IAPE '19, Oxford, United Kingdom
ISBN: 978-1-912532-05-6

Rethinking bus transit in a developing country of the Middle East: Energy consumption and emissions of alternative fuel bus technologies in the Greater Beirut Area

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ABSTRACT
This study investigates the potential reductions in energy use, greenhouse gas and pollutant emissions from natural gas, hybrid and battery electric buses compared to diesel bus in real driving conditions in Lebanon, a developing country of the Middle East with an unsustainable road transportation system. A Euro V compliant 12-meter bus is considered in the modelling, and appropriate real driving cycles are developed for four operating conditions including severe congestion, peak, off-peak and bus rapid transit operation. Results show that accounting for additional energy consumption from the use of climate control auxiliaries can significantly impact the performance of all bus technologies in this context, by 26.4% for compressed natural gas bus and up to 45% for parallel-hybrid electric bus. The energy consumption and environmental performance of all fuel bus technologies improve considerably in free-flowing traffic conditions, making bus rapid transit operation the most beneficial. Battery electric buses are found to be the best performers in all traffic conditions, conditional on having a clean energy supply at the power plants. Compressed natural gas buses do not provide significant GHG emission savings compared to diesel bus, but offer substantial reductions in the emission of harmful pollutants.

Keywords
Real driving conditions; alternative fuels; transit buses; energy consumption; greenhouse gases; pollutant emissions; developing countries.

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 public transit buses in the USA use alternative fuels or hybrid technology, with 16.9% using hybrid-electric technology, 16.7% using natural gas fuels and 7.4% using biodiesel [1]. Some of the main reasons for the switch away from conventional fuels are the usually increasing oil prices, and the adverse environmental impacts of gasoline and diesel vehicles compared to the advantages of low-carbon fuels. This is especially true when comparing gasoline and diesel fuels to natural gas which burns much cleaner at relatively low price, making it an attractive alternative fuel for buses. In addition, new environmental regulations and incentive programs, such as those implemented in the U.S. state of California have encouraged the introduction of advanced bus technologies having zero tailpipe emissions during normal operation, such as battery electric buses.

However, these advances have yet to take hold in developing countries with limited resources and inadequate road transportation infrastructure. This is the case in Lebanon where public transport is highly inefficient and ineffective, with people relying exclusively on their motorized vehicles and having to live with extensive traffic congestion and air pollution. This makes the road transportation system in Lebanon one of the most unsustainable in the Middle East region [2]. However, the recent discovery of offshore natural gas reserves has raised interest in exploring the use of this fuel and other clean fuels in the local road transportation sector, and prompted new studies for revitalizing the public transport system. Therefore, this study assesses the energy and environmental performance of alternative fuel buses in real world local conditions in order to determine the savings potential of each technology relative to conventional diesel bus.

2. OVERVIEW OF PUBLIC TRANSPORT IN GBA
The public transport sector in Lebanon consists of public and private buses, minivans and taxis (exclusive and shared-ride), all operating ad-hoc without centralized management or coordination. The sector is under the jurisdiction of the Railways and Public Transport Authority (RPTA) which currently operates only 37 buses on nine routes between three main hubs in the Greater Beirut Area (GBA) where over 2 million people reside, meeting less than 3% of the total demand for public transport [3]. This is because the majority of rail and bus assets, including vehicles and stations, were damaged in the Lebanese war of 1975-1990, with much of the remaining assets out of operational service due to limited resources and mismanagement issues. As a result, private operators have emerged to satisfy the remaining demand, most of which operate without a license and do not abide by regulations and standards related to safety, emissions or passenger comfort, among others. For example, there are no dedicated bus stops in GBA and therefore no fixed service schedules on bus routes, which leads to an overall poor quality of service and very low occupancy rates of about 1.2 passengers per vehicle for taxis, 6 for vans and 12 for buses [2].

Consequently, public transport accounts for less than a third of total passenger transport activity in the GBA [4]. This limited

DOI: http://dx.doi.org/10.17501

share of the market (compared to about 53% for typical European cities) continues today as the sector has not seen any further development in the service network or any improvement in fuel or bus technologies over the past two decades. However, in early 2018, a national strategy for public transport was proposed by the RPTA aimed at restructuring the public transport sector at a cost of over USD 53 million, including the organization of service operations, the upgrading of infrastructure and the enforcement of regulations. In parallel, the World Bank approved a USD 295 million loan for the launch of a bus rapid transit (BRT) system consisting of 120 clean fuel buses operating along the northern entrance of the GBA on a physically separated and dedicated lane over 28 kilometers with 28 new stations. In addition, the BRT system would operate inside Beirut along a 12 km outer ring road where buses can run on a reserved right lane, serving 21 new bus stations, and a 16 km inner ring road where buses would run with traffic on the right lane, serving 19 new bus stops [5].

All of this presents real opportunities for significantly improving the performance of the public transport sector over the currently unsustainable business-as-usual scenario, expanding its market share at the expense of the polluting passenger vehicles on the road, and further reducing road transport emissions with the planned use of cleaner fuel bus technologies.

It is also noteworthy that while buses constituted only 1% of the total road vehicle fleet in Lebanon in 2010, they nonetheless accounted for a significant share of fuel consumed in transport in the same year, at around 5.6% of total road transport energy consumption, with the majority of these vehicles operating on diesel fuel [6]. Furthermore, 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 as shown in Figure 1, which is a direct consequence of the expected increase in transport activity. Note that these trends assume 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) of reducing national GHG emissions according to the 2016 Paris agreement's Intended Nationally Determined Contribution (INDC) [7].

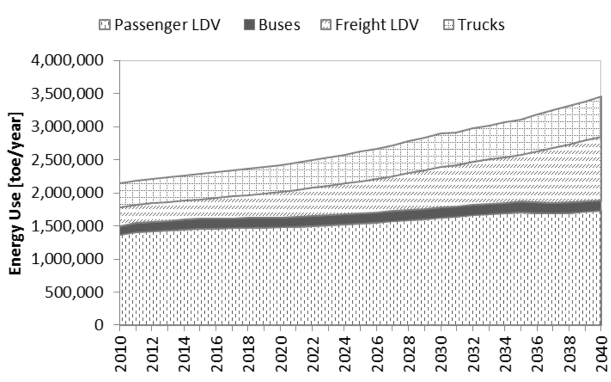

Figure 1: Baseline projection of energy use in road transport in Lebanon [3].

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 direct GHG emissions of CO_2, CH_4 and N_2O, mainly from road transport [8]. Figure 2 illustrates the increasing trend of GHG and criteria pollutant emissions, with some emissions increasing by over 200% between 1994 and 2010.

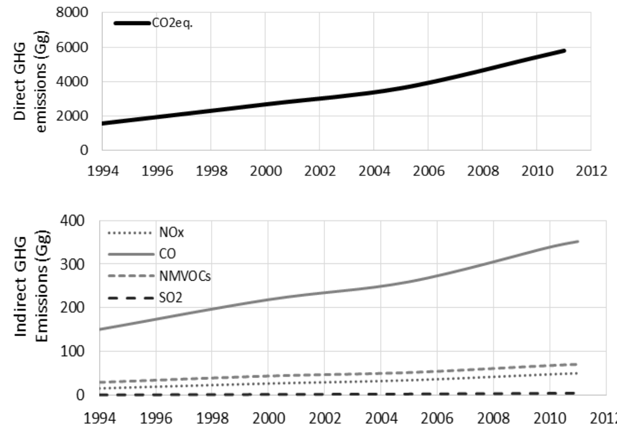

Figure 2: GHG and pollutant emission trends for road transport in Lebanon [3].

Therefore, the revitalization of the public transport sector and the use of clean fuel bus technologies are essential for mitigating the currently unsustainable trends of energy use and emissions, thereby helping to ensure that Lebanon can meet its INDC commitments.

3. MODELING METHODOLOGY

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 software tool "Advanced Vehicle Simulator" (ADVISOR) developed by the National Renewable Energy Laboratory (NREL) [9]. A Euro V compliant 12-meter bus is used as a common platform for all considered bus technologies.

The modeling requires the following inputs:

a) weather conditions;

b) local driving patterns on the bus route, namely the variation of bus speed over time known as the vehicle driving cycle, reflecting bus stop duration and frequency, trip length, traffic conditions and driver behavior; and,

c) vehicle characteristics such as the mass of the vehicle and its main components, and the vehicle's powertrain control strategies for the use of the fuel and the electric energy stored in the battery, in addition to the auxiliary power loads for heating and cooling of the cabin.

The data for local driving patterns were developed by conducting an on-road travel survey using a GPS device placed on-board a bus in operation in the GBA, and subsequently creating representative bus driving cycles for the GBA following a similar methodology as for passenger vehicles detailed in [10]. Data was collected over a period of five months, covering all times of the day from 5:00 am to 7:30 pm and therefore all traffic conditions (severe congestion, peak and off-peak).

The collected data served to capture standard bus operation in GBA which involves low speeds and frequent stops of relatively short duration. For BRT bus operation, and since this service has

DOI: http://dx.doi.org/10.17501

not yet been implemented in the GBA, the BRT driving cycle was developed using design data provided by local stakeholders describing the proposed dedicated lane service with relatively high speeds and fewer stops (every one kilometer). 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 required vehicle characteristics for the energy and emissions modeling of the considered bus technologies were obtained from original equipment manufacturer (OEM) bus data sheets.

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 in ADVISOR for the different technologies considered in this study to account for differences in the powertrain component architectures. A reference diesel bus is first specified and its energy consumption and GHG emissions are simulated in ADVISOR to serve as the baseline for comparison with other bus technologies. The other bus technologies are then modelled using the same glider mass (the mass of the vehicle without the powertrain components) as the reference bus, but accounting for additional weight from the battery pack and electric motor, and any other differences in powertrain components and engine power and efficiency maps, but maintaining the same driving performance. This results in different total mass values for the different bus vehicles.

The vehicle characteristics of the reference bus are shown in Table 1, and the total mass of the considered bus technologies are shown in Table 2.

Table 1: Characteristics of the reference bus.

Glider Mass (kg)	Aerodynamic Drag Coefficient (-)	Frontal Area (m^2)
10,600	0.52	7.5

Table 2: Total mass of bus vehicle (kg).

Diesel bus	CNG bus	Series hybrid bus	Parallel hybrid bus	Electric bus
14,515	14,800	15,940	15,450	16,250

The power consumption of auxiliary systems used on the considered buses, which can significantly affect fuel consumption, were accounted for in the bus models, as presented in Table 3 [11].

Table 3: Auxiliaries power consumption.

Fuel bus technology	Electro-mechanical auxiliaries power	Climate control auxiliaries power
Diesel and CNG buses	9,000 W	13,400 W
Hybrid and electric buses	5,250 W	14,000 W

The model outputs are the resulting bus energy consumption and on-road emissions as simulated on the developed GBA driving cycle.

4. RESULTS AND DISCUSSION

The modeling results presented in this section cover three types of impacts: energy consumption, greenhouse gas emissions and pollutant emissions.

4.1.1 Energy consumption

The results for energy consumption for each of the fuel bus technologies in GBA off-peak driving conditions are shown in Figure 3. 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. Note that these results are for full bus occupancy as a conservative estimate.

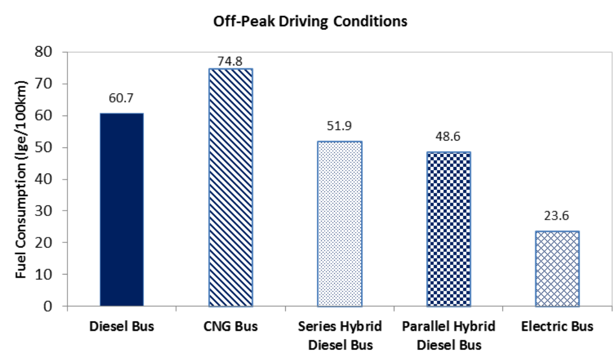

Figure 3: energy use of the assessed bus technologies in off-peak driving conditions.

As can be seen from the figure above, the diesel bus has the second highest consumption after CNG bus with 60.7 lge/100km. The CNG bus consumes more energy than diesel by 23% due to the lower energy content of natural gas, however with cleaner air emissions as discussed in the following subsection on emissions. In contrast, 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 liter gasoline equivalent per 100 kilometers than diesel and are the most efficient technology out of all those considered.

While the above figure clearly shows the energy efficiency advantage of alternative fuel bus technologies compared to the standard diesel bus, the possible variations of driving conditions in the real world, namely peak traffic, severe congestion and a

DOI: http://dx.doi.org/10.17501

BRT-type of operation on a dedicated lane currently being considered for bus service in GBA, can change the energy performance of each technology and its overall benefit relative to the other technologies considered.

Figure 4 compares fuel consumptions under these four scenarios for the reference diesel bus, illustrating the significant impact of traffic conditions on fuel consumption.

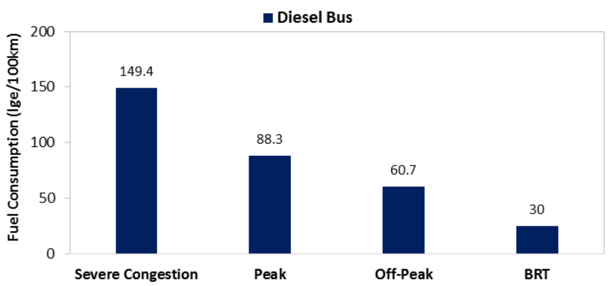

Figure 4: energy use of the diesel bus technology under different types of driving conditions.

The results show that improved fuel consumptions are achieved as the driving conditions become more free-flowing relative to severe congestion, from 41% for peak traffic conditions to 80% for BRT type of 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 traffic. 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 behaviour, which impact powertrain efficiency.

A similar trend is observed for all other bus technologies, as shown in Figure 5 for electric bus as an example.

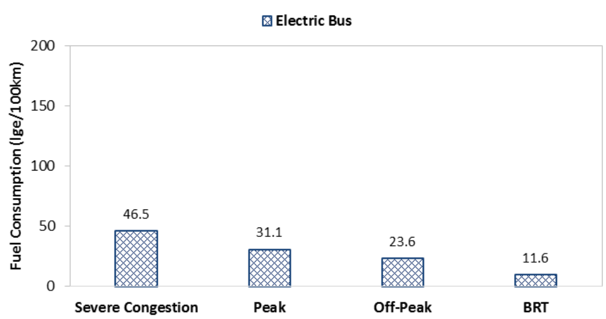

Figure 5: energy use of electric-bus technology under different types of driving conditions.

Electric buses remain the most efficient out of all the technologies considered under all driving conditions, and are the most robust against variations in those conditions, as illustrated in the minor differences in energy consumption for the electric bus across the different conditions considered.

However, 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 Figure 6 (without use of air conditioning) and Figure 7 (with use of air conditioning) below. 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).

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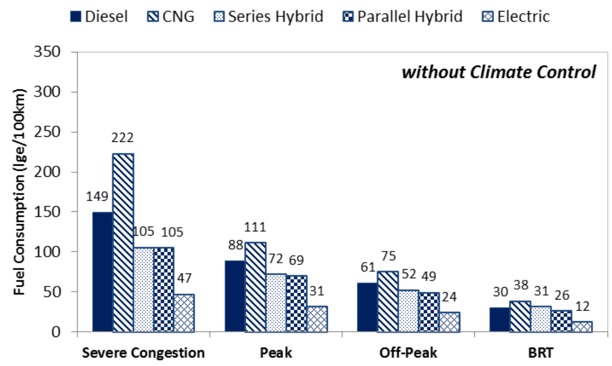

Figure 6: energy use of the assessed bus technologies without use of climate control auxiliaries.

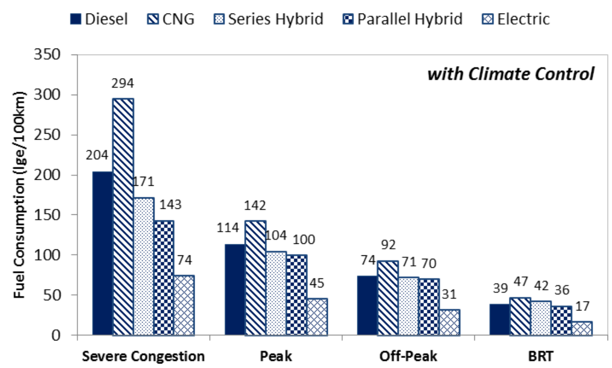

Figure 7: energy use of the assessed bus technologies with use of climate control auxiliaries.

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.

As the figures above show, the considered bus technologies consume on average 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 bus has the highest fuel consumption in liter gasoline equivalent 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 bus 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

ISBN: 978-1-912532-05-6

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 type of operation than for standard bus operation, and that the electric bus in BRT operation is the most fuel-efficient.

4.1.2 GHG emissions

The GHG emissions (CO2, CH4 and N2O) for all bus technologies when operating without climate control auxiliaries in off-peak conditions are presented in Figure 8, and in Figure 9 when operating with the use of climate control.

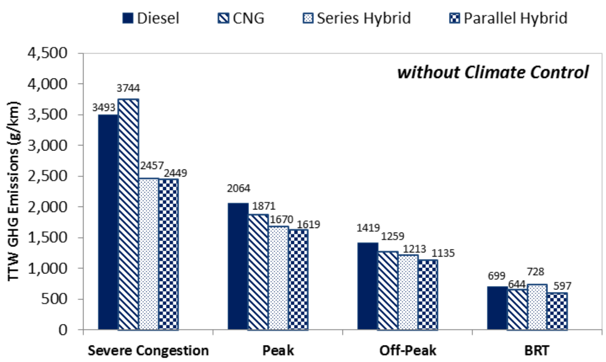

Figure 8: GHG emissions of the assessed bus technologies without use of climate control auxiliaries.

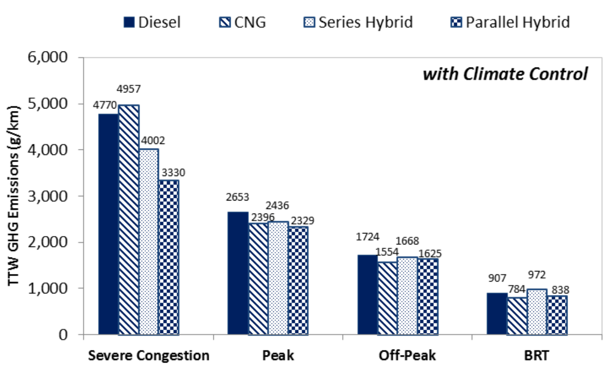

Figure 9: GHG emissions of the assessed bus technologies without use of climate control auxiliaries.

It can first be observed from comparing the above figures that the use of climate control auxiliaries has a significant impact on GHG emissions for all bus technologies. For example, additional GHG emissions from the use of climate control range 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 consumed to power auxiliaries as explained in the previous sub-section.

The lowest GHG emissions for all bus technologies occur under BRT operation, and are significantly lower than those estimated under standard bus operation. The difference is smallest when operating without the use of climate control auxiliaries, where parallel-hybrid technology is estimated to emit 40% less GHG emissions in BRT compared to off-peak conditions. This difference becomes even more significant when using climate control auxiliaries where CNG bus is estimated to emit 84.1% less GHG emissions in BRT compared to severe congestion traffic. This environmental benefit 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 service where series-hybrid has a higher contribution than diesel (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.

Note that GHG emissions for electric bus are zero under all conditions since the use of the battery for on-road operation does not consume hydrocarbon fuels, and therefore the on-road emissions, known as tank-to-wheel (TTW) emissions, are zero. This makes electric bus 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 for recharging batteries on-board, and therefore the total contribution of this technology to GHG emissions should account for generated emissions on the electricity supply side, known as well-to-tank (WTT) emissions. Reducing the quantity of WTT emissions depends on having a clean energy mix at the power plant [12]. Therefore, electric 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 [13]. Figure 10 contrasts the WTT GHG emissions under current (2015) and future (2030) electricity mix scenarios for Lebanon, showing significant potential reductions in these emissions if the energy mix is cleaned up by 2030.

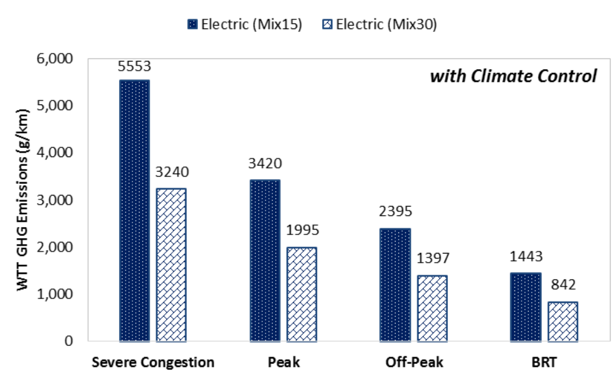

Figure 10: WTT GHG emissions of electric bus technologies under the 2015 versus 2030 electricity mixes.

4.1.3 Pollutant emissions

The emission results for each criteria pollutant are presented in this subsection by type of driving conditions for all considered bus technologies, except electric buses which have zero on-road pollutant emissions. The results are compared against the corresponding EURO VI emission standards, where applicable. Note that emission standards are for bus operations without the

DOI: http://dx.doi.org/10.17501

use of climate control auxiliaries; however, the results used are for bus operations with use of climate control auxiliaries as 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 11 presents the modeling results for VOC emissions, and shows that all bus technologies are compliant in almost all driving conditions with only one exceedance (by 2.1%) for CNG bus in severe congestion conditions. Hybrid technologies are the next best performers after fully-electric buses, with equivalent performance by CNG bus technology as conditions become more free-flowing.

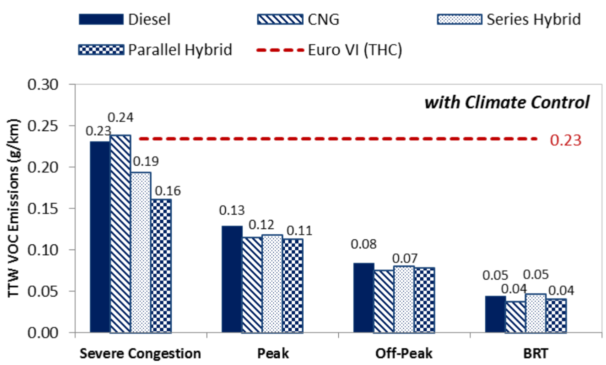

Figure 11: VOC emissions of the assessed bus technologies under all driving conditions.

For CO emissions shown in Figure 12 below, exceedances are again estimated in severe congestion conditions only, by 18.5% (series hybrid) and 48.1% (CNG), with CO emissions in all other conditions well below the standards. Therefore, all of the considered bus technologies can be effective contributors to cleaning the air quality inside the city and in urban areas if traffic congestion is reduced, or if bus service on a dedicated lane is implemented similar to a BRT type of operation.

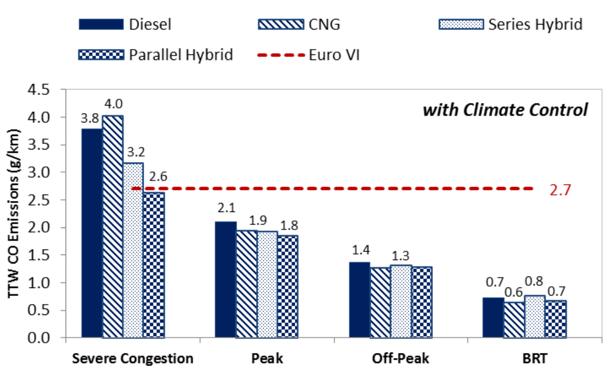

Figure 12: CO emissions of the assessed bus technologies under all driving conditions.

The picture for NOx, shown in Figure 13 below, is drastically different than for the previous two pollutants, as the Euro VI standards are much more stringent. Only operating under BRT conditions allows all technologies to be in compliance with the standards. Otherwise, exceedances in standard bus operation are estimated to range between 44% (parallel-hybrid) in off-peak conditions, and 322.8% (diesel) in severe congestion.

It is also noteworthy that CNG bus is significantly less NOx emitting than diesel and hybrid technologies under al driving conditions, making it the second preferred choice after battery electric bus.

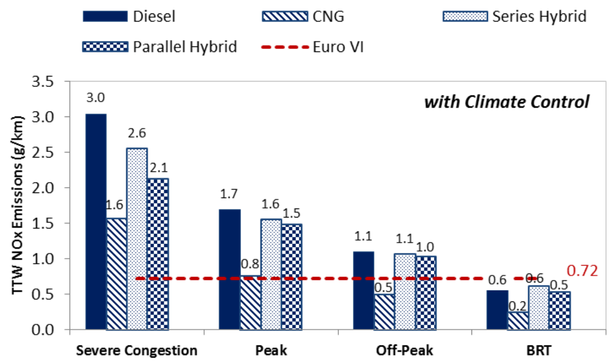

Figure 13: NOx emissions of the assessed bus technologies under all driving conditions.

For the PM10 results shown in Figure 14 below, all bus technologies are in compliance with the standards when under free-flowing conditions, namely BRT and off-peak operation. Maximum exceedances of 60.6% and 199.4% are estimated for diesel in peak conditions and CNG in severe congestion, respectively. Therefore, while all alternative fuel bus technologies are beneficial when it comes to VOC and CO emissions, a BRT-type of service on a dedicated bus lane is necessary for dealing with NOx and PM emissions effectively.

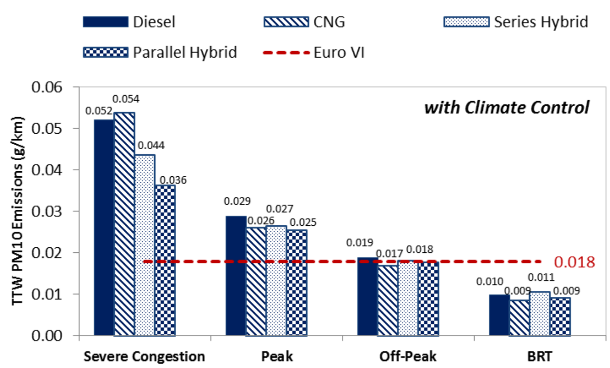

Figure 14: PM emissions of the assessed bus technologies under all driving conditions.

For SOx emissions shown in Figure 15 below, where no standard is available, the assessment results show that emissions in BRT operation are significantly lower for all bus technologies compared to other traffic conditions, with CNG bus being the best performer (after zero-emission electric buses which are not shown in the figures) across all driving conditions.

DOI: http://dx.doi.org/10.17501

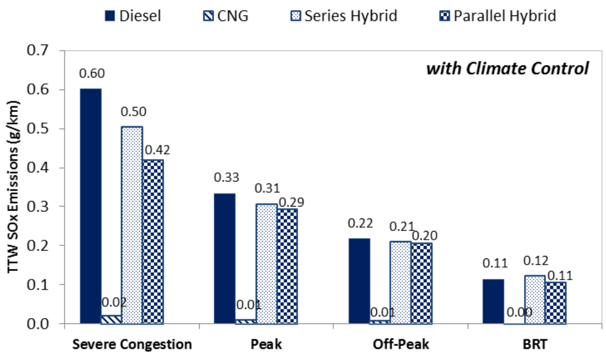

Figure 15: SOx emissions of the assessed bus technologies under all driving conditions.

Finally, comparing the performance of each technology across all five pollutants, it can be seen that CNG bus is relatively the best performer (after zero-emission battery electric buses) under all but the most congested driving conditions. This makes CNG bus relatively attractive for cleaning up polluted cities in developing countries such as Lebanon, especially until electric bus technology becomes more affordable and recharging infrastructure for electric buses becomes available.

Furthermore, and as explained in the previous sub-section for GHG emissions, it is important to keep in mind that the electricity for recharging batteries on-board electric buses involves emission of WTT pollutants from electricity generation on the power plant side. Therefore, it is important for Lebanon to clean up the energy mix at the power plant level by switching to cleaner fuels such as natural gas and renewable energy sources. 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 a BRT type of service.

WTT pollutant emissions for electric buses are reported in Figures 16 and 17 under the current 2015 and future 2030 resource mix.

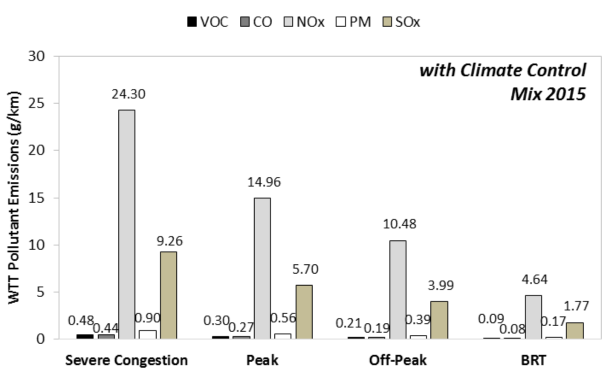

Figure 16: WTT pollutant emissions of electric bus technologies under the 2015 electricity mix.

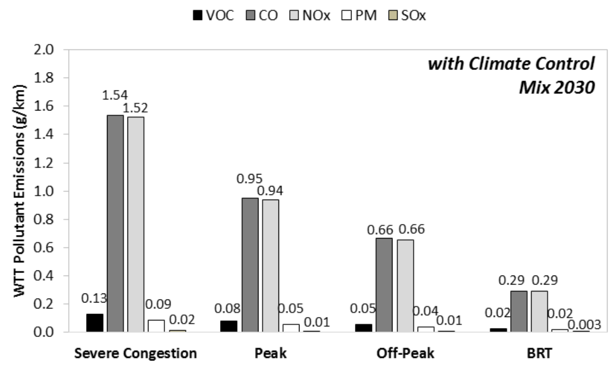

Figure 17: WTT pollutant emissions of electric bus technologies under the 2030 electricity mix.

As can be seen in the comparison of the figures above, the additional WTT emission from electricity generation is 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 internal combustion engine (ICE) technology in the power plants, and therefore this can also be mitigated in the future by using more efficient, cleaner technologies.

5. CONCLUSION

This study assessed the potential savings in terms of energy consumption, GHG and pollutant emissions from different alternative fuel bus technologies relative to diesel bus in GBA real driving conditions. The analysis of the modelling results show that:

- Battery-electric buses are the most efficient in terms of emission savings, but this is dependent on the use of electricity generated from a clean energy mix such as natural gas and renewable energy sources.
- Parallel hybrid technology also presents substantial emission reductions compared to diesel bus, making it the second preferred choice after battery electric buses, except when it comes to NOx and SOx pollutant emissions where compressed natural gas bus is cleaner.
- Series hybrids are good performers in peak traffic conditions, but their energy consumption and emission savings are significantly affected 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 GHG emissions relative to diesel bus, but have the advantage of emitting much lower amounts of some of the harmful pollutants, namely NOx and SOx, than all other technologies except battery electric buses.
- 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 best performing technology in all driving

conditions. Electric powertrains are in fact the most robust against variations in traffic conditions.

However, the costs of the vehicle technologies and required backbone infrastructure for natural gas and electricity, which are not considered in this study, can have significant implications on the overall potential for implementing these technologies, especially in developing countries with limited resources. It is therefore important to assess the total cost for each technology relative to its expected energy and environmental benefits in order to properly rank its applicability in the local context.

Finally, it is also 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.

6. ACKNOWLEDGMENTS

This project was funded by the United Nations Development Program (UNDP), with support from the Lebanese Ministry of Energy and Water and several local stakeholder companies and agencies which supplied valuable data and feedback.

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