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GIF GUIDANCE: CLEAN TECHNOLOGY OPTIONS FOR BUSES

Prefeasibility Analysis

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Cover image: New electric bus in the workshop. iStock

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Table of Contents

List of Figures

List of Tables

Photo: A new diesel electric hybrid super bus for public transport in Malmo, Sweden. iStock.

Context

Reducing greenhouse gas (GHG) emissions and improving air quality are among the most pressing challenges of cities worldwide. Urban transport systems are a considerable contributor to both these problems, therefore transitioning to clean and sustainable technologies is paramount to achieving the required emission reductions.

A key player in this transition is the introduction of efficient public transport systems. These enable a modal shift from private vehicles to more efficient mass transportation systems, therefore reducing overall GHG emissions. However, conventional diesel heavy-duty vehicles such as buses may produce toxic emissions that private vehicles do not. Hence, when planning this modal shift, it is imperative that the public transport systems incorporate clean bus technologies such as: Euro 6 conventional diesel, compressed natural gas (CNG) or biofueled buses, hybrid electric buses, fully electric buses, or hydrogen fuel cell buses.

While many cities around the world put significant technical and monetary resources into enabling this transition, the technical-economic feasibility of deploying these vehicles in different cities is not fully understood, nor is the achieved environmental benefit.

Clean technology buses, such as electric buses, are often put into service with no prior technical evaluation. This jeopardizes service provision and may result in unintended consequences, including pushing customers towards more pollutant modes such as motorcycles. Furthermore, when pre-feasibility analyses are performed, they lack the necessary details to provide meaningful and reliable results and may provide overly optimistic scenarios, which also challenge the actual transition into cleaner technologies. This often results in more suitable options being overlooked, or technologies being hastily adopted only to increase the system cost at no real benefit.

To steer decision makers into a productive transition, this document provides a parametric pre-feasibility evaluation guide to assess the feasibility of incorporating alternative energy vectors and bus technologies into public transport systems. The document's objective is to allow non-specialist task team leaders (TTLs) and non-specialized transport technical advisors to undertake a thorough pre-feasibility evaluation that considers the full range of bus technology options under local technical and economic conditions. This will allow TTLs to determine which technologies should be discarded and which show promise and merit further attention in the form of a full feasibility analysis. Also, the guide will help evaluators identify additional enabling actions that are required for the successful implementation of suitable options.

Moreover, once a decision is made on which technology to take forward, this analysis should be complemented with a deep feasibility analysis, involving technology experts able to assess any fast-evolving technologies in the project's context.

Photo: Hybrid Volvo bus serving
a Västtrafik line. iStock.

CHAPTER 1

Introduction to Available Clean Technology Buses

Bus transportation is currently dominated by diesel-technology buses. Although some markets are gradually transitioning to compressed natural gas (CNG) or even to electricity, for the most part, diesel buses tend to be the most cost-effective and are the go-to solution around the world. In general, countries seeking to adopt other technologies have had to make an active effort for the transition to happen, usually through the adoption of more demanding environmental standards for transportation, the investment of taxpayer money, or by providing benefits or incentives to foster the transition of the private sector.

Due to its extensive use, diesel technology will be the baseline of this study. Within diesel buses however, there is a wide spectrum of possibilities, and some of them are more environmentally friendly than others. The first clean technology bus (CTB) to be considered in this guide will be the diesel Euro VI. Even if it can be considered a "conventional" technology rather than a new one, Euro VI standards entail a significant reduction in toxic emissions of buses when compared to previous standards. Furthermore, despite being introduced in 2012, only 15.2 percent of all diesel buses currently comply with the standard.[1]

Given that transitioning to Euro VI standards has a major impact on toxic tail-pipe emissions, and its transition does not necessarily imply changes to current infrastructure for those systems already relying on diesel, this option should not be discarded. Granted, diesel Euro VI buses still have similar GHG emissions as previous standards, but it may be the only option for markets that, for example, cannot afford electric or hybrid solutions and do not have alternative fuels as an option.

In other cases, alternative fuels are an option. Biodiesel technology will be evaluated as a second type of CTB to be considered. Biodiesel buses run on a type of biofuel manufactured from organic oils and fats, which may be blended into conventional diesel fuel up to certain proportions or even used as a whole. Based on the fuel's vegetable origin, biodiesel is considered, to some extent, a carbon neutral fuel, and thus a significant alternative to conventional diesel fuels. However, it should be noted that GHGs are generated by the cultivation of energy crops, and thus the carbon neutrality is affected to a greater or lesser extent. This aspect will be assessed later in the document.

[1] Diesel technology emission standards are divided as follows: Euro VI (15.2 percent), Euro V (28.3 percent), Euro IV (17.2 percent), Euro III (22.5 percent), Euro II (4.9 percent), Euro I (1.9 percent), Others (10 percent). SAEIDIZAND, Pedram; Global Bus Survey. UITP - The International Association of Public Transport, 2019.

In the third place, natural gas is the last fossil-fuel based technology that will be addressed as a possible solution, using both CNG and liquid natural gas (LNG) technologies. Buses running on natural gas, particularly Euro VI buses, are capable of attaining very low pollutant emissions without the need of complex and reliant exhaust aftertreatment systems, while presenting similar operational capabilities as diesel technologies in terms of range (approximately 350 kilometers) and refueling time (5 minutes). This technology uses lighter, quieter engines than diesel, which can help deal with the noise pollution present in many cities. Furthermore, for those locations where natural gas is produced, or can be imported cheaply, the transition from diesel to natural gas can be profitable.

Another CTB that has been getting a lot of attention this past decade is the electric bus. This technology has the characteristic of producing zero direct GHG and toxic tail-pipe emissions during operation, and if supported by renewable energy sources, zero lifecycle emissions could be achieved as well. The main obstacle right now is the economic factor: an electric bus can have an upfront cost of 2 to 3 times more than its competitors, and even if operational expenditures are typically lower, recuperating the investment can be very challenging. Moreover, adopting electric buses also involves getting into a very different environment: recharging a battery is very different from refueling a tank, both from an infrastructure and operational standpoint. All these issues will be dealt with in depth in this guide.

Finally, another important CTB presented in this guide is the hydrogen fuel-cell bus. Hydrogen has been known to be a favorable energy vector to which conventional fuels might converge in the future. These CTBs are capable of the same service capabilities as conventional buses, with considerably lower levels of local pollutants and GHG emissions, an effect that could be enhanced if hydrogen production is done through renewable energy sources. Hydrogen, however, does pose some challenges, especially regarding its storage and refueling, and, for now, is more expensive than its alternatives.

This guide begins by establishing the minimum conditions that should be in place to consider a technology feasible. This will be done in Chapter 2, starting with the general local political context and analysis of the project's planning, and moving on to more specific technical conditions for each technology regarding energy vector availability and standards and regulations to consider.

Once the general context has been established, Chapter 3 presents a brief description of the technical aspects of each technology, which involves considerations on bus selection, fueling or charging infrastructure, energy consumption and modes of operation. After going through this chapter, the TTL should have a clear understanding of the more technical or physical implications of each technology and should have the tools to argue whether a technology would be feasible. A detailed description of all CTBs is presented in the Annex on bus technology and charging infrastructure. It is strongly recommended that the evaluator reads this annex before starting the evaluation.

In Chapter 4, a methodology for comparing the environmental impact of each technology is presented. This includes assessing the potential reduction in GHG emissions of each vehicle technology, as well as local toxic emissions. In Chapter 5, the economic performance of the different technologies is assessed by estimating CAPEX and OPEX expenditures and calculating the levelized cost of ticket (LCOT) of the different technologies under varying financial scenarios and considerations.

Using the results from the previous sections, Chapter 6 presents and evaluates the cost-benefit of implementing each technology. The guide concludes with Chapter 6, a results evaluation and a discussion of the potential technical, environmental, and financial risks the evaluator should consider for the different technologies.

Photo: Blue electric bus is charged by pantograph at the station. iStock.

CHAPTER 2

Enabling Conditions

The following section will guide the analysis of the enabling conditions for the deployment of CTBs by addressing the contextual readiness regarding policy priorities, project planning, energy vector availability and existing standards and regulations.

2.1 Local context

Deploying alternative technologies generally requires a large investment, particularly in the case of electric and hydrogen buses. Before starting a feasibility study, it is important to understand the socioeconomic context of the city/state/country and the local authorities' priorities. To assess this, throughout this section different questions are listed as part of a binary scoring system, where an affirmative answer is a 1 and a negative one a 0. This way, the higher the accumulated score of each table, the better the prospects to incorporate CTBs.

Table 1 offers a series of simple YES/NO questions that help assess local priorities regarding clean transportation technologies. These questions are to be answered when addressing local authorities. It goes without saying that the score is merely a guideline, and the assessment should ideally be based on direct contact with local stakeholders.

Table 1. Local context assessment matrix

Question	Score	YES	NO
Are local authorities interested in transitioning to cleaner transportation technologies?	(1 if Y / 0 if N)		
Are the following among the priorities of local authorities?			
a. Improving air quality	(1 if Y / 0 if N)		
b. Reducing greenhouse gas emissions	(1 if Y / 0 if N)		
c. Producing a modal change from private to public transport	(1 if Y / 0 if N)		
d. Improving bus service quality	(1 if Y / 0 if N)		
e. Reducing city noise	(1 if Y / 0 if N)		
Is there an established budget for any of the above?	(1 if Y / 0 if N)		
Are there any projects in place regarding "green" technologies, whether in the energy, transport, or residential sectors?	(1 if Y / 0 if N)		
Has there been an investment in "green" technologies over the last 5 years, whether in the energy, transport, or residence sectors?	(1 if Y / 0 if N)		
Do implementing agencies/operators have the required knowhow/skills such as procurement, planning, maintenance, repair capacity, contract management and performance evaluation for the deployment and management of CTBs?	(1 if Y / 0 if N)		
Total score	0 to 10		

Also, evaluating the deployment of sustainable mobility policies provides further understanding regarding local maturity and support for clean transport technologies. In some cases, policies are oriented to a specific technology (mostly electric), and in others, they are technology neutral and focus on goals being met.[2] Some of these are[3] shown in Table 2.

Table 2. Local policy assessment matrix

Policy	Score	YES	NO
Zero emissions vehicles mandate	(1 if Y / 0 if N)		
Fuel economy standards	(1 if Y / 0 if N)		
Vehicle emission standards	(1 if Y / 0 if N)		
Fiscal incentives for the purchase of alternative vehicles (electric, hydrogen, CNG, etc.)	(1 if Y / 0 if N)		
Low emission vehicle goals	(1 if Y / 0 if N)		
Fiscal incentives for industrial development in alternative vehicles	(1 if Y / 0 if N)		
Fiscal incentives for charging/refueling stations	(1 if Y / 0 if N)		
Charging/refueling infrastructure regulations	(1 if Y / 0 if N)		
Total score	0 to 8		

If the overall score of both tables is low, then moving forward with the implementation of any CTBs could result in a high-risk investment. Risk and overall results analysis are undertaken in Chapter 7.

2.2 Project planning

The implementation of most of these technologies entails a considerable investment and could therefore pose a considerable risk to the long-term sustainability of the transport system. Adequate project planning can help identify and reduce these risks. The checklist below guides the project planning assessment. As for the section below, Table 3 condenses the checklist and provides a binary scoring system where an affirmative answer is a 1 and a negative one a 0.

- **Has a rigorous passenger demand study been performed?**

  A rigorous demand forecast is the steppingstone to any transport implementation study. Understanding the travel demand and modal share and identifying bottlenecks or inefficiencies in transport are usually the reasons why a project of investment in public transportation is undertaken. This must be coupled with a reliable demand study to determine the routes and fleet necessary to address the current problems and meet future demand. Also, although most transport economic evaluations focus on system costs and expenditure streams, when analyzing

[2] Styczynski, A.B. & Hughes, L. (2019). *Public policy strategies for next generation vehicle technologies: An overview of leading markets.*

[3] International Energy Agency. (2019). *Global EV Outlook 2019.*

the impact of implementing a given technology on the incremental ticket price, it is important to understand the number of tickets that will be sold. If this step has been skipped, it is probably worth going back to it, especially if the project involves the purchase of a large fleet.

- **Have the bus routes and bus stops been defined?**

  Coupled with a demand study comes the definition of the routes in which the CTBs are to be deployed. Bus routes must be defined seeking to generate the greatest possible positive impact on the location, and this includes transportation efficiency, but also air quality, noise pollution, passenger comfort, etc. The necessary fleet will derive from the route's alignment and estimated number of passengers for each route. The alignment is also the basis for the calculation of the buses' energy consumption and operational requirements.

  The number of bus stops and the distance between bus stops also plays an important role in the driving conditions of the buses. The more stops per kilometer, the lower the mean speeds of the service, and therefore, the higher the number of vehicles needed. Also, more stops usually mean higher energy consumption and more time on the road until a refuel/recharge is available.

- **Are the traffic conditions of the routes known?**

  Traffic conditions vary greatly within a city and knowing which will affect the bus system is fundamental. Without a certain degree of confidence in this information, it is not possible to project the operation of the buses, fleet needed, expected fuel consumption, etc.

- **Are the bus terminal locations defined and can they accommodate charging infrastructure?**

  In line with bus route definition, bus terminal locations are not redundant for some of the CTBs analyzed, particularly those with lower range. The operative schedule depends on where buses are to be refueled/recharged, how long it takes for them to do a whole trip around the routes, how buses from different lines are to interact with each other, etc. Having these elements defined will give the results of the study a greater degree of certainty.

  The space available in the refueling/recharging infrastructure in the bus terminal should also be taken into consideration; not all technologies have the same requirements.

- **Has the necessary fleet already been calculated?**

  If the fleet has already been calculated, it is important to understand under what conditions this was done, and what type of vehicle was considered. As will be seen moving forward, the operating conditions of CTBs may vary from that of conventional diesel buses, and therefore, if the fleet was calculated based on a specific expected operation, it must be ensured that the selected CTBs can cope with it. Regardless, having a fleet calculation in place usually means most of the above questions have been considered, and can be a good starting point to understand the effects that CTBs would have on the system.

Table 3. Project planning checklist matrix

Project planning	Score	YES	NO
Has a rigorous passenger demand study been performed?	(1 if Y / 0 if N)		
Have the bus routes been defined?	(1 if Y / 0 if N)		
Are the traffic conditions of the routes and expected commercial speeds known?	(1 if Y / 0 if N)		
Have the bus stops been defined?	(1 if Y / 0 if N)		
Have the locations of the bus terminals been determined?	(1 if Y / 0 if N)		
Has the fleet size already been calculated?	(1 if Y / 0 if N)		
Total score	0 to 6		

2.3 Energy vector and vehicle market availability

The following section presents a guideline for the analysis of each technology. Questions are divided into two main groups: one that addresses the local energy vector's readiness regarding deployment and distribution infrastructure, and a second group that analyzes the vehicle market. As per the prior sections, answers are either a 1 for a positive answer or a 0 for a negative one. However, in this case answers are compounded, meaning that if a given question is affirmative, the following will also be affirmative. It is important to note that when asked if a given bus technology is being used as part of the public transport system, it means as part of the normal service, with buses operating within the overall fleet, and NOT as a demo pilot where a single unit is being tested as a free service in a given constrained operation.

Table 4. Energy vector and vehicle market availability assessment

Diesel Euro VI (ultra low sulphur <10ppm)	Availability		
	Score	YES	NO
Energy Vector			
Is it used in public transport applications (i.e., buses)?	(1 if Y / 0 if N)		
Is it used in the transport sector in general (i.e., cars)?	(1 if Y / 0 if N)		
Is there an ultra-low sulfur diesel distribution system?	(1 if Y / 0 if N)		
Total score	0 to 3		
Vehicle Local Market			
Are there diesel Euro VI buses circulating within the city transport system?	(1 if Y / 0 if N)		
Are there diesel Euro VI bus models present in the national market?	(1 if Y / 0 if N)		
Do the main bus manufacturers/importers offer diesel Euro VI bus models in the region?	(1 if Y / 0 if N)		
Total score	0 to 3		

Table 4. Energy vector and vehicle market availability assessment, cont.

Biodiesel	Availability		
	Score	YES	NO
Energy Vector			
Is it used in public transport applications (i.e., buses)?	(1 if Y / 0 if N)		
Is it used in the transport sector in general (i.e., cars)?	(1 if Y / 0 if N)		
Is there a biodiesel distribution system?	(1 if Y / 0 if N)		
Total score	0 to 3		
Vehicle Local Market			
Are there biodiesel buses (B100)[4] circulating circulating within the city transport system?	(1 if Y / 0 if N)		
Are there biodiesel (B100) bus models present in the national market?	(1 if Y / 0 if N)		
Do the main bus manufacturers/importers offer biodiesel (B100) bus models in the region?	(1 if Y / 0 if N)		
Total score	0 to 3		
Natural gas	**Availability**		
	Score	YES	NO
Energy Vector			
Is it used in public transport applications (e.g., buses)?	(1 if Y / 0 if N)		
Is it used in the transport sector in general (i.e., cars)?	(1 if Y / 0 if N)		
Is there distribution infrastructure for natural gas (i.e., a distribution grid)?	(1 if Y / 0 if N)		
Total score	0 to 3		
Vehicle Local Market			
Are there natural gas buses circulating within the city transport system?	(1 if Y / 0 if N)		
Are there natural gas bus models present in the national market?	(1 if Y / 0 if N)		
Do the main bus manufacturers/importers offer natural gas bus models in the region?	(1 if Y / 0 if N)		
Total score	0 to 3		
Hybrid technology	**Availability**		
	Score	YES	NO
Energy Vector			
Is diesel used in public transport applications (i.e., buses)?	(1 if Y / 0 if N)		
Is it used in the transport sector in general i.e. cars?	(1 if Y / 0 if N)		
Is there an ultra-low sulfur diesel distribution system?	(1 if Y / 0 if N)		
Total score	0 to 3		

[4] B100 indicates pure biodiesel.

Table 4. Energy vector and vehicle market availability assessment, cont.

Hybrid technology	Availability		
	Score	YES	NO
Vehicle Local Market			
Are there hybrid buses circulating within the city transport system?	(1 if Y / 0 if N)		
Are there hybrid bus models present in the national market?	(1 if Y / 0 if N)		
Do the main bus manufacturers/importers offer hybrid bus models in the region?	(1 if Y / 0 if N)		
Electric technology	**Availability**		
	Score	**YES**	**NO**
Energy Vector			
Is it used in public transport applications (i.e., buses)?	(1 if Y / 0 if N)		
Is it used in other transport applications (i.e., cars)?	(1 if Y / 0 if N)		
Is the electric grid robust?	(1 if Y / 0 if N)		
Total score	0 to 3		
Vehicle Local Market			
Are there electric buses circulating within the city transport system?	(1 if Y / 0 if N)		
Are there electric bus models present in the national market?	(1 if Y / 0 if N)		
Do the main bus manufacturers/importers offer electric bus models in the region?	(1 if Y / 0 if N)		
Total score	0 to 3		
Hydrogen	**Availability**		
	Score	**YES**	**NO**
Energy Vector			
Is it used in public transport applications (i.e., buses)?	(1 if Y / 0 if N)		
Is it used in the transport sector in general (i.e., cars)?	(1 if Y / 0 if N)		
Is there a hydrogen distribution system?	(1 if Y / 0 if N)		
Total score	0 to 3		
Vehicle Local Market			
Are there hydrogen (fuel cell) buses circulating within the city transport system?	(1 if Y / 0 if N)		
Are there hydrogen (fuel cell) bus models present in the national market?	(1 if Y / 0 if N)		
Are there bus importers interested in commercializing hydrogen (fuel cell) buses in the region?	(1 if Y / 0 if N)		
Total score	0 to 3		

2.4 Standards and regulations requirements

When deploying clean technology buses, standards and regulations must be reviewed to determine if the legislative framework is in place. This includes the homologation of buses, as well as refueling/charging infrastructure requirements and road preparedness. In general, if this type of technology is already deployed in the country, regulations have already been defined, though some work may need to be done to adapt/revise these for the local legislation.

Also, if the energy vector is readily available, most of the regulations needed for storage and refueling are probably already in place. This means that, if this section were assigned a score, it would probably be similar to the one in section 2.2 (Project Planning). However, hybrid, electric and hydrogen technologies are relatively new in most countries and therefore global standards are still in development. This is particularly true for hydrogen systems. Therefore, this section will not be assigned a score per se. Instead, Table 5 presents some regulations that should be in place. The evaluator will establish if:

- regulations are on par with international practices;
- regulations are under par but being developed; or
- regulations are under par and not on the agenda.

Table 5. Standards and regulations to consider in the assessment

	Diesel/hybrid	Biodiesel	Natural gas	Hydrogen	Electric/hybrid
Internationally accepted standards	EU 2007/46/CE ASTM D975-08a EURO VI US BIN SAE J313	EU 2007/46/CE EN 14214 ASTM D6751-08a EURO VI US BIN	ANSI/CSA NGV CNG ISO 15500-1:2015 LNG ISO 12614-1:2021 EURO VI US BIN	ISO 13.985 ISO 19.881 ISO 17268 ISO 14687 ISO 23828 ISO 12619-1:2014 ISO 12619-12:2017 SAE 257X	IEC 62893-1 IEC 61851-1:2017 ISO 6469-1:2019 UN/ECE 100
Buses homologation	Passenger vehicle applications (M categories) require particular safety standards. European homologations of buses (2007/46/CE) are many times considered as valid by countries outside Europe and can serve as a reference for countries without the necessary standards. Particular standards for acceptable fuels are also necessary to ensure engine operation and limit toxic emissions.	Requirements are similar to those of conventional diesel buses. Particular standards must be in place to ensure the quality of the biofuel, given that the composition is different to conventional diesel.	CNG vehicles may have the storage tanks on the roof or cryogenic LNG tanks attached to the chassis. In either case this implies modifications to the bus structure, and added vehicle weight, which may be in contraposition of current regulations. Natural gas requires particular certificates for storage and transmission of fuel in buses.	Similar considerations to those of CNG must be considered, regarding bus weight and height. High pressure hydrogen gas systems require particular certificates for storage and transmission in vehicles. Being a highly flammable fuel, many standards are specific for hydrogen.	Electric buses, particularly slow charge electric buses, can be much heavier than conventional diesel buses because of the weight of their batteries. High voltage batteries and powertrain entail possible electrocution hazards and require particular standards.

Table 5. Standards and regulations to consider in the assessment, cont.

	Diesel/hybrid	Biodiesel	Natural gas	Hydrogen	Electric/hybrid
Road infrastructure	Buses' heavy weight compared to passenger vehicles can lead to accelerated degradation of road infrastructure if it is not prepared for heavy duty vehicles. ASTM provides road and paving standards for materials, mechanical performance, requirements, etc.	Same considerations as diesel.	Considerations regarding vehicle's maximum allowable height and weight per axle may have to be revised to ensure CNG buses can operate given the bigger size and weight of these buses compared to conventional diesel.	Considerations regarding vehicle's maximum allowable height and weight per axle may have to be revised to ensure hydrogen buses can operate given the bigger size and weight of these buses compared to conventional diesel.	Considerations regarding vehicle's maximum allowable height and weight per axle may have to be revised to ensure electric buses can operate given the bigger size and weight of these buses compared to conventional diesel.
Charging/ refueling facilities	Refueling stations require the building of underground bunkers with storage tanks. This, as well as the fuel dispensing requires heavy regulation given the inherent risk of fire or explosion of fuels to ensure safety of the operation.	Refueling facility standards may need some revision to ensure biodiesel fuels are considered in law. However, changes from conventional fuel are minor, and imply mostly ensuring the fuel does not degrade by being stalled in tanks for a long time.	Natural gas charging facilities require particular habilitations as it is stored at high pressures or in cryogenic tanks (LNG). The involvement of a national regulatory entity is typically necessary to go over safety standards. These will need to revise CNG and LNG storage at terminals, CNG and LNG dispensers. International standards can serve as guidelines or be used as local norms.	Hydrogen fueling facilities require entirely different regulations than diesel or biodiesel, given that it is a gaseous, high pressure fuel. Given the small size of hydrogen molecules, they can penetrate and degrade materials, and therefore require particular storage considerations.	It can be assumed that high voltage regulations for the required transforming stations and electric transmissions are already in place. However, additional regulations must be in place for the handling of high voltage systems in bus terminals, as is the case with public charging stations.
Waste management	Buses can typically be incorporated into existing scrap programs if these are in place.	Buses can typically be incorporated into existing scrap programs if these are in place.	Buses can typically be incorporated into existing scrap programs if these are in place.	Waste management is not a big issue for hydrogen technologies. However, certain design-for-recycling standards for fuel cell systems could be considered.	Waste management is particularly important for electric and hybrid electric vehicles because of the toxicity of the batteries. Even if it is generally not a "make or break" issue, establishing the responsibilities and way of disposal of the batteries should be done at the beginning of the project, to ensure they do not end up causing health hazards for the population or the contamination of land and soil.

Engaging local stakeholders in technical vehicular homologation/regulation departments will be key to understanding and correctly assessing the work to be done. Given that regulatory measures may take a rather long time to be sanctioned, these issues should be considered from the start of the project, to avoid unnecessary delays.

Once local enabling conditions have been evaluated, the vehicle technical performance needs to be evaluated. For this, throughout the following section the expected specific vehicle fuel/energy consumption, and consequent vehicle range, is calculated and compared to the service distance requirements. It is strongly recommended that before proceeding to the following section the evaluator goes through the annex on bus technology and charging infrastructure.

Photo: An electric self-driving bus is used in tourist transportation. iStock.

CHAPTER 3

Technical Prefeasibility Analysis

One of the big advantages of conventional diesel fleets is their versatility. The high specific energy content (measured in megajoules per liter, or MJ/L) and stability of petroleum derivatives allows conventional vehicles to have significant autonomy, independent of the required operating conditions, using a very simple and low-cost fuel storage system. Furthermore, if operating conditions are such that the vehicle must refuel during operation, this can be done in a matter of minutes. As a result, conventional vehicle fleets are very versatile, with the same vehicle being able to cover a wide range of services without returning to base. All of this, in combination with the maturity and robustness of the technology, allows for small vehicle reserve fleets of 6 percent to 10 percent depending on the average age, overall size, and the number of services that the fleet must cover (the bigger the fleet the smaller the percentage of reserve fleet required). Also, in many cases the refueling infrastructure is already in place, reducing the overall required investment.

Whereas all of the above applies to hybrid and biodiesel fueled buses, other technologies analyzed throughout this document have clear limitations in terms of autonomy, charging times and, thus, versatility, when compared to conventional diesel vehicles. Therefore, to analyze the techno-economic feasibility of deploying a given technology in each system, it is imperative to understand if the former can cover the required service without the need of a large incremental fleet.

Natural gas buses can use a liquid (LNG) or compressed (CNG) storage system. LNG buses have a similar autonomy and refueling time to diesel buses, and therefore should be able to provide the same service cover as a conventional diesel fleet. However, given that natural gas vehicles have spark ignition engines, maintenance requirements could result in a slightly larger reserve fleet.

Compressed gas fuel technologies, such as CNG or hydrogen fuel cell buses, have lower range and higher refueling times than diesel buses. However, in either case these differences are not considerable and, unless the daily required range of the service is far in excess of the capabilities of these vehicles, additional fleet requirements should not be more than 5 percent.

Finally, given the low energy density of battery systems compared to diesel, electric buses are the most susceptible of the analyzed technologies to autonomy and charging times restrictions, and therefore, understanding the operation strategy and schedule is very important to establish if this technology can be used to provide a given service without a large reserve fleet. If at this stage the service schedule is unknown or assumed to be a flat dispatch schedule, then it can be safely stated that if a slow charge electric bus cannot cover the required daily distance, then the use of this technology will require a larger reserve fleet compared to a diesel fleet. If the schedule has peak and valley fleet dispatches, then it could be possible to rotate buses throughout the day and cover the required service without the need of increasing the size of the fleet. On the other hand, fast charge electric buses would have to be able to cover the distance between charges, which is normally the route distance. Thus, in this case, the analysis is binary: either the bus can cover the service or not.

Throughout this section, the expected vehicle fuel consumption and autonomy in local operating conditions will be estimated to assess the capability of the different technologies to comply with the service requirements.

3.1 Vehicle range and fuel consumption

Vehicle specific fuel/energy consumption is a key parameter to establish the technical, economic, and environmental performance of any technology. It is greatly dependent on local operating conditions and vehicle characteristics. Table 6 outlines the characteristics of both 12 and 18-meter buses of each of the evaluated technologies. It is important to note that, in the case of the fully electric vehicles, Table 6 details the nominal energy capacity of the vehicle battery pack and the operational battery capacity. The latter is 80 percent of the nominal battery capacity and is the parameter that the evaluator must use to calculate the expected range per charge of the different electric alternatives. The reason for these is that, as shown in the literature and practical experiences around the world,[5] operating batteries below the 20 percent charge level causes premature degradation of the system.

Table 6. Representative CTB characteristics

Bus tech	Bus length [m]	Max. PAX	Fuel storage capacity	Battery capacity [kWh]	Operational batt. capacity [kWh]	Vehicle weight [kg]	AC max power [kW]	Max. engine/motor power [kW]
D-Euro VI	12	80	200L	N/A	N/A	10,300	18	210
	18	120	400L	N/A	N/A	14,500	27	230
Biodiesel	12	80	200L	N/A	N/A	10,300	18	210
	18	120	400L	N/A	N/A	14,500	27	230
CNG	12	80	200m3 (NPT)	N/A	N/A	11,800	18	210
	18	120	400m3 (NPT)	N/A	N/A	19,000	27	230
LNG	12	80	200m3 (NPT)	N/A	N/A	11,800	18	210
	18	120	400m3 (NPT)	N/A	N/A	19,000	27	230
D-HEB	12	80	200L	30–60	24-48	12,000	18	150/200
	18	120	400L	60–90	48-72	16,000	27	200/360
BEB-RC	12	80	N/A	60–100	48-80	13,000	18	200
	18	120	N/A	100–160	80-128	17,000	27	250
BEB-SC	12	80	N/A	200–350	160-280	14,500	18	300
	18	120	N/A	350–450	280-360	19,000	27	360
HFCEB	12	80	30–50 kg H2	30–60	N/A	14,500	18	200
	18	120	50–70 kg H2	60–90	N/A	19,000	27	240

Note: D-EuroVI=diesel Euro VI, CNG=Compressed Natural Gas, LNG=Liquefied Natural Gas, D-HEB=Diesel Hybrid Electric Bus, BEB-RC=Battery Electric Bus – Rapid Charge, BEB-SC=Battery Electric Bus – Slow Charge, HFCEB=Hydrogen fuel cell electric bus

[5] ROGGE, Matthias; WOLLNY, Sebastian; SAUER, Dirk Uwe. Fast charging battery buses for the electrification of urban public transport—a feasibility study focusing on charging infrastructure and energy storage requirements. Energies, 2015, vol. 8, no 5, p. 4587-4606.

In order to allow the evaluator to customize the energy consumption analysis to local conditions, the present methodology establishes a baseline fuel/energy consumption (driving with no passengers, over a flat route, and with no air conditioning) to which incremental fuel/energy consumptions due to passenger capacity, route slope and air conditioning requirements must be added to replicate local operating conditions. Therefore, the specific fuel/energy vehicle consumption can be calculated as:

$$Consumption_n = Consumption_n^0 + Consumption_n^{PAX} + Consumption_n^{Slope} + Consumption_n^{AC},$$

Where $Consumption_n^0$ refers to the vehicle's baseline specific fuel/energy consumption, $Consumption_n^{PAX}$ considers the specific fuel/energy consumption increase induced by passengers, $Consumption_n^{Slope}$ considers the slope effect, and $Consumption_n^{AC}$ establishes the specific fuel/energy consumption induced by the use of the air conditioning system.

Baseline specific fuel/energy consumption are shown in Table 7 for both bus rapid transit (BRT) or exclusive lanes (mean velocity of 18 km/h) and stop-and-start driving conditions (mean velocity of 11 km/h). In either case, these assume:

- No passengers
- Flat route
- No air conditioning.

Table 7. Baseline range and consumption for each technology without AC[6]

Bus technology	BRT - 12m bus	BRT - 18m bus	Stop-and-start - 12m bus	Stop-and-start - 18m bus
	$Consumption_n^0$	$Consumption_n^0$	$Consumption_n^0$	$Consumption_n^0$
D-Euro VI [L/km]	0.31	0.44	0.37	0.51
Biodiesel [L/km]	0.31	0.44	0.37	0.51
CNG [m3/km][7]	0.38	0.54	0.45	0.64
LNG [L/km]	0.38	0.54	0.45	0.64
D-HEB [L/km]	0.26	0.37	0.31	0.43
BEB-SC [kWh/km]	0.90	1.20	0.95	1.25
BEB-RC [kWh/km]	0.75	1.00	0.85	1.10
HFCEB [kgH2/km]	0.05	0.07	0.06	0.08

[6] All consumption values were obtained through field work done by the authors.
[7] Nominal at 25°C and atmospheric pressure.

The incremental specific fuel/energy consumption induced by passenger capacity, geography, and climate conditions, at both mix traffic Stop & Go and BRT driving conditions, for 12-meter and 18-meter buses of each type of technology are presented in Tables 8, 9 and 10, respectively. Table 8 provides incremental specific fuel/energy consumption for buses operating at full and medium capacity. Based on expected demand the evaluator can use one of these two options.

Table 8. Incremental fuel/energy consumption over the baseline condition given passenger capacity (PAX=Medium and PAX=Full)

PAX	Consumption							
	BRT - 12m bus		BRT - 18m bus		Stop & Go - 12m bus		Stop & Go - 18m bus	
Bus technology	Medium	Full	Medium	Full	Medium	Full	Medium	Full
D-Euro VI [L/km]	0.07	0.14	0.10	0.21	0.08	0.16	0.12	0.24
Biodiesel [L/km]	0.07	0.14	0.10	0.21	0.08	0.16	0.12	0.24
CNG [m3/km]	0.08	0.17	0.13	0.25	0.10	0.20	0.15	0.30
LNG [m3/km]	0.08	0.17	0.13	0.25	0.10	0.20	0.15	0.30
D-HEB [L/km]	0.06	0.12	0.09	0.17	0.07	0.14	0.10	0.20
BEB-SC [kWh/km]	0.20	0.35	0.25	0.50	0.20	0.40	0.30	0.60
BEB-RC [kWh/km]	0.10	0.25	0.20	0.40	0.15	0.30	0.25	0.45
HFCEB [kgH2/km]	0.01	0.02	0.02	0.03	0.01	0.02	0.02	0.04

Table 9 provides incremental specific fuel/energy consumption values for the different vehicles for hill and mountain conditions, which translate to mean positive slopes of 1.5 percent and 2.5 percent, respectively. Based on local geography the evaluator can use one of these two options if required.

Table 9. Incremental specific fuel/energy consumption over the baseline condition given varying route's slope (Geography=Hill and Geography=Mountain)*

Slope	Consumption							
	BRT - 12m bus		BRT - 18m bus		Stop & Go - 12m bus		Stop & Go - 18m bus	
Bus technology	Hill	Mountain	Hill	Mountain	Hill	Mountain	Hill	Mountain
D-Euro VI [L/km]	0.03	0.07	0.04	0.10	0.04	0.11	0.06	0.16
Biodiesel [L/km]	0.03	0.07	0.04	0.10	0.04	0.11	0.06	0.16
CNG [m3/km]	0.04	0.09	0.05	0.12	0.05	0.14	0.07	0.20
LNG [m3/100 km]	0.04	0.09	0.05	0.12	0.05	0.14	0.07	0.20
D - HEB [L/km]	0.02	0.06	0.04	0.08	0.03	0.10	0.05	0.13
BEB - SC [kWh/km]	0.10	0.15	0.10	0.20	0.10	0.20	0.15	0.25
BEB - RC [kWh/km]	0.05	0.10	0.10	0.15	0.10	0.15	0.10	0.20
HFCEB [kgH2/km]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02

* Hill geography considers a mean positive slope of 1-2%, and Mountain geography considers a mean positive slope of 2-3%.

Finally, Table 10 provides incremental specific fuel/energy consumption values for the different vehicles using air conditioning systems in tropical or subtropical climates. Based on local climate conditions the evaluator can use one of these two options if required.

Table 10. Incremental specific fuel/energy consumption over the baseline given varying loads of air conditioning for different climate conditions (Subtropical and Tropical) *

AC	Consumption							
	BRT - 12m bus		BRT - 18m bus		Stop & Go - 12m bus		Stop & Go - 18m bus	
Bus technology	Subtropical	Tropical	Subtropical	Tropical	Subtropical	Tropical	Subtropical	Tropical
Diesel Euro VI [L/km]	0.14	0.35	0.21	0.53	0.22	0.57	0.35	0.86
Biodiesel [L/km]	0.14	0.35	0.21	0.53	0.22	0.57	0.35	0.86
CNG [m3/km]	0.19	0.48	0.29	0.72	0.30	0.78	0.48	1.17
LNG [m3/km]	0.19	0.48	0.29	0.72	0.30	0.78	0.48	1.17
Diesel HEB [L/km]	0.11	0.29	0.18	0.44	0.19	0.48	0.29	0.72
BEB-SC [kWh/km]	0.40	1.00	0.60	1.50	0.65	1.65	1.00	2.45
BEB-RC [kWh/km]	0.40	1.00	0.60	1.50	0.65	1.65	1.00	2.45
HFCEB [kgH2/km]	0.02	0.06	0.04	0.09	0.04	0.10	0.06	0.15

* The AC nominal power considered for a 12-meter bus is 7 kW and 18 kW for subtropical and tropical climates, respectively. In the case of 18-meter buses, the nominal power considered is 11 kW and 27 kW, respectively.

Once the different vehicle specific fuel/energy consumptions have been established, using the vehicle's fuel/energy capacity detailed in Table 7, the range per charge of the different CTB can be calculated as:

$$Range_n = \frac{Fuel/energy\ Capacity}{Consumption_n}$$

It is important to note that, as mentioned above, in the case of battery electric vehicles, range must be established based on the operational battery capacity of the vehicle established in Table 6. For all other technologies, the fuel storage capacity must be used.

Based on the above, other than for rapid charge electric vehicles, comparing the calculated $Range_n$ to the required daily distance of the system will show the viability of implementing a certain technology in the expected system. In other words, for the technology to be viable, the vehicle range should be higher than that of the required operating range ($Range_n > Range_{operation}$). In the case of fast charge electric buses, vehicle range must be compared to route length, given that it is assumed that these vehicles will charge once per trip.

If a given technology cannot cover the required daily distance of the system, or in the case of RC electric buses the route distance, additional charging events will be required. This is possible, but understanding the impact on the service schedule or reserve fleet requires a more detailed analysis, which escapes the scope of this evaluation. However, a few pointers on risk and evaluation are provided in Chapter 7at the end of the document for the examiner to consider.

Photo: Electric bus charging at a station. iStock.

CHAPTER 4

Environmental Analysis

Once the technical assessment for each technology has been made, an environmental analysis can be performed to understand the impact each of these have on the environment. Environmental impact studies of transportation technologies usually cover two parts: carbon footprint or greenhouse gas (GHG) emissions, and air quality related emissions. GHG emissions are a global polluter and therefore their reduction requires an international collaboration. In this regard, the Paris Agreement details the contributions of GHG emissions reductions pledged by most industrialized countries. On the other hand, air quality is a local concern and has a direct impact on people's health.

This part of the guide aims to give the TTL the tools to perform an initial quantitative assessment of the GHGs and toxic emissions resulting from each available technology. The results on fuel or consumption found in the previous chapter will be used for this section, and, likewise, the results from this section will afterwards be used to perform a cost–benefit analysis of each technology.

4.1 Carbon footprint

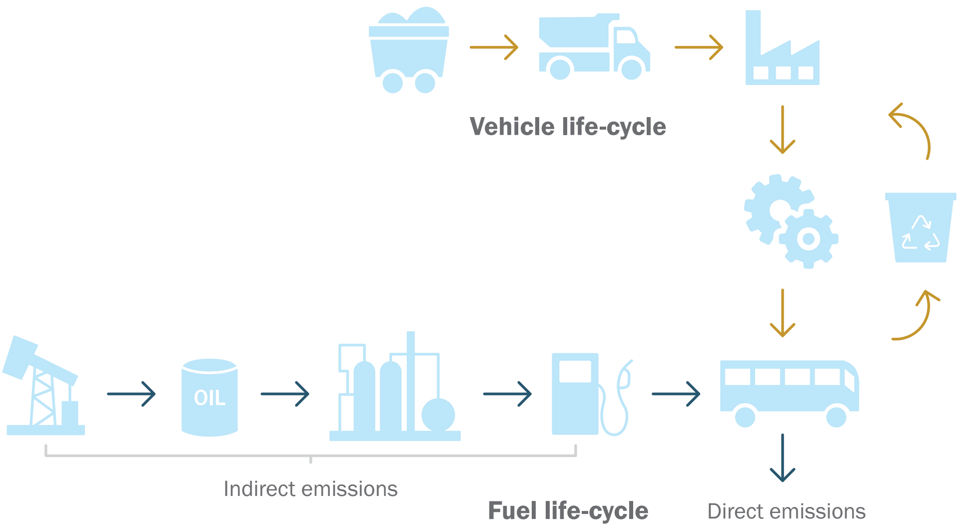
As illustrated in Figure 1, the complete carbon footprint of any vehicle involves the full life-cycle emissions of the vehicle and those of the fuel/energy vector. The vehicle life-cycle or embedded emissions are those produced during the entire production and disposal process of the vehicle, all the way from raw material extraction and refining to end-of-life scrappage and recycling. On the other hand, the life-cycle emissions of the fuel/energy vector consider the GHG emissions related to the extraction, refining and/or production of the fuel used (indirect emissions) and those produced by the vehicle while operating (direct emissions).

In the case of a bus, due to the large amount of energy used over the lifetime of the vehicle, the embedded emissions are relatively small when compared to fuel/energy life-cycle emissions and will be therefore neglected in this initial approach.

The fuel life-cycle emissions can be classified as indirect and direct emissions. For instance, in the case of diesel fuel, indirect emissions are those produced during oil extraction, refining, transportation, etc., until the fuel is transferred to the refueling station, ready to be pumped into the vehicle. These emissions are measured in terms of mass of GHGs emitted (g) per unit of energy of fuel produced (kWh). In the case of electric buses, because the "fuel" is electricity, indirect emissions are those related to electricity generation and distribution process.

Alternatively, direct emissions are those that are produced during vehicle operation. These are measured in mass of GHGs (g) generated per energy of fuel consumed (kWh). Because electric vehicles do not have combustion engines, they produce no direct emissions.

Figure 1. Vehicle and fuel life-cycle illustration. When assessing the carbon footprint of a technology, both the vehicle's and the fuel's life cycles must be appraised.



In the previous section, fuel consumption was expressed in the most used unit for each technology, for example, specific fuel consumption of diesel buses was expressed in liters/kilometer, or, in the case of hydrogen, kilograms/kilometer. However, when analyzing the energetic or environmental performance of different technologies, it is useful to use a single unit for ease of comparison. Therefore, the first step of this section will be to transform all previous consumption results to kilowatt-hour/kilometer (kWh/km).

To do this, the lower heating values (LHV) of each fuel are used. The lower heating value of each fuel expresses how much energy is available in a fuel per unit mass or volume. Table 11 shows the lower heating values of each of the analyzed fuels in this guide. To get the fuel consumption of each fuel in kWh/km, one must simply multiply the fuel consumption obtained in the previous section with the lower heating value of the corresponding fuel. As can be seen, electric technologies are not included since they are already expressed in kWh/km.

Table 11. Lower heating values of analyzed fuels

Technology	Lower heating value
Hydrogen	33.3 kWh/kg
CNG	10.8 kWh/m3
Diesel	10 kWh/L
Biodiesel	9.2 kWh/L

Adding direct and indirect emissions, we get the total GHG emissions of the fuel cycle per energy of fuel consumed. When this is multiplied by the fuel consumption of the vehicle, we get the emissions of the vehicle per kilometer, as shown in the following equation:

$$E_i = F_{c,i}\left(F_{IE,i} + F_{DE,i}\right),$$

where *Ei* is the overall GHG emissions of technology *i* per kilometer, measured in g/km; $F_{c,i}$ is the fuel consumption of technology *i* in kWh/km; and $F_{IE,i}$ and $F_{DE,i}$ are the fuel's indirect and direct emissions of technology *i*. This way, the carbon footprint of all the evaluated technologies can be calculated and compared.

Next, an approach to estimating direct and indirect emissions of electric, hydrogen, biodiesel, diesel and CNG technologies is presented.

INDIRECT EMISSIONS (WELL-TO-PUMP)

Electricity generation

Electric buses have no direct emissions, and their indirect emissions are those related to the production and distribution of electricity. Therefore, to calculate the carbon footprint of this technology, the electric matrix of the city/country must be assessed.

Each technology of electric generation has a particular impact on the environment related mainly to the fuels used and the energy efficiency of the processes in place. For this analysis, emissions related to the building and preparing of power plants were not considered. There are many reasons for doing so, one of them being to simplify the analysis, but also that it can be argued that electricity generation infrastructure will not be modified by the project in question, and therefore all plants are already operational. Consequently, only operational emissions must be considered.

Not accounting for infrastructure emissions means that solar, wind, hydroelectric, geothermal, and other renewable energies are considered to have no related emissions. Table 12 shows the emissions associated with the most used electricity sources. These results were obtained from the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model developed by Argonne National Laboratory.

GREET models produce well-to-pump and well-to-wheel analysis of a wide variety of fuels and have an extensive list of processes that can be used to build the pathway of production for each one. The results shown here were developed using the default processes and pathways for the United States. Therefore, they can be used as a reference, but should be adapted to fit local electricity production if more accurate results are needed.

Table 12. Equivalent greenhouse gas emissions per kilowatt-hour of electricity for some of the most common electricity generation sources

Type of generation	gGHG/kWh
Nuclear	7
NG-fired simple cycle gas turbine	690
NG-fired combined-cycle	430
NG-fired internal combustion engine	690
NG-fired steam turbine	690
Oil-fired internal combustion engine	880
Oil-fired steam turbine	960
Oil-fired gas turbine	1,050
Coal-fired IGCC plant	930
Coal-fired steam turbine	1,010
Biomass (U.S. mix)	63

In order to use this table, the electricity mix of the particular location analyzed must be obtained first. Once the percentage of energy that each type of generation actually generates is known, the overall emission factor of the electricity mix can be calculated. As stated before, solar, wind, hydroelectric and other renewable energy sources can be considered to produce zero grams of greenhouse gasses per kilowatt-hour generated.

Fuel production

For all other technologies apart from electric, the indirect emissions are those related to the fuel production, from the moment it is extracted in its original, natural state, to the moment it is at the fuel station ready to be used. Again, the GREET model was used to obtain the emissions related to each fuel, and the most common fuel production pathways are provided for each one, so the TTL can chose the one most suited to the project at hand. Tables 13 to 17 show the indirect emissions of each fuel used per kilowatt-hour of fuel produced.

Table 13. Equivalent greenhouse gas emissions per kilowatt-hour of gaseous hydrogen at fuel station from the most common hydrogen sources

Type of production	gGHG/kWh
Steam methane reforming	340
Production from coal	590
Production from pet coke	700
Electrolysis	*

* Depends on electricity source. Normally is 1.4 kWh of electricity per kWh of H2.

Table 14. Equivalent greenhouse gas emissions per kilowatt-hour of CNG for local extraction and LNG imports

Type of production	gGHG/kWh
Local extraction and distribution	52
Import LNG and regassification of LNG	84

Table 15. Equivalent greenhouse gas emissions per kilowatt-hour of LNG for local extraction and LNG imports

Type of production	gGHG/kWh
Local extraction of NG, liquefaction and distribution	65
Import LNG and distribution	70

Table 16. Equivalent greenhouse gas emissions per kilowatt-hour of diesel from local extraction, refining and transportation

Type of production	gGHG/kWh
Local extraction and refining of crude oil	50 to 70

Table 17. Equivalent greenhouse gas emissions per kilowatt-hour of biodiesel fuel produced from soybeans and tallow

Type of production	gGHG/kWh
Production from soybeans	110
Production from tallow	72

DIRECT EMISSIONS (PUMP-TO-WHEEL)

Finally, as stated before, direct emissions are those related to the operation of the buses. In this case, electric and hydrogen have zero greenhouse gas emissions because no combustion takes place in the vehicles. In the case of biodiesel, combustion does take place, but it can be considered that CO2 emissions during operation are equal to those absorbed by biodiesel sources during growth and are therefore also zero. Table 18 shows the direct emissions of all technologies analyzed.

Table 18. Direct emissions of analyzed technologies, expressed in equivalent greenhouse gas emissions per kilowatt-hour of fuel consumed

Technology	gGHG/kWh
Electric	0
Hydrogen	0
CNG	203
Diesel	270
Biodiesel	0

Adding direct and indirect emissions, we get the total GHG emissions of the fuel cycle per energy of fuel consumed. When this is multiplied by the fuel consumption of the vehicle (calculated in the previous sections), we get the emissions of the vehicle per kilometer, as shown in the following equation:

$$E_i = F_{c,i}\left(F_{IE,i} + F_{DE,i}\right)$$

It can also be useful to express emissions in terms of tons of GHG per year, and therefore analyze how many tons of GHG emissions are saved when switching from one technology to another. To do this, the emissions calculated in this section must simply be multiplied by the total annual kilometers traveled by the bus fleet.

4.2 Air quality

The second part of the environmental impact study consists of studying the impact of each technology on air quality emissions. These emissions are toxic or harmful to citizens' health and the environment. Although these emissions include carbon monoxide (CO), unburned hydrocarbons (UHC), volatile organic compounds (VOC), nitrogen oxides (NOx) and particulate matter (PM), due to the nature of diesel vehicles this study will focus on the latter two. As stated before, electric and hydrogen-based buses produce no emissions during operation, so changing to that technology would result in a complete elimination of air quality emissions.

To estimate the PM and NOx of each technology, the Handbook of Emission Factors for Road Transport (HBEFA) was used. The HBEFA was developed on behalf of the Environmental Protection Agencies of Germany, Switzerland, and Austria and with the support of Sweden, Norway, and France, and it provides emission factors for all current vehicle categories for a wide variety of traffic situations.

Table 19 shows the resulting PM and NOx emissions of each analyzed technology under stop-and-start and BRT operation, similar to what was used in the previous sections. It must be mentioned that these emissions can vary depending on the particular model of bus used and accessing this information can be challenging and requires very expensive equipment to effectively measure. These results show mean trends of a variety of measurements available in the HBEFA and are to be used as a reference only.

Table 19. PM and NOx emissions for each analyzed technology under two operating conditions: stop and start and BRT

Technology	Stop & Go (11 km/h)		BRT (18 km/h)	
	PM (mg/km)	NOx (g/km)	PM (mg/km)	NOx (g/km)
Electric	-	-	-	-
Hydrogen	-	-	-	-
CNG E VI	17	0.6	15	0.5
Diesel EIII	380	18	320	16
Diesel E V	90	10	80	8
Diesel E VI	9	1	8	0.8
Biodiesel*				

*Depends on biodiesel source. If there is not enough information on biodiesel used, the values for analog diesel technologies can be used, having around 10 percent more NOx emissions but 20 percent to 50 percent less PM emissions.[8]

[8] Pullen & Saeed. (2012). An overview of biodiesel oxidation stability.

Photo: Mercedes-Benz Citaro FuelCell Hybrid at a bus stop. iStock.

CHAPTER 5

Economic Evaluation

Once the technical viability of each technology has been assessed, the economic and financial performance of the different technologies needs to be considered. Many aspects of this assessment do not differ from that performed for a conventional bus transport study, namely assessing CAPEX and OPEX, analyzing the financial viability of the project together with a cost benefit analysis and a risk assessment. However, there are some aspects that present some differences such as additional or varying CAPEX and OPEX, the potential access to "green" funding, and the additional environmental benefits of the different technologies. Also, it is important to note that this analysis is at a prefeasibility level and should not be used as the final results of the future service. The evaluation will include technological and financial aspects pertinent to each technology's service indicators, aiming to provide the evaluator an "apples to apples" evaluation of the different systems.

The analysis will focus on estimating the levelized cost of ticket (LCOT) for each technology. This is considered a more comprehensive parameter to understand the impact of the different technologies on the cash flow and end product price of the transport system. It is analogous to the LCOE (levelized cost of electricity) concept applied to evaluate the economic performance of different power generation technologies. Put simply, the LCOT is the average price the ticket should have over the lifetime of the transport system for the investment to break even, i.e., to achieve a net present value (NPV) of zero. Instead of analyzing the NPV of the total cost of ownership (TCO) for the system, the LCOT incorporates the revenue stream into the analysis. This will allow decision makers to understand the impact of introducing a given technology into the expected cost of the service, thus making an informed decision on affordability or additional subsidy or government contribution needed to keep the cost of the system at a given value.

5.1 Parameters used to calculate the LCOT

The guide is complemented with a spreadsheet that will allow the evaluator to calculate the LCOT of the different fleets under different financial assumptions and incentive scenarios. This section will, therefore, describe and establish the different parameters required to calculate the LCOT. Reference values will be provided for the evaluator to use in case local information is not available. Finally, different financial scenarios will be defined to help the evaluator on assessment of the impact of different variables on the LCOT and establish the sensitivity analysis.

CHARGING INFRASTRUCTURE COST (CIC)

The CIC is the cost of building the vehicle charging infrastructure. It includes not only the basic equipment costs, but also all process and support facilities, such as fuel handling and storage, waste treatment, maintenance, etc. Table 20 provides reference values for the cost per bus of the different technologies charging infrastructure. These values are representative of cost incurred for fleets of 20 to 100 buses. Larger fleets may be positively affected by economies of scale, or, in the case of electric fleets, impose a higher infrastructure price per vehicle given the need for high power installations. These values can also vary significantly depending on location and should be used with caution. Also, for some technologies, such as hydrogen, there is a limited amount of information available on these costs given the lower market penetration of the technology. Having said this, charging infrastructure investments are usually small compared to fleet costs and should therefore not have a considerable impact on the overall economic evaluation.

Table 20. Infrastructure cost for the different technologies[9] [10]

Bus technology	Infrastructure cost [US$]	Number of buses supported	Total cost per vehicle [US$/bus]
Diesel Euro VI	480,000	90	5,350
Biodiesel	480,000	90	5,350
CNG	390,000	90	4,350
LNG	390,000	90	4,350
Diesel HEB	480,000	90	5,350
BEB-SC	25,000	2	12,500
BEB-RC	56,000	8	7,000
Hydrogen	1,320,000	90	14,500

FLEETS COST

In conventional diesel fleets, vehicles are considered a single asset and purchased as such, meaning that the bus operator or fleet owner will acquire the buses from a concessionary and become sole owner of the vehicles. However, given the high cost of batteries and hydrogen fuel cells, together with the inevitable degradation and eventual replacement of these throughout the life of the vehicle, it is now common to separate these from the vehicle itself.

Based on the above, the vehicle cost will be broken up into glider and body, powertrain, and energy storage system. This will allow for a more thorough understanding of the vehicle cost structure and provide insight into establishing new business models used to distribute risk and capital expenditures related to battery or fuel cell (FC) replacement and degradation. For example, under current practices, vehicles are acquired as a single asset, meaning that replacement components are capital expenditures required by the system at a given point in time. On the other hand, if the glider vehicle body and powertrain are acquired by the operator and the battery/fuel cell systems are leased to a third party, the latter become an operating expenditure of the system.

[9] HOOFTMAN, Nils; MESSAGIE, Maarten; COOSEMANS, Thierry. Analysis of the potential for electric buses, European Copper Institute – Vrije Universiteit Brussel, 2019.

[10] Hinicio DB, 2017. Considering a fleet of 90 buses.

Table 21. Vehicle unit cost for 12-meter buses with AC systems [11] [12] [13] [14]

Bus technology	Glider and body [US$]	Powertrain [US$]	Energy storage system [US$]	Vehicle cost [US$]
Diesel Euro VI	180000	20000	0	200000
Biodiesel	180000	25000	0	205000
CNG	180000	20000	30000	230000
LNG	180000	20000	30000	230000
Diesel HEB	180000	40000	30000	250000
Electric – SC	180000	120000	150000	450000
Electric – RC	180000	120000	45000	345000
Hydrogen	290000	240000	80000	610000

Table 22. Vehicle unit cost for 18-meter buses with AC systems. Considered to be 25 percent more expensive than 12-meter buses.

Bus Technology	Glider and body [US$]	Powertrain [US$]	Energy storage system [US$]	Vehicle cost [US$]
Diesel Euro VI	225000	25000	0	250000
Biodiesel	225000	30000	0	255000
CNG	225000	25000	40000	290000
LNG	225000	25000	40000	290000
Diesel HEB	225000	50000	40000	315000
Electric – SC	225000	150000	190000	565000
Electric – RC	225000	150000	55000	430000
Hydrogen	365000	300000	100000	765000

In an ideal scenario, where the leasing company does not charge an additional cost besides the asset price, the overall cost of the system should not change. However, it is likely that the leasing company will not only assume the overhead cost related to their operation, but will also need to hedge risks related to the uncertainty of battery life and performance, which would result in an added premium. Therefore, the main reasoning behind these kinds of new business models is not so much to improve the projected economic performance of the transport system, but to make the inclusion of new technologies viable by distributing, and hence reducing, the technical and financial risks associated with the operational uncertainties and higher capital costs of new technologies.

[11] Edward Boyd Ben Madden. Economic Case for Hydrogen Buses in Europa. Technical report, Ballard, 2017.

[12] N. de Miguel, R. Ortiz Cebolla, B. Acosta, P. Moretto, F. Harskamp, and C. Bonato. Compressed hydrogen tanks for on-board application: Thermal behaviour during cycling. International Journal of Hydrogen Energy, May 2015. doi: 10.1016/j.ijhydene.2015.03.035

[13] Pedro Orbaiz, Nicolás van Dijk, Santiago Cosentino, Nicolas Oxenford, Mauro Carignano, and Norberto Marcelo Nigro. A Technical, Environmental and Financial Analysis of Hybrid Buses Used for Public Transport. In SAE Technical Paper Series. SAE International, apr 2018. doi: 10.4271/2018-01-0424.

[14] Euro VI bus price provided by Mercedes-Benz and Agrale at Argentina

Because this guide targets the prefeasibility analysis level, the complexity of proposing and evaluating new business models exceeds the scope of the work at hand and therefore the traditional expenditure and business model will be applied. However, the technical considerations and the sensitivity analysis undertaken in the following section will allow the evaluator to establish the best conditions for each technology and the potential risk entailed by variations in the different financial parameters of the system.

In line with the above, the replacement of battery systems or fuel cells, when pertinent, will be treated as a capital expenditure in the specified year. Furthermore, while the degradation of the battery or fuel cell system is likely to affect the operation of electric, hybrid or hydrogen fleets, the impact of this on the fleet operation and the subsequent requirement of additional vehicles or charging capacity is not only related to the vehicle range per charge but also to the operation and dispatch schedule of the service. Therefore, throughout this economic analysis it will be assumed that over the life of the battery or fuel cell, the established fleet can satisfy the required distance of the service. Also, the increase in vehicles' specific energy consumption due to the higher inefficiencies of the systems as they degrade is also not accounted for at this stage.

FIXED AND VARIABLE OPERATING AND MAINTENANCE COSTS (FOM AND VOM)

The fixed operation and maintenance costs (FOM) are related to the number of vehicles in the fleet and are normally expressed in [$/vehicle-year]. They include labor, equipment, and overhead charges. Table 23 describes the different FOM costs that the economic evaluation will consider and, when possible, provides a suggested default value to use in case local estimates cannot be found.

Table 23. FOM expressed in [$/vehicle-year] required by the public transport system

Staff	The overall cost of staff is composed of the total of all or some of the below components. Salary costs need to be determined based on local conditions as they may differ both in type and sum from one country to the next.
Security	Cost related to the payment of security personnel salaries
Drivers	Cost related to the payment of bus drivers' salaries
Terminal agents	Cost related to the payment of terminal operations personnel salaries
Mechanics	Cost related to the payment of bus mechanics' salaries
Inspectors	Cost related to the payment of inspectors' salaries
Manager	Cost related to the payment of managers' salaries
Back office	Cost related to the payment of back office personnel salaries
Director	Cost related to the payment of directors' salaries
Vandalism	This is the cost associated with the repair of vehicles due to vandalism. Different from conventional maintenance, which is normally related to km traveled by the units, this cost is related to a % of the vehicle cost (around 6%).
Insurance	Cost related to the payment of the insurance coverage of the fleet (around 2% of vehicle cost).
Vehicle registration	Cost related to annual vehicle registration payment (around 3% of vehicle cost).

Variable operation and maintenance costs (VOM) are usually related to the kilometers traveled by the fleet and expressed in [$/km]. Throughout this analysis, the fuel/energy cost is not included in the VOM and is treated as a separate expense in the following section. Therefore, the only variable cost related to the fleet operation is vehicle maintenance. Given that the different vehicles evaluated have very different powertrains and energy storage systems, their maintenance cost varies. Table 24 provides provides suggested VOM cost per km, taken from literature, for the different evaluated technologies.

Table 24. VOM expressed in [$/km], for the different evaluated technologies[15]

Technology	VOM cost [US$/km]
Diesel Euro VI	0.22
Biodiesel	0.22
Natural Gas – CNG	0.30
Natural Gas – LNG	0.30
Diesel HEB	0.22
Electric – SC	0.15
Electric – RC	0.15
Hydrogen	0.26

FUEL/ENERGY COSTS

The fuel/energy costs are treated as an annual expense. These are calculated based on the specific fuel/energy consumption of the vehicles, the local tariff of the different fuels or electricity and the kilometers travelled by the fleet per year. Below, Table 25 suggests that fuel/energy costs be used as a reference by the evaluator. It is important to keep in mind that the evaluator should search for local costs to carry out a more reliable analysis. In cases where this is not possible, the reference values should be used instead.

Table 25. Suggested fuel/energy costs[16, 17, 18, 19, 20, 21, 22, 23]

Technology	Fuel/energy cost
Diesel	0.80 – 1.50 [US$/L]
Biodiesel (B100)	0.70 – 0.98 [US$/L]
CNG	0.20 – 0.92 [US$/m3]
LNG	0.55 – 0.76 [US$/m3]
Electricity	0.05 – 0.30 [US$/kWh]
Hydrogen	4.00 – 7.00 [US$/kg]

[15] Eudy, Leslie, Matthew Post, and Matthew Jeffers. *American Fuel Cell Bus Project Evaluation: Third Report.* No. NREL/TP-5400-67209. National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2017.

[16] Industrial hydrogen cost from conventional and renewable sources: https://www.sciencedirect.com/topics/engineering/hydrogen-production-cost. KAYFECI, Muhammet; KEÇEBAŞ, Ali; BAYAT, Mutlucan. Hydrogen production. In Solar Hydrogen Production. Academic Press, 2019. p. 45-83.

[17] US Energy Information Administration, Ultra Low Sulfur Diesel Retail Prices, 2019: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emd_epd2dxl0_pte_nus_dpg&f=a

[18] Global Petrol Prices, Natural Gas prices for business, 2020: https://www.globalpetrolprices.com/natural_gas_prices/

[19] Global Petrol Prices, Electricity prices for business, 2020: https://www.globalpetrolprices.com/electricity_prices/

[20] U.S. Department of Energy – Energy Efficiency and Renewable Energy, Clean Cities Alternative Fuel Price Report, January 2020: https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_jan_2020.pdf

[21] Global Petrol Prices, Diesel prices, 2020: https://www.globalpetrolprices.com/diesel_prices/

[22] LNG retail price provided by Y.P.F, Argentina

[23] Secretaría de Energía, Precios de biodiesel: https://glp.se.gob.ar/biocombustible/reporte_precios.php

CARBON PRICING

The main driver behind the transition away from conventional diesel vehicles is their impact on local pollution and the need to reduce carbon emissions across all sectors of the global economy. Throughout the previous section, this guide provided a toolset for the evaluator to calculate the carbon dioxide emission coefficient [gCO2/km] of the different technologies, as well as that of other pollutants such as nitrous oxides and particulate matter. The economic tool provided will allow the evaluator to allocate a price to the carbon emissions [$/tCO2] of the different technologies and evaluate the impact of this on the fleet economic performance. This will also allow the evaluator to calculate the cost of abatement of CO2 emissions of the different technologies compared to the reference diesel fleet.

INFLATION AND PRICE ESCALATION INDEXES

Inflation accounts for the effects of price escalation with time. Normally when systems have a long-life duration the analysis is done in constant dollars (i.e., no inflation rate is applied) to avoid the distortion caused by many years of inflation. However, given that fuel escalation is very relevant to this analysis, different escalation indexes are available for the evaluator to analyze the impact of price escalation on the LCOT of a given fleet. This includes:

- FOM and VOM escalation indexes;
- Fuel/electricity escalation index;
- Ticket price escalation index;
- Additional revenue (subsidy) escalation index; and
- Carbon pricing escalation index.

Unless required, it is recommended that only fuel/electricity price escalation indexes are included in the evaluation as part of the sensitivity analysis in the following section. Volatility of liquid fuel prices is normally independent of the overall expected inflation rate of a given country and may be paramount to understanding the projected cost of conventional diesel vehicles.

FIXED CHARGES

These are charges that are incurred from the moment the fleet and charging infrastructure are placed in service until they have been fully depreciated. They include the following components.

Depreciation

This is the method by which companies allocate the cost of a tangible asset over its useful life. For tax purposes, businesses can deduct the cost of these assets as business expenses. The period over which the total cost of the plant is reclaimed as well as the portion claimed over each year is determined by the government. This means that in certain cases the tax life of an asset can be shorter than its book life. The base line for this study is that the book life and tax life of the transport system are assumed to be equal and equal to the vehicle life. However, as mentioned in the pertinent section below, the provided tool allows for the evaluator to use different asset depreciation schedules such as 5- or 7-year modified accelerated cost recovery system (MACRS) depreciation schedule. The evaluator can also assume a short-term linear depreciation schedule. Of course, this will only be relevant if the local tax authority allows for such methods. Depreciating assets faster will benefit capital intensive fleets such as electric and hydrogen fueled systems as this will allow for a higher free cash flow in earlier years of operation, making the business opportunity more attractive and less risky for investors.

Equity return

When part of the transport system initial investment is financed through equity, by selling ownership in the form of stock, the stock owners are entitled to an equity return. This return is only applied on the unamortized investment (i.e., the part that has not been depreciated).

Interest on debt

When debt is acquired to finance the initial investment, an interest rate must be paid to the financing body. As with equity returns, this rate is only applied to the unamortized investment.

Income taxes (IT)

The income tax rate is imposed by the government. The tax is calculated by multiplying the taxable income by the income rate. The taxable income is set by the overall income of the transport system, minus deductibles. These include tax depreciation, interest on debt and the systems total (i.e., fixed, variable and fuel) operating expenses.

Incentive programs

Incentive programs such as government tax credits, investment tax credits, loan guarantees and others are sometimes used to facilitate the uptake of a given technology. As mentioned above the current tool allows the evaluator to assume MACRS schedules, incorporating a carbon price and/or allocating a government subsidy to a given technology. Of course, it is highly recommended that either of these tools is only used if local conditions enable them.

ANNUAL PASSENGERS TRANSPORTED (PT)

The overall passengers transported each year by the fleet (pax/year) is calculated as the passengers per km per vehicle estimated, times the km travelled per day, times the days of service throughout the year, times the fleet availability factor. The fleet availability factor is the percentage of the fleet that covers the nominal mean distance of the service. Different technologies may have different availability factors as the need for maintenance, reserve buses or additional buses may differ from one technology to the next. Although establishing the required additional fleet is a more thorough analysis than that presented in this guide, it is recommended that, if the range of a given technology is too close or insufficient when covering the mean daily distance of the system, the evaluator should analyze the sensitivity of the fleet availability on the LCOT for that technology.

DISCOUNT RATE

The discount rate, also known as the weighted average cost of capital (WACC), is used to calculate the present value of money. It is the product of the debt rate times the percentage of debt financing plus the equity return rate times the percentage of equity financing.

5.2 Sensitivity analysis scenarios

Throughout this section, three evaluation scenarios will be proposed for the evaluator to analyze not only the economic performance of the different technologies, but also their sensitivity to changes in different variables. It is strongly recommended that the evaluator modify the scenarios based on local economic conditions and realistic parameters, while maintaining the goal of the different scenarios. Also, the evaluator is encouraged to analyze the impact of having a bigger modal shift from private vehicles to buses when implementing clean technologies compared to conventional diesel vehicles. There is currently little well sourced literature regarding the modal shift incurred by the implementation of electric or hydrogen vehicles compared to conventional fleets, but one can compare how many more passengers would be required to offset any potential increase in bus fare when implementing these technologies.

REFERENCE SCENARIO

This scenario should replicate current conditions of the public transport system in the evaluated location. Results of this scenario will be used to establish a baseline to which results from other scenarios will be compared against. Additionally, results attained in this scenario for the conventional diesel fleet will be used as the baseline for all comparison. The proposed economic and financial parameters are detailed in Table 26.

Table 26. Financial and economic assumptions proposed as reference scenario

Reference Scenario						
Financial/Economic Assumptions						
	Diesel	Hybrid	N. Gas	Biofuel	Electric	Hydrogen
Debt Conditions						
Debt percentage	70%	70%	70%	70%	70%	70%
Debt rate	17%	17%	17%	17%	17%	17%
Debt term (years)	5	5	5	5	5	5
Cost of equity	12%	12%	12%	12%	12%	12%
Weighted average cost of capital (discount rate)	15.5%	15.5%	15.5%	15.5%	15.5%	15.5%
Asset Depreciation Terms						
Book life (years)	10	10	10	10	10	10
Depreciation basis	100%	100%	100%	100%	100%	100%
Annual depreciation rate (%)	10%	10%	10%	10%	10%	10%
Vehicle end-of-life value (%)	20%	20%	20%	20%	20%	20%
Price Escalation Indexes						
Ticket price escalation						
Fixed O&M escalation						
Variable O&M escalation						
Fuel/electricity escalation						
Additional revenue/subsidy escalation						
Clean Tech Incentives						
Investment tax credit	0%	0%	0%	0%	0%	0%
Price of CO2 ($/T)	$ -	$ -	$ -	$ -	$ -	$ -
Additional revenue/subsidy ($/pax)	$ -	$ -	$ -	$ -	$ -	$ -
Taxes						
Income tax rate	35%	35%	35%	35%	35%	35%

The scenario is based on current bus purchase schemes applied in some countries of Latin America such as Argentina and Brazil. Under these conditions, the operators pay 30 percent of the vehicle price upfront and contract a debt from the vehicle dealership for the remaining 70 percent to pay back over the first five years of vehicle operation. This scenario has a high weighted average cost of capital (WACC), which is not beneficial for high capital cost technologies, such as electric or hydrogen FC buses. Given that the analysis is done in US dollars, a price escalation rate of 2 percent is assumed for all expenses and revenue streams. Finally, the scenario does not include any clean technology incentives.

HIGH VOLATILITY FOSSIL FUEL SCENARIO

The only change in this scenario compared to the reference scenario is that the fuel price escalation index for fossil fuels is higher than that of other energy vectors (Table 27).

Table 27. Fuel/electricity price escalation index in a high fossil fuel volatility scenario

High Volatility Fossil Fuel Scenario						
Financial/Economic Assumptions						
	Diesel	Hybrid	N. Gas	Biofuel	Electric	Hydrogen
Fuel/electricity price escalation	5%	5%	3%	2%	2%	2%

GREEN FINANCING SCENARIO

In addition to the fuel prices escalation indexes of the previous scenario, this scenario tries to replicate the impact that accessing "green" loans (low interest-long term) would have on the LCOT of low emission technologies (electric, biofuel, hydrogen and hybrid).

Table 28. Green Financing Scenario

Green Financing Scenario						
Financial/Economic Assumptions						
Debt Conditions	Diesel	Hybrid	N. Gas	Biofuel	Electric	Hydrogen
Debt percentage	70%	90%	70%	90%	90%	90%
Debt rate	17%	5%	17%	5%	5%	5%
Debt term (years)	5	5	5	5	5	5
Cost of equity	12%	12%	12%	12%	12%	12%
WACC (discount rate)	15.5%	5.7%	15.5%	5.7%	5.7%	5.7%

Photo: Electricity filling station for charging row electric buses at the final stop of the city route. iStock.

CHAPTER 6

Cost-Benefit Analysis

Using the information and results generated in the previous sections, in this section the cost-benefit analysis of the different technologies will be performed. For this, the cost effectiveness of emission abatement will be calculated. The latter is defined as:

$$CE_x = \frac{LCOT_x - LCOT_{ref}}{T_y/pax_{ref} - T_y/pax_x} \left[\frac{US\$}{T}\right],$$

where the subscripts ***x*** and ***y*** denote the technology and emission being analyzed and ***ref*** denotes the reference technology to which clean technologies are being compared. Therefore, the cost effectiveness of applying technology ***x*** on mitigating emission ***y*** is defined as the increase in the ***LCOT*** incurred by implementing technology ***x*** compared to the reference technology, over the passenger specific emission ***y*** reduction induced by implementing technology ***x***. The T_y/pax_x can be easily calculated as the T_y/km of the vehicle over the pax/km of the service.

As a result of this analysis, the cost effectiveness of implementing the different technologies to mitigate different emissions under the various financial scenarios should have been calculated to complete the tables below.

Reference Financial Scenario			
Tech/Emission	[US$/tCO2]	[US$/tPM]	[US$/tNOx]
Electric			
Hydrogen			
CNG			
Biodiesel			
Hybrid Diesel			
Diesel E VI			

High Volatility Fossil Fuel Financial Scenario			
Tech/Emission	[US$/tCO2]	[US$/tPM]	[US$/tNOx]
Electric			
Hydrogen			
CNG			
Biodiesel			
Hybrid Diesel			
Diesel E VI			

Green Financial Scenario			
Tech/Emission	[US$/tCO2]	[US$/tPM]	[US$/tNOx]
Electric			
Hydrogen			
CNG			
Biodiesel			
Hybrid Diesel			
Diesel E VI			

Photo: Public bus at Granville Street Bridge in downtown Vancouver. iStock.

CHAPTER 7

Results and Risks Evaluation

Throughout this document, the considerations that a preferability evaluation of clean bus technology implementation must include have been discussed and, when possible, quantified. In the following section, potential results will be analyzed, and the potential risks inferred by them will be discussed, to ultimately provide the evaluator with a clear-cut tool to establish if a given technology merits a feasibility analysis or if at this stage it is fair to discard it as an option until local conditions mature and favor its implementation.

7.1 Enabling conditions results and risks evaluation

Throughout Chapter 2, the enabling conditions for the implementation of the different technologies were analyzed and, when possible, quantified. It is very important for the evaluator to understand that the more developed these enabling conditions are, the higher the certainty of the values assigned to the input parameters, and thus the higher the fidelity of the obtained results and overall evaluation. The more assumptions needed, the higher the uncertainty and therefore the higher the risk of project failure.

LOCAL CONTEXT RESULTS AND RISKS EVALUATION

Tables 1 and 2 provide a series of questions for assessing the local context and policies in place that support the introduction of clean transport technologies. By combining the results, it is possible to establish if the current initiative is a standalone project, part of a growing agenda, or an established local agenda.

Table 29. Clean transport local context evaluation matrix.

	TABLE 1, SCORE 0-3	TABLE 1, SCORE 4-6	TABLE 1, SCORE 7-10
TABLE 2, SCORE 0-3	STANDALONE PROJECT	STANDALONE PROJECT	GROWING AGENDA
TABLE 2, SCORE 4-6	STANDALONE PROJECT	GROWING AGENDA	ESTABLISHED AGENDA
TABLE 2, SCORE 7-8	GROWING AGENDA	ESTABLISHED AGENDA	ESTABLISHED AGENDA

Standalone project

As shown in the table above, if a question has a low score followed by a medium score, it can be concluded that the current project resembles a standalone endeavor or that it is one of the first initiatives in terms of clean transport projects undertaken by the jurisdiction. This is not necessarily a dealbreaker, as there is always a first project or initiative from which to grow. Moving forward will depend on the scores attained during project planning scores (Table 3) and the different technologies in Table 4. It should be noted that the lower the established local support and backing of a clean transport agenda is, the higher the possibility of project failure, due to future changes in local political support, lack of budget, changes in government priorities, etc. Therefore, the project will develop in a high risk and unstable environment. This is a growing concern for the most novel technologies such as hybrid, full electric and hydrogen buses.

Growing agenda

If the overall score attained in either table is medium or high in one and low in the other, it could be established that although it is still not a mature agenda, there is explicit and measurable support for the clean energy and transport initiatives. This will enable a deeper discussion with local authorities and pinpoint established and lacking items of the agenda. Also, the evaluator will be able to access useful information from past experiences, which will help reduce uncertainties and thus identify specific risks and risk mitigation strategies. Of course, having some local support is good but will not ensure project success. Additional information from Tables 3 and 4 is still required to move forward and identify which technologies are most appropriate.

Established agenda

If the overall score attained in both tables is high or high in one and medium in the other, it means that the clean transport agenda is mature and has strong backing by local authorities and residents. This is a very encouraging start, as local information regarding ongoing projects related to clean transport should be available, there is a recurrent approved budget to back these initiatives, the government is actively working on improving the quality of the public transport system and local citizens back the overall endeavor. All of this helps reduce project risks not only because there will be tangible local information related to the operation of related systems, but also because as the agenda matures and local residents appreciate the benefits of clean sustainable transport systems, they become strong supporters of these and will allow for greater flexibility in terms of cost and short term performance. Also, although this is not certain, the higher the score attained in this section the higher the provability of higher scores in Table 3 and in at least for one technology in Table 4.

PROJECT PLANNING OUTLOOK AND RISK EVALUATION

Planning is by definition a method for reducing risk. The higher the level of planning and project analysis, the higher the degree of certainty on project requirements, and therefore, the lower the risk of project failure. Table 3 provides 6 questions to help assess the level of project planning done up to this stage. As mentioned above, having certainty about the transport system requirement helps narrow down system parameters and make informed assumptions when information is lacking.

Similar to what has been done for the local context evaluation, the level of prefeasibility project planning is established as follows:

- Table 3 score ≤ 2: insufficient planning.
- 2 < Table 3 score ≤ 4: average planning.
- 4 < Table 3 score ≤ 6: adequate planning.

Moving forward and evaluating the different technologies under unknown operating conditions may lead to:

- Underestimation of system requirements.
- Underestimation of technical requirements of the fleet and charging infrastructure, which poses an increasing risk for the proper assessment of capital-intensive technologies (electric and hydrogen). Underestimating the required range and expected specific energy consumption and subsequent range per charge of these technologies may result in a misleading technical viability result, which will in turn put the entire technical and economic viability of the project in jeopardy.
- Also, given the lower versatility of some clean bus technologies compared to conventional buses and the higher depot space required for the charging infrastructure, not knowing the location of the terminals and the available space could pose a significant operational problem which may halt the entire endeavor.

All of the above, in combination with a low to medium local context support score, will certainly result in unmanageable and unacceptable risk of project failure that will jeopardize the entire public transport system. Therefore, at this stage, it is worth noting that, if the overall evaluation so far has attained a combination of low and medium scores for both the local context and project planning evaluations, it is difficult to assume that the prefeasibility analysis performed will produce reliable results. Also, answers to questions in Table 3 are required to perform the analysis suggested in these sections and it is therefore strongly advised that before addressing the technical, environmental and economic evaluations, proper project planning is undertaken to answer all questions in Table 3.

7.2 Energy vector and vehicle market availability results and risks evaluation

Differently to the results analyzed in the previous section, which are technology independent, this component seeks to establish the availability of the different energy vectors present in the region/city of interest, as well as that of the commercial availability of the buses they power. To do this, Table 4 provides specific questions related to the availability of the different energy vectors and their related clean bus technology. These go from more conventional solutions, such as Euro VI diesel buses and ultra-low sulfur diesel required to power these, all the way to availability of a hydrogen supply and fuel cell buses. The results of these evaluations will help discard technologies and energy vectors that are currently not available in the location of interest.

Table 30 combines results of a given energy vector and the required bus technology in a two-entry table as done in section 7.1. By doing this, it is possible to assess the overall viability of introducing a given bus technology and the level of technology readiness.

Table 30. Energy vector and clean bus technology availability

	Energy vector score =0	Energy vector score =1	Energy vector score =2	Energy vector score =3
Vehicle market score =0	Bus Technology Not viable	Bus Technology Not viable		
Vehicle market score =1	Bus Technology Not viable	Bus Technology Viable for pilot scale project	Bus Technology Viable for pilot scale project	
Vehicle market score =2		Bus Technology Viable for pilot scale project	Bus Technology Viable for pilot scale project	Bus Technology suitable for scale implementation
Vehicle market score =3			Bus Technology suitable for scale implementation	Bus Technology suitable for scale implementation

In contrast to Table 29, some conditions in Table 30 are self-excluding and present an untenable situation. For example, there cannot be CNG buses in a city if there is no natural gas distribution network in the country of interest.

Bus technology not viable

If a given energy vector scores 0, this means that there is either no reliable infrastructure or no distribution network in the region to supply this fuel/energy source. On the other hand, if the vehicle market evaluation scores 0, it means that there is no company or subsidiary offering that technology. In both cases, it is concluded the pertinent bus technology must be discarded as a whole, and should not even be considered for a pilot project as part of the larger fleet.

The reason behind this is that when either of the above conditions is present there are considerable uncertainties related to:

- Unit cost of energy source, vehicle unit and charging infrastructure.
- Certification or homologation procedure of vehicle and energy infrastructure will be weak and underdeveloped.
- Timeframe for vehicle import and energy source infrastructure or logistics deployment is unknown.
- Vehicle maintenance and support is nonexistent in the country, posing a high technical risk for the project's medium term success.
- Vehicle retail presence and support is unclear.

Therefore, based on the above, before considering the relevant technology for any kind of deployment, considerable work needs to be done on establishing the required market conditions and investment to build upon a reliable energy and vehicle market.

Bus technology viable for pilot scale project

This is an intermediate condition where both the energy vector availability or the bus technology availability score 1 or 2. In any case, this condition states that there is at least a reliable energy/fuel distribution system at a national level and that bus manufacturers and/or importers are interested commercializing the relevant technology. Of course, as shown in the table above, the level of certainty grows as the score of each requirement gets higher. There are three sublevels of certainty:

- Both scores are 1: This means that, although the energy vector is available, it has not been used in transport applications. Therefore, standards and regulations are probably not in place and infrastructure and fuel/energy cost of delivery and conditions are uncertain. In terms of the vehicle market, the infrastructure is incipient and probably nonexistent. Again, this probably means that the vehicles' standard requirements, costs, maintenance, and post-sale services are very weak or nonexistent. Therefore, proceeding with a system prefeasibility analysis at this stage is not recommended. The evaluator should recommend, based on previous scores attained in Section 7.1 (Enabling conditions and results and risks evaluation), and if conditions merit, proposing a small initiation pilot project or scrap technology until both the energy and vehicle markets mature.
- One score is 1 and the other 2: This condition implies that either the transport market or the energy vector logistics and distribution system are more established. Independently of which of the two requirements has attained a higher score, this is a clear improvement compared to the previous scenario. There should be a higher degree of certainty related to system costs and the application of the energy vector to transport applications, even if it is in the light duty sector. This would imply that standards and regulations are in place and that the vehicle market is somewhat developed. Under these conditions, unless scores in previous evaluations are very low, it is fair to say that although the technology does not merit a preferability evaluation to be used as the main bus technology of the BRT system, conditions would support a pilot test of a few units operating as part of the overall BRT fleet.
- Both scores are 2: If both the energy vector and bus market availability score 2, it means that the energy vector is being used for general transport applications and that the relevant buses are present in the national market. This is a borderline condition, which could merit including the technology in the prefeasibility analysis or not, depending very much on the overall scores attained so far and the level of standards and regulations identified in Section 2.4 (Standards and regulations requirements). Also, the evaluator must consider the size of the local market, the relevance of the local experience and the applicability of the latter to the city of interest. For example, if the evaluation is taking place in a city north of Brazil, and the evaluator is focusing on CNG buses, which are present in the country but in a city 2,000 kilometers south of the city of interest, where topographic and operating conditions are completely different, then it is fair to say that these experiences are not relevant to each other. If, in addition, the city of interest has a natural gas grid and supplies are currently available but not reliable, then it is safe to say that the technology should not be evaluated further. On the other hand, if the local experience is relevant, then the evaluator could decide to include the technology in the broader evaluation. The existence of national transport applications of the relevant technology will help acquire relevant information related to cost, performance, post-sale market, and access to several vehicle

retailers, thus narrowing down potential uncertainties. Therefore, under these conditions, it is a safe to say that even if the evaluator decides to exclude the technology as an option for the BRT system, he should recommend that, if local authorities remain interested in this technology, the latter merits a proper pilot project.

Bus technology suitable for scale implementation

If either the energy vector or the vehicle market availability scores 3, it means that there is relevant and current information available regarding the performance of the relevant bus technology as well as the value chain of the energy vector. Under these conditions, the evaluator should be able to acquire most of the required information with a given degree of certainty to move forward with the prefeasibility evaluation of this technology.

7.3 Standards and regulations requirements

As mentioned in the pertinent section, given the different level of maturity and the different nature of the different technologies, considerations and international standards and regulations are very different for each vehicles. However, Table 5 provides the evaluator guidelines of the different standards and regulations used in the different international markets. Based on these and the local established requirements, it is possible to establish if standards and regulations for the different technologies are:

- on par with international practices;
- under par but being developed; or
- under par and not on the agenda of local authorities.

Having proper standards and regulations related to vehicle safety and fuel/energy infrastructure and handling is essential to reduce implementation and operation risks related to safety, durability, quality, maintenance, and performance, both technical and environmental. However, if for whatever reason these standards are not in place, this is not a dealbreaker, as long as the evaluator recommends local authorities start working on implementing the lacking regulations, and makes sure that these are explicitly required in any purchase, tender or contract undertaken during project execution. It goes without saying that the lower the level of standards and regulations in place, the higher the risk of the project.

7.4 Technical prefeasibility analysis results and risk evaluation

Based on the analysis so far, the evaluator must have a good idea of the local context in which the project is being developed, identified weakness in project planning and discarded the clean bus technologies that are not a viable option due to the lack of the energy vector required or a nonexistent or incipient bus market. Furthermore, for the technologies that have made the cut, the evaluator must have evaluated the necessary standards and regulations required for a safe and stable implementation of these and identified areas where local regulations are insufficient or nonexistent.

Moving forward with the evaluation, throughout Chapter 3 of the document, a methodology was presented. The methodology made reference to incremental values used to estimate the specific energy/fuel consumption of the different technologies operating under present conditions that resemble those of the future transport system. The specific energy/fuel consumption of the different vehicles is an important input for both the environmental and economic evaluations undertaken in Chapters 4 and 5 of this guide, but it is also key to establish the expected range per charge of the different technologies.

VEHICLE RANGE AND OPERATION RISKS

For all technologies, other than rapid charge electric vehicles, comparing the calculated Range_n to the required daily distance of the system will help evaluate the capability of the different technologies to cover the daily distance of the required routes. In other words, if the expected vehicle range is higher than the operating range (Range_n >Range_operation) required by the system, it is then safe to say that the required fleet to cover the system's needs will be similar in size to that of a conventional diesel fleet. In the case of fast charge electric buses, vehicle range must be compared to route length, given that it is assumed that these vehicles will charge once per trip.

If a given technology cannot cover the required daily distance of the system, or in the case of rapid charge (RC) electric buses, the route distance, additional charging events will be required. Of course, this is possible, but understanding the impact on the service schedule or reserve fleet requires a more detailed analysis which is beyond the scope of this evaluation. However, a few pointers are provided for the evaluator to assess the risk of incorporating a given bus fleet.

Biodiesel, hybrid, and LNG buses have a comparable or larger range than a conventional diesel bus, with refueling times that are also very similar. Therefore, the technical capability of these buses of covering the system requirements with at least the same fleet as that of conventional diesel buses should not be a problem. In the case of the LNG engine, maintenance could be slightly higher than that of the conventional systems and therefore an additional reserve fleet of up to 5 percent could be required. This should be discussed with the bus manufacturer. It is very important to establish a realistic fleet size as this will be one of the main inputs for the economic analysis.

CNG and hydrogen fuel cell buses could have a lower range than a conventional diesel bus. However, refueling times are similar to those of a conventional fleet and, therefore, if proper planning is undertaken, no additional fleet should be required in addition to that necessary for longer maintenance periods in the case of the CNG fleet. Again, this should be discussed with the bus manufacturer.

Given the limited energy capacity of batteries, compared to conventional diesel vehicles, and the relatively long charging times **of slow charge (SC) electric buses** (two to four hours), if the bus cannot cover the required daily distance of the system on the operational capacity of the battery, then additional charging events during the day will be required. If the system has a constant dispatch schedule throughout the day, then additional vehicles will be required to cover the system compared to a conventional diesel fleet. If the bus dispatch schedule has peaks in the morning and afternoon and a valley during midday, then a secondary charge could be performed during this time, reducing the need for an additional fleet. However, it is also well established that electric batteries degrade over time, meaning that vehicle range will diminish over the years, putting further stress on battery capacity requirements. Evaluating all this with a proper degree of certainty escapes the scope of this analysis, and therefore, to reduce the potential risk of underestimating the required fleet and arriving at misleading economic assessments of the technology, the following is proposed:

1. If an SC electric bus requires 75 percent or more of its battery nominal capacity to cover the daily distance required by the system, then the risk of needing additional buses to cover the system requirements increases. To quantify this risk, it is recommended that for every percent the battery state of charge drops below 25 percent, an additional 1 percent fleet is incorporated compared to the established conventional diesel fleet.
2. If the required battery energy capacity to cover the daily distance is greater than 85 percent, then at this stage the risk incurred is considered too high for the technology to be a technically viable option and should be discarded.

A final consideration that the evaluator must consider when assessing the technical viability of SC electric buses is that these will require prolonged periods of time for charging and, therefore, if the expected bus system is required to be a 24-hour service, an additional night fleet will have to be included.

In the case of **rapid charge electric buses**, the analysis is binary. If the bus cannot cover the route distance with 80 percent of the battery nominal capacity under the worst operating conditions, it can then be established that the rapid bus charge technology is not suitable for this transport system. The bigger the difference between required range and the bus operational range the safer the implementation, i.e., if the bus requires 40 percent of its nominal battery capacity, it means that it could go two times around the route before needing another charge, making it safe to assume that the technology could cover the required service with no problem.

CHARGING INFRASTRUCTURE AND OPERATION RISKS

Having a detailed layout of the bus terminals and depots at this stage of the project is not reasonable or viable, so it is very difficult to make a clear assessment of the infrastructure requirements. However, the following pointers might help the evaluator identify potential future risks.

Terminal location

In a conventional bus operation that uses diesel buses, the terminal location is not a grave concern. If the bus system is relatively old, it might be in the middle of a residential area that grows around the terminal over the years. If the system is new or relatively new, the terminal is normally located in the city periphery where land prices are low and environmental regulations more lenient. In either case this may impose future problems for the BRT fleet. If the terminal is located in the middle of a highly populated area, land availability and real estate prices and regulations might impose a restriction when it is necessary to install the charging infrastructure of CBTs.

Euro VI, biodiesel or hybrid buses: The operation of the system using Euro VI diesel or biodiesel buses as well as hybrid buses is exactly the same as with other conventional lower standard diesel buses, and therefore terminal requirement in terms of space, regulations and location should not be different to those of a conventional system.

Natural gas and hydrogen buses: Whether it be CNG, LNG or hydrogen, the regulations and restrictions imposed for facilities destined to manage and store high pressure or cryogenic fluids may impose additional restrictions for the location of the bus terminal. Also, additional space will be required for the fuel storage, gas conditioning and dispensing facilities. This will potentially result in the bus terminal having to be placed farther away from the route starting point, which will increase the off-service mileage and increase fuel consumption and required range of the fleet. In the case of the evaluated technologies, this is not a grave concern.

Rapid charge electric buses: For rapid charge electric buses to be a viable option, the bus charging infrastructure must be along the bus route, preferably at one or the other end, or the bus terminal must be close enough to the route end point for buses to be able to go to the terminal at the end of a given number of rounds and charge. This is a strong imposition and might make the use of this technology unviable posing a considerable risk for the project if not considered early on. However, if either of these requirements can be met, then the additional land requirement for the use of this technology, compared to a conventional diesel bus operation, is not considerable. On the other hand, depending on the size of the fleet, the energy consumption of the buses and the dispatch schedule, power requirements for the charging infrastructure might be considerable. More details on this can be found in the technical description annex. However, the evaluator can assume that the system will require roughly one 400 kW charger for every five to eight buses (80-50kW per bus) and that the charging infrastructure will be used throughout the day.

Slow charge electric buses: The most common suggested charging strategy for slow charge buses is to have them all charging overnight at once or in two turns, and then operate on one charge throughout the day. This poses a couple of potential risks. First, assuming that buses are charged using 100kW charging stations, the overall power to charge the entire fleet at the same time will be considerable and will only be used over a short period of the day. If the bus terminal is located in the periphery of the city, then grid stability or capacity might be a problem. Another important aspect of this is space availability. In conventional terminals, once buses have gone through the service area, they are parked tightly making an efficient use of space. If the parking area is not equipped with charging infrastructure and buses need to be moved around in this area, a significant increase in space will be required.

7.5 Environmental analysis results and risk evaluation

Like any analysis, results are only as good as the inputs considered. Therefore, establishing realistic local conditions and inputs is crucial to make a realistic environmental analysis of the different bus technologies.

GREENHOUSE GASES BUS EMISSIONS

Establishing the direct GHG vehicle emissions (tank-to-wheel, or TTW, emissions) is normally not complicated, as it is directly related to the carbon footprint of the fuel, the bus specific energy consumption and the distance covered. Therefore, if a proper estimation of the bus specific fuel consumption under local operating conditions has been performed (Chapter 3), vehicle direct emissions should be straightforward.

The uncertainty in this type of analysis lies in establishing the indirect vehicle emissions (well-to-tank, or WTT, emissions) originated when producing, transporting, and conditioning the different fuels/energy vectors. Throughout Chapter 3, the evaluator was provided a tool and reference values to estimate the carbon footprint of the different fuels/energy vectors in area of interest. Here is where the analysis may produce under or over GHG emission estimations. This is especially significant for the fuel/energy vectors such as electricity, hydrogen, and biodiesel, given that almost their entire carbon footprint is related to the TTW emissions and the latter may vary in orders of magnitude depending on the feedstock and overall production process used to generate them. The TTW emissions of LNG can also show considerable dispersion as natural gas liquification is a highly energy intensive process and evaporative methane emissions could be significant if the fuel is transported over long distances or stored for prolonged periods of time.

Based on the above, the environmental performance of the different technologies may show misleading results if the WTT GHG emissions of the different energy vectors are not well established and evaluation inputs fitted to local conditions.

Therefore, if the evaluator is unsure of the precise production process of a given energy vector, it is recommended that he establishes a best and worst case scenario and analyzes both to establish the dispersion between the results and the sensitivity of these on the overall environmental performance of the relevant energy vector. If these scenarios produce very different results, then the risk of overestimating or underestimating the environmental benefits is potentially high, and results must be handled with care as they will impact the cost-benefit analysis and overall conclusions of the report.

POLLUTANT BUS EMISSION

In this case, bus direct emissions are the only source analyzed, and therefore the most important aspect of this evaluation is establishing the fleet operating conditions. It is also worth noting that pollutant emissions of all technologies with internal combustion engines, especially diesel and biodiesel engines, are highly dependent on maintenance. Therefore, while the emission intensity factors used consider vehicle age, they assume a proper upkeep of the fleet. If maintenance of these buses is neglected throughout the life of the fleet, toxic pollutant emissions may be orders of magnitude higher than those calculated in the analysis, posing a high risk to air quality indexed in the city of interest.

END-OF-LIFE VEHICLE DISPOSAL

The end-of-life vehicle disposal of conventional diesel buses is a well-known procedure. Also, while some of the vehicle components such as oil filters, and fluids like oil, brake fluid, refrigerant, etc., are considered toxic waste, their storage and final disposal is well established. Batteries, on the other hand, once disposed, are also considered a toxic and hazardous waste by the Basile Convention. However, to date, there are no recycling facilities for lithium-ion batteries, and therefore, the disposal of electric, hybrid and fuel cell vehicles might pose a considerable environmental risk.

7.6 Economic analysis results and risk evaluation

As noted above in the environmental performance evaluation, the biggest risk for an economic performance evaluation is using unrealistic or overoptimistic inputs in the analysis. If the economic evaluation of a given technology is done on solid technical and financial bases, then, even if the use of that technology results in a more expensive system, knowing this will help understand what is required and use this and the cost-benefit analysis to decide if the investment is worth doing. On the other side, if the economic evaluation shows unrealistic economic performance of a given technology and the project is approved, then the risk of severely crippling or de-financing the public transport system in the future becomes a serious concern.

So far, the evaluator has been given leads and tools to establish realistic operating conditions; to establish specific fuel consumptions; to eliminate bus technologies from the analysis based on their availability and their required energy vector in the local market; and to assess risks related to bus range, fleet size, terminal location; and to use standards and regulations to reduce safety related risks. Therefore, in order to arrive at sensible economic conclusions, the evaluator must focus on establishing realistic inputs to enter into the financial models.

ECONOMIC RISKS ASSOCIATED WITH TECHNOLOGICAL UNCERTAINTIES

In Chapter 4, reference values for the different costs concerned in the evaluation are provided. However, if the evaluated questions have attained scores that have categorized them as "**Bus Technology suitable for scale implementation**," then local values for most of the economic analysis inputs should be available. However, some of the evaluated technologies still present uncertainties that impose considerable risks to the economic outlook of the system.

Battery and fuel cell degradation

Given the maturity of internal combustion engine technologies, it is likely to operate for 10 to 15 years. As mentioned above, the main risk related to engine degradation due to lack of maintenance is linked to the increase in the level of emissions of the fleet. This is an environmental risk and a hazard to people's health, but, unfortunately, these risks are not internalized into the economic evaluation of a technology and currently do not pose an economic risk to the operation of the public transport system.

On the other hand, fuel cells and batteries used in hydrogen, hybrid, and fully electric vehicles degrade over time, and will most likely need to be replaced at least once throughout the life of the vehicle, and twice if buses are expected to operate for 15 years or if the service operating conditions are very intense. Also, both systems are expensive and represent a considerable portion of the overall cost of the bus. For example, a 350 kWh lithium iron phosphate battery typically used in a 12-meter slow charge bus could represent as much as 50 percent of the bus price. Therefore, realistic replacement costs and timeframes in the economic evaluation of the relevant technologies are a must.

Impact on hybrid buses: In the case of hybrid buses, batteries are not the primary energy storage system, but rather a buffer that helps increase the overall efficiency of the vehicle by allowing the engine to operate independently of the powertrain requirements. It allows for the use of an electric drivetrain which in turn enables regenerative braking. Also, battery systems for these vehicles are considerably smaller than for slow charge fully electric vehicles. Therefore, battery degradation will impact slow charge fully electric vehicles. In this case, battery degradation will result in an increase of vehicle specific fuel consumption, but should not hinder vehicle range, as the latter is given by the diesel fuel tank. For these reasons, the impact of battery degradation on the economic and technical performance of hybrid buses is relatively low and as a result so is the risk associated with it.

Impact on fully electric buses: In the case of fully electric buses, the battery is by far the most expensive component of the vehicle and its performance and range are directly related to the health of the system. Battery replacement not only implies a significant cost over the life of the vehicle, but also, as the battery degrades, the range per charge of the bus is reduced. This means that if this was not considered by the system in its technical evaluation, the daily distance covered by each unit will be reduced, requiring additional vehicles and personnel. All of this will have a considerable impact on the economic performance of the transport system.

Impact on fuel cell buses: As mentioned in the technology description section of the guide, fuel cell vehicles are like hybrid vehicles but use a fuel cell rather than an internal combustion engine as their power unit. However, unlike with engines, the life expectancy of fuel cells ranges from five to eight years depending on the use, purity of hydrogen used and other operation factors. As they degrade, fuel cells lose efficiency and power. As a result, both battery packs and the fuel cell will need replacing at least once over the life of the bus.

VEHICLE END-OF-LIFE VALUE

Normally, when 12-meter diesel buses operating in a formal BRT or in a conventional urban public transport system get to the end-of-life mark established by the local authority, they are sold to smaller operators of towns and villages or to others for transport applications with more lenient regulations. Whatever the case, the secondhand market for these vehicles is well established and the percentage of the original price can be included in the economic analysis with certainty.

In the case of 18-meter diesel buses, this is not necessarily the case, as the applicability of these buses is considerably more limited and their use in other BRT systems will probably be prohibited.. Therefore, their end-of-life value is more difficult to estimate. The evaluator should try to understand what the secondhand market is for these vehicles in order to reduce the uncertainty around their end-of-life value.

In the case of new technologies, the uncertainty of the vehicle end-of-life price is increased considerably, and although the initial price of these vehicles is much higher than that of diesel buses, assuming an equivalent percentage as the end-of-life price could be misleading.

There are several reasons for this:

a. There is currently not a hybrid, electric, or fuel cell bus secondhand market.

b. Players in secondhand markets normally have little to no access to financing and therefore acquiring expensive capital assets is a problem.

c. Batteries and fuel cells degrade with time and therefore the use of these vehicles in 10 years' time is questionable. Also, the likelihood that someone will purchase a 10- or 15-year-old bus that needs a new battery or fuel cell is uncertain.

d. Batteries and fuel cells are still under development; therefore, prices, performance and duration are expected to improve soon, making current models obsolete and considerably less valuable.

e. Vehicle end-of-life disposal regulations and costs are uncertain. Disposed batteries are considered hazardous waste by the Basile Convention. Therefore, electric vehicle battery disposal may become a costly procedure further discouraging a secondhand market.

It is important that the evaluator assess the impact of the above by doing a sensitivity analysis. Given that both battery/fuel cell replacement and vehicle end-of-life are events that occur in the mid- to long -term future of the project, their impact could be marginal, depending on the assumed weighted cost of capital.

ECONOMIC RISKS ASSOCIATED WITH FINANCIAL UNCERTAINTIES

Many clean bus economic analyses are excessively optimistic in terms of the financial conditions the system will attain. It is also a common occurrence that evaluators focus on the system costs rather than on both costs and revenue. In order to understand the impact that using one or another technology will have on the system fare, it is important to consider realistic costs, financial conditions, and revenue streams.

Chapter 5 proposes three scenarios as guidelines for the evaluator. However, as mentioned above, it is very important that realistic financial conditions for the location evaluated are used in every scenario put forward. Presenting results based on low interest rates, long-term debt repayment periods, etc., that are unrealistic will only raise expectations and may result in a high-risk outlook for the long-term sustainability of the transport system.

Photo: Trolleybus at Arnhem Centraal railway station in the Netherlands. iStock.

Annex: Clean Bus Technology and Charging Infrastructure

This section addresses key aspects of each vehicle technology along with its infrastructure and fleet management requirements and considerations. First, a brief overview is presented for each bus technology included in the guide. Technical characteristics are provided, and the advantages and disadvantages of each technology are presented and discussed.

In addition, a technical brief for each technology's refueling/recharging infrastructure is provided, describing not only its main components, but also the special considerations and requirements for each technology.

Technology descriptions

As mentioned above, this section provides a technical overview, describing the vehicle's main characteristics along with the basic refueling/recharging infrastructure requirements of the following technologies:

- Diesel Euro VI buses;
- Biodiesel Euro VI buses;
- Natural gas Euro VI buses (CNG and LNG);
- Hybrid diesel Euro VI buses;
- Fully electric buses (fast charge and slow charge); and
- Hydrogen fuel cell buses.

DIESEL EURO VI

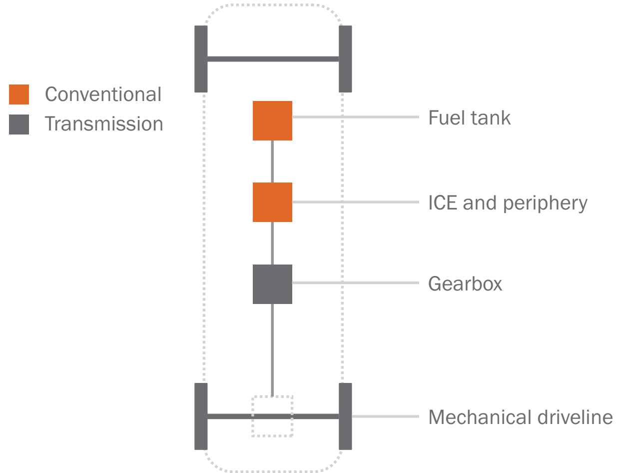
Diesel fueled vehicles are the most used technology in heavy duty transport applications, including the public transport sector. The technology has evolved to be robust and predictable with established supply lines for both fuel and vehicle components, a secondhand market, established technical and maintenance services, among others. However, diesel urban fleets are among the main sources of local toxic emissions affecting urban air quality (carbon monoxide (CO), nitrogen oxides (NOx) and particulate matter (PM)). In terms of GHG emission, while diesel buses are a source of emissions within the transport sector, it is known that promoting modal shifts from the use of private vehicles to mass transport systems can result in a considerable reduction of overall GHG transport related emissions. Therefore, given that the current guide seeks to provide insight into the benefits of incorporating low emission technologies into BRT systems, it is considered that the combination of the mass transport system together with Euro VI diesel bus technologies will result in a reduction of overall GHG and pollutant emissions of the city in question's overall transport system.

Vehicle technology

Figure 1 shows the powertrain of a conventional diesel Euro VI bus. In all regards, it is the same as any other conventional internal combustion vehicle, with the main components consisting of a fuel tank, an internal combustion engine (ICE) and its periphery (auxiliary systems), and the transmission system which is composed of a torque convertor, a gearbox, and the mechanical drive line. The main difference between a Euro VI bus and a lower standard bus lies in engine technology and the exhaust after-treatment systems, which must, based on the applied standard, result in considerably lower pollutant emissions in steady-state, transient and real drive conditions.[24]

An important aspect to highlight about the diesel conventional powertrain is its overall low energetic efficiency. This is mainly a consequence of the relatively low efficiency of the ICE (<45 percent) compared to other power units such as electric batteries and fuel cells, and the fact that all the kinetic energy embedded in the moving vehicle is consequently dissipated in the braking system, resulting in a poor overall driving energy efficiency (<20 percent in urban driving conditions) and, thus, high specific fuel consumption.

Figure 2. Powertrain of a Diesel Euro VI bus



However, the low energy efficiency of the vehicle is completely offset by the high energy density of diesel fuel (LHV = 36 MJ/L). This allows a 12-meter bus with a 200-liter fuel tank to have a range of 300 to 400 kilometers in urban driving conditions. This, coupled with short refueling times of about 5 minutes,[25] allows buses to have a high operating flexibility and high usage factors, being able to operate through a complete 18-hour working day in different bus routes without the need to refuel. Additionally, diesel buses require lower maintenance levels than other ICE technologies, such as CNG, which results in vehicles parked at depot for shorter periods of time. Thus, there is no need to consider a large reserve fleet to comply with the operation.

In terms of emissions, Euro VI standards are among the strictest emission standards for conventional vehicles to date. The standards limit toxic emissions for all conventional vehicles: passenger cars, light commercial, light duty, and heavy-duty vehicles. Vehicles complying with these

[24] https://dieselnet.com/standards/eu/hd.php#stds

[25] Nesterova, N. N., et al. "Clean buses for your city. Smart choices for cities." (2013).

standards are equipped with special systems to lower toxic emissions and require high standard fuels. In the case of diesel Euro VI buses, these systems include exhaust gas recirculation (EGR) systems, diesel particulate filter (DPF) systems, and selective catalytic reduction (SCR) systems to mitigate emissions. As a result, Euro VI vehicles can reduce from 50 percent to 90 percent of NOx and PM toxic emissions compared to Euro V standards. However, it must be pointed out that, when fueled with fossil diesel, GHG emissions generated by these buses will be comparable to those of previous standards and no appreciable GHG emission reduction will be attained.

Furthermore, noise pollution is another aspect of diesel buses that should be highlighted. Diesel engines produce high noise levels while operating, and thus diesel buses are responsible for a significant amount of noise pollution in cities. This will not be greatly improved by the introduction of Euro VI buses compared to earlier bus standards.

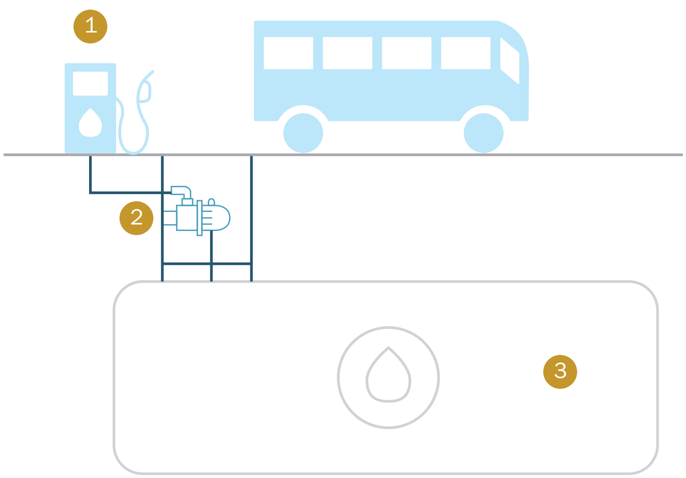
In terms of fuel supply and logistics, incorporating diesel Euro VI buses will require the use of ultra-low sulfur fuels. However, this should not result in new investments related to fuel transportation systems as these are the same as for lower quality fossil fuels. However, market availability of ultra-low sulfur diesel (ULSD<50 ppm of sulfur) must be ensured. Consequently, this may imply changes in fuel supply lines, crude oil importations, refining processes, and distribution networks.[26] The latter could be costly to set up and therefore increase the risk profile of the deployment of the technology. Also, ULSD is more expensive than high sulfur diesel fuels, which will of course impact the cost of operation of the system.

Euro VI diesel buses have a high commercial availability, given that there is a substantial number of manufacturers offering this type of vehicle. Therefore, Euro VI buses present relatively low purchase costs within CTBs (of about US$200,000 per unit for 12-meter buses).[23]

Infrastructure

Diesel Euro VI bus fleets require the same refueling infrastructure as other diesel fleets. The basic components of a diesel refueling station are shown in Figure 3 below.

Figure 3. Diesel refueling station



[26] Alves, Bianca Bianchi, et al. Green Your Bus Ride: Clean Buses in Latin America. No. 133929. 2019.

As can be seen, the main components of the refueling infrastructure are:

1. **Underground storage fuel tank:** Its function is to store the fuel for the entire fleet's operation for a certain established period. Storage infrastructure should consider avoiding mixing the ultra-low sulfur diesel fuel with other diesel types. Therefore, if different quality fuels are required, each must be stored in an individual tank.
2. **Submergible turbine pump (STP):** Delivers the fuel from the storage tank, through the dispenser into the vehicle's storage tank. It is the main active component that allows for a fast refueling process.
3. **Dispenser:** The dispenser is used to carry out the refueling process itself. The dispenser delivers the fuel through a hose into the vehicle's storage tank. It includes a user interface indicating to the user the volume of fuel being dispensed. Each dispenser can present more than one hose, which allows the user to refuel more than one bus at a time.

An important aspect of diesel refueling infrastructure is that it is already present in almost every region that manages diesel fleets. This infrastructure can be used for Euro VI buses, avoiding the need for investments in infrastructure. This also means that, if a new bus service is being deployed, and infrastructure must be built from scratch, the safety standards are probably already in place, and it is likely there will be a local company with the necessary knowhow to plan and build the bus terminals.

Summary

Table 31 below summarizes the main technical, environmental, and economic advantages and disadvantages of Diesel Euro VI buses:

Table 31. Main advantages and disadvantages of Diesel Euro VI technology

Advantages	Disadvantages
Great reduction of toxic emissions compared to previous diesel vehicle standards	GHG emissions are not greatly reduced compared to previous standards
High operating range and flexibility	Although low, still has toxic direct emissions
Short refueling time	Overall low energy efficiency
Refueling infrastructure likely already in place	High levels of noise
Technology is commercially available	Requires the availability of ULSD
Low maintenance level requirements	ULSD is more expensive than conventional diesel

BIODIESEL

As the name suggests, biodiesel technology uses a biofuel manufactured from an organic sustainable oil, the combustion properties of which resemble those of fossil diesel fuel. If produced in a sustainable and environmentally friendly manner, biofuels offer the possibility of reducing the overall GHG emissions of a vehicle's daily operation.

Biodiesel can be obtained through the processing of a variety of raw materials such as vegetable oils and animal fats. The oils most used include rapeseed, soybean, palm, and sunflower. Additionally, short chain alcohols are important components of biodiesel, used as additives, providing a higher oxygen content to the fuel and having a direct impact on emissions reduction. Alcohols such as methanol and ethanol are the most frequently used. **It is very important to stress that as for all energy vectors, understanding the life cycle of their production is crucial. For biofuels to be sustainable these must be produced in a sustainable manner. This means NO deforestation of natural forests and no burning of natural ecosystems to enable agriculture. There have been environmental disasters because of land clearing to produce biofuels. This must not be encouraged in any way.**

Vehicle technology

Biodiesel buses are either directly manufactured to work with biodiesel, or can be diesel buses, which through minor engine modifications are able to work with biodiesel blended into diesel fuel up to certain proportions. Therefore, a biodiesel bus's powertrain is the same as that of a conventional diesel bus (see Figure 1). Thus, it presents the same limitations in terms of energy efficiency.

Due to the fuel's lower energy density (around 33 MJ/L depending on feedstock), biodiesel buses present slightly lower driving ranges than diesel buses, of about 330 to 380 kilometers. However, biodiesel technology presents the same operating flexibility and versatility as diesel, with the same refueling times as the latter, which allows the technology to replace a diesel fleet completely without major concerns. Moreover, from a maintenance point of view, this technology requires a similar level of maintenance as that of diesel, only needing a more frequent change of lubricating oil, and thus there is no need to consider the addition of an extra reserve fleet.

Regarding emissions, depending on the biodiesel's blend and its production process, this technology could potentially reduce emissions of local toxic pollutants with respect to diesel, with the exception of NOx. The absence of sulfur in the fuel and the presence of oxygen causes a significant reduction of PM emissions. Regarding GHG emissions, as biodiesel is manufactured from organic sources that capture carbon from the atmosphere during their production, the net contribution of carbon to the atmosphere throughout the operation of the bus could be greatly reduced compared to fossil diesel fuels.

Nonetheless, as has been pointed out before, GHGs emissions are generated throughout the cultivation process of crops destined for biofuels' production. On one hand, nitrous oxide (NO) is generated when fertilizers are used to raise yields of crops. Furthermore, when forest lands are converted to be used for energy crop plantations, the carbon dioxide absorption of the forests is lost. In addition, organic matter in the soil breaks down, releasing carbon dioxide. All these aspects show that the production of biofuels leads to GHG emissions to a greater or lesser extent. In other words, there is a trade-off between the carbon dioxide reductions when biofuels are used instead of fossil fuels and the GHGs generated by the production of biofuels.[27] Therefore, a life-cycle assessment is necessary when analyzing the viability of this type of technology.

[27] Hanaki K., Portugal-Pereira J. (2018) The Effect of Biofuel Production on Greenhouse Gas Emission Reductions. In: Takeuchi K., Shiroyama H., Saito O., Matsuura M. (eds) Biofuels and Sustainability. Science for Sustainable Societies. Springer, Tokyo. https://doi.org/10.1007/978-4-431-54895-9_6

Regarding noise pollution, biodiesel buses have the same noise levels as their conventional diesel counterparts, and therefore, the replacement of diesel technology with biodiesel does not represent an advantage in this regard.

Infrastructure

In relation to the refueling infrastructure, biodiesel can rely on the same infrastructure as diesel (see Figure 3). However, fuel integrity is a remarkable aspect to consider when assessing biodiesel storage. Biodiesel presents high degradation rates when exposed to air and when subjected to high temperatures (nearly 40 percent degradation levels can be observed for fuels stored at temperatures of 40ºC).[28] Therefore, to maintain fuel quality at the required standard levels, a fuel recirculation system should be considered when it is to be stored for long periods of time.

Summary

The technical advantages and disadvantages of the biodiesel technology are presented in Table 32 below:

Table 32. Main advantages and disadvantages of Biodiesel technology

Advantages	Disadvantages
Potentially low GHG net emissions	Still produces some toxic direct emissions
High operating range and flexibility	Overall low energy efficiency
Short refueling time	High levels of noise
Diesel buses can be adapted for the usage of biofuels relatively easily	If no proper storage systems are used, fuel quality could be compromised
Similar refueling infrastructure as diesel	May require use of additives and higher frequency of maintenance due to oil degradation

NATURAL GAS

Natural gas is sometimes considered as a transition fuel towards future cleaner technologies, given that it represents the cleanest carbon-based fossil fuel with the lowest specific carbon emission intensity. Natural gas technology buses are divided into compressed natural gas (CNG) and liquefied natural gas (LNG) buses. Both vehicles run on the same internal combustion engines, with the main differences between the two technologies being the state of the fuel when stored. This results in very different storage, refueling infrastructure and vehicle on-board fuel storage systems.

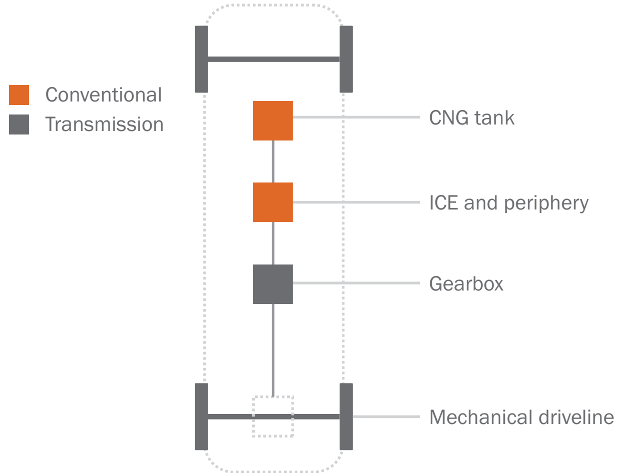
Vehicle technology

On the one hand, CNG is typically delivered by a standard natural gas distribution grid to the refueling station, where it is then compressed and dispensed into the vehicle. The fuel is stored in a compressed gaseous state inside the vehicle's high-pressure storage tank, being continuously handled in a gaseous state.

[28] Leung, D. Y. C., B. C. P. Koo, and Y. Guo. "Degradation of biodiesel under different storage conditions." *Bioresource technology* 97.2 (2006): 250-256.

A simplified CNG powertrain showing the vehicle's main components is presented in Figure 4. The powertrain is composed of a high-pressure storage tank, an internal combustion engine with its auxiliary components, and a gearbox and mechanical drive line which connect to the transmission.

Figure 4. Powertrain of a CNG bus



On the other hand, LNG is delivered to the refueling station by truck inside special cryogenic tankers in a liquified state. Once at the station, the fuel is pumped out of the tankers into cryogenic storage tanks. When the bus is to be refueled, LNG is pumped into the vehicle's onboard cryogenic tanks, which have a cooling system to keep the fuel in a liquid state. Considering Figure 4, the main difference between CNG and LNG vehicles is that the latter has cryogenic fuel tanks and a special internal cryogenic fuel handling system. Although the fuel is kept in a liquified state inside the storage tank, when the engine is running the fuel is pumped through a vaporizer before entering the combustion chamber of the engine. This means the engines of CNG and LNG vehicles operate in very similar ways. The rest of the powertrain is the same.

Both CNG and LNG buses present high operating flexibility, with driving ranges of 300 to 350 kilometers, and refueling times slightly higher than that of diesel (5 to 10 minutes). Therefore, natural gas bus technologies can comply with diesel driving requirements with no major concerns. However, as natural gas ICEs are spark ignited, they require more frequent maintenance to keep the bus in optimum working condition. Because of this, the buses need to spend longer periods of time at depot for maintenance purposes, and thus, a reserve fleet is needed to meet the operation's demand. In general, a 5 percent increase of the total fleet is enough to solve this potential problem.

Regarding emissions, natural gas has a lower carbon intensity than diesel, meaning that the fuel emits less carbon dioxide per MJ of heat release. However, given that diesel engines allow for higher compression ratios, these are considerably more efficient that natural gas engines (Diesel engine peak efficiency around 45 percent, Natural gas peak efficiency 38 percent). Therefore, TTW GHG emission reductions will depend on the operation. Also, in terms of WTT emissions, since CNG has a very simple conditioning process and compression does not require a considerable amount of energy, the WTT emissions of CNG are low. On the other hand, natural gas liquefication is a highly energy intensive process. In addition to this, evaporative methane emissions during transport and storage are inevitable due to liquid boil off. Therefore, LNG WTT emission may be considerable. As for all other energy vectors a life-cycle analysis must be undertaken to establish the overall GHG emissions of the system.

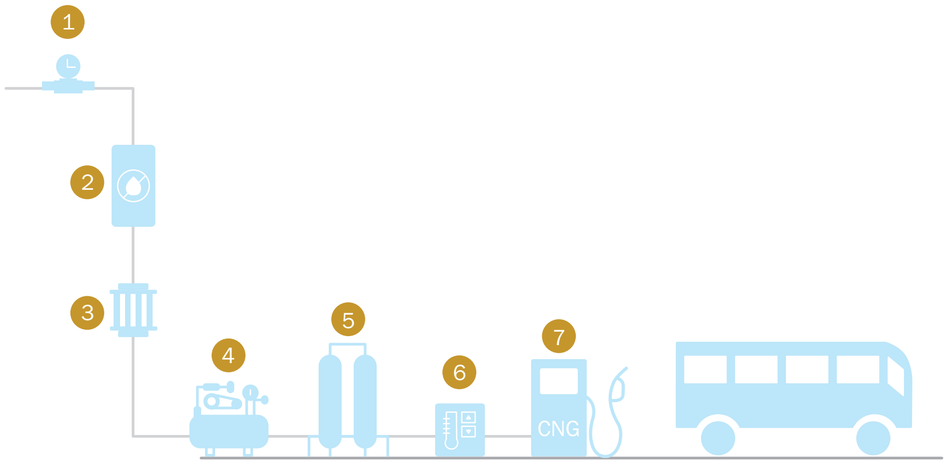
In terms of pollutant emissions, natural gas inherently emits very low PM,[29] and thus it could help improve air quality. However, natural gas engines can produce high levels of NOx, therefore, Euro VI standards should also be required to achieve results similar to those demanded for diesel Euro VI buses.

An additional benefit of natural gas engines is that, because they are spark ignited, these are considerably quieter[30] and lighter than diesel engines, resulting in a reduction of noise pollution for the city.

Infrastructure

Natural gas refueling infrastructure presents substantial differences when it comes to CNG or LNG. As shown in Figure 5, a basic CNG fast-fill refueling station consists of the following main components:

Figure 5. CNG fast-fill station



1. **Gas line:** the gas line serves as the fuel input to the CNG refueling station. The gas is delivered directly to the station through the regional gas distribution grid. The gas line is connected to the grid through a utility gas meter which measures the overall gas consumption of the whole station.
2. **Gas dryer:** the gas dryer is a crucial safety component within the system. Its function is to eliminate moisture from the gas, given that its presence within the gas could cause the formation of liquid water after the compression phase before high pressure storage. Liquid water is the precursor to the formation of corrosive compounds through combinations with components in

[29] Seungju Yoon, John Collins, Arvind Thiruvengadam, Mridul Gautam, Jorn Herner & Alberto Ayala (2013) Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies, Journal of the Air & Waste Management Association, 63:8, 926-933, DOI: 10.1080/10962247.2013.800170

[30] Milojević, Saša, Dobrosav Gročić, and Dragić Dragojlović. "CNG propulsion system for reducing noise of existing city buses." *Journal of Applied Engineering Science* 14.3 (2016): 377-382.

natural gas. When these compounds are present within the storage system, which works under a consumption-refill pressure cycle, damage and failure can result.

3. **Filter:** solid particles and contaminants present in the gas flow are retained by the filter. These particles in the natural gas can cause damage in the sealing components of the refueling station and inside the vehicle's storage tank.

4. **Gas compressor:** the compressor pressurizes natural gas coming from the grid up to the dispensing pressure.

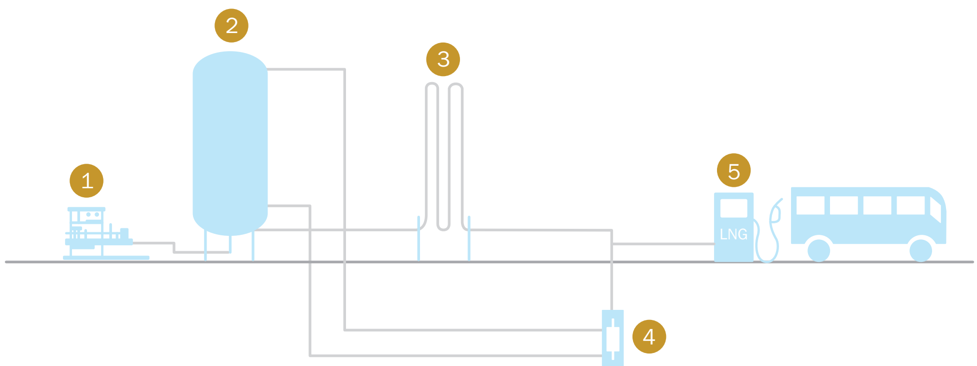
5. **Storage:** once compressed up to the dispensing pressure, CNG is stored in high-pressure storage vessels. These work as buffer systems between the compression and the dispensing processes.

6. **Regulating plant:** it consists of a sequencing and temperature compensation system which allows for the dispensing of the gas into the vehicle at the correct pressures.

7. **Dispenser:** is the piece of equipment through which the refueling process is carried out. The dispenser includes the fueling nozzle, which is handled by the user to deliver the fuel into the vehicle's pressure tank at 200–250 bar. As in the case of diesel, these devices include a user interface that allows the personnel to know the amount of fuel being dispensed.

Figure 6 displays a basic LNG refueling station layout. The main components present in this type of refueling station consist of the following:

Figure 6. LNG charging station



1. **LNG cryogenic pump skid:** it is a piece of equipment used to unload the LNG from the delivering truck into the station's storage tank.

2. **LNG storage tank:** it consists of a cryogenic tank that stores LNG at low temperature and pressure. The amount of fuel stored should be enough to supply the entire fleet's daily operation.

3. **Low pressure vaporizer:** it serves as a pressure and temperature control system to set the fuel to the required temperature and pressure before the bus refueling process starts.

4. **Submerged cryogenic pump:** a special cryogenic pumping system is used to deliver the fuel through the dispenser into the vehicle's storage tank.

5. **Dispenser:** the dispenser is used to carry out the refueling process. The dispenser includes a special cryogenic hose and nozzle used to deliver the LNG safely into the vehicle's storage tank.

Considering the above, the presence of an existing gas distribution grid is a crucial when deciding on the deployment of either technology. In the case that such distribution grid is not present in the region nor is an LNG import hub, the development of such infrastructure implies a considerable investment that may hinder the overall development of natural gas technology. Thus, this might justify the implementation of LNG infrastructure.

Summary

Table 33 below lists the main technical advantages and disadvantages for natural gas technology.

Table 33. Main advantages and disadvantages of natural gas technology

Advantages	Disadvantages
Medium to high range and flexibility for CNG and LNG, respectively	Low energy efficiency
Short refilling time	Still produces some toxic direct emissions (NOx, CO)
Little or no PM emissions	Higher maintenance requirements
Lower noise levels	Similar GHG emissions as diesel
	Bigger reserve fleet required

HYBRID TECHNOLOGY

Hybrid technology consists of the combination of two different sources to power a vehicle, being the most common the conventional-electric configuration. The latter is achieved by the combination of a battery pack with an internal combustion engine (ICE) that work together to power the vehicle. In this sense, hybrids can be used with any conventional power unit, that is, any technology mentioned above. However, to keep things simple, a hybrid diesel Euro VI vehicle will be analyzed.

The integration of an electric powertrain and an internal combustion engine allows hybrid vehicles to increase engine efficiency and apply regenerative braking. This allows for higher overall energy efficiency, and thus, for lower specific fuel consumption. This in return results in lower GHG. Also, the smart use of the ICE may result in zero toxic emissions in given areas of the city, but not along the overall route as the ICE will have to eventually start. Therefore, in order to guaranty the use of a low emission vehicle, the ICE must comply with Euro VI emission standards.

After a promising start at the beginning of the decade, hybrid technology deployment has been lagging in the international bus market. This is mostly due to the predominance of conventional diesel vehicles and the increased focus on the development of zero emissions buses,[31] such as hydrogen fuel cell buses and, more commonly, battery electric vehicles. In this sense, the fast-growing electric vehicle industry has taken a substantial portion of CTB market share worldwide (which, it must be said, is still a small portion of the overall sector).

[31] PARTRIDGE, Julius; WU, Wei; BUCKNALL, Richard. Development of bus drive technology towards zero emissions: a review. *Hybrid Electric Vehicles*, 2017, p. 33.

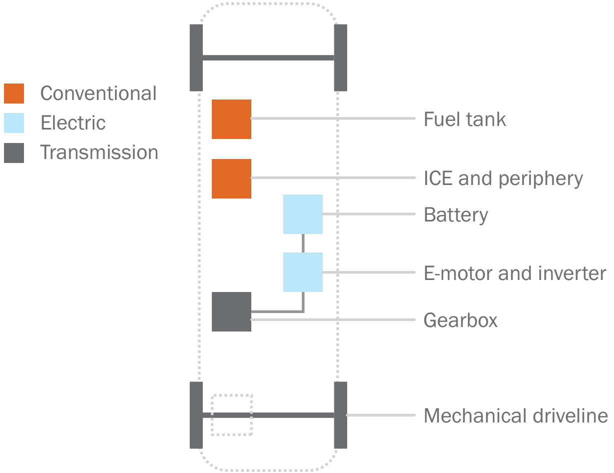
Vehicle technology

Under a hybrid configuration, the way in which each power source works depends on whether the vehicle's architecture is parallel or serial. Other architectures exist, but these two are the most common.

Parallel-architecture hybrid vehicle

Under a parallel architecture (see Figure 7), the conventional powertrain and the electric powertrain are integrated in a way that both systems can directly power the transmission of the vehicle, given that both powertrains are attached directly to it (in parallel). The conventional powertrain is composed by an ICE, and by an electric powertrain with a battery pack and an electric motor. The ICE powers the vehicle while charging the battery pack. Then, under certain driving conditions, the vehicle can run purely with electric power through the electric motor. This feature could reduce noise levels while the bus operates, and thus mitigate noise pollution to certain extent.

Figure 7. Parallel hybrid powertrain

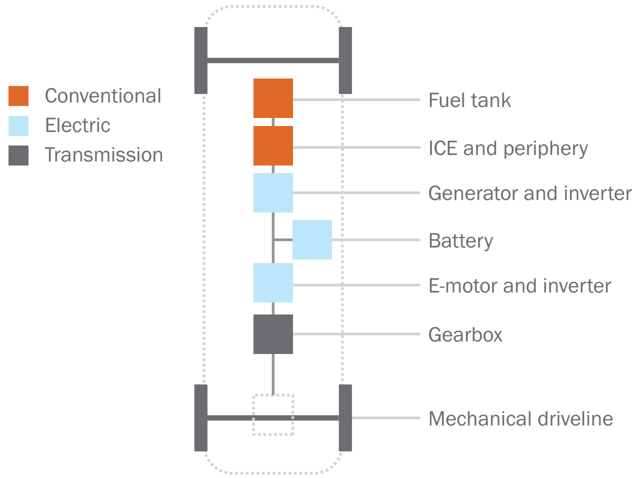


In addition, this type of architecture can reduce the overall fuel consumption of the vehicle through its regenerative system, which recovers energy through the braking events of the vehicle's operation. This attribute allows the bus to recover a certain proportion of the energy that would otherwise be dissipated through the brakes in the form of heat. The electric motor/inverter is attached to the transmission while the vehicle is braking, and thus can generate electric energy and recharge the battery to a small degree.

Series-architecture hybrid vehicle

Under a series hybrid architecture (see Figure 8), the ICE works purely as a generator, producing electricity that may go to the battery to power the electric drive or both. The engine will come online when required by the control system. The electric drive is connected to the wheels and provides power to accelerate the vehicle forward and regenerates power when braking.

Figure 8. Serial hybrid powertrain



In other words, the hybrid technology combines the best aspects of both conventional and electric technologies: the high energy density of conventional fuels with the high efficiency of the electric powertrain to generate work. Therefore, hybrid buses present driving ranges in excess to those of conventional buses, which combined with short refueling times result in high operational flexibility.[22]

Regarding GHG emissions, hybrid buses working under a serial architecture emit less pollutants than conventional buses, given that, as mentioned above, the ICE works at an optimal point of operation which reduces consumption. Also, the battery system allows the vehicle to operate purely electrically for short distances, which results in higher efficiencies, particularly under stop-and-start driving conditions.

From an infrastructure point of view, the main advantage of hybrid technology is that it requires the same refueling infrastructure as its conventional counterpart. Whether for diesel, biodiesel or natural gas, the vehicles rely on the same infrastructure to refuel. Therefore, there is no need of further investment on refueling infrastructure rather than on the vehicle itself.

As for maintenance, hybrid powertrains require similar maintenance costs as their conventional counterparts, with some possible savings regarding brake wear, given the use of regenerative braking. However, when analyzing the vehicle's full life cycle, the cost of replacing the batteries should also be considered.

Summary

Table 34 lists the main technical advantages and disadvantages identified for hybrid buses.

Table 34. Technical advantages and disadvantages of hybrid buses

Advantages	Disadvantages
High range and flexibility	Higher upfront costs
Short refueling time	Battery replacement
Higher energy efficiency	
Lower GHG emissions	
Lower toxic direct emissions (NOx, CO, PM)	
Lower noise levels	

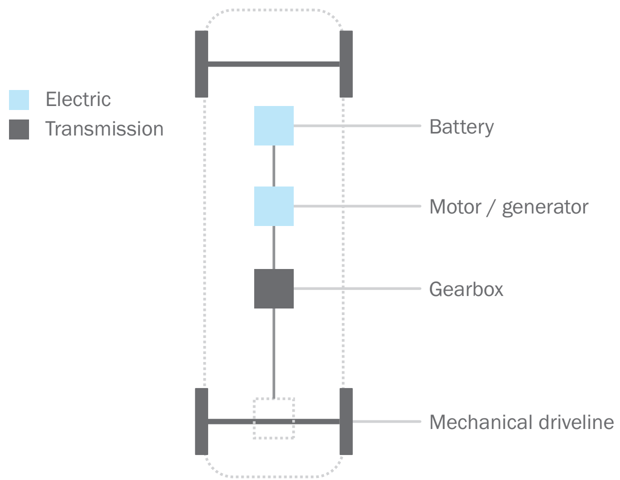
ELECTRIC

Battery electric buses (BEBs) are a still-evolving technology that has achieved great momentum around the globe over the last decade. This is mainly due to technology's capacity of reducing local pollutant emission and noise, as electric buses produce non-toxic emissions while in operation. Thus, BEBs are labeled as zero-emission vehicles. Of course, as for all other technologies, overall GHG emissions calculations must include the carbon intensity of the electricity generation network.

Vehicle technology

BEBs rely on a rechargeable battery integrated into the bus as the main energy storage device. The latter acts as the vehicle's power source, delivering energy to an electric motor that powers the mechanical drivetrain through the transmission system.

Figure 9. Electric bus powertrain



The vehicle consists mainly of a battery where electric energy is stored, an electric motor/generator, and the transmission.

BEBs can be classified as slow charge (SC) and rapid charge (RC) electric buses, according to battery charging capacity and battery recharging time. SC buses carry a large battery pack with an energy capacity (typically 200 kilowatt-hour to 350 kilowatt-hour for a 12-meter bus) ideally sufficient to provide the required range for the bus to be able to operate the entire day without the need for recharging. Due to the large battery capacities and given that these do not allow for large charging power capacities, recharge events normally take two to five hours and are carried out at the bus depot overnight.

RC buses have a smaller battery capacity (typically 60 kilowatt-hour to 100 kilowatt-hour for a 12-meter bus) but are capable of recharging in about 22 minutes. Hence, the charging process is carried out at intermediate stops, either at the passenger stopping points (opportunity charging), or at a depot between each route lap.

From an operational performance point of view, the service characteristics will determine which type of electric bus is more suitable for a given service.

In terms of environmental benefits, electric buses produce zero local toxic emissions. In terms of GHG emissions, these will be directly related to the electric grid's carbon footprint. The higher the carbon footprint, the higher the resulting GHG emissions related to the bus's operation.

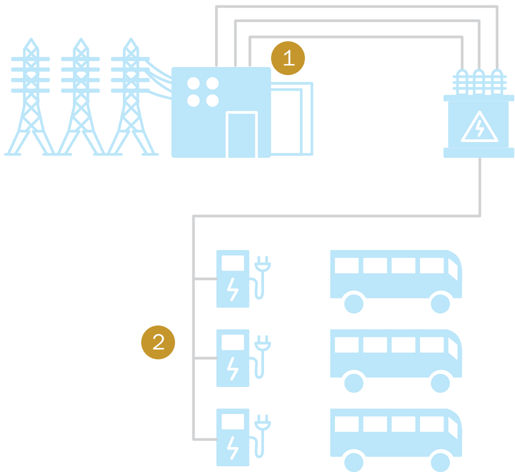
BEBs' recharging infrastructure costs do not entail a high investment compared to other technologies. This means that the technology's high cost relates exclusively to the purchase of the bus, which is a direct result of the cost of the battery. The BEB bus purchase price remains as a significant barrier to the adoption of this technology. However, the lower operating costs of electric buses could balance, under certain conditions, this high upfront cost.

Infrastructure

Regardless of the electric bus type (either rapid charge or slow charge), the basic charging infrastructure needed to operate an electric bus fleet is mainly composed of a power substation and switchgear, and electric chargers. This is shown in Figure 10 below:

1. **Power substation and switchgear:** a substation, as part of an electrical generation, transmission, and distribution system, transforms voltage for electricity consumption. It includes transformers to change the voltage levels between high transmission voltages and lower distribution voltages for final user consumption. In addition, the switchgear works as the station control unit, used to protect the electrical equipment such as the chargers. It allows to de-energize the equipment for maintenance activities to be done.
2. **Chargers:** electric bus chargers are the elements through which the charging process is done. The bus is connected manually to the charger through a hose with a standardized connector. The charging power varies depending on the required C-rate[32] and the battery technology of the bus.

Figure 10. Electric bus charging station



[32] The C-rate is a measure of the rate at which a battery is charged/discharged relative to its maximum capacity. E.g.: 1C rate means that the charge/discharge current will charge/discharge the entire battery in 1 hour.

As shown above, a charging station generally contains multiple electric chargers, given that multiple buses are charged simultaneously. This is true for both RC and SC technologies. The main difference between RC and SC technologies depends on the power capacity installed at the station, and the number of chargers needed to fulfill the operation of the fleet. In addition, the number of buses that could be managed with one charger depends on the vehicle's technology as well.

Rapid charge infrastructure

RC buses can either recharge along the route through an opportunity charging structure, or recharge at depot after each lap. Opportunity charging requires the deployment of several charging spots throughout the operating route, more specifically at the bus stops. These pieces of equipment are known as pantographs, and they allow the bus to partially charge during short periods of time while stopping at each bus stop. Pantographs operate automatically without the need of extra personnel. Additionally, given that each vehicle unit must enter operations fully charged, fast-charging chargers must be installed at depot as well. These may be plug in or pantograph chargers. Regarding costs, pantographs have higher purchase costs than that of plug-in chargers, however, they require less personnel to be operated, and therefore could result in an overall cheaper option.

For an RC structure, the electric chargers generally require high installed power capacities, given that these pieces of equipment manage high loads, of about 250 kW to 400 kW. These values depend on the required C-rate and the battery technology of the bus. With respect to the number of chargers needed, in general 1 RC charger is enough to fully supply the operation of 8 buses.

Slow charge infrastructure

Regarding SC technology, charging infrastructure is installed at depot, where the vehicles are charged overnight while parked. Taking Figure 10 as a reference, the main difference between SC infrastructure and depot RC charging infrastructure depends exclusively on the type of chargers used. In other words, SC technology makes use of chargers that handle less charging power than that of RC technology, ranging from 50 kW to 150 kW. In general, one charger is enough to supply 2 SC buses.

Summary

Table 35 and Table 36 summarize the main technical advantages and disadvantages presented in electric technology, for both rapid charge and slow charge systems, respectively.

Table 35. Main advantages and disadvantages of RC electric buses

Advantages	Disadvantages
Zero tailpipe emissions	High vehicle purchase costs
Short charging time periods	Moderately high cost of fast recharge infrastructure
Low operating costs	Short driving ranges reduce operating flexibility
Low noise levels	GHG emissions dependent on electric grid carbon footprint
Powertrain highly efficient	Depending on the location of the pantographs, there may be a risk of vandalism
Battery less susceptible to degradation and cycling	

Table 36. Main advantages and disadvantages of SC electric buses

Advantages	Disadvantages
Zero tailpipe emissions	High vehicle purchase costs
Medium driving ranges allow high operating flexibility	Considerable recharging time periods
Low operating costs	GHG emissions dependent on electric grid carbon footprint
Low noise levels	Slightly higher energy consumption than RC buses due to battery weight
Powertrain is highly efficient	Battery more susceptible to degradation and cycling

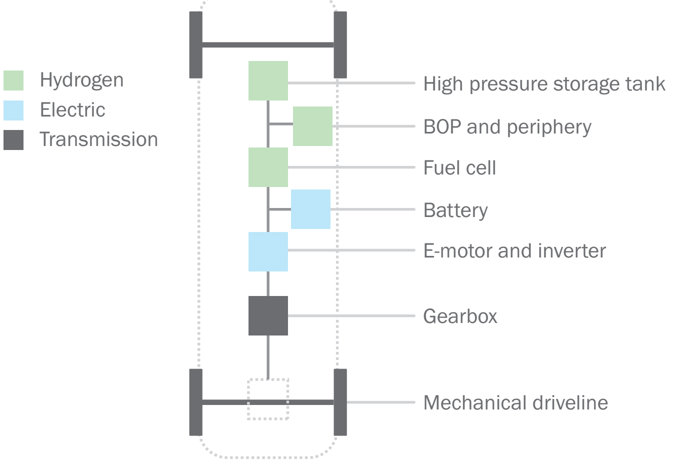
HYDROGEN

Hydrogen is considered a promising energy vector that could replace the use of fossil fuels in the mobility and transport sector in the long run. Contrary to what is commonly thought, the use of hydrogen is highly popular within the industrial sector and is produced at large scale. Today most global hydrogen production is done by reforming or gasification of fossil fuels, mainly natural gas and coal. This makes current hydrogen production a medium to high carbon intensity industry. However, significant efforts are being made to produce green hydrogen using renewable electricity in large electrolyzers. This would allow for a zero-emission energy vector to be used across the entire economy, including transport.

Vehicle technology

Hydrogen is a gaseous fuel used within electrochemical cells, known as fuel cells. Fuel cells convert the chemical energy of hydrogen into electricity. This can be then used to power a vehicle through a hybrid fuel cell-electric drive configuration. As shown in Figure 8, the main components of this serial hybrid vehicle consist of a high-pressure hydrogen storage tank, a fuel cell stack and its balance-of-plant (BOP) components (such as pumps, sensors, heat exchanger, compressor, etc.), a battery that stores electric energy, an electric motor with an inverter, and the transmission system composed of the gearbox and the mechanical driveline.

Figure 11. Hybrid hydrogen-electric fuel cell bus powertrain



The fuel cell acts as the onboard electric energy source, generating electricity both charging a small battery and powering the electric drive.

Fuel cell buses present a high operational flexibility, given by their hybrid powertrain. Hydrogen on-board high-pressure storage (of about 350 bar)[33] allows buses to reach medium to long distances on one charge (300–350 km)[34] with short refueling times of about 7–10 minutes.

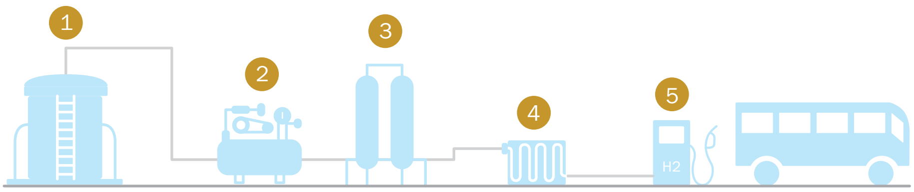
Hydrogen can be obtained through industrial processes, and then delivered to the station either compressed or liquified. Or it can be produced on site through electrolysis, and hence no transportation is needed. GHG emissions associated with fuel cell buses rely exclusively on the carbon footprint of the hydrogen production.

Regarding technology costs, fuel cell electric buses present the highest upfront costs of all the technologies assessed in this guide. This is mainly because fuel cell components are still under development and are costly to manufacture. Moreover, refueling infrastructure demands specific equipment for the handling of hydrogen, which adds to the technology's initial total cost.

Infrastructure

Figure 12 shows the layout of a hydrogen refueling station. The basic components of this type of infrastructure consist of the following:

Figure 12. Hydrogen refueling station basic components



1. **Low-pressure storage tank:** Low-pressure storage tanks help store hydrogen produced either on site or delivered to the station, holding enough hydrogen to meet the fleet operation demand. To this end, hydrogen is stored at 20 to 200 bar pressure for several days. The volume to be stored is calculated based on the number of anticipated refueling processes per day, which relates to fleet operation.
2. **Compression system:** Compressors bring the hydrogen to the pressure level needed to dispense the hydrogen. Hydrogen compression is used to overcome the pressure difference between low-pressure storage (20 to 200 bar) and refueling pressure of up to 1,000 bar. Different compressors can be used to achieve necessary compression, which are to be selected according to the design of the refueling station (capacity utilization, energy consumption, cost-effectiveness, etc.).

[33] BERGER, Roland. Fuel Cell Electric Buses—Potential for Sustainable Public Transport in Europe: A Study for the Fuel Cells and Hydrogen Joint Undertaking. *FCH JU: München, Germany*, 2015.

[34] Nesterova, N. N., et al. "Clean buses for your city. Smart choices for cities." (2013).

3. **Medium/high pressure storage tank:** Medium and high-pressure storage tanks are used to store the high-pressure hydrogen that will refuel the vehicles. These have two pressure stages: a medium pressure stage ranging from 200 to 450 bar, and a high-pressure stage ranging from 800 to 1,000 bar. The hydrogen from the low-pressure storage tank can be transferred directly to the high-pressure tank through a high-pressure compressor. Once in the high-pressure tank, the pressure is high enough to refuel the vehicle's tank. Another possibility consists in using the medium-pressure storage tank, filling the vehicle's tank until a pressure balance is reached. Then the refueling process is completed via either the high-pressure storage tank (known as cascade refueling), or through the medium-pressure storage tank using a booster compressor.
4. **Precooling system:** The precooling system aims to ensure that the vehicle's tank does not overheat during the refueling process. Since hydrogen is compressed during refueling, it heats up. Depending on ambient temperature, fuel delivery temperature and target pressure in the vehicle tank, precooling is necessary to stay within the temperature limits established in the SAE J2601/2 refueling protocol.
5. **Dispenser:** The dispenser is used to carry the refueling process, pumping the fuel into the vehicle. The dispenser includes the fueling nozzle, which delivers the compressed hydrogen into the vehicle's pressure tank at 350 bar,[35] and on the other hand, it includes the user interface, which displays hydrogen pressure and volume being dispensed.

It is important to note that, if hydrogen is produced on site, the electrolyzer should be included in the infrastructure layout.

Summary

Table 37 lists the main technical advantages and disadvantages of hydrogen technology buses:

Table 37. Fuel cell hybrid electric buses' advantages and disadvantages

Advantages	Disadvantages
Zero tailpipe emissions	High infrastructure and vehicle upfront costs
Higher energy efficiency than conventional powertrains	GHG emissions depend on hydrogen production source
Short charging time periods and high operational flexibility	New technology
Low noise levels	Low fuel cell life expectancy

[35] Adolf, Jörg, et al. "Energy of the future?: Sustainable mobility through fuel cells and H2; Shell hydrogen study." (2017).

Transport accounted for 37% of CO_2 emissions in 2021 from end-use sectors due to the highest reliance on fossil fuels[1] While it was one of the sectors most affected by the Covid-19 pandemic, emissions resumed rising as pandemic restrictions were lifted and the uptake of alternative fuels remains limited. Achieving Net Zero Scenario requires implementing a broad set of policies, including new Clean Technology Buses. This guide provides technical subsidies to assess the feasibility of incorporating alternative energy carriers and bus technologies into public transport systems.

[1] Source: https://www.iea.org/topics/transport

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