/kWh	€/sm3	€/L
		Bus Efficiency	km/kWh	km/kWh	km/kWh
		Annual Running (O&M) Cost (EUR)			

Figure 53. Input data required to calculate the TCO of diesel, CNG or electric buses

Additionally, in the case of the eBus, some extra data on the infrastructure should be provided (Figure 54).

Additional Electric Bus Inputs (CAPEX)	
Infrastructure Charging Stations	
BEV Charger (in Depot) Cost (EUR)	
Bus to Charger Ratio	
Fast Terminal (Oppurtunity) Charging Station (EUR)	
Bus to Charger Ratio	
Electric Control Box Cost (EUR)	
Bus to Control Box Ratio (Depot)	
Bus to Control Box Ratio (Terminal)	
Effective Battery Size (kWh)	
BEV Purchasing Cost	
Option A:	
Total Unit Cost in EUR (Bus + Battery)	
Option B:	
Body Cost (EUR)	
Battery Cost (EUR)	
Total Unit Cost (EUR)	

Figure 54. Input data required on eBus infrastructure

4.2.2. Verification of the performance of the TCO model

In order to verify the functioning of the TCO model developed, the data provided in the *Electric Buses in Cities* report was used [16]. The verification method has been to apply the same hypotheses made by BNEF to demonstrate that their same results are obtained with the TCO model presented above.

4.2.2.1. Baseline TCO comparison in the diesel case

To calculate the TCO, BNEF considers the following assumptions:

Table 7. Assumptions considered by BNEF for diesel buses

VARIABLE	VALUE CONSIDERED
Lifetime	15 years
Distance travelled per year	60.000 km
Vehicle efficiency	4,1 miles per gallon
Vehicle capital costs	$450.000
Refuelling infrastructure[10]	$0
Other operating costs	$34.877 per year
Fuel price	$2,5 per gallon

With these assumptions the TCO results are:

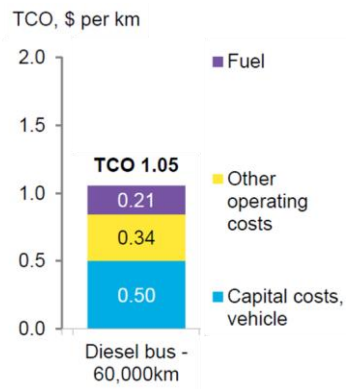


Figure 55. TCO results of a diesel bus-BNEF

Applying the same assumptions, the TCO model gives this result[11]:

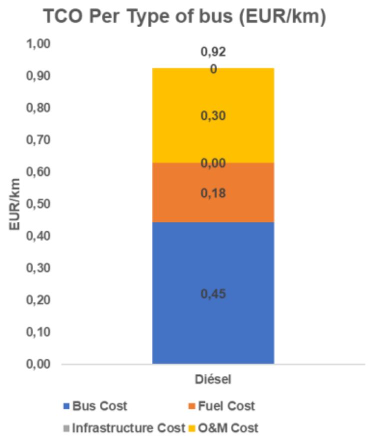


Figure 56. TCO results of a diesel bus-Own elaboration

If the conversion factor between USD dollars and euros is applied (around 0,89€/$), it is verified that the model works properly for the case of diesel vehicles.

[10] It is assumed the infrastructure already exists in established cities

[11] It should be noted that some conversion operations have been carried out.

4.2.2.2. Baseline TCO comparison in the CNG case

To calculate the TCO, BNEF considers the following assumptions:

Table 8. Assumptions considered by BNEF for CNG buses

VARIABLE	VALUE CONSIDERED
Lifetime	15 years
Distance travelled per year	60.000 km
Vehicle efficiency	21 miles per MMBtu
Vehicle capital costs	$540.000
Refuelling infrastructure[12]	$0
Other operating costs	$34.877 per year
Fuel price	$15 per MMBtu

With these assumptions the TCO results are:

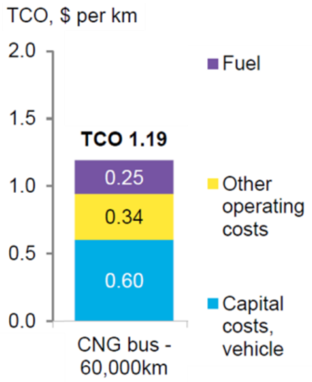


Figure 57. TCO results of a CNG bus-BNEF

Applying the same assumptions, the TCO model gives this result:

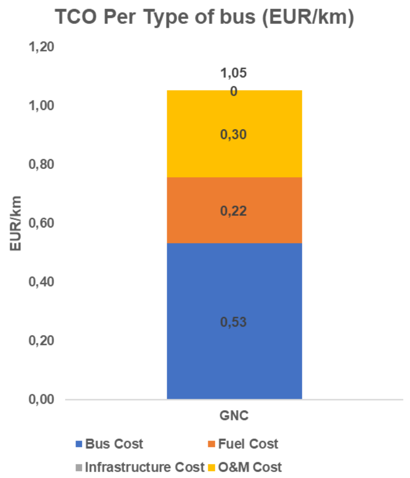


Figure 58. TCO results of a CNG bus-Own elaboration

If the conversion factor between USD dollars and euros is applied (around 0,89€/$), it is verified that the model works properly for the case of CNG vehicles.

[12] It is assumed the infrastructure already exists in established cities

4.2.2.3. Baseline TCO comparison in the eBus case

To calculate the TCO, BNEF considers the following assumptions:

Table 9. Assumptions considered by BNEF for eBuses

VARIABLE	VALUE CONSIDERED
Lifetime	15 years
Distance travelled per year	60.000 km
Battery size	250 kWh
Vehicle efficiency	0,5 miles per kWh
Vehicle capital costs	$570.000
Refuelling infrastructure	Slow depot charging at $50,000 per charger. Bus-to-charger ratio 2:1.
Other operating costs	$26.127 per year
Fuel price	$0,1 per kWh

With these assumptions the TCO results are:

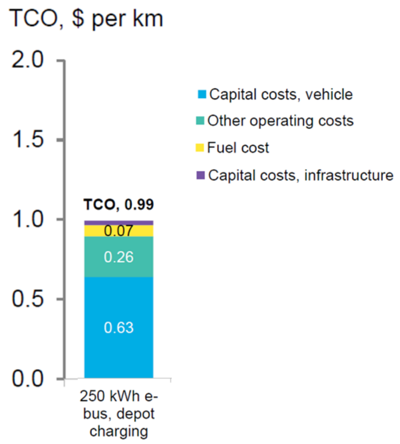


Figure 59. TCO results of an eBus bus-BNEF

Applying the same assumptions, the TCO model gives this result:

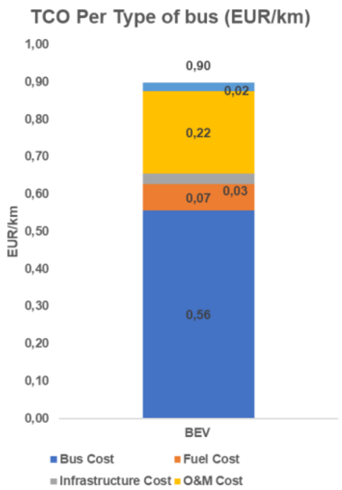


Figure 60. TCO results of an eBus bus-Own elaboration[13]

[13] The 0,02 €/km corresponds to the cost of replacement of the battery

If the conversion factor between USD dollars and euros is applied (around 0,89€/$), it is verified that the model works properly for the case of eBuses.

4.2.3. Results of real cases obtained with the model

Once the performance of the TCO model is ensured, the TCO of four deployment cases in Spanish cities have been calculated with the aim of extracting conclusions on what have been properly done by those municipalities or on the contrary to extract lessons learnt to avoid replicating errors.

Since part of the information has been provided in a confidential manner either by the operator of the fleet or by the eBus manufacturer, certain data are not disclosed in the explanation of each case. However, all the information used is real, unless expressly stated otherwise.

4.2.3.1. The case of Badajoz

The city of Badajoz has the largest fleet of electric buses in Spain and the largest in percentage in Europe. The city, by means of its private operator Tubasa, incorporated 15 BYD eBuses in May for 475.000€. With a 16-hour battery life (348 kWh of battery) and they represent the 35% of the entire fleet of 42 buses. In addition, Tubasa has already made the purchase of another 15 buses from the same provider that are not yet in operation.

The TCO of these 15 first buses has been analysed, bearing in mind that they are being charged at the depot thanks to 15 double charging points of 100kW (250.000€). Additionally, Tubasa has installed two secondary substations of 800 kVA in order to be able to supply the necessary energy [50]. Lacking O&M cost data because it is a recent project, the data provided by BNEF has been used [16].

Considering these input data, the TCO resulting from this case is displayed in Figure 61.

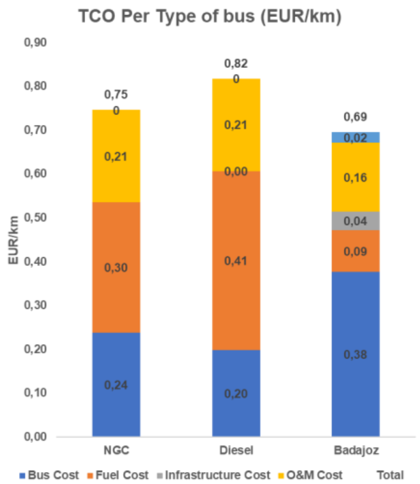


Figure 61. TCO results of the case of Badajoz-Own elaboration[14]

BNEF estimates the cost of a case similar to this one (depot charging plus a battery of 350kWh and similar mileage) in 0,92$/km, or converting it to approximately 0,82€/km). Thus, Badajoz reduces costs by 16% compared to the reference case, this is partly due to the fact that the cost of fuel in Europe is higher than that of the United States.

[14] The light blue segment in the eBus chart indicates the cost of replacing the battery. Same applies for the other three cases.

In addition, the cost reduction compared to using diesel buses for Badajoz results in a similar figure and the solution chosen by Badajoz has an 8% lower TCO than if CNG buses had been used.

The reasons for the TCO of Badajoz to be so positive are mainly three:

- As the bus provider is Chinese, the cost of the eBus is considerably lower than the current average offer in other markets.
- The strategy of Tubasa focuses on making the most possible use of the eBuses purchased. That is, its operation is prioritised whenever possible, which increases the annual mileage, a key factor in the TCO, as will be seen in Section 4.3.

Additionally, Tubasa carries out an active management of the fleet, meticulously supervising the correct operation of the eBuses (analysing variables such as the driving style) and always trying to keep the eBuses in the optimum operating range to avoid the accelerated discharge of the battery.

It should be noted that in the short term the TCO of this case will improve even more since Tubasa is in the process of making modifications to the Chinese software to increase the autonomy range by 30%.

4.2.3.2. The case of Madrid

Nowadays Madrid accounts for around 40 electric buses provided by many different manufacturers. Recently the EMT (Empresa Municipal de Transportes) have closed a deal of 20 eBuses with Irizar, which will be delivered throughout this year and will complete the previous 15 eBuses already delivered.

The new order received from the EMT contemplates the supply of 20 buses belonging to the second generation of the Irizar ie bus (12m). The main difference with the initial model lies in the advantages incorporated, especially those related to technological innovation and design. The new model reduces the weight by 10% and incorporates more efficient batteries with a faster charging, among other issues.

In this case, the contract has only involved the purchase of the vehicles and at no time is the charging infrastructure mentioned. It could be that Madrid already has other eBuses and the available infrastructure is sufficient or may only need minimal modifications. In any case, the cost of the charging infrastructure will be considered negligible.

Once again, lacking O&M cost data because it is a recent project, the data provided by BNEF has been used [16].

Considering these input data, the TCO resulting from this case is displayed in Figure 62.

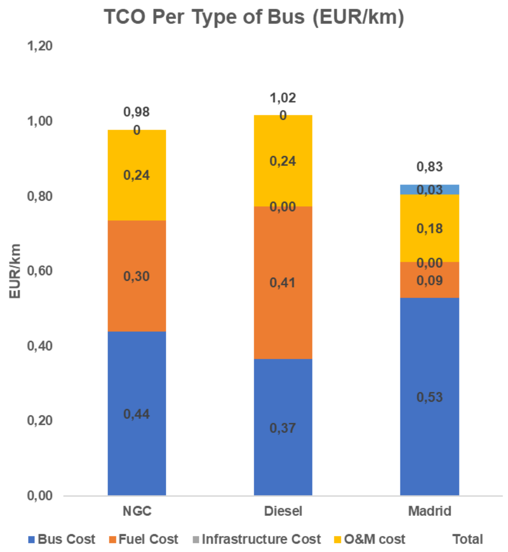


Figure 62. TCO results of the case of Madrid-Own elaboration

In the case of Madrid, when not considering the recharging infrastructure, the positive difference with respect to the other two technologies is even greater. Once again, it is verified that for the case contemplated the eBus turns out to be the best choice.

4.2.3.3. The case of Bilbao

Desde diciembre de 2016 dos autobuses eléctricos Irizar i2e de 12m circulan por Bilbao. La autonomía de dichos vehículos es de 200km gracias a la batería de sodio-níquel de 376 kWh, aunque se utiliza en rutas más cortas [51].

Se ha analizado el TCO de este caso con el objetivo de ver si ha habido una mejora notable en la competitividad de los eBuses en los últimos años.

Considering the aforementioned, the TCO resulting from this case is displayed in Figure 63.

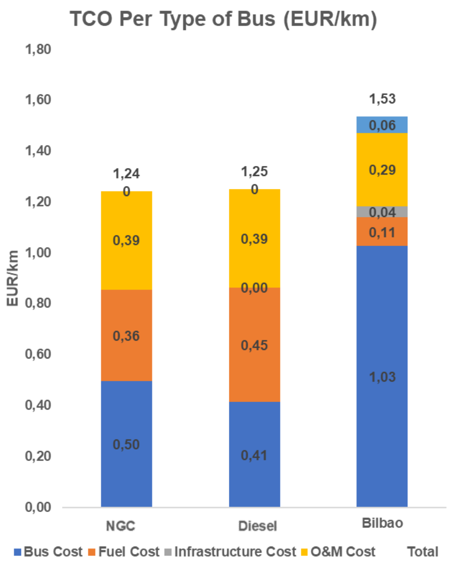


Figure 63. TCO results of the case of Bilbao-Own elaboration

As can be seen, in this case the eBus has a competitive disadvantage compared to the other two technologies and what is more, the three of them have TCOs well above what is currently seen in the market.

The reasoning behind that fact is that the eBuses were purchased in 2016 and as has been proven in the two previous cases related to 2019, the viability of the electric technology has improved considerably in recent years. Above all, it can be highlighted the reduction in the purchase price of the eBus, which although it was not a dramatic reduction, the impact is noticeable in the TCO and, on the other hand, the improvement of technology and the price of batteries has been remarkable.

The intention of the municipality of Bilbao is to continue renewing the fleet with electric buses. In fact, this year the city council has tendered the municipal public transport service proposing a fleet renewal plan that includes electric buses [52]. It can be intuited that the new units will have a better TCO, however, the winning private operator will have to take into account several factors if eBus will be the most advantageous technology of the analysed ones:

- It is convenient to maximize the use of eBus, prioritizing its use and trying to have the highest possible annual mileage.
- Due to the battery technology of the first Irizar bus family, the useful life of the battery was shorter than what is currently available. The selected battery technology should allow to delay the replacement of batteries as much as possible.
- The public tender indicates that the maximum age allowed by the city council for the bus fleet is 12 years [52]. It would be advantageous to increase the useful life as much as possible.

If these recommendations are considered the resulting TCO notably improves, reaching reasonable values (Figure 64).

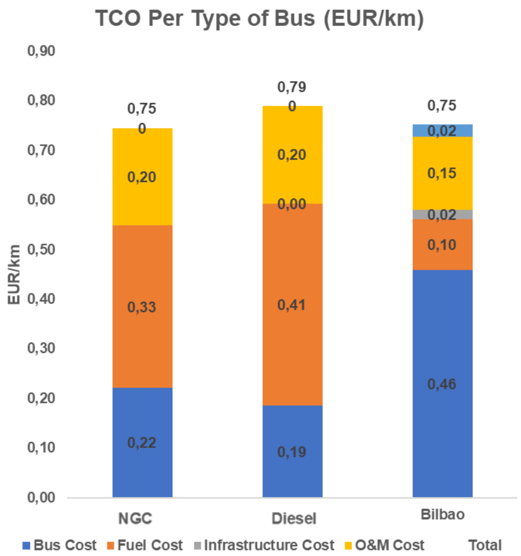


Figure 64. Improved TCO results of the case of Bilbao-Own elaboration

4.2.3.4. The case of Vitoria

Vitoria has launched the project called EIB that includes the purchasing of 13 eBuses and the fast-charging system for two points of the route and slow-charging system for the depot, the signalling and the communications. Irizar has been awarded the contract for the implementation of the so-called 'express bus' along with the construction company Yarritu and the LKS engineering. The three partners will also be responsible for the maintenance of the fleet during the 15 years of useful life estimated [53].

The contract contemplates the purchasing of 13 Irizar ie tram eBuses (seven articulated buses of 18m and the remaining six of 12m) that will cover a route of 10 kilometres, as well as two opportunity charging stations (pantographs) and seven double charging points of 50kW for the depot.

The input data for the TCO model shown in Table 10 has been extracted from the public tender documents.

Table 10. Input data for the TCO model of Vitoria

Term	Value
Opportunity charging – fast charging	2.498.345,05€
Depot charging – slow charging	761.679,20€
12m Irizar ie tram	528.846,85€
18m Irizar ie tram	784.740,51€
Battery size - 12m Irizar ie tram	90 kWh
Battery size - 18m Irizar ie tram	150 kWh

Considering these input data, the TCO resulting from this case is displayed in Figure 65.

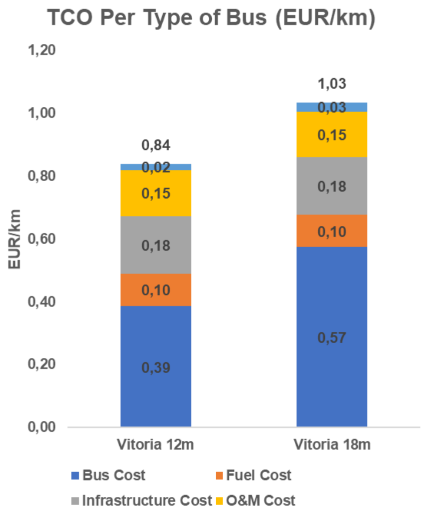


Figure 65. TCO results of the eBus case in Vitoria-Opportunity charging

As can be seen, the 12m eBus is in the usual TCO range, but the 18m eBus is more expensive. If the combination of both is considered it may seem somewhat more expensive than the previous cases, but it should be considered that this project has been carried out in substitution to building a new tram line. If all the costs associated considered (including civil works), in order of magnitude, the BEI project is ten times less expensive than the tram alternative [2].

The infrastructure of the pantograph is expensive in comparison to plug-in solutions and the deployment it is not usually worth the investment if only few bus units are considered. However, in certain cases it may be economically more advantageous. For example, if for Vitoria it is only tested considering the depot charging, the TCO gets worse (Figure 66).

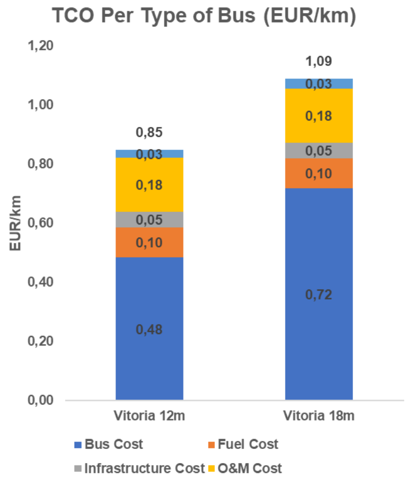


Figure 66. TCO results of the eBus case in Vitoria–Depot charging

4.3. ECONOMIC SENSITIVITY ANALYSIS

Keeping in mind the results of the TCO model, a sensitivity analysis has been carried out in order to assess the impact of each variable in the final TCO and in this way, be able to identify the most crucial factors when speaking about economic viability of public transport buses.

Two different evaluations have been carried out, under the name of "Sensitivity to individual variables" and "Sensitivity to competing variables".

4.3.1. Sensitivity to individual variables

First, individual variables have been modified maintaining the rest as constant in order to assess their weight in the final result. For this evaluation the useful life of the eBus, the annual mileage, the capital cost of the bus, the cost of the charging infrastructure, the price of electricity, the O&M costs and the financing costs have been considered.

Table 11 shows the summary of values obtained from the sensitivity analysis, that will further be explain in following subsections.

Table 11. Summary of the sensitivity analysis

	Variation	TCO impact
Useful life (years)	15 to 14 years	5,7%
	11 to 10 years	10%
Annual mileage (km)	80.000km to 75.000km	5,8%
	50.000km to 45.000km	15,5%
Capital cost of the vehicle	±10.000€	±1,14%
Cost of the charging infrastructure	±10.000€	±1,15%
Cost of electricity supply	c€/kWh	0,9%
Operating costs	±10.000€	±9,62%

Although the management of the use of the battery is often given great importance to avoid having to replace it before its time, the replacement year is a variable that hardly affects the TCO.

4.3.1.1. Sensitivity to the useful life of the eBus

The impact of each useful year subtracted from the total is considerable. The relationship between the reduced useful year and the increase in TCO is not linear. For instance, reducing from 15 to 14 years increases the TCO by 5,7%, while reducing from 11 to 10 years increases by 10%. Therefore, the sooner the eBus in question is replaced, the more negatively the TCO will be affected.

4.3.1.2. Sensitivity to annual mileage

It is one of the variables that most affects the final outcome. In this case, the relationship is not linear either. Reducing from 80,000km to 75,000km increases the TCO by 5,8%, from 50,000 to 45,000km by 15,5%. Therefore, once again, the less kilometres a bus travels per year, the higher the TCO of the solution will be.

4.3.1.3. Sensitivity to the cost of the vehicle

The capital cost of the bus linearly affects the TCO. For each, ±10.000€ the TCO is affected in ±1,14%.

4.3.1.4. Sensitivity to the cost of the charging infrastructure

The charging infrastructure cost linearly affects the TCO. For each, ±10.000€ the TCO is affected in ±1,15%.

Comparing technologies, the CAPEX costs of the TCO are usually lower when conductive rather than inductive charging is applied. The cost advantage of conductive technology is explained by the lower complexity of the equipment. On the contrary, inductive technology presents cost benefits in operating expenses. Therefore, both the OPEX of the vehicle and the OPEX of the infrastructure result in lower values of TCO. Therefore, an increase in annual mileage would benefit the inductive bus system [22].

4.3.1.5. Sensitivity to the price of electricity

The impact on the TCO of the variation of the cost of electricity supply is minimal. It may considerably affect the network reinforcement if needed, which would impact on theCAPEX of the TCO in the same way as the infrastructure cost of section 4.3.1.4.

However, the cost of the electricity tariff affects 0.9% for every c€/kWh.

4.3.1.6. Sensitivity to the operating annual cost

Other annual operating costs apart from the electricity supply linearly affect the TCO, but with a considerably higher impact. For each ± 10.000€ TCO varies ±9,62%.

4.3.2. Sensitivity to competing variables

Apparently, the vast majority of public authorities and municipalities are convinced of the need to replace diesel buses, either by their own conviction or by environmental policy requirements. Nowadays the uncertainty remains in whether to change the fleet to gas vehicles or change it to electric vehicles, although it seems that the balance is falling in favour of the eBus.

This section aims to compare similar eBus and CNG variables to discover in which cases the eBus TCO is favourable compared to the CNG and to understand the impact of certain factors.

4.3.2.1. Impact of tariffs

Performing the sensitivity analysis to evaluate the effect of electricity tariff/CNG changes in the TCO, assuming that the rest of the factors are constant, the obtained results are gathered in Figure 67.

Green: TCO de BEV < CNG		EUR/kWh							
		0,03	0,1	0,15	0,2	0,25	0,3	0,35	0,4
EUR/sm3	0,1	-0,8%	5,4%	9,4%	13,0%	16,4%	19,5%	22,4%	25,1%
	0,2	-4,3%	2,1%	6,2%	10,0%	13,5%	16,8%	19,8%	22,6%
	0,3	-7,8%	-1,2%	3,1%	7,0%	10,6%	14,0%	17,1%	20,0%
	0,4	-11,3%	-4,4%	0,0%	4,0%	7,8%	11,2%	14,4%	17,4%
	0,5	-14,8%	-7,7%	-3,2%	1,0%	4,9%	8,4%	11,7%	14,8%
	0,6	-18,2%	-11,0%	-6,3%	-2,0%	2,0%	5,6%	9,1%	12,2%
	0,7	-21,7%	-14,2%	-9,4%	-5,0%	-0,9%	2,9%	6,4%	9,6%
	0,8	-25,2%	-17,5%	-12,5%	-8,0%	-3,8%	0,1%	3,7%	7,0%
	0,9	-28,7%	-20,8%	-15,7%	-11,0%	-6,7%	-2,7%	1,0%	4,5%
	1	-32,2%	-24,0%	-18,8%	-14,0%	-9,6%	-5,5%	-1,7%	1,9%
	1,1	-35,7%	-27,3%	-21,9%	-17,0%	-12,5%	-8,3%	-4,3%	-0,7%
	1,2	-39,1%	-30,6%	-25,1%	-20,0%	-15,3%	-11,0%	-7,0%	-3,3%
	1,3	-42,6%	-33,8%	-28,2%	-23,0%	-18,2%	-13,8%	-9,7%	-5,9%
	1,4	-46,1%	-37,1%	-31,3%	-26,0%	-21,1%	-16,6%	-12,4%	-8,5%

Figure 67. Sensitivity analysis electricity tariff vs. CNG tariff

Considering current level of tariffs, the TCO of the eBus is more competitive than in the case of CNG. Usually, if the electricity supply contract is negotiated and not taken for granted slightly better TCO result could be obtained.

4.3.2.2. Impact of the investment cost

Performing the sensitivity analysis to evaluate the effect of the unit cost of the eBus/CNG bus in the TCO, assuming that the rest of the factors are constant, the obtained results are shown in Figure 68.

Green: TCO of BEV < CNG		eBus Unit Cost (EUR)							
		300.000	400.000	450.000	500.000	550.000	600.000	700.000	800.000
NCG bus Unit Cost (EUR)	200.000	-9,3%	6,1%	12,3%	17,7%	22,5%	26,7%	34,0%	40,0%
	300.000	-25,8%	-8,0%	-0,9%	5,3%	10,8%	15,7%	24,1%	30,9%
	400.000	-42,2%	-22,1%	-14,1%	-7,0%	-0,8%	4,7%	14,2%	21,9%
	500.000	-58,6%	-36,2%	-27,3%	-19,4%	-12,4%	-6,3%	4,3%	12,9%
	600.000	-75,0%	-50,3%	-40,4%	-31,8%	-24,1%	-17,3%	-5,6%	3,9%
	700.000	-91,4%	-64,4%	-53,6%	-44,1%	-35,7%	-28,3%	-15,5%	-5,1%
	800.000	-107,9%	-78,5%	-66,8%	-56,5%	-47,4%	-39,3%	-25,5%	-14,1%
	900.000	-124,3%	-92,6%	-80,0%	-68,8%	-59,0%	-50,3%	-35,4%	-23,2%

Figure 68. Sensitivity analysis eBus cost vs. CNG bus cost

EBus capital costs are expected to decrease in the near future, if that is the case, most of the contemplated scenarios result in better TCO than in the case of CNG.

4.3.2.3. Impact of technology efficiency

Performing the sensitivity analysis to evaluate the effect of the eBus/CNG efficiency in the TCO, assuming that the rest of the factors are constant, the obtained results are shown in Figure 69.

Green: TCO 0f BEV < CNG		Efficiency of the eBus (km/kWh)							
		0,10	0,20	0,30	0,50	0,70	0,90	1,00	1,10
Efficiency of the NCG bus (km/sm3)	1,30	13,3%	-7,1%	-16,2%	-24,6%	-28,7%	-31,0%	-31,8%	-32,5%
	1,50	16,6%	-3,0%	-11,8%	-19,9%	-23,8%	-26,0%	-26,8%	-27,5%
	1,70	19,1%	0,1%	-8,4%	-16,3%	-20,1%	-22,2%	-23,0%	-23,7%
	1,90	21,1%	2,5%	-5,7%	-13,5%	-17,1%	-19,2%	-20,0%	-20,6%
	2,10	22,7%	4,5%	-3,6%	-11,1%	-14,7%	-16,8%	-17,6%	-18,2%
	2,20	23,4%	5,4%	-2,7%	-10,1%	-13,7%	-15,8%	-16,5%	-17,1%
	2,30	24,0%	6,1%	-1,8%	-9,2%	-12,8%	-14,8%	-15,5%	-16,2%
	2,50	25,1%	7,5%	-0,3%	-7,6%	-11,1%	-13,1%	-13,9%	-14,5%

Figure 69. Sensitivity analysis eBus efficiency vs. CNG efficiency

Both ICE and electric motor technologies have been known for several years, therefore there is no big improvement of efficiency expected from that side. However, the efficiency of the eBus could be widely improved by optimally operating eBus fleets, given that the efficiency is highly sensitive to many operation variables.

4.3.2.4. Impact of infrastructure cost

Performing the sensitivity analysis to evaluate the effect of the cost of eBus/CNG infrastructure in the TCO, assuming that the rest of the factors are constant, the obtained results are shown in Figure 70.

Green: TCO of BEV < CNG		Unit Cost per bus of the eBus infrastructure (EUR)							
		50.000	150.000	200.000	250.000	300.000	350.000	400.000	450.000
Unit Cost per bus of the NCG infrastructure (EUR)	0	-13,5%	-1,4%	3,8%	8,4%	12,7%	16,5%	20,0%	23,3%
	50.000	-19,5%	-6,7%	-1,3%	3,6%	8,0%	12,1%	15,8%	19,2%
	100.000	-25,5%	-12,1%	-6,4%	-1,2%	3,4%	7,7%	11,6%	15,2%
	150.000	-31,5%	-17,4%	-11,5%	-6,1%	-1,2%	3,3%	7,4%	11,1%
	200.000	-37,5%	-22,8%	-16,6%	-10,9%	-5,8%	-1,1%	3,1%	7,1%
	250.000	-43,5%	-28,2%	-21,6%	-15,8%	-10,4%	-5,5%	-1,1%	3,0%
	300.000	-49,5%	-33,5%	-26,7%	-20,6%	-15,0%	-10,0%	-5,3%	-1,0%
	350.000	-55,5%	-38,9%	-31,8%	-25,4%	-19,6%	-14,4%	-9,5%	-5,1%

Figure 70. Sensitivity analysis eBus vs. CNG infrastructure cost

It should be noted that in previous TCO analysis the cost of CNG infrastructure have been considered null to reflect that most of that infrastructure has already been deployed. However, if municipalities with only diesel bus fleets are considering the transition to CNG fleets, that cost should also be taken into account.

4.4. ENVIRONMENTAL COST FOR SOCIETY

As previously mentioned, in Spain, transport emissions account for 25% of the total GHG emissions. Also 1/3 of road traffic emissions are concentrated in urban agglomerations and 30% of road traffic emissions are due to heavy vehicles. Taking all these data into account, one can see the great potential for reducing GHG emissions of the urban public transport.

4.4.1. Current environmental cost for society

Many municipalities opted for CNG buses when concern for climate change and air quality arose and started becoming an issue in cities (Salamanca, Zaragoza, Madrid, etc.). The already mentioned Grupo Ruiz pleads environmental advantages when choosing CNG buses over diesel buses, even if it supposes a more complex operation and maintenance. In their Corporate Social

Responsibility Report of 2015, they list the following environmental advantages compared to diesel bases on their operating data:

Table 12. Difference in environmental impacts CNG buses vs. diesel buses [42]

Emissions	Tons
Carbon monoxide (CO)	-46,8
Hydrocarbons (HC)	-18,6
Nitrogen oxides (NO_x)	-133,7
Particulate matter (PM)	-2,3

The EMT also highlights the reduction of the improvement in air quality (reduction of NO_x, PM emissions) that the CNG vehicles could carry, as shown in Figure 71 [44].

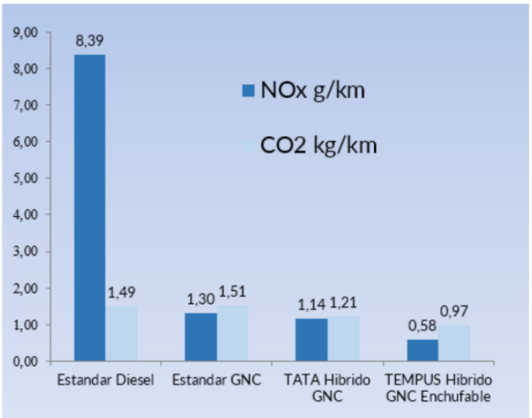


Figure 71. CO_2 and NO_x emissions of diesel and NCG buses

However, natural gas is usually considered as "transitional" fuel, because although their origin is fossil, their combustion has lower combustion emissions than conventional fuels. However, it is not completely clear if that improvement in emissions is a reality for HDV, Sedigas [10] and Transport & Environment [54] state otherwise. The data gathered from Sedigas on HDV indicates that even if there is CO_2 emission reduction with CNG buses, CO and NO_x emissions are higher (Figure 72).

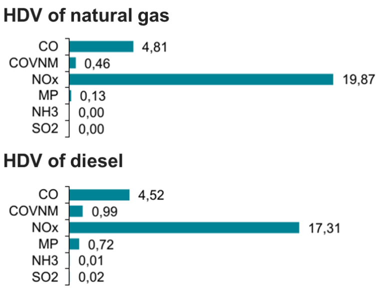


Figure 72. Average unit emissions of the Spanish heavy vehicles fleet (g/kg of consumed fuel) [10]

Anyway, the real environmental alternative to the use of fossil fuels seems to be that of the electric bus. It should be noted that the actual reduction in emissions depends above all on the generation mix with which the charging is made. For instance, with the current generation mix in Spain each electric bus pollutes 0,246 kg/kWh [55].

Taking the baseline cases as reference, the buses in question would pollute the CO_2 emissions shown below during their useful life.

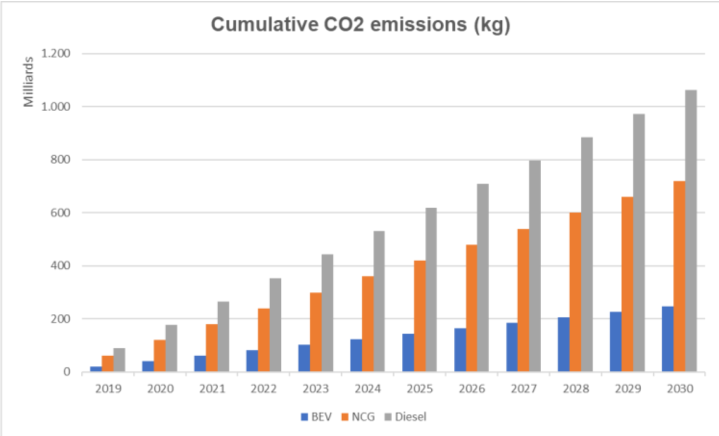


Figure 73. Technology comparison of cumulative CO_2 emissions

Many cities coincide in pointing the sector of "road transport" as the main cause of the polluting emissions in general, and especially outstanding in what refers to the emissions of oxides of nitrogen (NOx). In fact, the city of Madrid indicates that the traffic of the capital is responsible for 75% of the levels of NOx that are recorded on average in the city (in many specific points the contribution of vehicle emissions far exceeds 80%) [56].

Therefore, NOx emissions have been accounted for by technology with the data provided by the EMT. CNG's annual bus contribution is 78 kg NOx while the circulation of diesel means 503 kg NOx.

	eBus	Diesel	CNG
Annual NOx emissions (kg/year per bus)	0	503	78

Figure 74. Annual NOx emissions per bus

In any case, what is detrimental to health is the concentration of NOx in the air at every moment. When the maximum limit is exceeded is when these types of emissions are harmful. Therefore, attention should be paid to the simultaneity of circulation of polluting buses, since they turn out to be large contributors to the problem of air pollution.

4.4.2. Environmental cost for society if charges for emissions are considered

Many cities are banning or limiting access of polluting cars with the goal of reducing air pollution and try to avoid harmful levels for human health (Madrid, Paris, New York and Oslo, among others [57]). In fact, in Europe pollution from diesel cars results in about 10.000 premature deaths and 6.640 M€ spent in health care according to an Oxford study [58].

A possible alternative is the promotion of public transport, which does not turn out to be a real alternative if the public buses also pollute. This is where electric buses can fit.

In a similar way to the carbon taxes imposed in some cities on polluting cars [59], a hypothetical scenario is presented below in which buses that emit CO_2 are charged. It should be noted that the intention of approaching this scenario is not to support the introduction of taxes, but to somehow evaluate the impact of internalising the environmental costs of emissions in a simple way and see how the economic landscape changes.

To perform this evaluation an option has been introduced to include environmental charges (per kgCO_2 emitted) in the TCO model explained in Section 4.2[15]. The user has the opportunity to introduce a charge both associated with the emissions and damage to health as input parameters (Figure 75**¡Error! No se encuentra el origen de la referencia.**).

	eBus	CNG	Diesel
Average CO2 emissions per technology	kg/kWh	kg/sm3	kg/L
Cost associated to emissions	€/kgCO2	€/kgCO2	€/kgCO2
Cost associated to health harm	€/kgCO2	€/kgCO2	€/kgCO2

Figure 75. Input parameters of environmental costs

Considering economic data from BNEF as reference and introducing average CO_2 emissions of the eBus taking into account the Spanish generation mix, Figure 76 shows the increasing values of the TCO as the charge to emissions changes (the CO_2 emission charges in the chart correspond to the sum of the charges to the emissions and the damage to health).

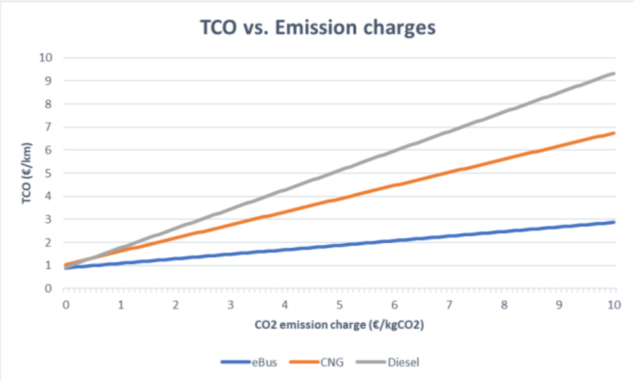


Figure 76. TCO results depending on CO2 charges

What is interesting is that at a relatively low charge (about 0,4 €/kgCO2) the diesel TCO exceeds that of the CNG due to the high CO2 emissions of this technology. In addition, with the current generation mix in Spain, the eBus immediately manages to obtain a considerable competitive advantage over the other two technologies.

This brief analysis allows to conclude that if the environmental costs generated by public transport are internalised in some way (it does not have to be through taxes), the eBus cost advantage for municipalities would be noticeable.

[15] The case of NOx or other emissions has not been analysed since their impact on the TCO is similar (linear as well).

5. RESULTS: INSIGHTS FOR MUNICIPALITIES

Considering everything mentioned in previous points, it is believed that the future of transport should be electrical. However, it is important to evaluate the complete solution for each municipality and not just focus on the purchase of the vehicle. The real implementation cases as well as the proposed calculations demonstrate that if this solution is correctly considered the eBus is economic and environmentally viable.

5.1. PROPOSED FINAL SOLUTION

The complete solution proposal should be a combination of elements, which should always be analyses together by the adopting municipality. The key elements that should every time be considered include RES, the charging infrastructure and the eBus (Figure 77).

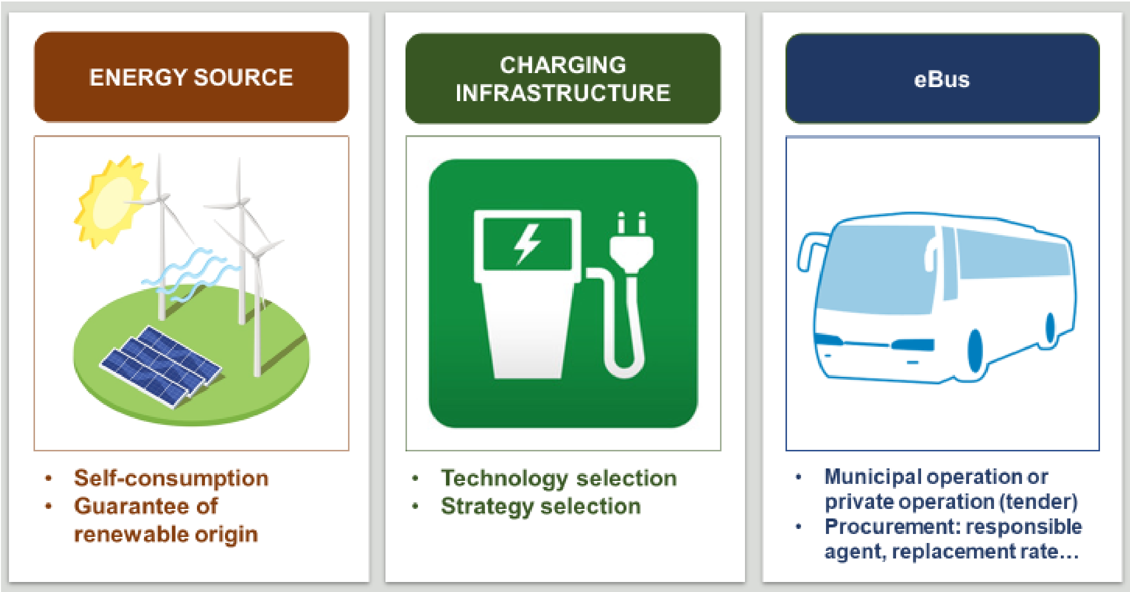


Figure 77. Final eBus solution

To design the complete solution, the municipality must make several decisions in each of the areas:

- RES: in the previous chapter it was considered that the bus is charged through the connection to the Spanish electricity network. However, to avoid the environmental impact to a greater extent and taking advantage of the fact that solar and wind technologies are already economically competitive, the ideal for municipalities would be to find a way to power the charging network for the eBus by RES.

  In this aspect, the possibilities are two: due to the new 244/2019 Real Decree, self-consumption [60] is a promising option. The municipality can install, for example, solar panels at the depot to supply charging energy, although there is need for some kind of compensation for the non-simultaneity of production and demand (e.g. batteries).

On the other hand, the installation could be connected to the electricity grid and have signed an energy supply agreement of renewable origin. In this case, certificates of guarantee of renewable origin are used, which nowadays by means of blockchain can easily verify the source of energy.

- Charging infrastructure: as explained in Section 3.1.2, technology and strategy selection must be carefully done by the municipality or the private operator based on its starting point.
- eBus: the responsibility party of purchasing the bus units will have to reasonably decide the replacement rate and the bus model to buy, considering the characteristics of the municipality and always valuing the available recharging solution.

This same view is shared by Proterra and many other manufacturers or relevant actors of the sector (Figure 78).

Figure 78. Example of the complete eBus solution of Proterra [46]

Taking into account these three elements, before starting any development it is important to analyse the viability of any solution. This initial analysis is of great importance to avoid making mistakes when implementing. The tools and indications given throughout this Master Thesis will help to see if from the beginning it is worth the transition to the electric bus of the adopting municipality. Not always the result will be favorable and sometimes the municipality will have to be flexible with the solution or will have to postpone the switching.

5.2. BARRIERS AND GUIDELINES FOR MUNICIPALITIES

Regardless of the archetype, all cities agree that the main drivers to consider the transition to eBuses are the reduction of carbon dioxide emissions from transport and, more importantly, the reduction of local pollution levels by eliminating emissions of nitrogen oxides and particles. Another key driver is industrial policy and the willingness to create local supply chains.

Anyway, as important as knowing the reason behind promoting the transition to eBuses is knowing the barriers that the adopter will need to overcome in the way.

5.2.1. Barriers for eBus project deployment in cities

Not all the barriers mentioned below apply to all cities. Different cities have different needs.

- Use of public space: many municipalities that have considered the adoption of electric buses have encountered problems with the use of public space. In fact, the charging solution is often limited to overnight charging to avoid the deployment of infrastructure by the city, although the opportunity charging may be more beneficial in some cases.
- Utility and infrastructure: network and charging infrastructure are key elements of eBus projects that planners and policy makers often do not have the capacity to evaluate. Continuous coordination among stakeholders related to infrastructure is necessary.
    - Charging infrastructure: the cost and time of installation, the underdeveloped supply chain, the space restriction and the lack of standards.
    - Grid: the location of supply and the constrained grid areas.
- eBus procurement limitations: as confirmed in this Master Thesis, nowadays eBuses have a much higher initial cost than diesel buses but a comparable TCO. Thus, traditional bus procurement models pose a barrier to the adoption of eBuses because they consider the initial cost as a key factor, rather than the TCO.

  Also, the underdeveloped supply chain, the lack of local supply chain arose as issues in many regions.
    - Battery uncertainty: falling battery prices slow-down the decision making of many municipalities. Additionally, there are unclear second life options.
- Fleet operation: the operation of the eBus fleet can be complicated, especially for new adopters or operators without experience in the field, given the lower flexibility of the eBuses. To this is added the uncertain residual value, the high energy consumption when there is cold weather and underdeveloped public transport network of some regions.
- Financing: as it happens with every emerging technology, there is uncertainty for finance companies that many times results in lack of financing options.
- Lack of environmental benefit consideration: the environmental benefits of the eBuses presented in Section 4.4 above are not usually monetised and are often omitted when evaluating the decision making, prioritizing only the initial capital costs. Municipal governments and bus operators should include them in the balance along with obvious costs and operational factors.
- Government support: governments not always establish mechanisms to directly or indirectly support eBus adoption, what difficulties transition capabilities for many municipalities.

- Stakeholder motivation: stakeholder motivation and collaboration are another key issue when planning large-scale electrification. This is indicated in Figure 79, where the difficulties in incorporating the different perspectives of the involved stakeholders in the electrification of public transport project of Stockholm are gathered [61].

Figure 79. Main unexpected issues faced during project implementation according to the survey respondents

- Modal shifts: experiences of failures with new technologies, competition from other mode of transport or the emergence of a substitution technology can affect the current trend of promoting the eBus.

5.2.2. Guidelines for adopting municipalities

All the recommended steps for a successful large-scale adoption eBuses that have been discussed throughout the document are summarised in Figure 80.

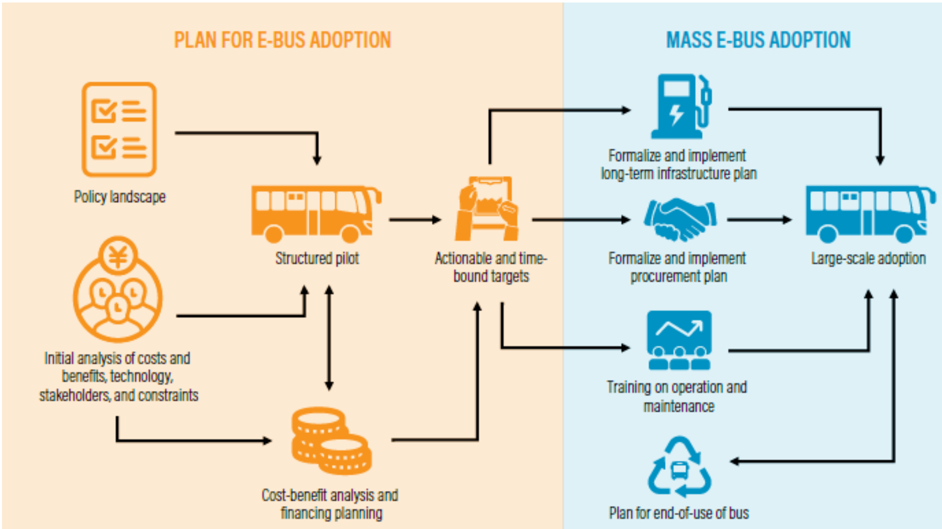


Figure 80. Steps to make to reach large-scale eBus adoption [15]

It is important that the municipality considers each and every step so that the implementation is carried out in the most efficient way possible.

5.2.2.1. Options to overcome eBus adoption barriers

There are many barriers in the eBus adoption process. In principle, many of them will be solved as the massive implementation progresses. Below are some possible solutions concluded from the work carried out in the Master Thesis:

- Identify stakeholders: the push of transit agencies and bus operators is key when it comes to adopting electric buses in cities, but their capacity is limited to promote the deployment of a project on their own. It is important to identify potential stakeholders from the beginning to facilitate the process. Actors that are able to enable measures such as national guidance policies, financial support regulations and city-level strategies could be key actors in the process.

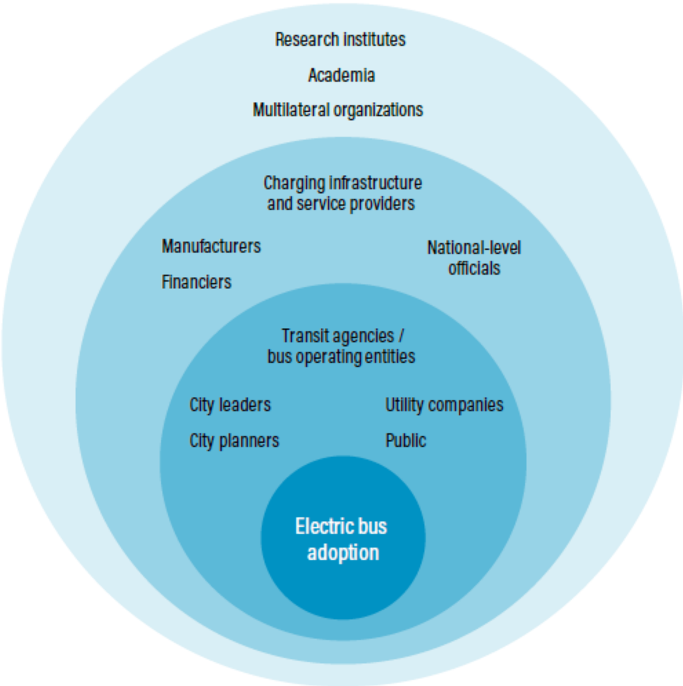


Figure 81. Stakeholders involved in the eBus adoption process [15]

- Fleet operation: gradual replacement of conventional buses from cities could significantly contribute to the easiness in adaptation of fleet operators.
  - Uncertainty around the residual value of the eBus: it is key to identify the responsible party for the proper disposal for both the eBus and batteries.
  - High consumption with cold weather: some manufacturers are using heat pumps in eBuses [2].
- Vehicle: the TCO should be assessed, not the initial cost. Trust alternative ways of financing if the down payment is not affordable.
- Charging infrastructure: the main area to improve today is the standardisation of communication protocols. Municipalities should force the utilisation of open interfaces.
- Electricity grid: the solution should be analysed together with utilities to receive the best assessment possible in grid matters.

- Government support: it is in the interest of all European citizens, in terms of wealth and industrial development, for the authorities to promote the development of a successful supply chain. EU is currently in an ideal situation to promote the eBus industry thanks to the great performance and leadership of certain manufacturers, private operators and municipalities.

5.3. ACTION PLAN FOR MUNICIPALITIES

Depending on the stage at which the municipality in question is located, the participating stakeholders and the key actions to take to deploy eBuses will differ. The aim of Figure 82 is to show briefly the actions that a municipality should take to reach mass-adoption, being able to start in any of the stages depending on the state of the municipality.

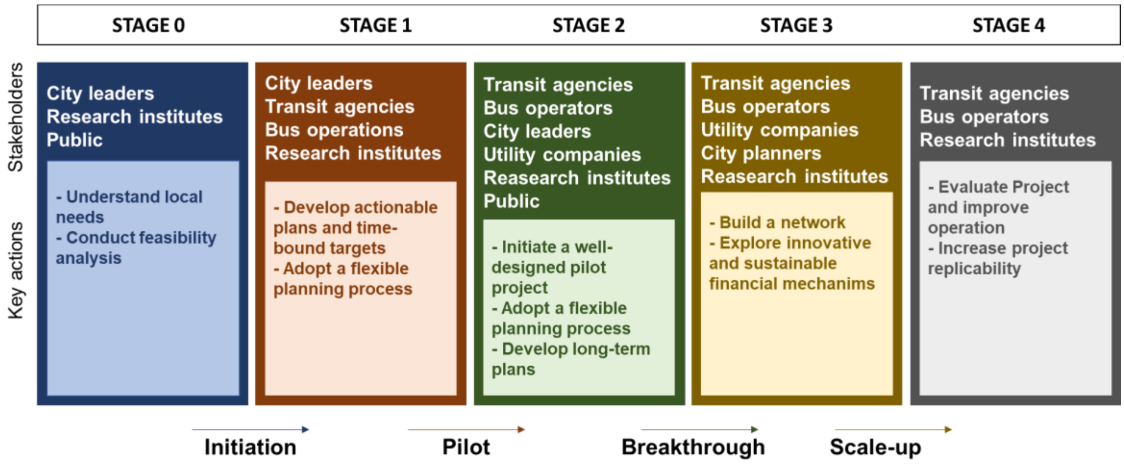


Figure 82. Key actions for city stakeholders at different development stages

6. CONCLUSIONS

Under current social expectations, increasing environmental requirements and the modification of the European Union to the transport policy, the process of replacing buses from convention to electric buses seems inevitable. The challenge, thus, is now in how to introduce new types of buses in the most cost-effective way (technically, economically and environmentally).

The process of electric bus implementation is complex, in terms of technical, transport, economic and ecological issues. These issues have a significant influence on the choice of bus fleet exchange variant and scenario. Local conditions considered in technological, human and economic senses are significant to select optimal variant and scenario of the fleet exchange process.

Taking into account the data available, the concerns surrounding the technological offer and the production capacity of eBuses in Europe seem unfounded. If local demand continues growing for this type of vehicles, everything indicates that this industry will grow exponentially in future years. Although in the medium-term China will continue to lead in all the segments of the value chain.

One of the keys for the future European positioning in the sector will be the measures taken by authorities and investments carried out by stakeholders to support the industrial policy and the development of this value chain.

The technological complexity in fleet management for new adopters is an important barrier to overcome to enable mass-deployment. There are several variables that affect the efficiency of an eBus, such as driver behaviour, quality of road, number of passengers, speed, topography and climate and each one of them has a different impact on it. What is clear is that the operation of an eBus is highly sensitive to both controllable and non-controllable factors. It is crucial to optimally manage variables that could be affected by operation decisions.

Another key action to perform by municipalities is a detailed initial analysis to understand the optimal solution design for each case, mainly in terms of charging technology and strategy. There is no system that offers the best possible starting position for all applications.

Environmentally and economically speaking, the main advantages of eBuses versus diesel alternatives are the environmental benefits in terms of exhaust emissions and air quality and the lower total cost of ownership (TCO). The lower TCO is a result of the lower cost per kilometre for running on electricity compared to diesel.

Currently, the transition is frequently slowed down due to high upfront costs of eBuses. Municipalities should avoid applying this short-term scope and evaluate the TCO of proposed solutions. What is more, it seems that in the medium-term the initial cost of eBuses will be balanced with diesel buses due mainly to battery cost reduction.

In addition, it has already been seen that the environmental impact produced by public transport is not monetised, which means that when comparing technologies, not all the costs are being considered. Some way to internalize these impacts should be found to really deploy the mobility solution with the lowest cost for society.

From the point of view of the municipality, in order to reach the large-scale implementation of eBuses, it is important to get the engagement of all the affected stakeholders and use decision tools, such as the one presented in this Master Thesis, to facilitate the understanding of a process with so many factors and variables involved. In addition, it should be noted that the diversity of origin of these factors (technical, environmental, financial, regulatory, social, etc.) requires the involvement of multidisciplinary teams with expertise in different segments of the process.

Adapting an eBus solution to the transport network is much more difficult than designing one from scratch. Optimal solutions are easier to achieve when starting with a blank slate. However, most European cities have developed transport networks. Hence, it is of vital importance that new adopters take into account the lessons learned from municipalities with eBus fleets and also that they be flexible in the process of designing the solution.

Finally, as in the case of any noticeable transition, the switching of fleets from conventional to to electric fleets entails many challenges. Nonetheless, with the collaboration of all the involved actors with a common goal of helping the worrying problem of air quality in cities and also contributing in the fight against a much greater problem as it is climate change, compensates for all efforts.

7. FURTHER DEVELOPMENT

Several development lines have been identified throughout the project, such as further modelling solutions to complete the whole decision-making tool or the continuous update of the analysis as more cities electrify their fleets and new data appear.

Decision-making tool

As has been demonstrated, the implementation process of the electric bus is complex, in terms of technical, transport, economic and ecological issues. Due to the multitude of variables that affect the process of fleet exchange, the development of more complex algorithms that support decision making is expected.

In this context, deeper correlation analyses on which factors are most influential in the use of energy could be useful to improve the eBus fleet operation.

Result validation

As the eBus adoption is an emerging trend, there is lack of real operation data. Therefore, as new cases are being implemented, it would be interesting to evaluate their performance, on the one hand, to validate the initial decision-making methodology and, on the other, to help identifying which of the current assumptions are wrong.

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