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SUSTAINABLE OIL AND GAS DEVELOPMENT IN LEBANON TRANSPORT SECTOR BUS STUDY

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COST BENEFIT ANALYSIS FOR THE USE OF NATURAL GAS AND OTHER LOW CARBO NFUELS IN THE TRANSPORT SECTOR IN LEBANON

Executed by
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1

INTRODUCTION

The use of cleaner-burning alternative fuels, such as natural gas instead of conventional diesel in public transportation vehicles is increasing rapidly. Recent statistics reveal that that 41.3% of U.S. public transit buses use alternative fuels or hybrid technology, with 16.9% using hybrid-electric technology, 16.7% using natural gas fuels and 7.4% using biodiesel (APTA, 2014). Some of the main reasons for the switch away from conventional fuels are the increasing oil prices and the environmental impacts of gasoline and diesel vehicles compared to the advantages of low-carbon fuels. This is especially true for natural gas which burns much cleaner than gasoline and diesel at relatively low price, making it an attractive alternative fuel for buses.

In Lebanon, the recent discovery potential of offshore natural gas reserves has raised interest in exploring the use of this cleaner fossil fuel in the local transportation sector. The study investigates the potential impacts of using natural gas and other alternative fuels in the Lebanese public transportation sector in terms of energy use, greenhouse gas (GHG) emissions and vehicle and infrastructure costs.

This report is structured as follows:

- **Section 2** provides an overview of the current state of mass transit in Lebanon including energy usage trends and projections in the Lebanese transportation sector.
- **Section 3** provides an overview of alternative fuel and bus characteristics considered feasible in the Lebanese context.
- **Section 4** provides a well-to-wheel (WTW) modeling and assessment of the emissions and energy use for each alternative fuel-bus technology under local driving conditions. The results of this assessment will serve as input for a cost-benefit analysis (CBA).
- **Section 5** provides a detailed CBA of the different fuel-vehicle and infrastructure options.
- **Section 6** provides an analysis of potential barriers facing the effective deployment of alternative fuel-bus technologies in Lebanon, with suggested enabling measures to overcome them.
- **Section 7** provides concluding remarks and policy recommendations.

2

THE STATE OF MASS TRANSIT IN LEBANON

The mass transit sector in Lebanon is under the jurisdiction of the Lebanese government's railway and public transportation authority known as the "Office des Chemins de Fer et des Transports en Commun" (OCFTC), also referred to as the Railways and Public Transport Authority (RPTA). The RPTA is an independent body operating under the Ministry of Public Works and Transportation (MoPWT) and consists of two directorates, the railways directorate and the bus transport directorate. The RPTA currently meets less than 3% of the total demand for public transport, operating only 37 buses on 9 routes in the Greater Beirut Area (GBA) (UNDP, 2015). This is because the majority of its rail and bus assets were damaged in the Lebanese war of 1975-1990, with much of the remaining assets out of operational service due to limited resources. The RPTA owns two bus depots located in GBA at rail yard sites, one at the Mar Mikhael station north of the GBA central business district, and the other one at the Furn el Chebbak yard south-east of the center.

Intercity bus service is assured by a number of private bus and minivan operators, some of which are licensed companies operating multiple lines with a variety of bus sizes. The remaining private operators are either intermediary companies which do not own any buses, individual owners of minibuses and minivans, or unlicensed drivers operating illegally. Approximately 4,000 of these vehicles are licensed to operate, while an estimated 8,000 operate illegally. Private operators assure service to and from a number of main public transportation hubs in GBA, namely the Charles Helou station and the Dora hub for bus service north of the GBA, and the Cola station and Hadath hub for service south of the GBA. Exclusive and shared-ride taxis assume the biggest share of road transport passengers due to the high number of these vehicles, with an estimated 33,000 licensed taxis (known as "red plates") and and additional 17,000 illegally procured and operated. However, all public transport vehicles operate with low occupancy rates of about 1.2 passengers per vehicle for taxis, 6 for vans and 12 for buses (MoE/URC/GEF, 2012).

In 2002, mass transport in GBA was estimated to serve 30% of demand for road passenger transport. This relatively low market share (compared to about 53% for typical European cities) has not seen any further development in the service network or any improvement in fuel or bus technologies. This makes public transport in Lebanon today relatively impractical compared with the attractiveness of owning a private automobile, due to an overall low quality of service in terms of network coverage and passenger comfort, and additional concerns about safety.

Also plaguing bus and taxi transportation are the absence of dedicated lanes and designated pickup/drop-off locations, and the lack of a coordinated system of operation using specified bus numbers on clearly defined routes and a fixed timetable.

On a worldwide scale of sustainable transportation (Fig. 1), the GBA ranks at the very bottom since it suffers from the same overdependence on motorized vehicles as North American cities, but without the equivalent GDP/capita. This is despite the fact that the GBA is an ideal candidate for having an effective public transit service due to the high population density across the entire city and surroundings, unlike cities with extensive urban sprawl such as North American metropolitan areas.

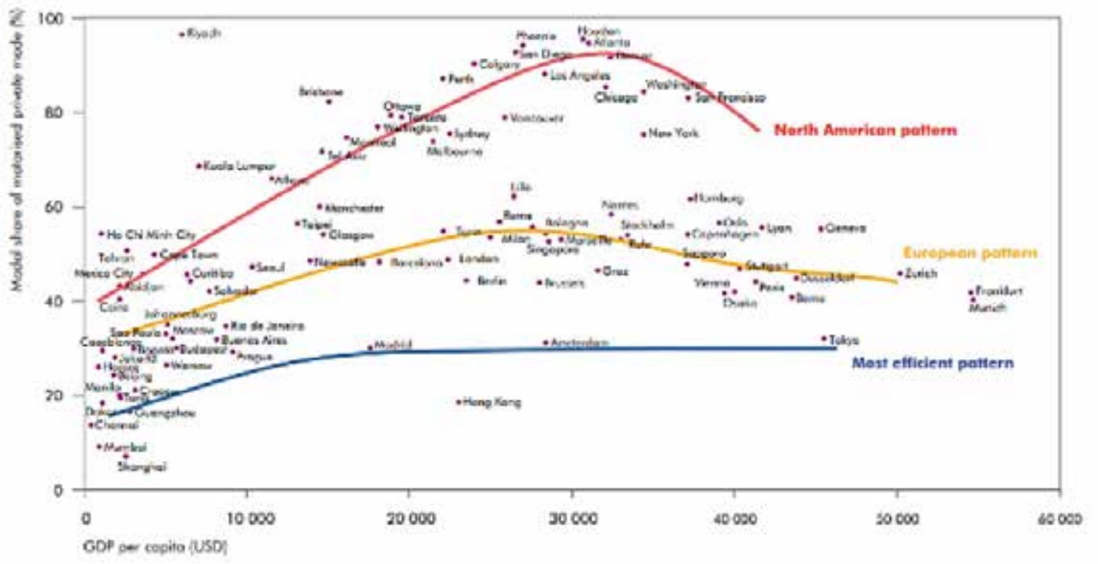

Figure 1: Modal share of motorized private mode vs. GDP/Capita (adapted).

Source: (IEA, 2008)

CURRENT STATE AND FUTURE PROJECTIONS OF ENERGY USE AND EMISSIONS IN THE LEBANESE LAND TRANSPORTATION SYSTEM

2.1

In Lebanon, road transport is the dominant mode for mobility, and passenger cars and light duty vehicles, including taxis and minivans, account for the largest share of road vehicles. Heavy duty vehicles (HDVs), namely trucks and buses, constituted only 2.4% of the total road vehicle fleet in 2010, but they nonetheless accounted for a significant share of fuel consumed in transport, at around 23% (5.6% for buses alone) of total road transport energy consumption in 2010. Non-renewable fossil fuels are the dominant energy source for road transport in Lebanon, and 99.2% of all road vehicles use gasoline and diesel fuels, with the majority of HDVs operating on diesel (Mansour, 2012), as illustrated in the fuel consumption figures in Table 1.

Table 1: Fuel consumption per transport mode in 2010.

Source: (Mansour, 2015)

TRANSPORT MODE	FUEL TYPE	LEBANON 2010 (KTONNE OF FUEL)
PC	Gasoline	1,324
LDV		280
Trucks	Diesel	361
Buses		117

A projection estimation of the growth of energy consumption in Lebanon's road transport sector up to 2040 shows a substantial increase compared to 2010 (by 13% in 2020 and 61% in 2040) (Fig. 2), which is a direct consequence of the expected economic growth and increase in transport activity. Note that the increase of energy consumption for buses assumes a revitalization of the public transport sector by 2040 in accordance with Lebanon's commitments to the United Nations Framework Convention on Climate Change (UNFCCC) under the 2015 Paris agreement's Intended Nationally Determined Contribution (INDC) (MoE, 2015).

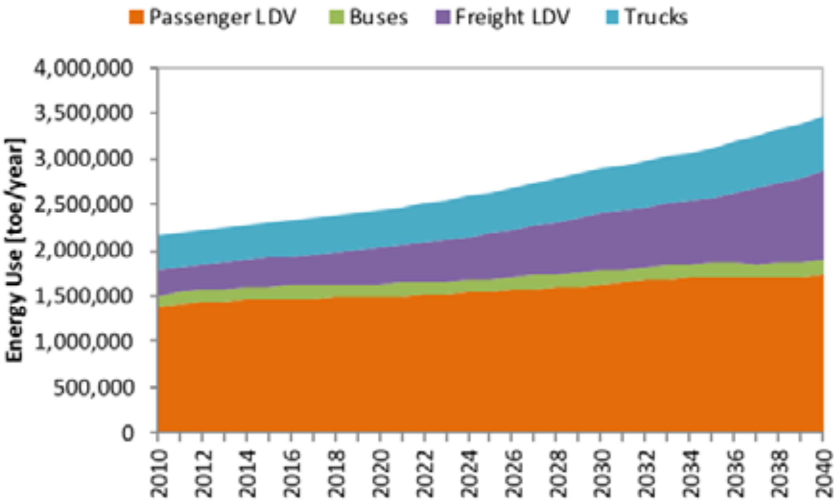

Figure 2: Baseline projection of passenger and freight energy use.
Source: (Mansour, 2015)

An estimated increase in CO_2 emissions follows closely the trend of the energy demand shown in the figure above since emissions are mostly related to fuel consumption. Transport in Lebanon currently accounts for around 23% of greenhouse gases (GHGs) and mainly from road transport (MoE/UNDP/GEF, 2016). However, buses are a relatively small contributor to the overall road transport emissions since the public transport system is currently very limited in scale and scope. Therefore, road emissions are mostly due to the growing numbers of passenger cars from 500,000 in 1994 to more than 1.2 million in 2010. Direct GHG emissions of CO_2, CH_4 and N_2O emitted from the road transport sector significantly increased from 1994 to 2010 by over 350%, with increasing trends for emissions of criteria pollutants, as illustrated in Figure 3.

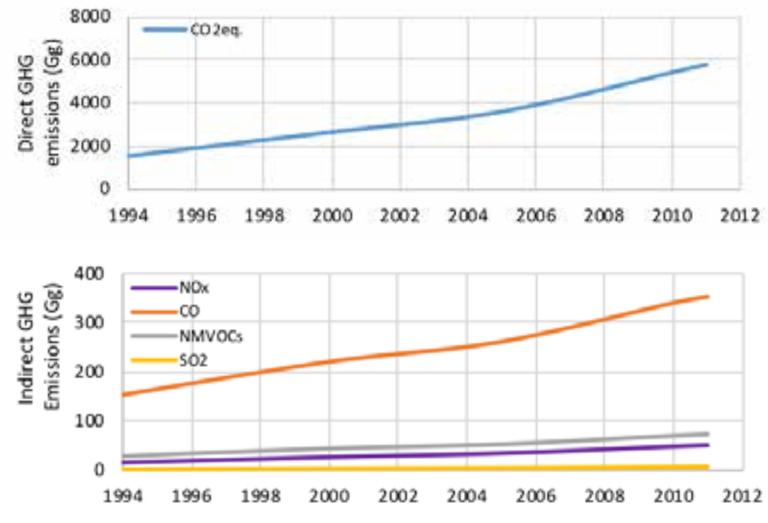

Figure 3: Emission trends for transport in Lebanon.
Source: (Mansour, 2015)

OPPORTUNITIES FOR AN EFFICIENT AND EFFECTIVE MASS TRANSIT SYSTEM

2.2

In March 2018, the World Bank approved a USD 295 million loan for the Greater Beirut Public Transport Project (GBPTP), also known as the Greater Beirut Urban Transport Project (GBUTP), which involves the launch of a Bus Rapid Transit (BRT) system consisting of 120 clean fuel buses operating along the northern coastal highway between Beirut's Charles Helou station and Tabarja north of Beirut, in addition to outer ring and an inner ring road portions inside Beirut. The system is expected to be operated and maintained by private operators under the supervision of the RPTA. The Northern BRT corridor infrastructure is 22.7 km long and follows the Northern Highway from Tabarja to Beirut (Charles Helou terminal). The alignment is a fully segregated BRT median lane (one BRT lane per direction) with 27 central stations and an average distance of 860 m between stations. Inside Beirut, a 20 km outer ring road would be used following the existing center ring road where the buses run on a reserved median lane with 19 central stations. The main BRT alignment is shown in Figure 4. Additional plans are to extend the BRT system south to Jiyeh in the future.

Figure 4: Proposed main BRT alignment.
Source: CDR (2017)

In addition, a 2013 study by the MoPWT's directorate general of land and maritime transport (DGLMT) has proposed comprehensive plans for restructuring and expanding the public transportation system in GBA under the pilot project "Revitalization of Public Transport in Greater Beirut" whereby an intercity network of 20 bus routes was identified (Fig. 5), along with 13 trunk bus routes in the GBA (Fig. 6). This project would involve the construction of a total of 911 new bus stops and 3 main terminals, and the acquisition of 250 buses, along with a telematics system to manage the coordinated operation of these assets. The combined GBA and intercity networks would serve as the feeder bus system for the proposed BRT project.

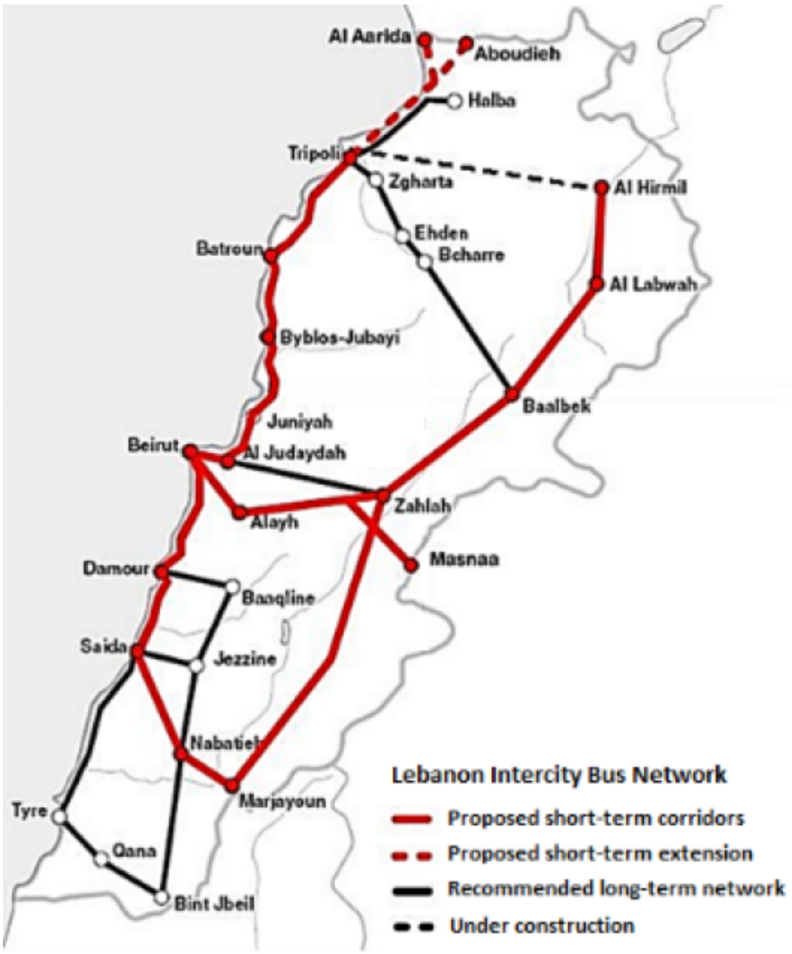

Figure 5: Intercity bus network proposed by the MoPWT's DGLMT.
Source: DGLMT (2013)

Figure 6: GBA bus network proposed by the MoPWT's DGLMT.
Source: DGLMT (2013)

Complementing the mass transit projects in the GBA is another recently approved public transport project in the Great Tripoli Area. A cooperation agreement between the European Investment Bank and the RPTA. The project will establish a comprehensive bus network system connecting the city and its suburbs, as well as a major transit station which will be built in the city's southern entrance.

However, despite all the promising plans and substantial funding, actual solutions on the ground are still a long time in the future, leaving the currently poor state of mass transit operations in Lebanon largely unchanged.

It is noteworthy however to summarize the opportunities for improvement from the proposed projects over the business-as-usual (BAU) scenario, as follows:

- Shorter trip duration when operating at higher speeds on dedicated lanes.

- Improved passenger safety and comfort when operators are properly trained and buses are maintained regularly.

- Higher market share when higher occupancy buses are used and after improving route and schedule coverage.

- More reliable and efficient operation with the use of information and communication technologies (ICT) and intelligent transportation systems (ITS).

- Lower emissions with the planned use of cleaner fuel-bus technologies.

- Lower operating costs with the potential use of newer market ready and cost-effective solutions.

3

AN OVERVIEW OF ALTERNATIVE FUELS AND TECHNOLOGIES IN BUSES

This section provides an overview of the main characteristics of conventional and alternative fuels used in buses and their corresponding bus engine technologies. Conventional or fossil fuels are being replaced by alternative fuels worldwide to reduce emissions and/or costs, but these fuels require the use of more expensive vehicle technologies and the installation of new infrastructure for fuel production, transformation, storage, transportation to markets and distribution at the pump.

There are four main types of fuel applicable for buses:

- Fossil fuels, namely diesel and natural gas in the form of liquid petroleum gas (LPG), liquefied natural gas (LNG) and compressed natural gas (CNG);
- Biofuels, namely biodiesel, bioethanol and biomethane (biogas) blends;
- Electricity; and,
- Hydrogen.

Different bus technologies are powered by one or a combination of fuels:

- Internal combustion engine technology which operates using diesel, LPG, natural gas or hydrogen fuels;
- Hybrid (series or parallel) and plug-in hybrid technologies which run using natural gas or biodiesel with electricity;
- Fuel-cell technology which uses hydrogen; and,
- Battery electric technology which is powered by electricity.

Some of the advanced fuels and their corresponding bus technologies are not considered feasible in the Lebanese context in the near-to-medium term, such as hydrogen fuel-cell buses. This technology is based on converting hydrogen into electricity using an electro-chemical reaction inside the vehicle's fuel cell, emitting only water vapor from the tailpipe and no other harmful GHG or pollutant emissions. However, this technology is still in development and requires a costly infrastructure, making it potentially feasible for the Lebanese market only in the long-term.

Similarly, biofuels which are derived from organic material (e.g. sugarcane, wheat, vegetable oils or organic waste) are also considered infeasible in Lebanon in the near-to-medium term due to the need for large-scale production or import of organic crops, and a number of sustainability challenges including agricultural, environmental and socioeconomic impacts. Biofuels are typically blended with conventional fuels to provide a cleaner fuel alternative (e.g. B7 and B30 biodiesel); however, they do not offer significant improvements in emissions over conventional fuels, while incurring additional costs in vehicle technology and infrastructure.

Some of the natural gas based fuels such as LPG and LNG are not widely used in city buses due to safety concerns and the high costs of the refueling infrastructure, and as such are considered unsuitable for use in bus service in the GBA.

Therefore, hydrogen, biofuels, LPG and LNG are not considered in this study. The fuel and bus technologies that are assessed in this study are diesel (as the reference fuel-bus technology), CNG, hybrid diesel-electric, and battery electric buses.

DIESEL

3.1

Diesel is the most commonly used fuel in buses today, providing high engine efficiency for relatively low vehicle and maintenance costs using existing refueling infrastructure. Diesel buses release GHG and pollutant emissions in the air, especially CO_2, particulate matter (PM) and nitrous oxides (NO_x). However, newer more stringent vehicle emission standards such as Euro VI mandate the use of cleaner diesel fuel with lower sulfur content, and on-board emission reduction systems such as a diesel particulate filter (DPF) or a catalytic converter to control tailpipe emissions. Figure 7 illustrates the evolution of European diesel bus emissions standards for PM and NOx since 1993 (Euro I) until 2013 (Euro VI), showing that diesel fuels and bus technologies compliant with the latest standards produce relatively very low emissions.

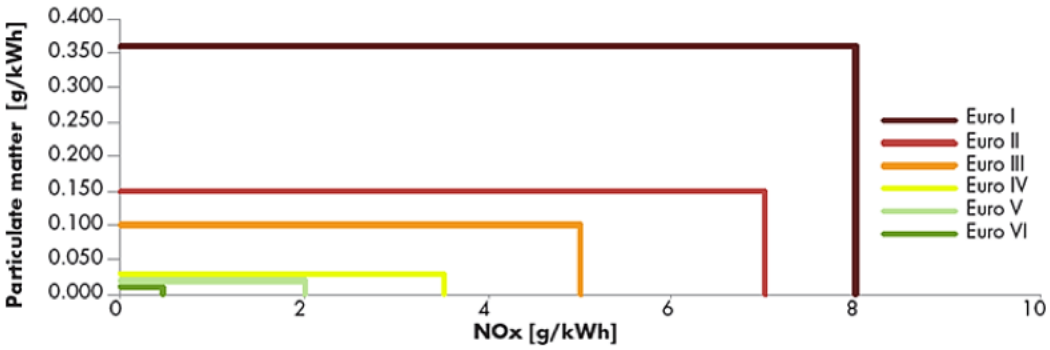

Figure 7: European standards for tailpipe emissions from diesel buses.
Source: (CIVITAS, 2016)

However, the main challenge with using diesel bus technology is the high cost of regularly monitoring and maintaining the on-board emission reduction systems. As a result, the recent trend worldwide has been to abandon diesel for cleaner fuels. In Lebanon, the use of diesel in passenger cars and light-duty vehicles (LDV) including mini-buses has been banned since 2001.

CNG

3.2

CNG is produced by compressing methane gas at high pressures of 200-250 bars, and it is stored on-board cars and buses in high-pressure cylinder tanks. CNG has a naturally high octane rating of 110-130, much higher than gasoline which is rated at 87-98 octane, meaning it is an easily ignitable fuel with comparable engine combustion performance to gasoline but with cleaner exhaust emissions. However, CNG engines have slightly lower efficiency than diesel engines which are capable of higher engine compression ratios. CNG also has lower energy density than gasoline and diesel, requiring more fuel quantity, and therefore more storage space, to deliver the same output.

The main advantages of CNG over diesel buses are the lower noise and cleaner emissions without the need for advanced emission control systems. CNG vehicles are considered safe if acquired from the OEM; however, retrofitting CNG buses is not advisable due to safety risks and the likelihood of lower performance in terms of emissions.

The same stations providing gasoline and diesel fuels can dispense CNG fuel. CNG stations include compressor equipment for compressing and dispensing natural gas. Fast-fill stations dispense CNG at 200 bars for a quick refill, and time-fill (or slow fill) stations are primarily used for refueling overnight. Figure 8 shows the main components of a fast-fill versus a time-fill station.

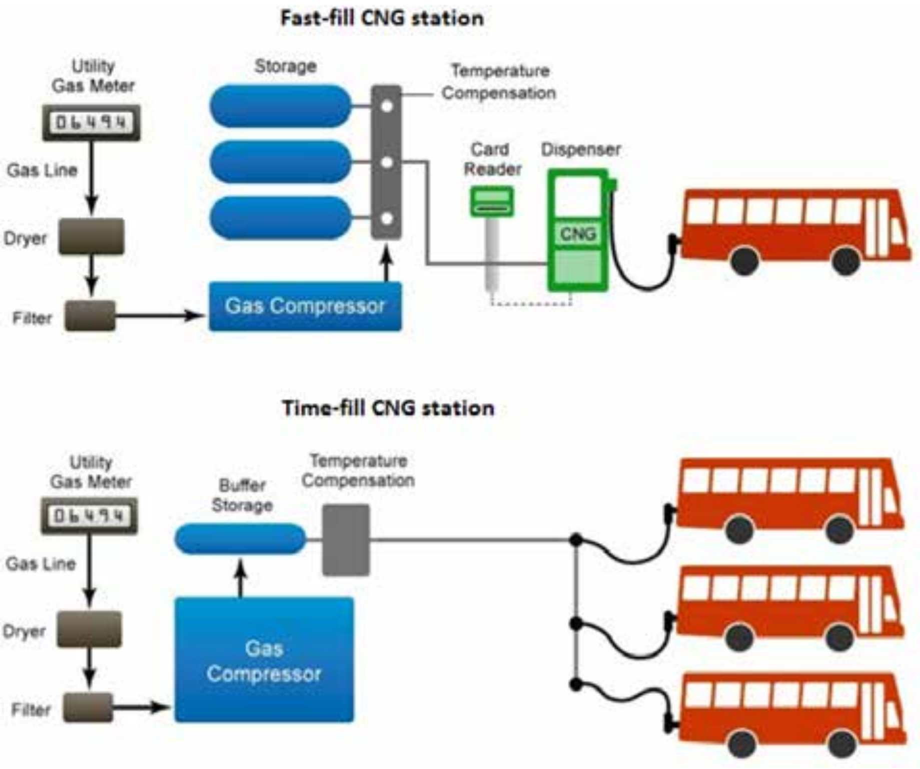

Figure 8: CNG station infrastructures.
Source: adapted from U.S. Department of Energy Alternative Fuels Data Center (http://www.afdc.energy.gov/)

ELECTRICITY

3.3

Electricity presents the most promising fuel for bus technologies in the long-term, in particular when it is generated from cleaner energy resources such as natural gas. Four types of bus technologies use electric power:

- Trolley buses, which are supplied continuously with electricity via overhead wires. Trolleys are the most mature electric bus technology, but require a costly infrastructure and have very little route flexibility outside the wired network. An on-board generator or auxiliary power unit (APU) are used to provide autonomous operation over short distances where no overhead wiring is available. This functionality will be provided by an on-board battery in the future, but this is not expected to greatly improve the route flexibility of trolley buses.

- Hybrid electric buses, which have a dual mode of operation using a battery and a conventional internal combustion engine that is also used for recharging the battery. Both series and parallel hybrid powertrain configurations are available, with both types consisting of an internal combustion engine (diesel, CNG), generator, battery and electric motor, differing only in their component layouts. Hybrids are fuel efficient when in heavy traffic, and can run in purely electric drive over short distances, such as through a city center.

- Plug-in hybrid electric buses, which are similar to hybrids but recharge from the grid.

- Battery electric buses (BEBs), which do not have an engine and are recharged from the grid. BEBs are considered as the cleanest technology on the market, producing zero road emissions and no engine noise. However, BEBs are currently more expensive to purchase, operate and maintain and have lower range than conventional technologies due to the limited energy storage capability of the battery.

Grid charging for BEBs and plug-in hybrid buses can be done over a long duration using high-power chargers, typically overnight at the main bus depot, or over a short duration at higher frequencies using fast-chargers along the bus line and at terminus. New charging station infrastructure is needed for this purpose, with different charging configurations available, as shown in Figure 9.

Overnight charging
Credit: EoBus.com

Continuous charging
Credit: http:// 1-smol.ru

Conductive charging
Credit: http://insideevs.com

Inductive charging
Credit: Arup

Figure 9: Electric bus charging configurations.

Overnight charging is done using DC chargers (typically 50-150kW power output) with a plug-in cable interface. This charging strategy is used for buses equipped with large batteries (typically 200-350 kWh) or running on shorter routes (less than 100km), but is otherwise not considered sufficient for meeting average daily autonomy needs of BEBs operating on typical bus lines, especially longer routes (100-250km) with higher passenger loads.

For the above reasons regular on-route charging is needed for buses equipped with smaller size batteries (typically 50-90kWh) or running on longer, busier routes. This charging strategy, known as opportunity charging, uses high-power fast chargers for either conductive charging with overhead pantographs (typically 150-450kW), or inductive charging with underground induction coils that transfer power wirelessly by a magnetic field to receiving plates on the underside of the bus. On-route charging time is expected to take less than 10 minutes.

It is important to note that battery storage and size as well as the charging infrastructure of electric bus technologies are still in development. However, technical and operational solutions are evolving rapidly, including innovative management strategies to reduce on-board energy consumption, and to optimize opportunity charging frequency and duration.

Note also that a stable power grid with dependable power supply and a clean electricity mix are required to operate BEB fleets in a reliable and environmentally beneficial way. The current power generation mix in Lebanon is based on 31.3% heavy fuel oil, 64% diesel oil and only 4.7% renewable resources (MoEW, 2010), with significant and chronic shortages in supply. This means that significant infrastructure investments are needed, in particular for generating electricity from natural gas, before BEBs can be operated in Lebanon.

On the other hand, the use of trolley buses in GBA would require extensive infrastructure investment with restricted route flexibility, therefore this technology is not considered in this study. And since plug-in hybrid buses are similar to hybrid and BEB technologies but with higher cost than hybrids and relatively lower performance than BEBs, this technology is also not considered in this study.

In summary, given the opportunities and challenges for the different fuels and bus technologies presented above as it applies for the Lebanese market, table 2 presents a summary of the final selection of the most viable options for fuel-bus technologies that can be assessed in the modeling of energy use and exhaust emissions under real driving conditions in the GBA.

Table 2: Final selection of existing and potential vehicle technologies considered for assessment.

TECHNOLOGY FUEL	CONVENTIONAL ENGINE	SERIES AND PARALLEL HYBRIDS	BATTERY ELECTRIC
Diesel	x	x	
CNG	x		
Electricity		x	x

4

ENERGY USE AND EMISSIONS ASSESSMENT OF BUS TECHNOLOGIES IN LEBANON

In order to assess the environmental impacts of the different fuel-bus technologies considered in this study, a modeling of their energy consumption and emissions in real world driving conditions was done using the commonly adopted software "Advanced Vehicle Simulator" (ADVISOR). This modeling tool was developed by the National Renewable Energy Laboratory (NREL) for system-level analysis of conventional and alternative fuel-vehicle technologies (NREL, 1996). The modeling methodology and the modeling results are presented in this section.

4.1

MODELING METHODOLOGY AND ASSUMPTIONS

An assessment of the environmental impacts of the applicable bus technologies consists of evaluating the energy use and emissions associated with vehicle operation activities for each vehicle type under specific driving and environmental conditions. This is illustrated in Figure 10.

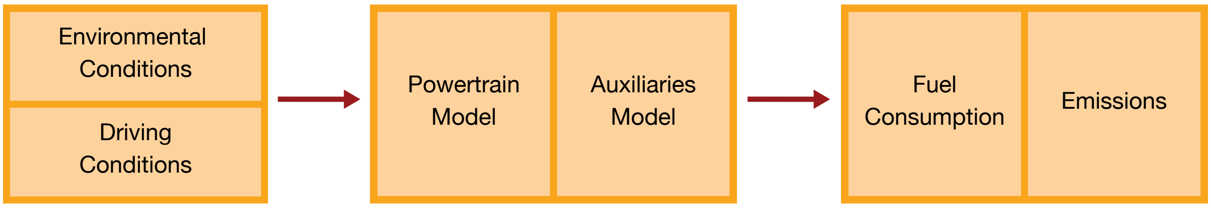

Figure 10: Overview of the modeling methodology for fuel-vehicle systems using ADVISOR.

The modeling requires the following inputs: a) weather conditions; and, b) local driving patterns on the bus route, namely the variation of bus speed over time known as a driving cycle, reflecting bus stop duration and frequency, trip length, traffic conditions and driver behavior, among others. The modeling outputs are the resulting bus energy consumption and on-road emissions.

The data for local driving patterns were developed by adapting similar bus driving cycles to the case of Lebanon through appropriate assumptions. Two types of bus operations were considered: a standard bus operation with frequent stops of relatively short duration similar to existing bus service in GBA, and a dedicated lane service with stops every one kilometer typical of BRT operation on the GBA coastal highway. As a result, four driving cycles were modeled representing the different types of traffic conditions encountered in GBA at different times of the day, namely:

- Severe congestion conditions characterized mainly by very low speeds (6 km/h on average) and very long idle times (67% of trip time),

- Peak traffic conditions characterized mainly by low speeds (11 km/h on average) and long idle times (36% of trip time) with frequent acceleration and deceleration,

- Off-peak traffic conditions characterized mainly by free-flow speeds (20 km/h on average, 21% idle time) on urban roads and highways; and,

- BRT service conditions characterized mainly by relatively higher speeds (36 km/h on average, 23% idle time) on a dedicated highway lane.

The bus model consists of detailed models of the powertrain and auxiliary systems such as air conditioning and bus doors' power units. Different bus models were developed for the different bus technologies considered in this study to account for differences in the powertrain component architectures, as illustrated in Figure 11.

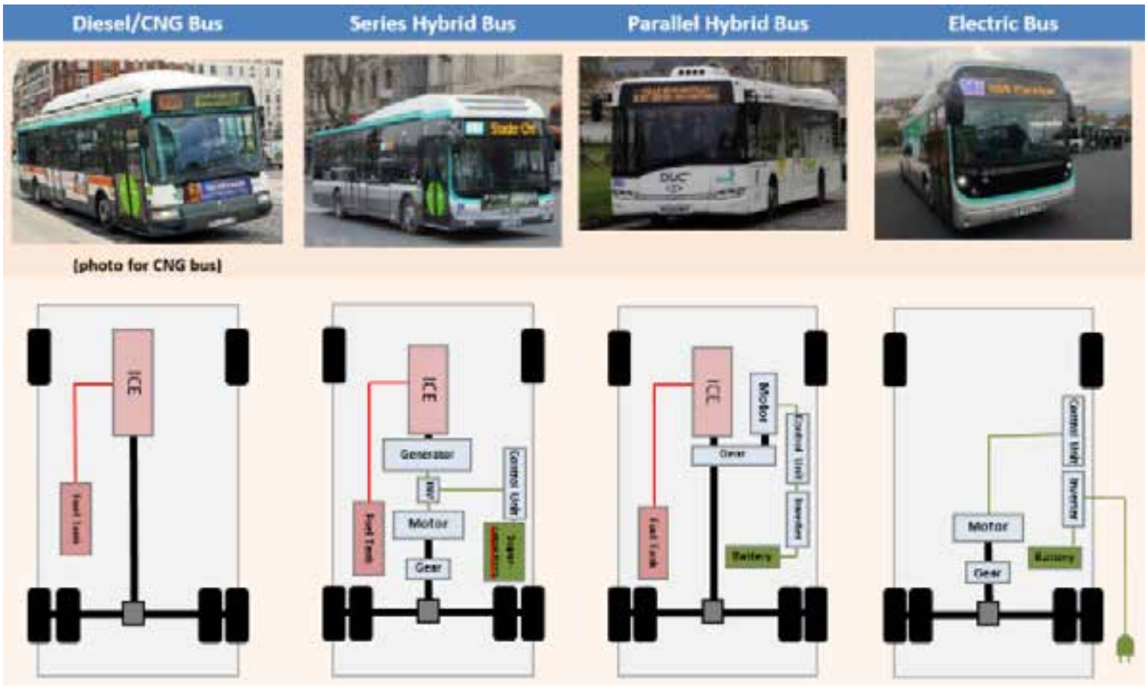

Figure 11: Overview of the different bus powertrain architectures.

As the figure shows, the powertrains of the different fuel-bus technologies differ by the component types used and their interconnections.

Diesel and CNG buses are both powered by an internal combustion engine (ICE), with the main difference being the presence of a fuel tank for CNG storage, shown on the rooftop of the CNG bus in the figure above. The main advantage of CNG over diesel is the lower carbon content of natural gas, allowing for cleaner fuel combustion.

Series-hybrid buses are powered by an electric motor, and the ICE serves to generate electricity to support the motor. Also in this architecture, batteries are used to recover braking energy, generating electric power which is used to propel the bus after a stop, thus increasing the bus efficiency.

In parallel-hybrid buses, both the ICE and the motor can provide traction, individually or together at the same time. A battery is used to recover braking energy, allowing the bus to operate on electric power until a speed of 20 km/h is reached where the ICE takes over.

The main advantage of both hybrid technologies is in the downsizing of the engine compared to conventional diesel buses, which reduces fuel consumption, thereby increasing efficiency.

Electric buses are powered by an electric motor which uses energy stored in the battery, and the battery is recharged from the grid. The main advantage of this technology is the high efficiency attained in relying exclusively on the electric motor compared to ICE.

The required data for the different bus models were obtained from original equipment manufacturer (OEM) bus data sheets that are provided in Appendix A. Note that the power consumption of auxiliary systems used on these buses, which largely affects the fuel consumption, were accounted in the bus models, as presented in Table 3.

Table 3: Auxiliaries power consumption.
Source: (Andresson, 2004)

	AUXILIARIES POWER EXCLUDING CLIMATE CONTROL AUXILIARIES	CLIMATE CONTROL AUXILIARIES POWER
Diesel and CNG buses	9,000 W	13,400 W
Hybrid and electric buses	5,250 W	14,000 W

MODELING RESULTS AND ANALYSIS 4.2

The modeling results presented in this section cover three types of impacts: energy use, greenhouse gas emissions and pollutant emissions for a Euro V compliant 12-meter bus with full occupancy.

4.2.1. ENERGY USE RESULTS

The results for energy use for each of the fuel-bus technologies are shown in Figure 12. The figure compares the fuel consumptions of the considered technologies under normal driving conditions, otherwise known as off-peak traffic conditions.

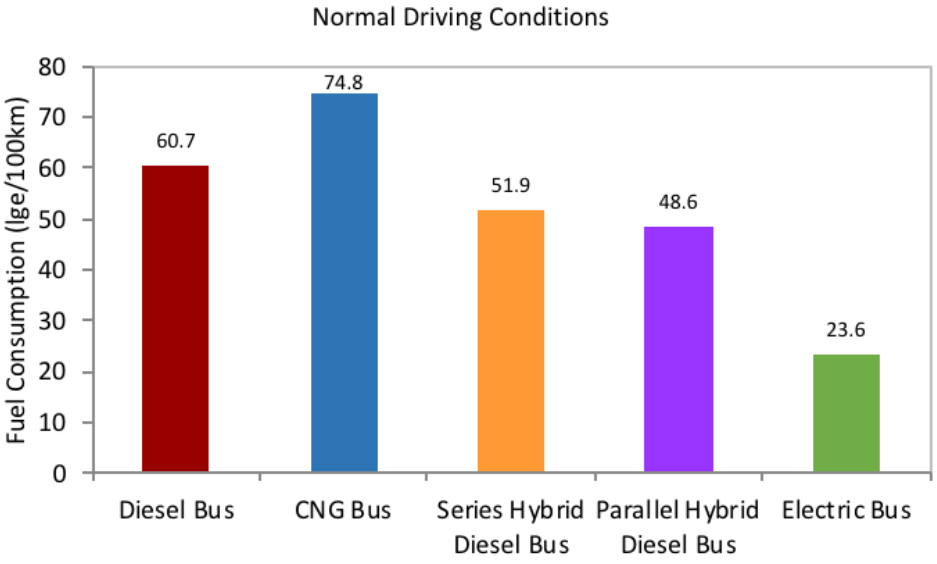

Figure 12: Cenergy use of the assessed bus technologies in normal off-peak driving conditions.

The diesel bus is considered the reference bus against which the fuel consumptions of all other technologies are compared in terms of liter gasoline equivalent (lge per 100 km). As can be seen from the figure above, the diesel bus has the second highest consumption after CNG with 60.7 lge/100km. CNG consumes more energy than diesel by 23% due to the lower energy content of natural gas, however with cleaner air emissions as will be discussed in the following subsection on emissions. Hybrid technologies are more fuel efficient than diesel by 14.5% for the series hybrid technology and 20% for the parallel hybrid technology, due to the partial reliance on the electric energy supplied by the battery on-board, as well as on the system of recovery of a part of the waste energy from braking that is available in these powertrains. Electric buses consume no actual fuel on-board; however, when accounting for the electricity consumed from the battery, they consume 61% less lge per 100km than diesel and are the most efficient technology out of all those considered.

While the above figure clearly shows the advantages of alternative fuel-bus technologies compared to the standard diesel bus, it is important to consider the consumption performance of all technologies under variations of driving conditions as is encountered at different times of the day. The modeling therefore includes three additional scenarios of common driving conditions, namely peak traffic, severe congestion and a BRT-type of operation on a dedicated lane, as is currently being considered for bus service in GBA. Figure 13 compares fuel consumptions under all four scenarios for the reference diesel bus, illustrating the significant impact of traffic conditions on fuel consumption.

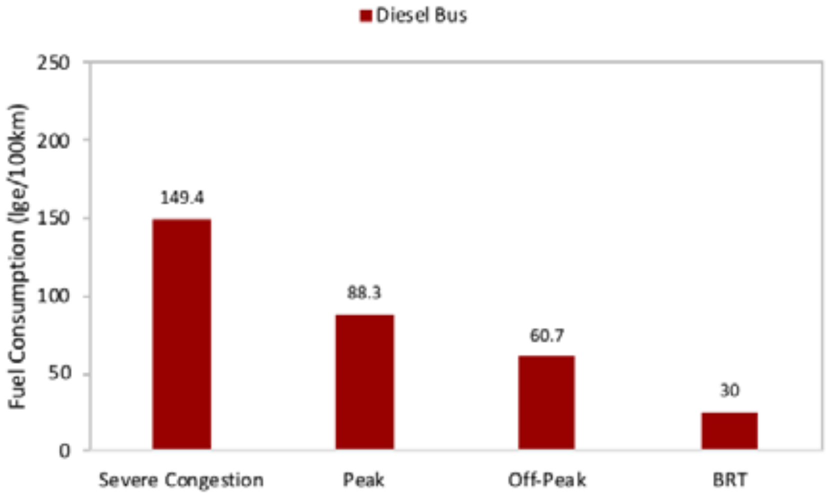

Figure 13: Energy use of the diesel bus technology under different scenarios of driving conditions.

The results show the improved fuel consumptions achieved as the driving conditions become more free-flowing relative to severe congestion, from 41% for peak traffic to 80% for BRT operations. This shows that BRT, which operates on a dedicated lane, is more fuel efficient than standard bus even when the latter is operating in off-peak driving conditions. As explained previously, the differences are due to the higher average speed on the BRT dedicated lane and the fewer numbers of stops for BRT service, among other related factors such as acceleration changes and driver behavior which impact powertrain efficiency.

A similar trend is observed for all other bus technologies, as shown in Figure 14.

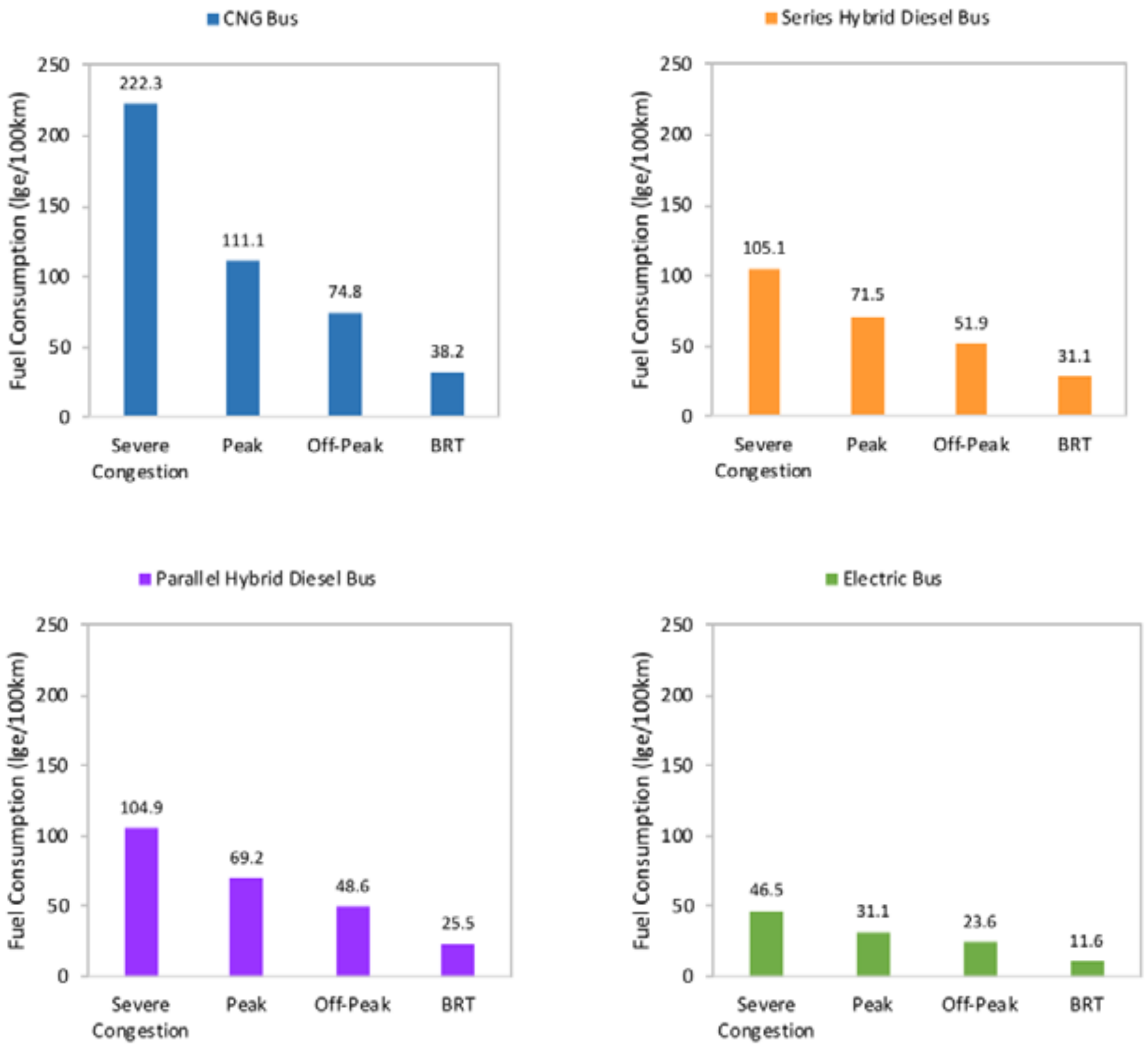

Figure 14: Energy use of the alternative fuel-bus technologies under different scenarios of driving conditions.

As the figure shows, BRT operations are more energy efficient regardless of bus technology, with electric buses being the most efficient out of all the technologies considered. In fact, electric powertrains are the most robust against variations in traffic and driving conditions, as illustrated in the minor differences in energy consumption for the electric bus across the different conditions considered.

It is noteworthy to point out however that all technologies become less efficient when accounting for the use of climate control auxiliaries for cooling or heating the cabin, as can be seen in the comparison between the below Figures 15 (without use of air conditioning) and 17 (with use of air conditioning). In fact, recent research has shown the need to account for additional fuel consumption due to the use of climate control auxiliaries as this can be a significant contributor to the total energy consumption (Mansour, Haddad, & Zgheib, 2018). In buses, the use of climate control auxiliaries is essential for ensuring passenger comfort in the cabin which can serve to increase ridership of mass transit. However, the resulting additional fuel consumption can drastically reduce the performance of these technologies from that reported by the OEMs, which can change the relative attractiveness of these technologies in different climate conditions.

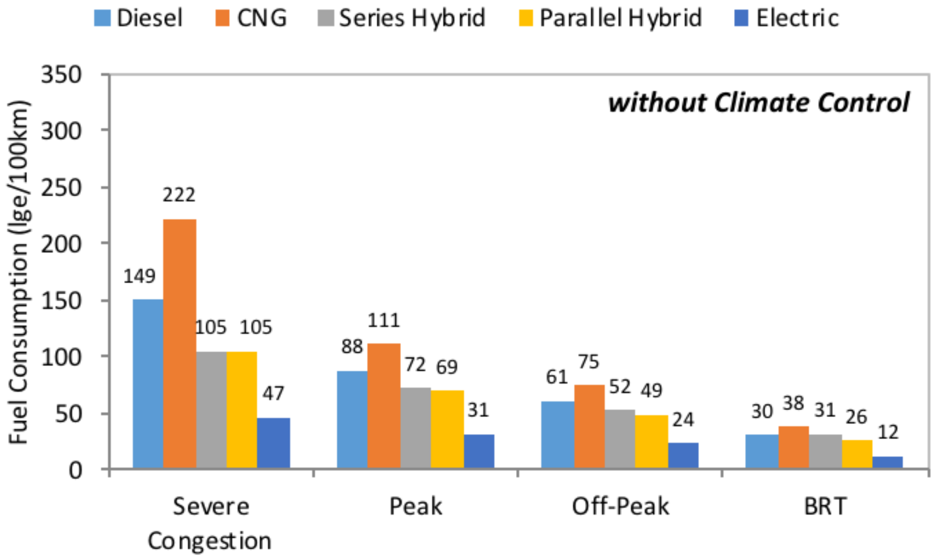

Figure 15: Energy use of the assessed bus technologies without use of climate control auxiliaries.

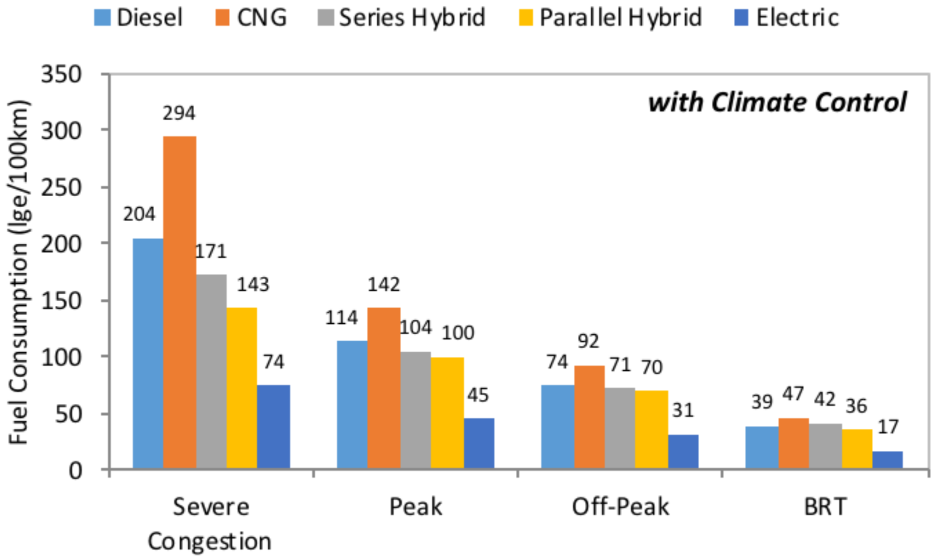

Figure 16: Energy use of the assessed bus technologies with use of climate control auxiliaries.

As the figures show, on average the considered bus technologies consume 29.2%, 26.4%, 45%, 40.8% and 44.7% more with the use of climate control auxiliaries than without them for diesel, CNG, series-hybrid, parallel-hybrid and electric buses, respectively.

CNG has the highest fuel consumption in liter gasoline equivalent (lge) under all driving conditions due to the lower energy content of natural gas compared to diesel fuel, as well as the lower CNG engine operating efficiency compared to diesel engines. Note that CNG consumption becomes highest under severe congestion conditions because CNG engines operate less optimally than diesel engines at low torques and low speeds that are characteristic of driving in severe congestion.

It is also noteworthy that the consumption of the series-hybrid engine slightly exceeds that of diesel under BRT conditions only (by 7.7%). This is because the efficiency of the diesel bus engine improves under free flowing driving conditions such as in BRT operation, whereas the efficiency of the series hybrid powertrain is penalized by the double energy conversion of the fuel. The fuel energy is converted first to electricity through the generator and then converted a second time to mechanical energy through the electric motor in order to propel the bus.

Overall, the modeling results show that all the considered technologies are more efficient under BRT than for standard bus operation, and that the electric bus on BRT is the most efficient.

4.2.2. GHG EMISSIONS RESULTS

The GHG emissions results (CO_2, CH_4 and N_2O) for all bus technologies are presented in Figures 17 and 18.

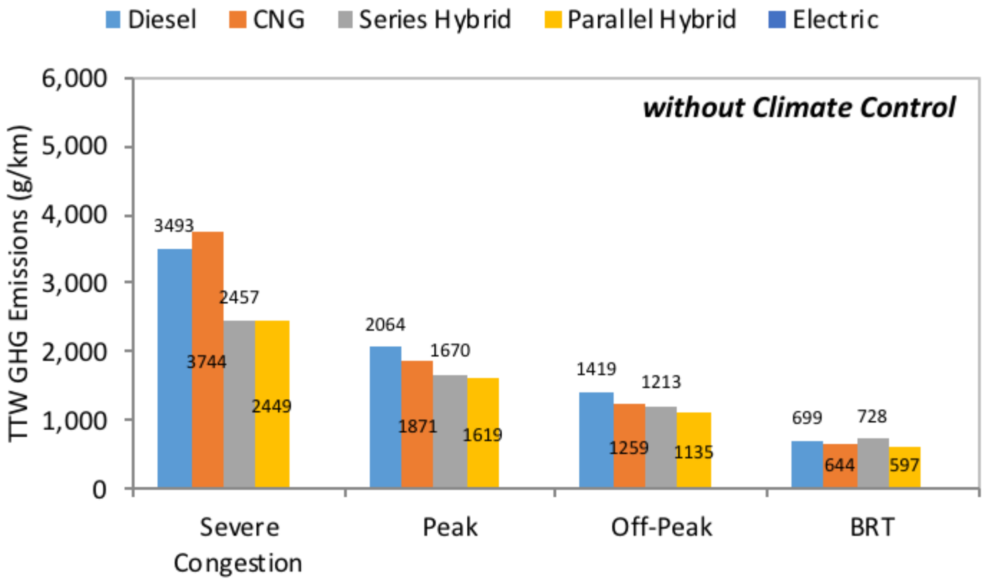

Figure 17: GHG emissions of the assessed bus technologies without use of climate control auxiliaries.

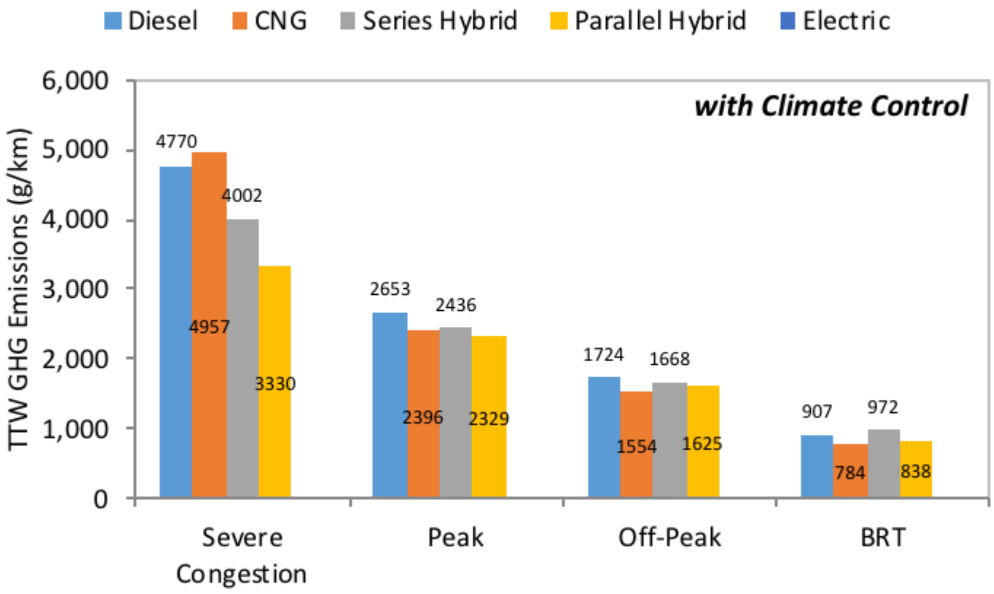

Figure 18: GHG emissions of the assessed bus technologies with use of climate control auxiliaries.

When comparing the above figures, it can first be observed that the use of climate control auxiliaries has a significant impact on GHG emissions for all bus technologies. For example, the difference ranges from 21.5% for diesel bus in off-peak driving conditions to 62.9% for series-hybrid technology in severe congestion conditions. This is due to the additional fuel consumption to power auxiliaries as explained in the previous sub-section 4.2.1.

GHG emissions for all bus technologies are significantly reduced under BRT operation compared to standard bus operation, from 40% less for parallel-hybrid technology without climate control compared to off-peak conditions, to 84.1% for CNG with climate control compared with severe congestion traffic. This is expected since BRT driving conditions are more free-flowing than all other standard bus operations, and therefore fuel consumption for any one technology is lower under these conditions than otherwise.

It is important to observe that for all driving conditions, diesel bus contributes the highest GHG emissions of all bus technologies, except in severe congestion where CNG bus technology has a higher contribution than diesel (by 7.2%), and in BRT operations where series-hybrid has a higher contribution than diesel bus (by 4.1%). This is due to the additional fuel consumption for CNG and the lower powertrain efficiency for series-hybrid, as explained in the previous sub-section 4.2.1.

Note that GHG emissions for electric bus are zero under all conditions since this bus technology does not consume hydrocarbon fuels for on-road operation. This makes electric buses the most advantageous technology for meeting Lebanon's INDC commitment in 2015 to reduce its GHG emissions from the transport sector over the 2015-2030 timeframe.

However, electric bus technology consumes electric energy that is generated at power plants and therefore the total contribution of this technology to GHG emissions should account for the supply side (i.e. the well-to-tank portion) which depends on having a clean energy mix at the power plant. Therefore, this technology would become much more beneficial under Lebanon's 2030 plans for a clean energy resource mix in the electricity sector where the current polluting mix relying on heavy fuel oil (HFO) and diesel oil would be completely replaced by natural gas and more renewable sources (MoEW, 2010). Figure 19 contrasts the WTT GHG emissions under current and future electricity mix scenarios for Lebanon.

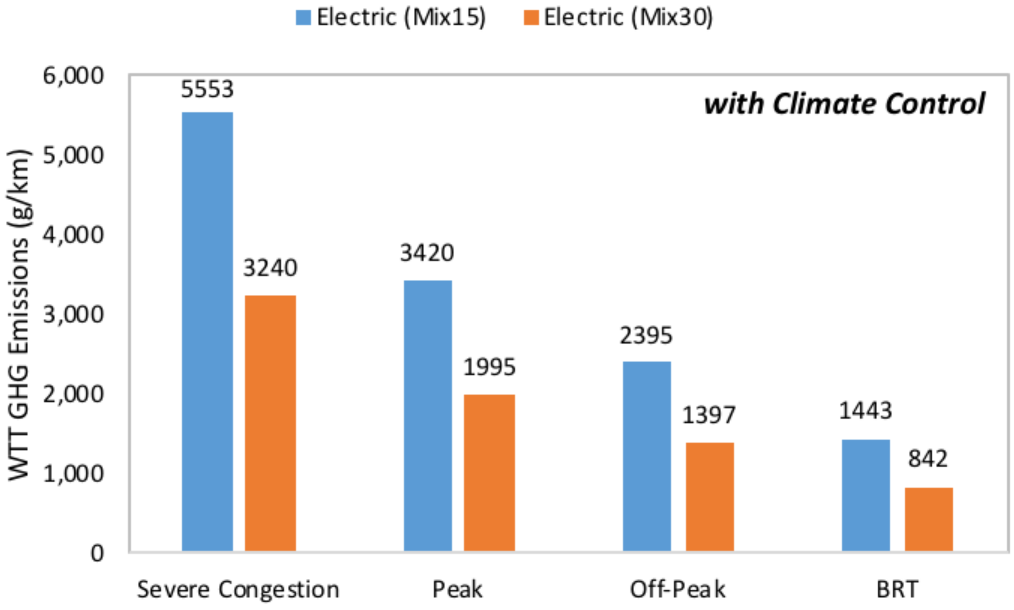

Figure 19: WTT GHG emissions of electric bus technologies under the 2015 and 2030 electricity mixes.

4.2.3. POLLUTANT EMISSIONS RESULTS

The emission results for each criteria pollutant are shown in Figures 20 to 24 by driving conditions for all considered bus technologies (note that electric buses have zero on-road pollutant emissions and therefore do not appear in the figures below). Each figure presents the modeled results relative to the corresponding EURO VI emission standards. Note that the emission standards are developed for bus operations without the use of climate control auxiliaries; however, the results below are for bus operations with use of climate control auxiliaries for a conservative comparison. Also note that the modeling is done for Euro V bus technologies, while the comparison is against the more stringent Euro VI standards; this is done to highlight the need for adopting newer bus technologies in order to be compliant with the newest standards.

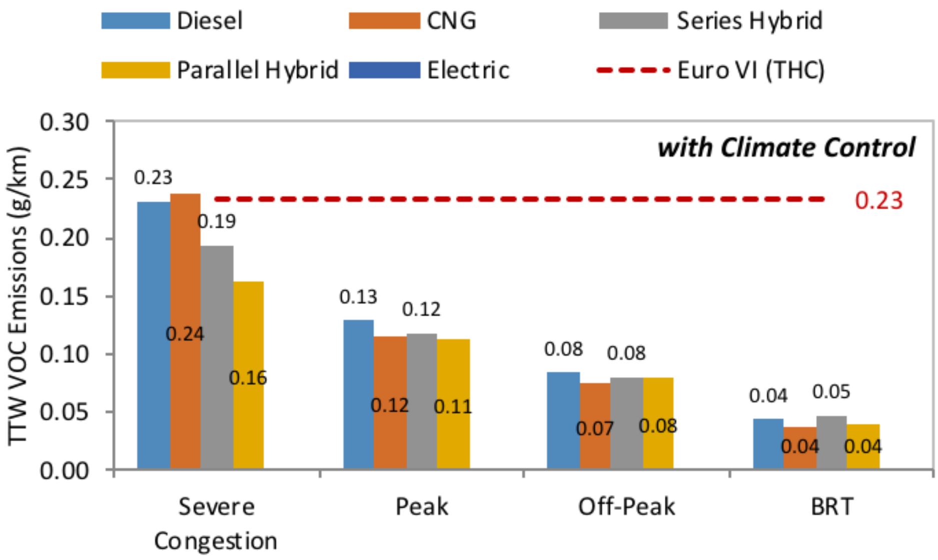

Figure 20: VOC emissions of the assessed bus technologies under all driving conditions.

As shown in Figure 20 for VOC emissions, all bus technologies are compliant in almost all driving conditions with only one exceedance (by 2.1%) for CNG in severe congestion conditions. Hybrid technologies are the next best performers after fully-electric buses, with equivalent performance by CNG as conditions become more free-flowing.

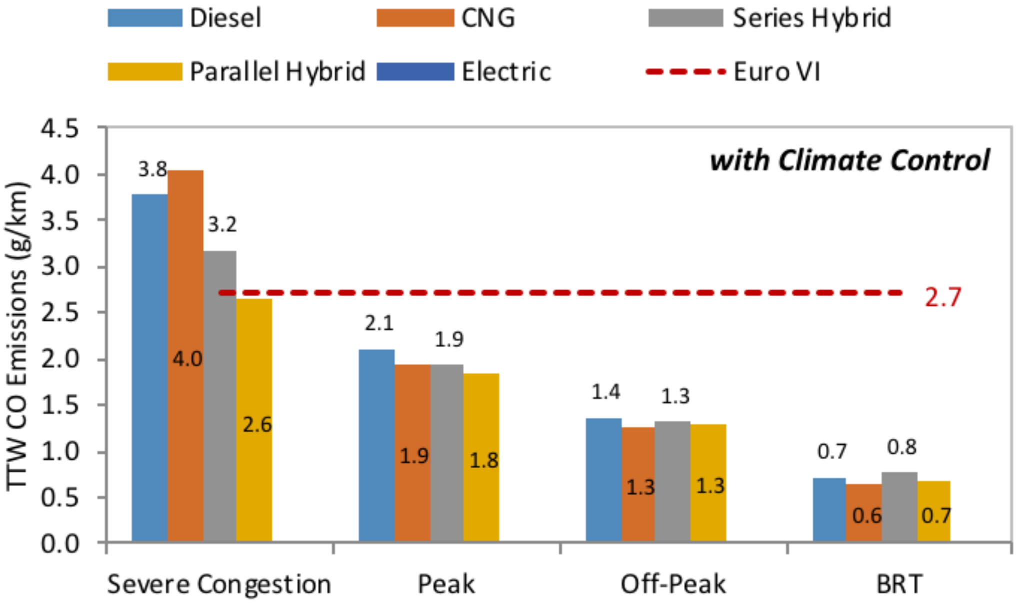

Figure 21: CO emissions of the assessed bus technologies under all driving conditions.

For CO emissions shown in Figure 21, exceedances by 18.5% (series hybrid) to 48.1% (CNG) are estimated in severe congestion conditions, with BRT conditions well below the standards. Therefore, BRT type of service can be considered as a contributor to cleaning the air quality inside the city and in urban areas.

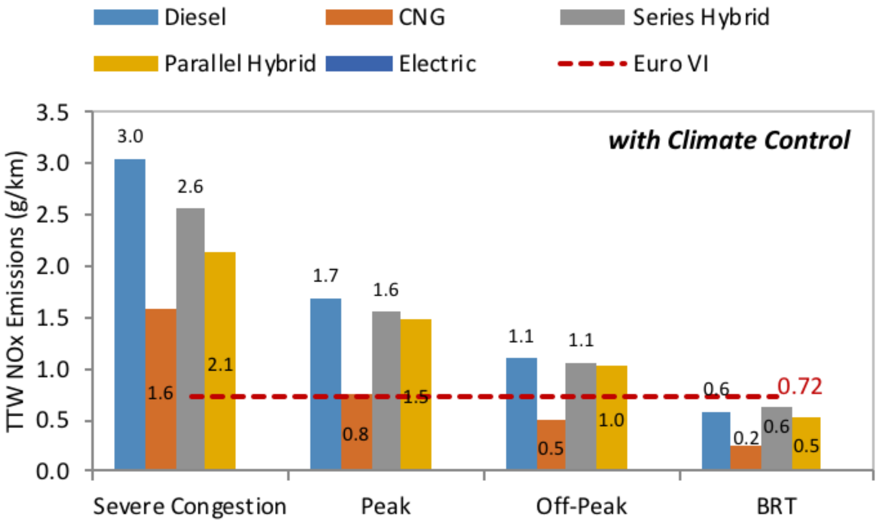

Figure 22: NO_x emissions of the assessed bus technologies under all driving conditions.

The picture for NO_x is different than for the previous two pollutants, as the Euro VI standards are much more stringent, as shown in Figure 22. Only BRT conditions are in compliance, with exceedances estimated at 44% (parallel-hybrid) in off-peak conditions to 322.8% (diesel) in severe congestion.

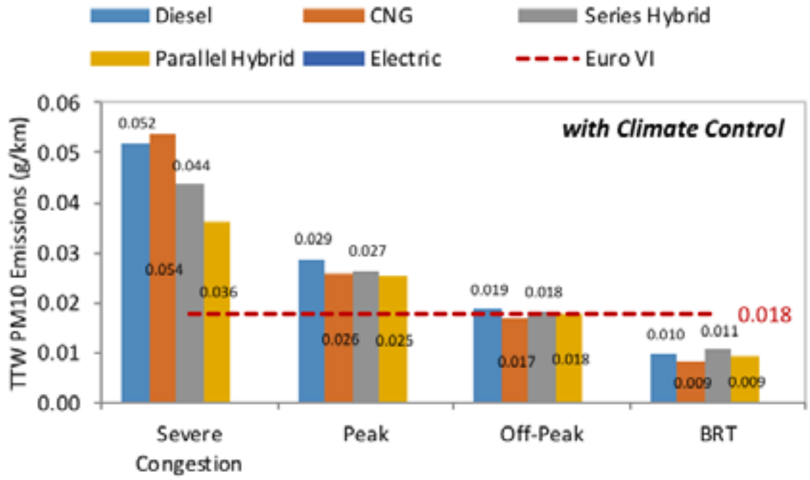

Figure 23: PM emissions of the assessed bus technologies under all driving conditions.

For PM_{10} results shown in Figure 23, all bus technologies are in compliance with the standards when under free-flowing conditions, namely BRT and off-peak. Maximum exceedances of 60.6% and 199.4% are estimated for diesel in peak conditions and CNG in severe congestion, respectively.

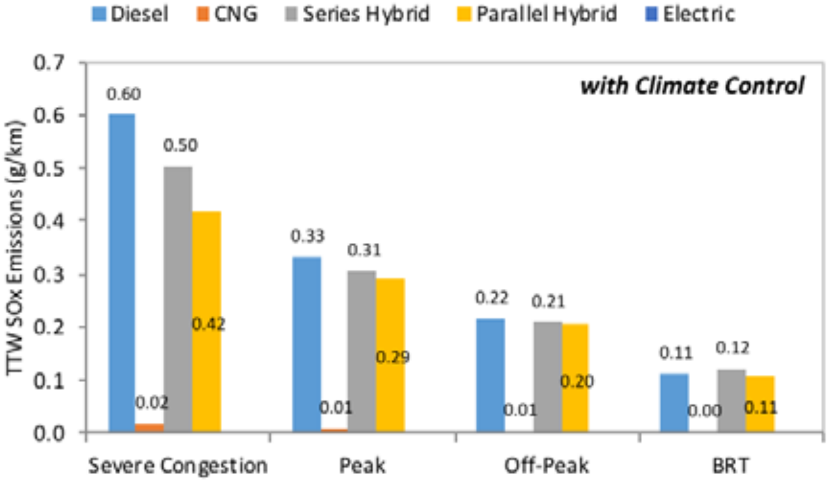

Figure 24: SO_x emissions of the assessed bus technologies under all driving conditions.

For SO_x emissions shown in Figure 24, where no standard is available, the assessment results show that BRT emissions are very low for all bus technologies, with CNG being the best performer (after electric buses) across all driving conditions.

Finally, as explained in the previous sub-section 4.2.2 for GHG emissions, it is important to keep in mind that while electric buses are the cleanest technology on the road, the electricity for recharging batteries on-board electric buses involves emissions of WTT pollutants from electricity generation on the power plant side, and therefore the energy sources used to generate electricity must also be clean. In Lebanon, the current resource mix for electricity generation is exclusively dependent on fossil fuels and is thus considered a polluting mix; however, the strategy of the MOEW is to rely on natural gas and other renewable energy sources to clean up the mix in the future (MoEW, 2010). Under a clean electricity mix, electric buses are the best technology for cleaning up the environment inside cities and urban areas, especially when operating in BRT conditions.

WTT pollutant emissions for electric buses are reported in Figures 25 and 26 under the current 2015 and future 2030 resource mix.

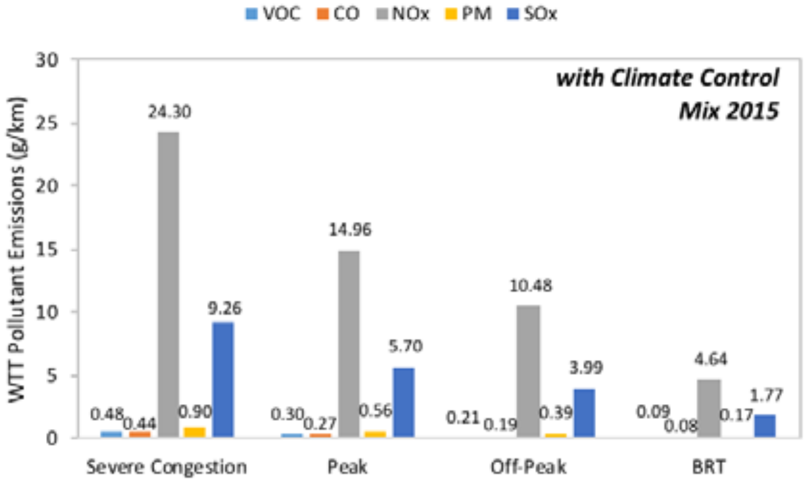

Figure 25: WTT pollutant emissions of electric bus technologies under the 2015 electricity mix.

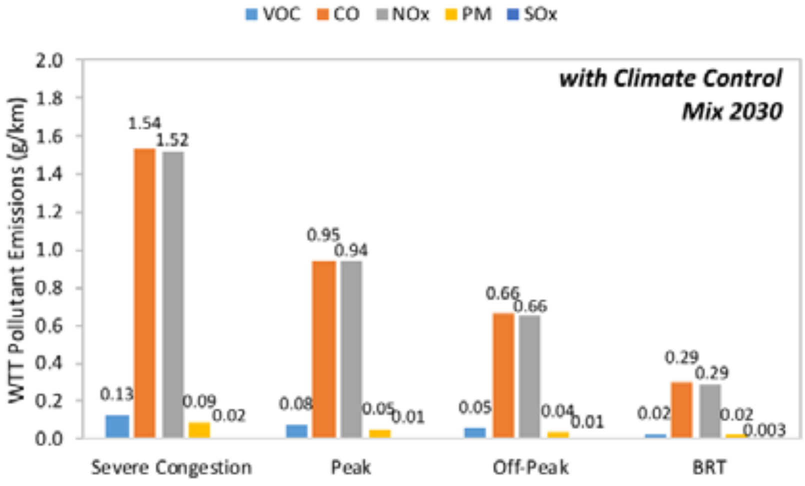

Figure 26: WTT pollutant emissions of electric bus technologies under the 2030 electricity mix.

As can be seen in the comparison of the figures above, the increased WTT emissions from electricity generation are significantly reduced under the 2030 mix for all driving conditions. Note that the estimated increase in CO emissions in 2030 versus the estimates for the 2015 mix is due to the use of natural gas ICE technology in the power plants, and therefore this can be mitigated in the future by using cleaner technologies.

4.2.4. SENSITIVITY ANALYSIS

A realistic assessment of the performance of bus technologies in real driving conditions should consider that buses do not operate at full-occupancy and with use of climate control auxiliaries all the time. Therefore, the modeling in this study also considered operation at half-occupancy without the use of climate control auxiliaries as a contrasting illustration of the performance of fuel-bus technologies under less demanding operating conditions. The results for fuel consumption and GHG emissions under all driving conditions for half versus full-occupancy are presented in Figures 27 and 28, and the results for pollutant emissions under severe congestion where exceedances were previously estimated are shown in Figure 29.

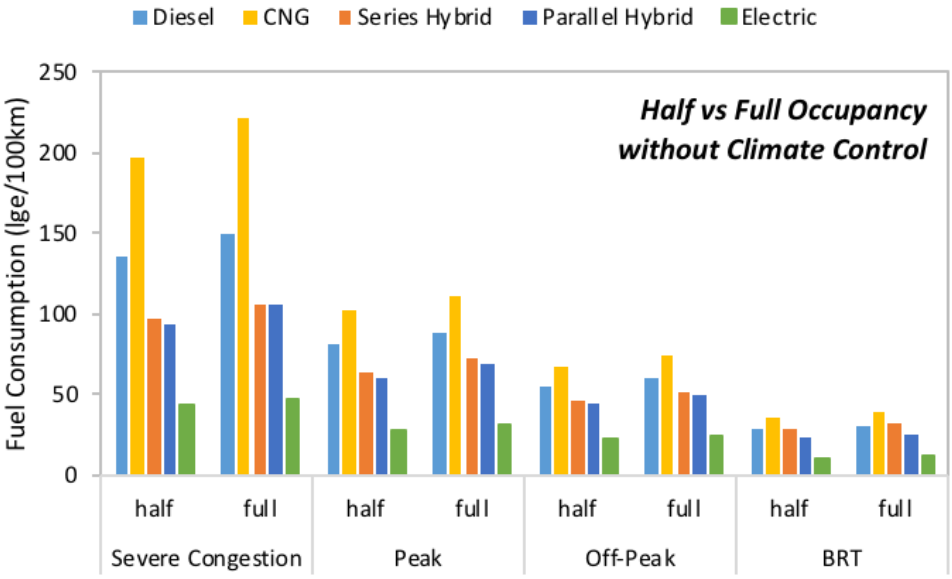

Figure 27: Energy use of the assessed bus technologies at half- versus full-occupancy.

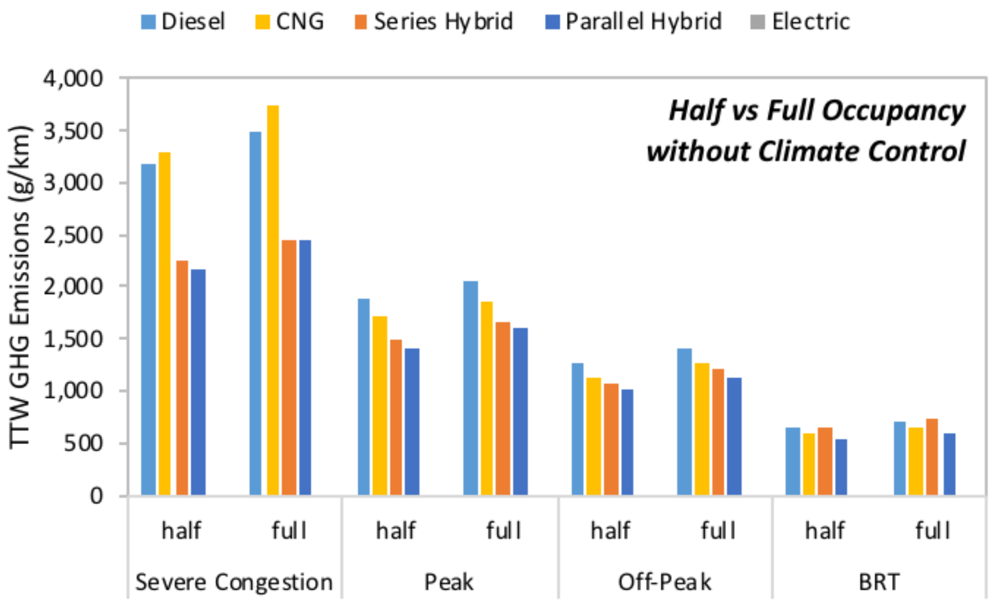

Figure 28: GHG emissions of the assessed bus technologies at half- versus full-occupancy.

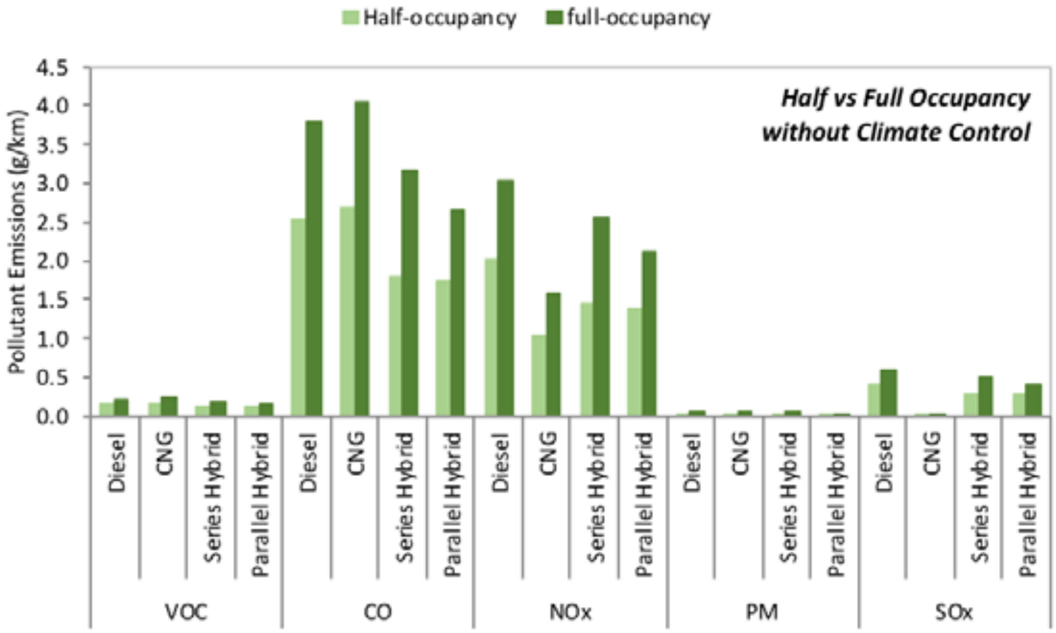

Figure 29: Pollutant emissions of the assessed bus technologies at half- versus full-occupancy under severe congestion.

As the figures above illustrate, energy consumption, GHG and pollutant emissions for half-occupancy without climate control auxiliaries are reduced by 33 % on average as compared to full-occupancy results.

5

COST BENEFIT ANALYSIS FOR SELECTED FUEL-VEHICLE TECHNOLOGIES

METHODOLOGY FOR THE COST-BENEFIT ANALYSIS

5.1

The CBA in this study compares the performance of each fuel-bus technology in terms of savings in GHG emissions and total costs relative to the reference diesel bus. The purpose of the CBA is to prioritize the considered technologies by their environmental contribution for the lowest cost. The specific cost components and the corresponding benefits are detailed in the following subsections. The CBA methodology follows the same approach detailed in the previous study on Sustainable Oil and Gas Development in Lebanon (SODEL) for passenger vehicles (Haddad & Mansour, 2017).

COST COMPONENTS AND ASSUMPTIONS

5.2

The considered costs for each fuel-bus technology include fixed capital costs for bus purchase and refueling infrastructure installation, and variable costs for vehicle operation and maintenance (O&M), as summarized in Table 4. Applicable cost estimates and assumptions used in this study are detailed in Table 5.

Table 4: Specific bus costs considered in the CBA.

COST COMPONENT	DESCRIPTION
Bus	Bus purchase cost estimated from a Lebanese market survey for diesel buses, and from worldwide industry data for alternative fuel-bus technologies.
Hybrid and electric buses	Cost of bus operation including the cost of consumed fuel, maintenance and repair, bat-tery, and insurance fees.
O&M	Fuel costs: computed from the vehicle energy consumption results under local real driv-ing conditions and local fuel price and electricity tariff.
	Bus maintenance and repair costs, including diesel particulate filter (DPF) costs are esti-mated from local bus operator data and published case studies in U.S. and European con-texts (CIVITAS, 2016).
	Battery costs estimated from worldwide industry data.
	Insurance fees computed according to local methods.
Infrastructure	Capital and operating costs of CNG refueling stations and electricity recharging stations are accounted for in two configurations each: fast-fill and time-fill. Station capital costs include storage, compression, dispensing and metering equipment for natural gas, and the power recharging equipment for electricity.

Table 5: Cost estimates and assumptions used in the CBA.

PARAMETER	ESTIMATES AND ASSUMPTIONS
Annual mileage	Estimated at 100,000 km.
Bus purchase costs	Estimated as follow: 264,000 USD for diesel bus; 300,000 USD for CNG bus; 360,000 USD for series and parallel hybrid buses; and, 492,000 USD for electric bus (with 122 kWh battery).
Battery costs	Estimated at 450 USD/kWh (McCall, 2011).
	Batteries assumed to be replaced once over the bus service life.
Discount rate	Assumed to be 12% per year (WBG, 2005).
Fuel costs	Local average of 0.73 USD/liter for diesel; 0.5 USD/liter gasoline equivalent for natural gas; and 0.13 USD/kWh for electricity.
Government subsidy	Bus purchase cost is subsidized 80%, in line with common practice by transit authorities in developed countries. Note that this gives BEB technology a competitive advantage com-pared to other technologies since it currently has the highest purchase cost.
	Custom and excise fees (5% of bus purchase cost) and registration fees (2% of us pur-chase cost) are subsidized by the government for public transit, and therefore not includ-ed in the total cost calculation.
Infrastructure costs	The supply infrastructures for natural gas and electricity, such as distribution pipelines for natural gas, or power plants and transmission lines for electricity, are assumed to be made available by the government for use by all sectors of the economy. Therefore, the capital costs of backbone infrastructure are not considered in the CBA.
	The capital and operating costs of bus stations, depots, maintenance yards and other supporting infrastructure are assumed to be the same for all bus technologies and there-fore not considered in this CBA.
	The cost of land for recharging station construction is not considered.
	Infrastructure cost is estimated at 50,000 USD per bus for CNG and electric buses (Tong, Hendrickson, Biehler, Jaramillo, & Seki, 2017).
Insurance fees	Estimated at 1,200 USD per year.
Labor costs	Assumed equal for all fuel-bus technologies and therefore not considered in the comparative analysis.
Other costs	All capital investments (vehicle and infrastructure) are assumed to be made at the start of operations.
	Costs of unexpected failures for any technology are not considered.
	Fleet operating and management costs are outside the scope of this study.
	VAT is considered 11% and road usage fees (“mécanique”) is 60 USD every 6 months.
Service life	Estimated at 1,200,000 km - 1,500,000 km over 12-15 years for all bus technologies, and estimated over 20 years for the CNG refueling stations and electricity recharging infra-structure.
Bus occupancy	Estimated half of the bus full capacity.
Salvage value	Zero at the end of bus service life.

The total costs for each fuel-bus technology, computed over the service life of the bus, and the total cost savings of buses compared to the reference diesel bus are presented in Table 6 for all operating conditions, namely severe congestion, peak, off-peak and BRT dedicated lane operation, respectively.

Table 6: Total costs of the evaluated bus technologies in USD/bus.km.

TECHNOLOGY	DRIVING CONDITIONS							
	severe congestion		peak		off-peak		BRT	
	USD/bus. km	%	USD/bus. km	%	USD/bus. km	%	USD/bus. km	%
Diesel	1.96	-	1.37	-	1.10	-	0.87	-
CNG	1.89	3.5	1.30	5.1	1.07	2.2	0.89	-2.2
Series hybrid	1.75	10.9	1.28	6.6	1.05	4.7	0.85	1.6
Parallel hybrid	1.59	19.2	1.24	9.8	1.04	5.0	0.81	6.0
Electric	1.33	32.4	1.02	25.9	0.87	20.7	0.74	14.9

Table 7 summarizes the actual bus ownership, operating and maintenance costs per bus-kilometer traveled under each operating condition for each of the considered technologies.

Table 7: Ownership and operating and maintenance costs of the bus technologies in USD/bus.km.

BUS	TECHNOLOGY	DIESEL	CNG	SERIES HYBRID	PARALLEL HYBRID	ELECTRIC
Ownership costs (USD/bus.km)		0.108	0.121	0.142	0.142	0.174
O&M costs (USD/bus.km)	severe congestion	1.853	1.772	1.606	1.443	1.153
	peak conditions	1.265	1.182	1.139	1.095	0.844
	off-peak conditions	0.989	0.952	0.903	0.900	0.697
	BRT operation	0.759	0.765	0.711	0.672	0.564

The results in the table above show that driving conditions greatly impact bus operating costs, as illustrated in Figure 30. Specifically, bus operating costs for all technologies are greatly reduced when operating at higher average speeds, as can be achieved in BRT operation on dedicated lanes. This is because there is less wear and tear in free flow conditions, with all engine technologies operating at higher efficiency. Specifically, BEBs have the lowest operating costs of all technologies.

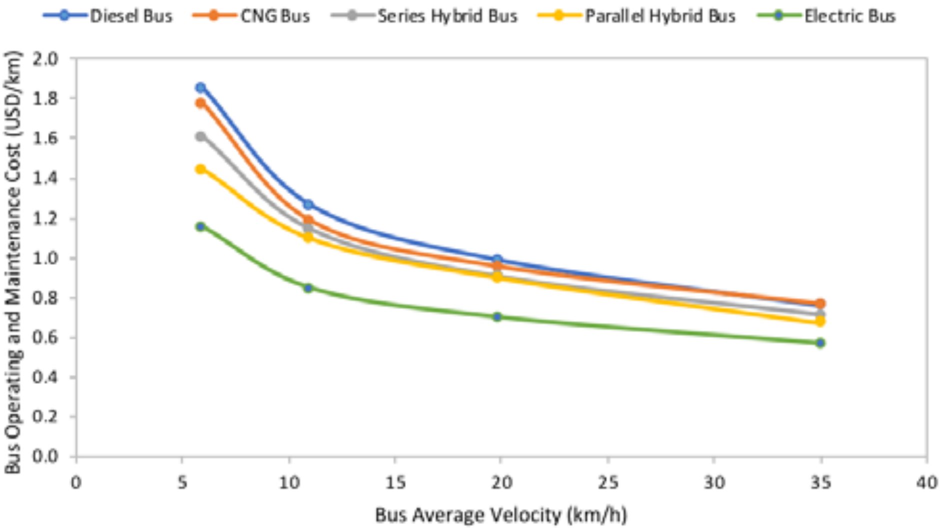

Figure 30: Operating and maintenance costs of fuel-bus technologies as function of bus average velocity.

Reviewing the existing measures for mass transit subsidies, several incentive schemes to encourage the transition to alternative fuel-bus technologies are already commonplace worldwide (ARB, 2015). The incentives mainly intend to reduce the bus purchase and ownership costs to encourage the transition to these technologies. Table 8 summarizes the computed economic costs for each fuel-bus technology of the above government subsidy schemes assuming an average annual mileage of 100,000 km per bus.

Table 8: Government subsidy for mass transit bus total cost in USD/bus.km.

BUS TECHNOLOGY	DIESEL	CNG	SERIES HYBRID	PARALLEL HYBRID	ELECTRIC
Government subsidy (USD/bus.km)	0.411	0.467	0.560	0.560	0.696

ENVIRONMENTAL BENEFITS 5.3

The TTW GHG emissions for each fuel-bus technology, computed in section 4, were compared to the GHG emissions of the baseline diesel bus and the resultant savings are presented in Table 9. Note that these results are for operation with the use of climate control auxiliaries.

Table 9: Tank-to-Wheel GHG emissions savings in g CO_2 eq./bus.km.

BUS TECHNOLOGY	DIESEL	CNG	SERIES HYBRID	PARALLEL HYBRID	ELECTRIC
severe congestion	-	81	586	1108	4360 (1372)(1)
peak conditions	-	269	195	335	2476 (654)(1)
off-peak conditions	-	196	72	83	1598 (330)(1)
BRT operation	-	113	-54	72	857 (91)(1)

(1) WTW GHG emissions savings of battery electric bus compared to diesel bus.

As can be seen from the table above, BEBs have the highest TTW GHG emissions savings compared to diesel bus regardless of driving conditions, however there are emissions on the WTT power plant side. Nonetheless, BEBs also present the highest GHG emissions savings on the WTW level.

COST BENEFIT ANALYSIS RESULTS

5.4

The TTW GHG emissions savings for each fuel-bus technology over the reference diesel bus were attributed to the corresponding total bus cost in order to prioritize the different technologies by their environmental-to-cost performance. Note that this method was used to avoid the sometimes controversial approach of assigning a carbon cost. The results are presented in Figure 31 for severe congestion conditions, and Figure 32 for BRT operation on a dedicated lane, as the two opposite extremes of city bus operating conditions.

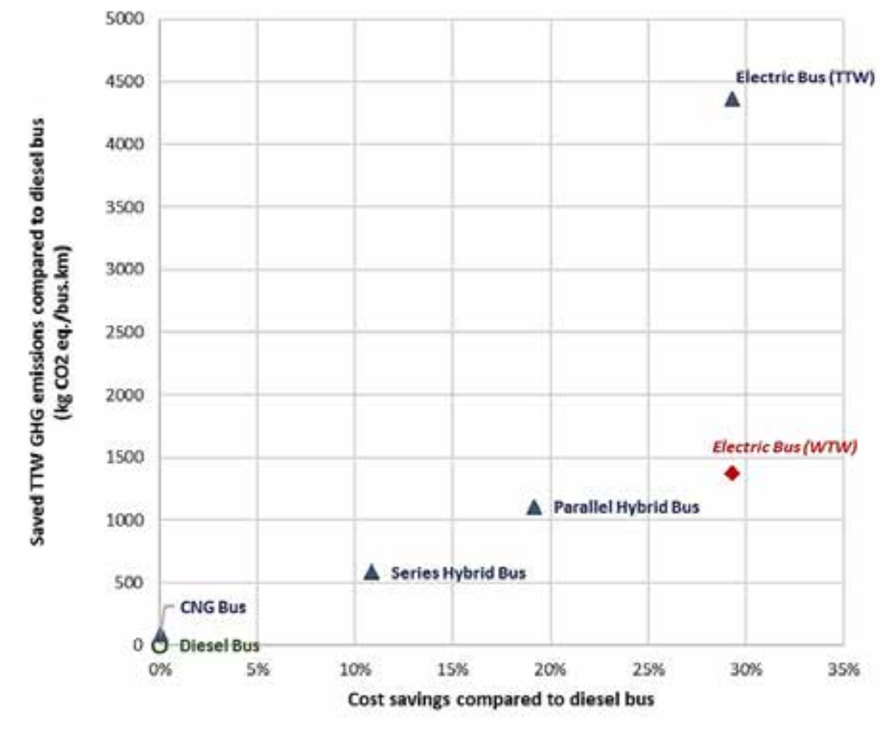

Figure 31: Environmental-to-cost performance of fuel-bus technologies relative to diesel bus in severe congestion operation.

As can be seen in the above figure, BEBs provide the highest TTW CO_2 emission savings at almost 30% lower total cost (capital and operating) than the baseline, making them the best performing technology. Note that this assumes the same percent level of subsidy across all technologies (80% of the purchase price of the vehicle, including customs, excise and registration) which means BEBs benefit from a larger subsidy amount since the vehicle purchase cost is highest. In addition, BEBs have a lower maintenance cost than diesel buses. However, the GHG savings contribution of this technology drops by nearly 67% when WTT emissions on the power plant side are taken into consideration, assuming electricity is generated from natural gas. This means a clean electricity mix is essential to be able to operate BEBs in an environmentally beneficial way.

Behind BEBs are the hybrid configurations, with parallel hybrids providing nearly double the environmental and cost savings than the series configuration under severe congestion conditions in the Lebanese context. This is because in these driving conditions, the bus idle time is high, and the diesel engine is turned on more often to power the climate control auxiliaries. Therefore, since the series hybrid powertrain efficiency is lower than the efficiency of parallel hybrid powertrain under these conditions, parallel hybrid bus is less costly to operate in this context, due to the lower fuel consumption.

CNG technology offers almost no improvement in CO_2 emissions or cost savings over the baseline diesel bus in severe congestion conditions, due to the higher ownership costs of the bus technology and the higher fuel consumption as a result of the lower fuel energy density of natural gas. However, it should be kept in mind that the environmental performance of CNG is much better than diesel when it comes to pollutant emissions, specifically NO_x.

It is important to note that battery technologies are advancing at an accelerated pace, which is expected to make electric bus technologies capable of higher electric autonomy with a longer extended battery service life. In this case, zero battery replacement cost could be assumed over the vehicle service life, which would make the BEB and hybrid technologies even more cost-effective.

In contrast with severe congestion conditions, the performance of the considered technologies under free flow conditions typical of BRT operation on a dedicated lane change significantly, as shown in Figure 32.

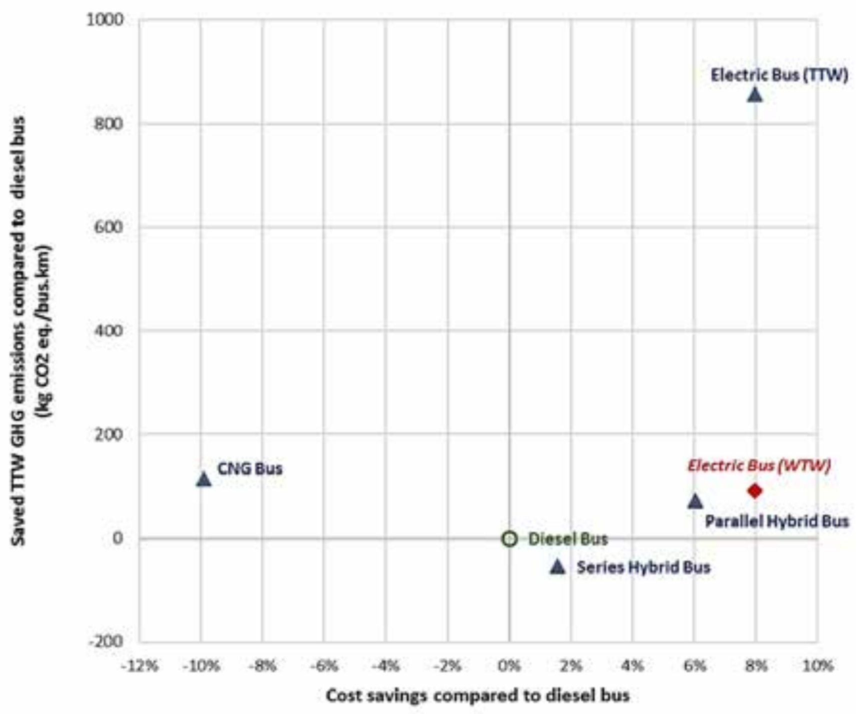

Figure 32: Environmental-to-cost performance of fuel-bus technologies relative to diesel bus in BRT operation.

As the figure above shows, diesel technology becomes much more efficient in free flow conditions, bridging the gap with electric buses and becoming more cost-effective than CNG. This is because diesel engines have their highest efficiency in free flow conditions.

BEBs remain the top performing technology, with 8% cost savings compared to diesel buses.

The series hybrid configuration becomes less environmentally beneficial than diesel in free flow conditions, since the bus is propelled all the time by the electric motor, which gets its electricity from an electric generator that is powered by the diesel engine. Therefore, the efficiency of the series hybrid bus is lower than the efficiency of the diesel bus due to the double energy conversion in the series hybrid powertrain, where energy is converted first from mechanical to electrical through the generator and then to mechanical again through the electric motor to propel the bus. Whereas, in diesel bus, the engine mechanical energy is used directly to propel the bus, while the engine is operating at high efficiency.

CNG bus technology was found to be only environmentally beneficial under BRT operation as it operates more efficiently, but at significantly additional cost since diesel technology becomes much more cost effective in free flow conditions due to lower fuel consumption.

Note that performance results of evaluated buses under peak and off-peak conditions will be in between the results presented above, with peak being closer to severe congestion, and off-peak more similar to BRT operation.

In summary, several important conclusions can be drawn from the cost-benefit results above, as follows:

- BEBs are the most efficient in terms of emission savings and costs, but this is dependent on subsidizing the purchase cost of the vehicle at the same rate as for the other less costly technologies, as well as generating electricity from a clean mix such as using natural gas in power plants.

- CNG bus provides little environmental and cost savings relative to diesel bus, but offers the advantages of less pollutant emissions, especially NOx. It is also suitable for BRT operation from an environmental perspective, but at higher cost relative to diesel, unless the price of natural gas is subsidized for public transport.

- The performance of series hybrids, which were found in the environmental assessment to be good performers in terms of energy use and emission savings, is now significantly affected by the use of climate control auxiliaries, making them less desirable than diesel technology, in particular under free flow conditions. However, parallel hybrids present good environmental-to-cost performance, making them the second preferred choice of bus technology after BEBs, under all driving conditions.

A sensitivity analysis on the price of diesel fuel and electricity tariff was done to assess their impact on the total cost of each fuel-bus technology, and ultimately on the choice of technologies, as shown in Figure 33.

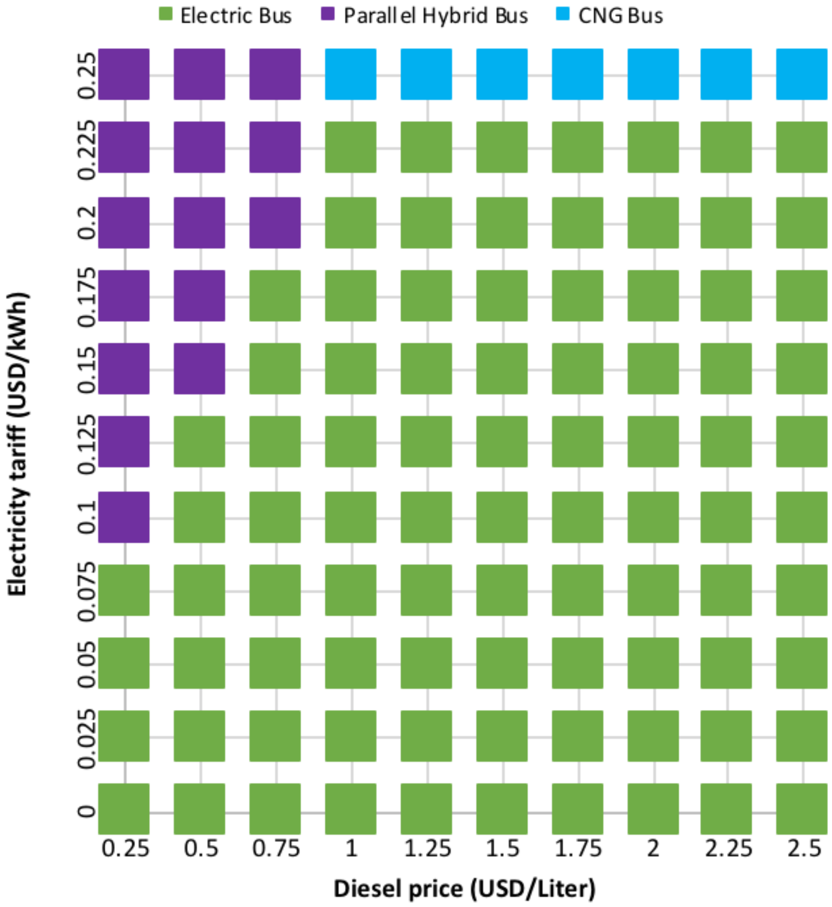

Figure 33: Sensitivity analysis on the total cost of fuel-bus technologies as function of electricity tariff and diesel price for a fixed CNG price of 0.5 USD/lge CNG.

As the figure shows, under a fixed price of natural gas at 0.5 USD/lge CNG, BEBs are the dominant technology unless electricity tariff becomes high (0.10 USD/kWh) and at the same time diesel prices become very low (below 0.75 USD/lge diesel), where parallel hybrids become more beneficial. On the other hand, CNG becomes the most beneficial technology if electricity tariff becomes very high (above 0.25 USD/kWh) for moderate to high diesel prices (1 USD/lge diesel and above).

Finally, for the dominant electric bus technology, additional sensitivity analyses on the price of diesel fuel, electricity tariff, charging infrastructure cost and maintenance cost was done to assess their impact on the total cost of BEBs relative to diesel on the two extreme bus operating conditions (severe congestion and BRT operation on dedicated lane), as shown in Figures 34 and 35.

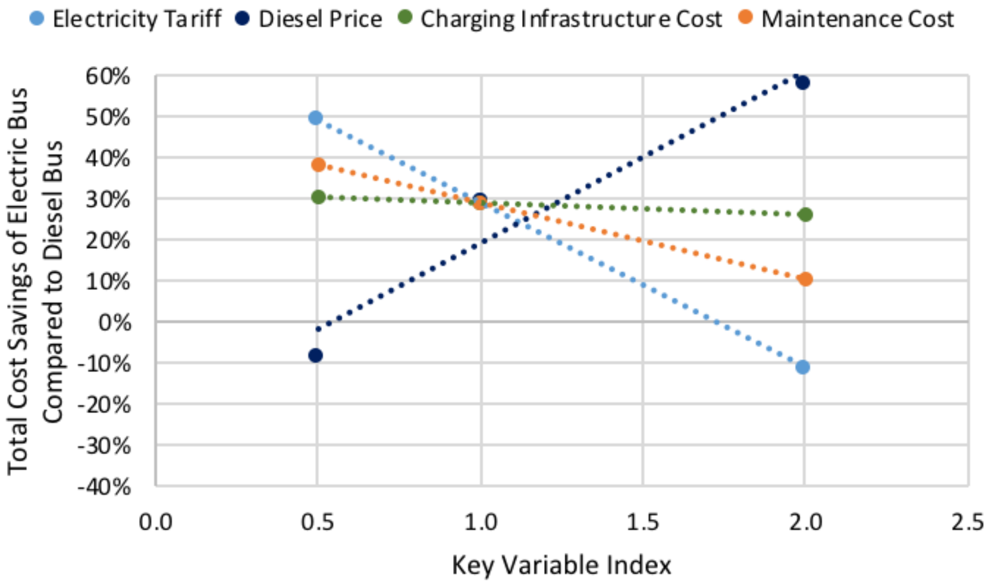

Figure 34: Sensitivity analysis for total cost savings of electric bus technologies relative to diesel bus in severe congestion operation.

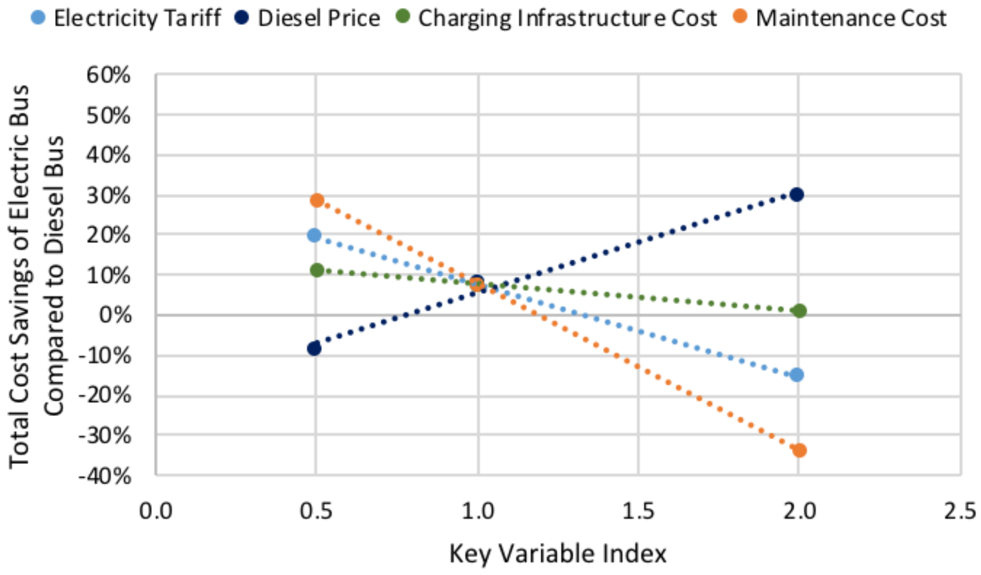

Figure 35: Sensitivity analysis for total cost savings of electric bus technologies relative to diesel bus in BRT operation.

The price of diesel fuel, electricity tariff, charging infrastructure cost and maintenance cost (referred to in the figures as “key variables”) were varied between half and double their initial values of 0.73 USD/liter, 0.13 USD/kWh, 50,000 USD/bus and 0.36 USD/km respectively. Some important conclusions can be drawn from this sensitivity analysis, as follows:

- The total cost savings of BEBs are sensitive to the electricity tariff and the diesel price under all driving conditions. For instance, if diesel price becomes double the current value of 0.73 USD/liter figure, and the electricity tariff is maintained at its current value of 0.13 USD/kWh, the cost savings of BEBs range between +30% and +60% relative to diesel bus. Similar trends in cost savings of BEBs are observed if the electricity tariff is incentivized for mass transit.

- The maintenance cost is also impactful on the total cost savings of BEBs. For instance, a reduction by half of the maintenance cost leads to increased cost savings by BEBs between +30% and +40% compared to diesel bus. It is noteworthy to mention that the maintenance costs of BEBs considered in this study are assumed identical to those of diesel bus because of the lack of maintenance cost data for BEBs. Note however that maintenance costs of BEBs are expected to be lower than those of diesel buses, due to having fewer components in electric bus powertrains. Therefore, the cost-saving results presented in this study underestimate the cost savings of BEBs, thus they are only indicative and should not be taken at their absolute values.

- The total cost savings of BEBs are not sensitive to the variation in the charging infrastructure cost, since this cost component (estimated at USD50,000 per CNG or BEB bus from previous studies) has a relatively small contribution to the capital cost.

Note also that the government subsidy plays an essential role in favoring the transition to cleaner bus technologies. The total cost savings of BEBs computed over the service life of the bus are illustrated in Figure 36 for different values of bus purchase subsidy and for all operating conditions. Under congested driving conditions, BEBs are always cost-effective when compared to diesel buses (over the service life of the bus) even when no subsidy is considered; however, diesel buses become cost-effective under free-flow driving conditions. To be competitive in congested conditions, BEB purchase cost needs to be subsidized by at least 20%, and up to 50% if the bus is to be operated in BRT-type of driving conditions. Note that BEBs ownership and maintenance costs are expected to decrease in the near future as the technology is improved, which can make BEBs competitive under free flow driving conditions for lower subsidy figures.

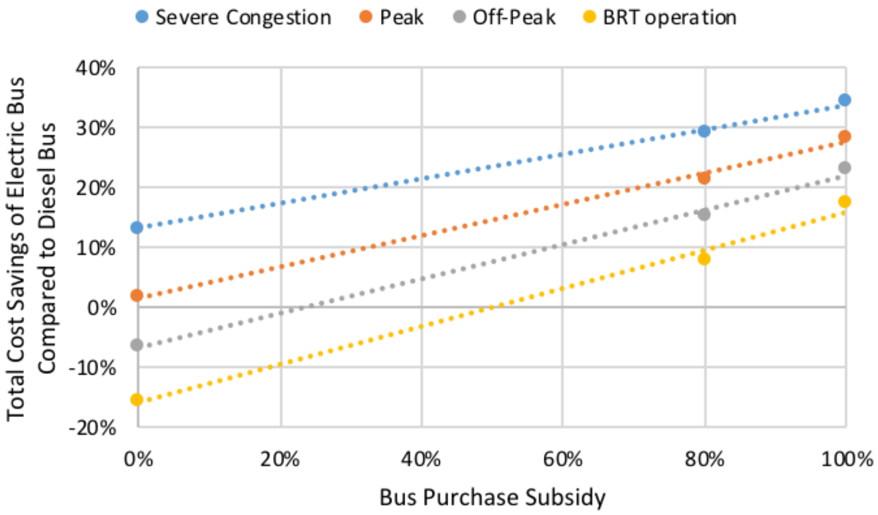

Figure 36: Total cost savings of electric bus technologies relative to diesel bus as function of bus purchase subsidy.

6

BARRIERS AND POSSIBLE ENABLING MEASURES FOR DEPLOYMENT OF ALTERNATIVE FUEL BUS TECHNOLOGIES IN LEBANON

GENERAL DESCRIPTION OF BARRIERS AND ENABLERS

6.1

The identified alternative fuel bus technologies, despite their promising potential for reducing environmental impacts and operating costs, nonetheless face different types of barriers to adoption and successful operation in the local context. For example, the high purchase cost of these technologies and the absence of backbone fuel distribution infrastructure pose a major challenge, in addition to the lack of any well-established and coordinated mass transit system in which to operate. Therefore, several enabling measures are needed to provide the proper framework for transitioning to the use of these cleaner bus technologies in a well-organized mass transit system, from financial incentives for reducing initial costs, to capacity building in human resources and infrastructure for proper operation.

The following methodology was used in this study to identify the main potential barriers and their corresponding enablers:

- Literature review and expert consultation meetings to identify and classify existing barriers facing bus operators in Lebanon under current conditions, and potential barriers to the possible adoption of alternative fuel bus technologies under a new centralized and coordinated mass transit system.

- Root-cause analysis of the classified existing and potential barriers and mapping to common enabling measures and solutions.

IDENTIFICATION OF BARRIERS FOR DEPLOYMENT OF ALTERNATIVE FUEL BUS TECHNOLOGIES IN LEBANON

6.2

The main conclusions from the undertaken analysis are as follows:

- The starter problem of not having an effective mass transit system is the current lack of urban transit planning, regulation, management and oversight of mass transit operations by the government.

- The main barriers are:

- The mismanagement of the existing old and unmaintained fleet, the poor bus network and the long travel time in common lanes with regular traffic.

- The high cost of new alternative fuel bus technologies and the absence of backbone fuel distribution infrastructure.

- The underdeveloped expertise with new technologies due to limited capacity of relevant institutions and insufficient number of specialized experts.

- The lack of regulatory framework to incentivize the use of low-carbon fuels in transport.

- The root cause to all barriers is the absence of transport policy at the national level, providing a coherent strategy for the mass transit sector to evolve into a sustainable, efficient and effective system (Haddad, Mansour, & Stephan, 2015).

Two main categories of barriers were identified, the economic and financial barriers, and the non-financial barriers which were further decomposed into sub-categories of barriers, namely the technical, policy/legal/regulatory, institutional/organizational capacity, and social awareness barriers.

6.2.1 ECONOMIC AND FINANCIAL BARRIERS AND ENABLERS

The main economic and financial barriers are the high costs of new bus technologies and their corresponding fuel infrastructure along with the lack of financial incentives in terms of customs, excise, tax and registration fees. The economic and financial barriers and the corresponding enabling measures are presented in Table 10.

Table 10: Financial barriers to the deployment of alternative fuel bus technologies.

ECONOMIC AND FINANCIAL BARRIERS	ENABLING MEASURES
Need for incentives for the private sector to transition to alternative fuel bus technologies under a new coordinated mass transit system operation.	• Provide financial subsidies for current bus operators to transition from ad-hoc operation of gasoline minivans and diesel buses to hybrid, electric and CNG bus technologies. • Adopt a Public-Private Partnership (PPP) or similar operating model as a potential solution for the inefficient and ineffective publically operated system.
High purchase cost of alternative fuel bus technologies.	• Exempt hybrid, CNG and electric buses from customs and excise fees. • Exempt hybrid, CNG and electric buses from VAT and registration fees. • Provide financial incentives to offset the high cost of batteries for electric and hybrid buses.
Absence of financial incentives for operating alternative fuel bus technologies.	• Exempt imported spare parts for bus maintenance from customs fees and excise tax • Remove fuel tax on CNG and electricity for public transport.
High implementation costs of recharging / refueling infrastructure required for electric and CNG buses.	• Build small-scale natural gas distribution infrastructure to serve the main bus depots and upgrade facilities to accommodate refueling / recharging stations.

6.2.2 NON-FINANCIAL BARRIERS AND ENABLERS

Financial measures cannot guarantee alone the success of deployment of alternative fuel bus technologies. There are also different types of non-financial barriers, consisting mainly of the lack of technical experience with the use of alternative fuel bus technologies, and the absence of institutional capabilities and a regulatory framework for an effective transition to these new technologies. The decomposition of non-financial barriers is presented in Table 11.

Table 11: Decomposition of non-financial barriers to the deployment of alternative fuel bus technologies.

TECHNICAL BARRIERS	ENABLING MEASURES
Lack of clean electricity source for powering electric buses.	• Develop the electricity infrastructure to run on natural gas and renewable fuel sources in order to provide clean power for mobility.
Concerns about driving range, load capacity limitations, service life and operating and maintenance costs of hybrid and electric buses.	• Establish pilot test-drive programs to build operator and driver experience with range and capacity capabilities of hybrid and electric bus technologies to prove their functionality on specific routes, in hot and cold weather conditions, and in peak and off-peak traffic conditions. • Establish pilot training programs to build maintenance experience with hybrid and electric buses especially with high voltage circuits and new motors in the powertrain, and to prove the durability of batteries in the local environment. • Establish maintenance and operation monitoring programs and centralized databases to provide operators with benchmark statistics and guidance information.
Concerns about reliability and safety of CNG buses.	• Establish pilot training programs to build maintenance experience with CNG buses, and to prove their reliability and safety in the local environment.
Concerns about battery disposal responsibilities and costs.	• Regulate the safe disposal of hybrid and electric bus batteries. • Develop a local industry for recycling and refurbishing electric batteries.

POLICY, LEGAL AND REGULATORY BARRIERS	ENABLING MEASURES
Lack of government policy to incentivize the use of low-carbon fuels in transport.	• Establish a clear government policy to reduce reliance on tax revenues levied on fuel imports, and develop a strategy roadmap to meet the government's INDC commitments to reduce GHG emissions by 15% by 2030.
Absence of standards for refueling/recharging, maintenance and inspection of alternative fuel buses.	• Establish standards, procedures and specifications for refueling and maintenance of CNG and electric bus systems, including for compression and discharge of natural gas, handling high electric voltage levels, adopting charging equipment interfaces, and specifying battery requirements and technologies. • Regulate fuel efficiency and emission standards for alternative fuel buses by updating decree 6603/1995 relating to standards for operating diesel trucks and buses, monitoring and permissible levels of exhaust fumes and exhaust quality. • Update and enforce bus inspection program requirements to cover CNG, hybrid and electric buses.
Lack of urban transit planning.	• Dedicate lanes for buses within GBA to improve service performance of the mass transit system, and to maximize environmental performance of alternative fuel bus technologies. • Encourage municipalities to build parking garages to free up urban road space and allow reservation of lanes for mass transit buses. • Implement intelligent transport technologies such as transit signal priority on red lights in order to reduce frequency and duration of stops in traffic for buses.

INSTITUTIONAL AND ORGANIZATIONAL CAPACITY BARRIERS	ENABLING MEASURES
Lack of service and maintenance specialists.	• Recruit and train bus drivers on eco-driving practices • Recruit and train specialized maintenance technicians.
Need for specialized bodies and experts in transporta-tion planning and operations at the relevant ministries and institutions.	• Recruit and train technical, managerial and control staff to plan, manage and oversee the proper operation of the mass transit system. • Collaborate with R&D centers to optimize the operation of the transport network using new developments in simulation, data science and artificial intelligence, and to develop technical solutions for complex problems. • Conduct and participate regularly in knowledge sharing events to follow up on advancements in emerging technologies.
Reliance on foreign supply channels for spare parts.	• Develop a local industry for manufacturing critical repair spare parts.

SOCIAL AWARENESS BARRIERS	ENABLING MEASURES
Lack of awareness of the ecological and economic benefits of alternative fuel bus technologies.	• Disseminate information (e.g. through media campaigns, online websites and mobile applications) about the fuel, cost and CO_2 savings of alternative fuel bus technologies to build awareness and confidence among operators and riders.

7

CONCLUSION

This study assessed the potential savings in terms of energy consumption, GHG and pollutant emissions and total costs from different alternative fuel-bus technologies relative to diesel bus in Lebanese real driving conditions. The results of the cost-benefit analysis performed in this study show that:

- Battery-electric buses are the most efficient in terms of emission savings and total costs, but this is dependent on providing the same rate of subsidy (80% of the purchase cost of the bus) as for the other technologies, as well as on generating electricity from a clean energy mix using natural gas and renewable energy sources in power plants.

- Parallel hybrids also present substantial emission reductions at less cost than diesel bus technology, making them the second preferred choice after battery electric buses.

- Series hybrids are good performers in peak traffic conditions, but their energy use and emission savings are significantly reduced when operating in hot or cold weather conditions which require the use of climate control auxiliaries, making them less desirable than diesel technology in those conditions. However, it is important to note that all technologies become less efficient overall when using cabin cooling or heating due to the additional fuel consumption required.

- Compressed natural gas buses do not provide significant savings in terms of greenhouse gas emissions and total cost relative to diesel bus, but have the advantage of emitting lower amounts of harmful pollutants, especially NOx, than the other technologies except electric buses.

Other important conclusions that can be drawn from the results of the energy and environmental modeling in this report are that:

- All of the considered technologies are more fuel efficient, and therefore less polluting under free-flow traffic conditions similar to BRT operation on a dedicated lane, as opposed to standard bus operation in traffic, with electric bus being the most performing technology (electric powertrains are in fact the most robust against variations in traffic conditions).

- CNG is also suitable for BRT type operation from an environmental perspective, but at higher cost relative to diesel.

However, the costs of backbone infrastructure for natural gas and electricity, which are not considered in this study, can have significant implications on the overall cost of implementing these technologies by the government. This is why it is useful to consider a phased construction strategy for these infrastructures that sets the appropriate scale and deployment timeline for each infrastructure type.

Since electric-bus offers the highest environmental benefits and is the most promising technology for the long-term, a sensitivity analysis was done on different cost components of this technology to determine its most important enablers in the local context. It was found that the total cost of battery-electric bus is affected most by the price of diesel fuel, the electricity tariff, and the cost of bus maintenance relative to diesel. This means that for electric bus technology to be attractive compared to diesel, it may be necessary to maintain government subsidy on electricity tariff for public transport, especially if diesel fuel prices are low. In addition, it is important to develop the necessary competencies for servicing hybrid and electric bus technology, as well as CNG buses, in order to reduce maintenance costs in the future.

Finally, it is important to note that the benefits of alternative fuel-bus technologies can only be maximized and sustained if the transition to these cleaner technologies is part of a comprehensive national transportation strategy for revitalizing public transportation services. This entails the development of a well-planned and coordinated mass transit network with the necessary support services for proper management and operation.

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9

APPENDIX

APPENDIX A: BUS FACT SHEETS

Figure A.1: Diesel Bus (figure shown is for illustration purpose only).

Table A.1: Specifications of Diesel Bus.

CATEGORY	PARAMETER	UNITS	VALUE
Dimensions	Length	mm	12,000
	Mass (half/full occupancy)	kg	14,300/16,750
	Fuel Tank capacity	l	250
Performance	Maximum velocity	km/h	85
	Fuel consumption	lge/100 km	39 - 47.5
	Driving range	km	600 - 900
Engine	Maximum power	kW/HP	228/310
	Maximum torque	Nm	1,300
	Engine Displacement	Liters	8.7
Cost		USD	264,000 - 435,000

Figure A.2: CNG Bus (figure shown is for illustration purpose only).

Table A.2: Specifications of CNG bus.

CATEGORY	PARAMETER	UNITS	VALUE
Dimensions	Length	mm	12,000
	Mass (half/full occupancy)	kg	14,800/17,250
	Fuel Tank capacity	l	1,280
Performance	Maximum velocity	km/h	70
	Fuel consumption	lge/100 km	53
	Driving range	km	350 - 400
Engine	Maximum power	kW/HP	213/290
	Maximum torque	Nm	1,100
	Engine Displacement	Liters	8.7
Cost		USD	300,000 - 485,000

Figure A.3: Series hybrid bus (figure shown is for illustration purpose only).

Table A.3: Specifications of series hybrid bus.

CATEGORY	PARAMETER	UNITS	VALUE
Dimensions	Length	mm	12,000
	Mass (half/full occupancy)	kg	15,450/17,900
	Fuel Tank capacity	l	180
Performance	Maximum velocity	km/h	70
	Fuel consumption	lge/100 km	38
	Driving range	km	600 - 900
Engine	Maximum power	kW/HP	210/286
	Maximum torque	Nm	1,000
	Engine Displacement	Liters	6.7
Generator	Maximum power	kW	140
Electric motor	Maximum power	kW	175
	Maximum torque	Nm	3,300
Battery	Capacity	kWh	11
	Maximum power	kW	200
	Voltage	V	630
Cost		USD	360,000 - 640,000

Figure A.4: Parallel hybrid bus (figure shown is for illustration purpose only).

Table A.4: Specifications of parallel hybrid bus.

CATEGORY	PARAMETER	UNITS	VALUE
Dimensions	Length	mm	12,000
	Mass (half/full occupancy)	kg	15,450/17,900
	Fuel Tank capacity	l	205
Performance	Maximum velocity	km/h	NA
	Fuel consumption	lge/100 km	38
	Driving range	km	600 - 900
Engine	Maximum power	kW/HP	177/240
	Maximum torque	Nm	918
	Engine Displacement	Liters	5.1
Electric motor	Maximum power	kW	118
	Maximum torque	Nm	800
Battery	Capacity	kWh	11
	Maximum power	kW	200
	Voltage	V	630
Cost		USD	360,000 - 640,000

Figure A.5: Electric bus (figure shown is for illustration purpose only).

Table A.5: Specifications of electric bus.

CATEGORY	PARAMETER	UNITS	VALUE
Dimensions	Length	mm	12,000
	Mass (half/full occupancy)	kg	15,000 - 18,000
Performance	Maximum velocity	km/h	NA
	Fuel consumption	lge/100 km	1.4
	Driving range	km	100 - 250
Electric motor	Maximum power	kW	160
	Maximum torque	Nm	400
Battery	Capacity	kWh	76 - 300
	Maximum power	kW	NA
	Voltage	V	630
Cost		USD	492,000 - 800,000