Decarbonization in European Public Transit

A Well-to-Wheels study of the bus fleets of Barcelona, Stockholm and Warsaw

DAVID HUGHES

Master of Science, Energy Innovation
Date: November 1, 2018
Supervisor: Francesco Fuso Nerini
Examiner: Francesco Fuso Nerini
School of Electrical Engineering and Computer Science

Abstract

It is a current objective in many cities to reduce GHG emissions and energy consumption in their public transit fleets. Specifically, the electrification of bus lines are being considered for their reduction potential and alignment with 'Smart City' trends. This thesis aims to examine this in the context of the public bus fleets of Barcelona, Stockholm and Warsaw. Past and present fleet data was compiled, along with future plans in order to form the basis for a Well-to-Wheel analysis for each city's fleet. The trend suggests that the carbon intensity of the energy mix is a critical component in determining just how effective bus fleet electrifcation is in reducing emissions and consumption. There is also evidence of future emissions being pushed upstream, showing local reductions but lacking in overall reductions. Municipalities often have direct influence over their public transit system, and hopefully the information presented in this thesis can be used to help them make more informed decisions as to what the results of their plans will be, in order to develop their cities in line with a truly smart and sustainable model.

Acknowledgments

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Chapter 1

Introduction

1.1 General Background

The larger topic followed in this thesis is that of decarbonization strategies in European cities, and stems from an initial task given by the KTH Energy Technology department. This was to aid in the creation of an introductory chapter in the DialoguE on European Decarbonisation Strategies (DEEDS) project. The DEEDS project is focused on generating a team of experts and stakeholders with backgrounds in policy, science, NGOs and others, in order to cultivate an ongoing dialogue on decarbonization pathways. Having representatives from a range of backgrounds ensures all stakeholders interests are considered, and allows for the inclusion of a wide range of decarbonization projects (DEEDS 2018).

The initial task was to consider the decarbonization strategies of three European cities. The cities chosen were Stockholm, Barcelona and Warsaw, in order to gain an idea of policies being implemented in North, South and East European cities, respectively. A review was made of these strategies, and is included in part in the Literature Review chapter. From there, the greater thesis was developed with the adviser's assistance.

Along with this task, the Master Curriculum followed was focused on Energy for Smart Cities, and provided by EIT InnoEnergy (EIT InnoEnergy 2018). The broad term 'Smart Cities' encompasses a range of technological developments and innovations focused on making life in cities cleaner and more efficient for those who live there (Ahvenniemi et al. 2017). It was thus of interest to consider the topics of decarbonization and smart city projects together.

Sitting at the crossroads of these concepts lies the public transit network of every city. In 2015, the transport sector was responsible for 24% of global CO_2 emissions. This has increased 68% since 1990, and demonstrates a need for decarbonization effort in this sector (IEA 2017b). Thus, cities have begun to look into alternative bus technology. This shift, from diesel based high emission fleets to alternative fuels, hybrids and recently fully electric based units has begun, but is moving slowly (Mahmoud et al. 2016). In an effort to accelerate this change, cities are looking into larger investments in alternative bus technology (European Commission Regional Policy Newsroom 2018; NGV Global News 2018; Transports Metropolitans de Barcelona 2017c).

Thesis Format

This paper looks at the cities of Barcelona, Stockholm and Warsaw, and examines the role transit buses will play in the future and what emissions and energy consumption may look like for different scenarios. It begins with a literature review encompassing the broader aspects of smart city projects and decarbonization efforts in the 3 cities. Then focus shifts to public transit buses specifically, addressing all bus technologies used across the 3 cities and introducing relevant projects in the field. After this, the background for the analysis performed is introduced, and the research gap is clearly explained. The Methodology chapter explains the setup of the analysis, the data collected and relevant equations used. The outcome of the analysis and some commentary is found in the Results and Discussion chapter, and finally the Conclusion provides some closing remarks, concerns and policy suggestions for the three municipalities.

1.2 Literature Review

1.2.1 The Concept of Smart Cities

The term ‘Smart City’ refers to a city that is technologically interconnected through a network of sensors, IT platforms, open data and programs that serve to make life within more efficient and smoother (Stockholms Stad 2017). It is thus a very broad term that is the product of various projects within a city, such as sensors in roads to optimize traffic flows and allow real time tracking of public transport, or availability of parking spaces. It also manifests itself in the form of waste bins that alert the city when they need to be emptied, optimizing waste collection times. Smart city projects can range from something as complex as using electric vehicles within the city to balance the grid as they charge (Latvakoski et al. 2015, p. 82), to as simple as an app that allows users to report road defects or graffiti to the municipality in order to get them repaired quickly (City of Boston 2017). The sum of these individual projects helps to make the city more interconnected and allow its citizens to go about their lives in a more efficient way.

Another big element in the smart city field is the implementation of the Internet of Things, or IoT, in which everyday devices or household appliances are outfitted with microcontrollers and the means necessary to transmit and communicate information. This is helping realize some of the above concepts, in that IoT will provide the framework necessary for parking spaces to communicate that they are free, or for street lights to be remotely controlled. IoT can also be applied within households, so that the laundry machine will start only during off-peak hours and cost the user less (Bourgeois et al. 2014, p. 3), or an Electric Vehicle will only charge when household consumption of electricity is at a minimum (Zhang and Markel 2016, p. 4). This type of automation is still being researched and optimized, but the end idea is that it promotes sustainability and makes life easier for citizens. Sustainable development is central to a Smart City, and it is important that these two concepts be interconnected at all steps (Ahvenniemi et al. 2017).

Finally, one of the critical challenges to the success of the smart city is of course the participation of the citizens. A city is only as smart as its citizens, and it is becoming ever more important for cities to hold awareness campaigns or provide materials to keep its citizens informed. Once engaged, citizens experience and feedback can then be used to determine where improvements can be made, pairing data collected with human opinions (Chang, Chiari, and Hutchison 2016).

1.2.2 Background on Well-to-Wheel Analysis

JEC Model

As mentioned in the previous section, the European RED model is reflected in this thesis. The RED, or *Renewable Energy Directive* model, is based on Directive 2009/28/EC, mandating that by the year 2020, at least 20% of the energy demand within the European Union is fulfilled by renewable energy sources (European Parliament 2009). The body responsible for this directive and consequent data found in the VTT Research Centre of Finland report is called the JEC, which is a longstanding collaboration between the Joint Research Center of the European Commission, the European Council for Automotive Research and Development (EUCAR), and the oil companies' association for the environment, health and safety in refining and distribution (CONCAWE) (JEC 2016a). The JEC is the body responsible for releasing the Well-to-Wheel analyses upon which both the VTT Research Centre of Finland report and this thesis are based, and their analysis will hereby be referred to as the JEC method or JEC model.

Well-to-Wheel

A Well-to-Wheel (WTW) analysis central to this study. The analysis consists of two parts, together providing an estimation of GHG emissions and energy efficiency. According to the European Commission, a WTW analysis differs from a normal Life Cycle Analysis (LCA) in that it does not account for the energy and emissions that are present in the construction of the vehicles or facilities, and in end of life procedures (Edwards, Hass, Larivé, Lonza, Mass, and Rickeard 2014, p. 17-18). The figure 1.1 was obtained from the JEC website and helps to further illustrate the concept (JEC 2016b).

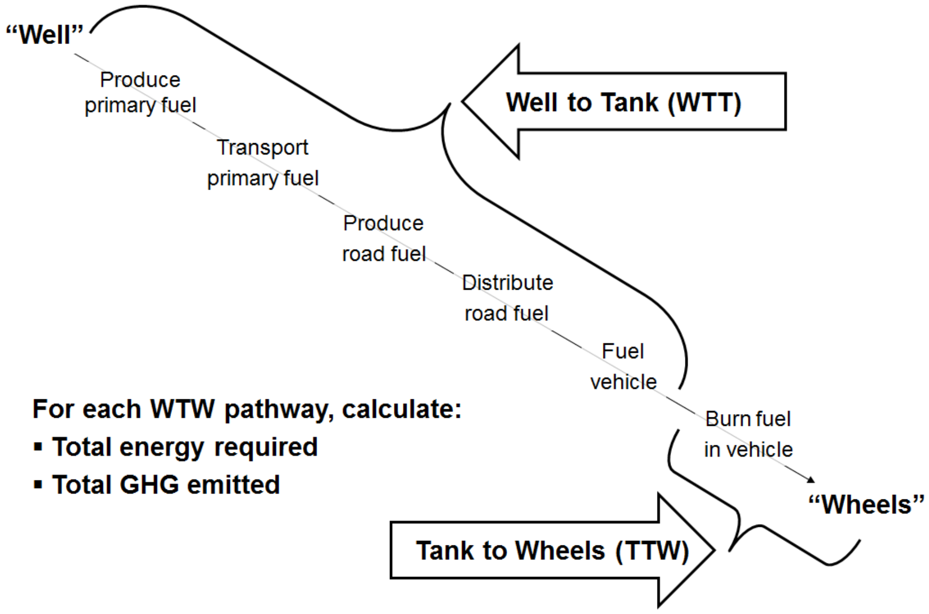


Figure 1.1: JEC Well-to-Wheels Description

Well-to-Tank

The first half of the WTW analysis consists of the Well-to-Tank (WTT) part, which accounts for all energy expended and corresponding GHG emitted in delivering the final fuel product through the supply chain and into the vehicle (Edwards, Hass, Larivé, Lonza, Mass, and Rickeard 2014, p. 15). The WTT phase is responsible for modeling, in an acceptable manner, the upstream emissions for the fuel production, and must take into account factors such as differing pathways for fuels like natural gas, which may be locally sourced or delivered via 4000km pipeline or LNG (Edwards, Hass, Larivé, Lonza, Mass, and Rickeard 2014, p. 19). Biofuels are categorized based on the means by which they are produced and the materials that they are made from (Edwards, Hass, Larivé, Lonza, Mass, and Rickeard 2014, p. 140-144).

Tank-to-Wheel

The second phase is known as the Tank-to-Wheel (TTW) phase, consisting of the energy expended and associated GHG emissions by the vehicle and fuel only (Edwards, Hass, Larivé, Lonza, Mass, and Rickeard 2014, p. 23). This is most heavily affected by the drivetrain and fuel type, but also by the environmental conditions, driving cycle, and number of passengers. For the purpose of this study, assumptions were made to reduce the number of variables involved, and allow for valid use of sourced data. These are discussed in the methodology section.

1.2.3 Bus Types and Drivetrains

The term ‘bus type’ as it is used in this report refers to any bus with a distinct fuel or drivetrain configuration. For clarity, the bus types found across all 3 cities are tabulated and split up based on fuel and engine type in table 1.1, as of 2015. All buses that no longer are used are marked with a “P” for past use, all current types being used are marked with an “X” and all planned introductions are marked with an “F” for future.

Table 1.1: Bus Type Presence in Cities, 2015

Bus Type	Barcelona	Stockholm	Warsaw
Diesel	X	P	X
Ethanol		X	
FAME RME (BioDiesel)	P	X	
CNG	X		F
Biogas		X	
LNG			X
Hybrid Diesel	X		
Hybrid Biodiesel		X	
PEHV		X	X
BEB	X	F	X

Relevant Biofuels

The Stockholm fleet makes heavy use of biofuels. As these come from a number of sources and upstream emissions vary greatly depending on where fuels are sourced from, care was taken to represent them in an appropriate manner. The biodiesel fuel used in Stockholm buses is 100% Rapeseed Methyl Ester, or RME (Maalinn 2015). Ethanol powered buses use ED95, which consists of 95% ethanol and 5% ignition enhancer, and comes largely from a sugar cane source imported from Brazil (Maalinn 2015; Sekab Biofuels and Chemicals AB n.d.).The corresponding emissions from the supply chain of ethanol are given in the Methodology section and are taken from the JEC, but it is important to note that the supply chain is heavily dynamic and can change drastically based on production methods. Being sourced from Brazil, a major biofuel producer, means that the possibility of deforestation from increased demand and practices such as pre-harvest burning may drive LCA emissions up by over 60% (Chilvers and Jeswani 2017). Stockholm biogas powered buses run on 39% sewage sludge, 19% municipal solid waste, and 19% food industry waste (Xylia 2018, p. 16). It was thus deemed appropriate to consider biogas in the context of the ‘organic waste’ pathway for the purpose of this study. Stockholm’s fleet of PHEBs then run on a combination of electricity and Hydrogenated Vegetable Oil, or HVO (Maalinn 2015).

Hybrid and Electric Drivetrain Types

Apart from the varying fuel types, there are also a variety of drivetrains involved in the study. This includes traditional internal combustion engines, hybrid engines, plug in hybrid electric drivetrains and fully electric drivetrains. Also noteworthy is the fuel cell powered drivetrain, but it is not covered in this section as none of the cities in this study currently employ fuel cell buses in their fleets.

Serial Configuration

Drivetrains in the serial or series configuration are set up so that the vehicle is propelled by an electric motor at all times. The internal combustion engine (ICE) powers a generator that supplies power both to the electric motor and to the battery, which stores energy for later use. This configuration takes advantage of the fact that the ICE need not be directly linked to the drivetrain, only to the generator, and can thus be placed more freely within the geometry of the vehicle. The storage of electricity is also simplified in this configuration, as the ICE may generate electricity as needed and send it to the battery, without the reliance upon regenerative braking, as is the case in the parallel configuration (Carter and Varghese 2017, p. 13).

Parallel Configuration

In the parallel configuration, the electric motor is driven only by the battery, and is charged via regenerative braking, where the power electronics in the electric motor allow it to run in reverse and provide the battery with charge. The ICE does not charge the battery. The advantages of this configuration include the ability to use setting appropriate drive configurations, and in low speed environments, more electric motor can be used than ICE, which leads to fuel, emissions and noise savings. When extra power is needed, the ICE can be engaged to assist. The electric motor may also be smaller for this reason (Carter and Varghese 2017, p. 14). Also noteworthy is the mixed configuration, in which a link between the ICE and battery is included, which allows for direct battery charging. This attempts to combine the benefits of both configurations (Carter and Varghese 2017, p. 14).

Plug-in Hybrid Configuration

The plug-in configuration is in essence any hybrid drivetrain that allows for the battery to be charged by external power. In this study, that source is assumed to be the national grid mix of the given country. With a larger battery, the so-called ‘degree of hybridization’ may be increased, which means that the amount of power supplied by the electric motor increases in comparison to that delivered by the ICE (Carter and Varghese 2017, p. 15).

Battery Electric Configuration

The battery electric bus (BEB) configuration includes no ICE drivetrain whatsoever, replacing it with a large lithium based battery. This drivetrain thus has zero tailpipe emissions and relies entirely on external sources of electricity to charge the battery, which means that a cleaner energy mix yields a lower overall emission bus (Carter and Varghese 2017, p. 18). The challenge of how to ensure adequate charge to the battery has been heavily discussed. Two main methods are employed currently, namely overnight and opportunity charging. Overnight charged buses contain larger batteries that take longer to charge, but supply a longer range, up to 250 km on a single charge. Opportunity charged buses have a smaller battery pack and smaller range of up to 50 km per charge, but can be charged fully in 10 minutes. Overnight buses are charged at the depot each night or have their battery swapped for a charged one, while opportunity charged buses are topped up constantly at fast charging stations along or at the end of their route (Mahmoud et al. 2016, p. 675-677).

1.2.4 Background on National Carbon Intensities

As the discussion surrounding electromobility grows, it is important to consider where the electricity comes from. Despite having no tailpipe emissions, electric and plug in enabled buses are only as clean as the grids from which they draw their power, and this can vary dramatically depending on the fuel sources used (Edwards, Hass, Larivé, Lonza, Mass, and Rickeard 2014, p. 33).

The IEA releases yearly reports, titled CO_2 Emissions From Fuel Combustion (IEA 2017b), which includes the carbon intensity from each country's electricity mix and a number of other indicators. This data was also available online from the OECD (IEA 2018), from which it was plotted to model the Carbon Intensities of Spain, Sweden and Poland from 2000-2015.

1.3 Case Studies

1.3.1 Barcelona

Decarbonization Progress

The city of Barcelona has taken measures to improve its historically poor air quality, doing so by setting out its climate roadmap for 2015-2017 (Ajuntament de Barcelona 2012). This has proven effective thus far, as the Area Metropolitant de Barcelona (2017) reported that from the year 2011-2015, carbon emissions in Barcelona decreased by 11% from 960,621 to 858,238 tons of CO_2 equivalent, exceeding the 10% goal set in 2010. The city has thus opted to increase the objective for 2030 to a reduction of 30% with respect to 2011.

Some areas in which the decarbonization efforts are focused are energy and air, public transit and mobility, climate change resilience, waste management, and biodiversity. Other related projects include the recent implementation of a low emissions zone surrounding the city.

Addressing the most prevalent areas of focus, it is first useful to look at energy and air. In 2002, the Municipality of Barcelona approved the *Barcelona Energy Improvement Plan 2002-2010* (PMEB), which assessed contemporary energy trends and set out 54 measures set on decreasing energy consumption and increasing the use of renewables. Moving to 2011, a follow up plan was approved, titled *The Energy, Climate Change and Air Quality Plan of Barcelona 2011-2020.* This plan seeks to continue to build upon progress made from the previous plan, using 2008 as a base year (Ajuntament de Barcelona 2011, p. 9-10).

Another area of focus worth mentioning further is that of urban mobility. The *Urban Mobility Plan for 2013-2018* (Ajuntament de Barcelona 2014) is focused principally on implementing the superblock (Catalan: *Superilla*) concept throughout the city. This concept involves restricting traffic along many roads and establishing better bike lanes in order to clear large areas of the city of both traffic and tailpipe emissions.

The other large transport oriented document, titled *Projectes innovadors en el sector del transport i la mobilitat* (Transport 2011), takes a broader approach, with three main goals. First is the goal that 15% of all vehicles in the city be hybrids by 2020. This is being promoted through subsidies for those willing to upgrade to hybrid cars, and by upgrading the public vehicles to hybrids and electric power (Transport 2011, p. 44-49). Second, the establishing of a reliable network for both carpooling and carsharing is in the works. This would decrease the number of cars on the road and increase the average occupancy of them at any given time, in turn decreasing emissions within the city limits. Also mentioned is the implementation of more taxi stands in order to decrease the amount of time that taxis circulate unoccupied (Transport 2011, p. 50-55). The third main objective of the document is to optimize transit options, by redesigning the bus routes, establishing dedicated HOV lanes, and adjusting the frequency at which buses run (Transport 2011, p. 55-59).

Barcelona Bus Fleet

The bus fleet of Barcelona is run by the Transports Metropolitans de Barcelona (TMB), who release yearly reports and outlooks on the city's public transit. Through these reports, bus data was available from 2005 onwards (Departament De Medi 2014; Transports Metropolitans de Barcelona 2016; Transports Metropolitans de Barcelona 2017a; Transports Metropolitans de Barcelona 2017b; Transports Metropolitans de Barcelona 2018). Barcelona's bus fleet composition over the years for which data was found is shown in figure 1.2. A trend away from diesel and towards alternative configurations, namely CNG and hybrid diesel drivetrains is present. Also shown is the temporary inclusion of biodiesel bus types, which were discontinued after 2012, principally due to the discontinuation of a state subsidy promoting the fuels use. Also noted were a higher fuel consumption and thus lower efficiency, and a lower reliability of biodiesel buses when compared with their regular diesel counterparts (Transports Metropolitans de Barcelona 2014). From 2010 onwards, diesel hybrids began to be introduced, and by 2013 the first CNG hybrids were introduced as well (Transports Metropolitans de Barcelona 2014). The annual reports, however, cease to make a distinction between the two hybrid types after 2014, so they are all reported in this study as diesel hybrids (Transports Metropolitans de Barcelona 2016, p. 62). This may give rise to slight underestimations in emissions and energy consumption, CNG is reported to have CO_2 emissions that at best are equal to those of diesel, results should still be representative (Nylund and Koponen 2012, p. 8). In terms of particulate emissions, which are not focused on in this study, a large discrepancy should be noted, as CNG buses emit vastly fewer particles than their diesel counterparts (United States EPA 2002). The city had initially invested in a large scale project to convert diesel and CNG buses to hybrids, but this was discontinued in 2015 in favor of a program for the procurement of 73 new hybrid buses (European Investment Bank 2017). The final component of the bus fleet is the electric bus, which was first introduced in 2013 as part of the ZeEUS Project (Transports Metropolitans de Barcelona 2014, p. 82), and has since begun to grow in usage.

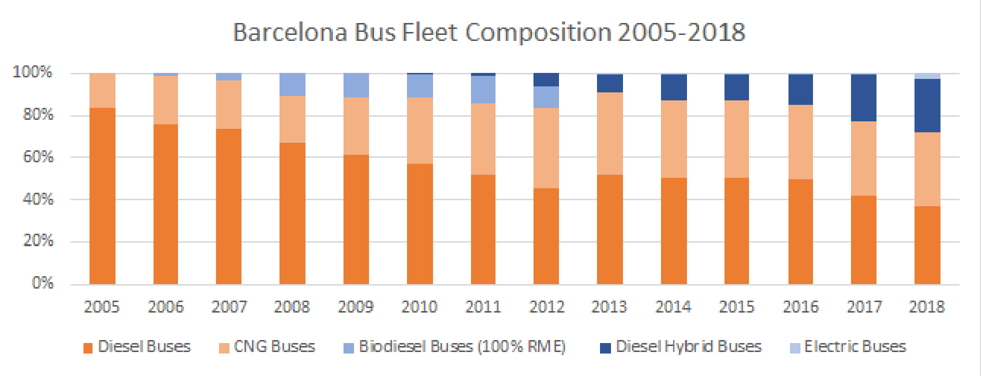


Figure 1.2: Barcelona Bus Fleet by Type

Spanish Electricity Mix

From 2000-2015, Spain has demonstrated a Carbon Intensity quite similar to the European Union 28 member state average, falling 33% over the period to a 2015 value of 293 gCO_2/kWh (IEA 2017b). The nation has begun phasing out coal as a generation source, managing increasing demand by using more gas and renewables, along with consistent nuclear and hydropower (IEA 2017b).

The Spanish national carbon intensity is as shown in the plot. A review of irregularities revealed that the global recession towards the end of 2008 started the large decrease in Intensity as demand dropped (Declercq, Delarue, and D'haeseleer 2011). This downward trend was continued into 2010, where a large amount of precipitation increased hydropower usage and kept emissions down, and conversely the spike in 2012 was due to a drought (The World Bank Group 2018; IEA 2017b).

1.3.2 Stockholm

Decarbonization Progress

The first climate oriented plan put together by Stockholm was called the Action Plan Against Greenhouse Gases and was introduced in 1998. The plan sought to limit GHGs in the year 2000 to that of the 1990 level, which corresponded to 5.4 tons of CO_2 equivalent per inhabitant per year (Lönngren and Nilson 2014, p. 7). The city exceeded this goal, reducing to just 4.5 tons by the end of 2000 and continuing to fall to 3.4 tons by 2009. The municipality reports that the majority of these emission reductions were reached by the continuing trend away from oil-fired heating and towards heat pumps and biofuel powered district heating, along with the move away from fossil fuel based vehicles and public transit buses (Lönngren and Nilson 2014, p. 7).

As a city with the desire to become fossil fuel free by 2050, Stockholm has set out conditions that will make this achievable moving forward. Concerning energy production, the main objective is to continue phasing out coal, fossil oil and gas in heating applications and substitute it for biofuels. In terms of energy consumption, stricter building regulations and upgrading of existing infrastructure will help ensure lower consumption. The transport sector can also contribute by increased use of public transit over cars, improving transport efficiency, and promoting the switch to biofuels and electric vehicles. It is however important to note that across all 3 of these categories, a reported risk is a limited availability of biofuels and a corresponding increase in price (Lönngren and Nilson 2014, p. 14-17).

One of Stockholm's notable measures taken to reduce citywide emissions is their congestion tax. The project consists of a zone surrounding the city with 18 toll points, charging travelers for entering and exiting the zone. Initially introduced in a pilot context in 2006, it gained popularity and was introduced full time in 2007 (Anas and Lindsey 2011, p. 75). The revenue from the charge is redirected into both road improvements and public transit improvements (Eliasson 2008, p. 396). The charge has been successful in reducing congestion by 20 percent, which as a result means lower travel times and lower emissions within the city (City of Stockholm 2012, p. 23).

Regarding waste, the city is seeking to improve recyclability of plastic to 2050 and increase the percentage of their makeup that is bio-based. As plastics are unable to be used by municipal waste heating plants, this improvement is desired in order to avoid leaving the material in landfills (Lönngren and Nilson 2014, p. 23).

Stockholm Bus Fleet

Stockholm's bus fleet is managed by Storstockholms Lokaltrafik AB (SL). From yearly reports, data was found back until 2010 for the composition of the fleet, and up until 2015. The trends are shown in figure 1.3, and show the city's strong commitment to phasing out diesel powered buses. In 2010, the bus fleet was powered by just 36.6% clean buses (AB Stockholms Lokaltrafik 2010, p. 38), and by just 2013 this number increased to 75% (AB Stockholms Lokaltrafik 2014, p. 20), and by 2017 has reached 100%, meaning fossil fuel powered buses have been completely phased out (Lönnqvist 2017, p. 17). Ethanol powered buses are also falling out of favor, being replaced by heavy investment in biogas and biodiesel. Yearly reports by SL from 2011-2013 show the consumption of CNG as a bus fuel, but in AB Stockholms Lokaltrafik (2011) it is noted that natural gas is only consumed in place of biogas when there is a shortage, and since there is more biogas ordered than there is CNG consumed, this is simply counted as biogas. Finally, the most recent developments involve investment in biodiesel hybrids, both standard hybrids and plug-in hybrid electric type (Stockholm County Council 2017, p. 18).

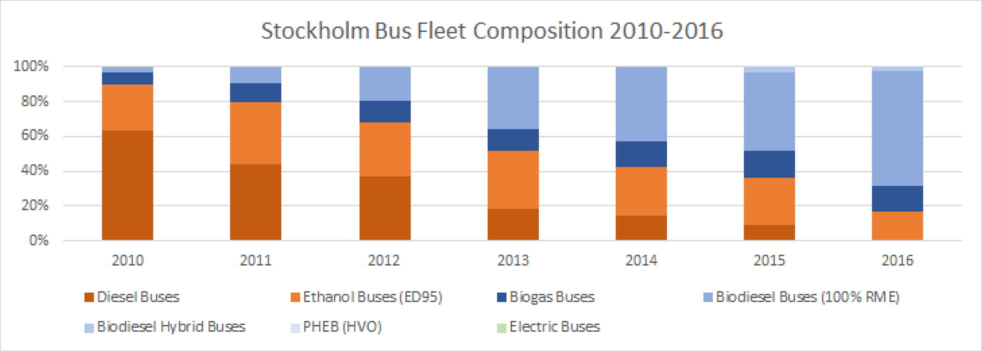


Figure 1.3: Stockholm Bus Fleet by Type

Swedish Electricity Mix

The Swedish national electricity mix has been considerably lower than the EU average for each year from 2000-2015, and still managed to fall by 50% to just 11 gCO_2/kWh in 2015. Over this time period, the country has been steadily moving away from coal and gas generation technologies, investing in alternative sources, and maintaining a strong nuclear and hydro generation capacity (IEA 2017b).

A look at the intensity evolution, however, shows quite some variation over the interval addressed. The large spike in 2003 was due to a year of low rainfall that ultimately reduced available hydro power, which at the time had to be covered by oil (Swedish Energy Agency 2004, p. 20). This occurred again in 2013, but with more renewables available, the result is not nearly as drastic (IEA 2017b, p. II.374). The winter of 2010-2011 was also exceptionally cold, and led to the dispatch of oil and gas resources to provide heat across the country (IEA 2017b, p. II.374). The effect of the recession in 2008 does not appear to be as strong in Sweden as it was in Spain.

1.3.3 Warsaw

Decarbonization Progress

The case of Warsaw is a unique one in that the city has shown dedication to decarbonization efforts that are largely led by local policies, in a country that has traditionally and continues to be heavily reliant on fossil fuels (Olszewski 2015). The city has done so mainly through efforts coordinated under their *Sustainable Energy Action Plan* (SEAP), put forth in 2011 and written in 2013 (Infrastructure Department of The City of Warsaw 2013). At this time, Warsaw emissions were as follows: 78% energy sector, 15% transport sector, 7% waste management and wastewater treatment (Infrastructure Department of The City of Warsaw 2013, p. 8-10). With a base year of 2007, the city seeks a total CO_2 emission reduction of 20% by 2020. This means that emissions by 2020 must not exceed 10.3 million tonnes per year, comparing with 12.9 million tonnes in 2007. As of 2016, this total is down to 11.7 million tonnes (CDP Open Data Portal 2016).

Taking a closer look at decarbonization strategies in the transport sector, the document titled *The Transportation System of Warsaw: Sustainable Development Strategy up to the year 2015 and successive years* (BDiK 2010) outlines the steps being taken. The approach is twofold: Modernize the transport and road systems themselves and to change the way that residents make use of transportation. To accomplish the first goal, a citywide transit authority is needed, along with continued efforts to replace buses and rolling stock, increase efficiency and better integrate transit methods (Infrastructure Department of The City of Warsaw 2013, p. 16-20). The second goal is best accomplished by public awareness campaigns promoting transit over personal vehicle use (Infrastructure Department of The City of Warsaw 2013, p. 30-37), development of a common ticket for all modes of transport, and expansion of park and ride lots (Infrastructure Department of The City of Warsaw 2013, p. 19-23).

Other sectors that were outlined in the SEAP include the housing and public building sectors, where thermal retrofitting is a popular approach to increased energy efficiency. Most buildings were constructed in a prefabricated style, using inefficient materials and taking advantage of cheap electricity prices and low concern for emissions. With a change in time and attitude, buildings are beginning to be modernized (Infrastructure Department of The City of Warsaw 2013, p. 11-15).

Warsaw, along with the other two cities, shows that decarbonization efforts include an effort to update the public transit fleet, thus providing the foundation for its inclusion in the main study of this thesis.

Warsaw Bus Fleet

The Warsaw bus fleet is managed by Zarząd Transportu Miejskiego w Warszawie (ZTM), or the Warsaw Public Transit Authority (Public Transit Authority of the capital city of Warsaw 2018), who also release yearly reports on bus fleet data, from which fleet numbers from 2010-2017 were found, shown in 1.4. From the data found, the composition until 2017 was made up of primarily diesel powered buses, followed by LNG, diesel plug in hybrids, and electric buses (Zarzaąd Transportu Miejskiego w Warszawie 2017, p. 22). An order of 110 CNG fueled buses is scheduled to begin shipping in early 2019 and will be completed by the end of next year (NGV Global News 2018). Also planned is the introduction of 130 fully electric buses, which are to be introduced by the end of 2021 (European Commission Regional Policy Newsroom 2018). These plans represent a large shift in Warsaw's trends towards electromobility and buses with fewer particulate emissions.

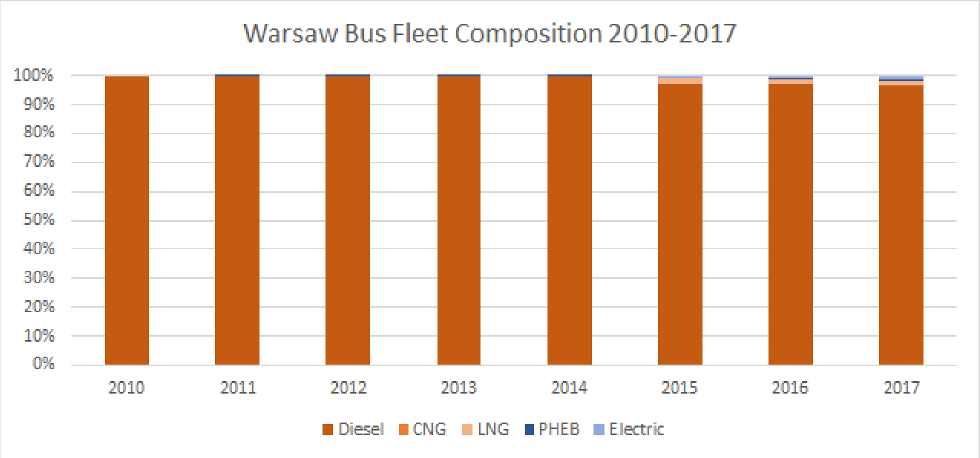


Figure 1.4: Warsaw Bus Fleet by Type

Polish Electricity Mix

Poland has long possessed a high Carbon Intensity compared to the European Union average, and this trend continues to 2015. From the aforementioned IEA data (2018), the Intensity has dropped 17.5% from the year 2000-2015 to a value of 730 gCO_2/kWh, of which a vast majority has come from coal. In recent years, however, there has been an introduction of renewables and gas in the energy mix, which have aided in reducing emissions from many years of almost exclusively coal based generation (IEA 2017b).

1.3.4 Other EU Programs and Projects

The ZeEUS Project

The *Zero Emission Urban Bus System* (ZeEUS) Project was launched by the European Commission, headed by the UTIP, and involves a consortium of 40 organizations that represent important stakeholders in the public transit scene across Europe. The project ran from 2013-2018 and set varying electrified bus solutions in place across European cities in 70 different use cases, testing their feasibility (UITP 2014). Coincidentally, three of the core use case demonstrations of the project took place in Barcelona, Stockholm and Warsaw (ZeEUS - Zero Emission Bus System 2014).

The Barcelona case consisted of 2 opportunity charged and 2 overnight charged 12m electric buses, and was designed to test the technology in the Mediterranean conditions. Upon finalization, it was realized that opportunity charging would suit the city best, but the cost of the associated infrastructure would also need to be taken into consideration. Future plans included fully electrifying bus line H16 by 2019 (UITP 2018a). In Stockholm's case, the objective was to demonstrate the electrified solutions potential for integration into the city center. This was observed with overall success, apart from issues relating to the size of the charging infrastructure located at both ends of the route. Also tested was a Plug in Hybrid Bus (PHEB) that was run on both wind power and 100% HVO fuel. Upon completion, the city has expressed interest in incrementally electrifying the remainder of its fleet (UITP 2018b). Finally, Warsaw took part in the project, implementing 10 buses in order to confirm that electric buses could perform as well as diesel buses in the city. This project also realized success, including a reduction in local CO_2 emissions and particulate emissions, along with noise. Curiously, the largest issue in Warsaw was also the installation of the charging infrastructure, which required land permits, energy supplier contracts, and ultimately a year and a half worth of planning. Future plans for Warsaw also involve investment in electrification, with 130 additional electric buses to be purchased by 2020 (UITP 2015).

The ZeEUS project and its results provide a solid foundation upon which to build a case for increased electromobility in the 3 cities covered, as all reported positive results. Thus, although the project is not covered any further in depth in this study, it is recognized as a point of entry for electric buses into each city's fleet, and the success of the ZeEUS project and future plans serve as a basis off of which to model the electric bus implementation in the scenarios presented later on.

Bus Fuel Study - VTT Technical Research Centre of Finland

In order to obtain an idea of the environmental performance of non electric bus types, a report released by the VTT Technical Research Centre of Finland Ltd, titled *Fuel and Technology Alternatives for Buses* (2012) was referenced. The report, carried out with the help of the IEA's Implementing Agreements on Alternative Motor Fuels and Bio-energy, was aimed at generating reliable, usable data on public transit buses. The report makes use of a life cycle analysis technique known as a Well-to-Wheel (WTW) analysis, the details of which are explained in the next section. It also provides a cost-benefit analysis of the various bus fuel types, addresses possible errors in reporting stemming from different supply chains, and includes some hybrid models in the study (Nylund and Koponen 2012, p. 3). The report takes into account the different emissions models used across different continents, providing data in 3 variations; the US **GREET** model, the Canadian **GHGenius** model, and the European Union **RED** methodology (Nylund and Koponen 2012, p. 3). As it concerns European cities, the latter is reflected in this study, and is described in detail in the Well-to-Wheel section.

1.4 Research Gap and Questions

This literature review has yielded available data on bus fleet composition and policies, WTW fuel emission factors, national energy intensities, along with numerous other related articles and reports. The Positive reviews of increased electromobility and success of Stockholm's biofuel based bus investments are also noted. However there was no study done that had focused on the average fleet emissions moving forward into the future, and how policy and bus type investment could shape this. This study seeks to shed light on this for all 3 cities, indicate how the future may look based on policies taken, and provide suggestions on how to best reduce energy consumption and harmful GHG emissions. In the context of smart cities, improved mobility is always a token issue. Doing this in a sustainable manner is a key objective for any smart city, and a solid projection of future fleet emissions will help to make the effects of policies taken more clear.

The research questions are then as follows:

How large are the potential effects of low emission bus models on current emissions and energy consumption, both locally and up the supply chain? How do public transit decarbonization strategies fit into the current trend of smart and sustainable cities?

Chapter 2

Methodology

The methodology chapter describes how the necessary information was acquired and the corresponding study completed. First, the three indicators are introduced and assessed for each bus type and each phase of the WTW analysis, with special treatment given to battery electric and plug in hybrid bus variants. Then the national carbon intensities are introduced, and the method for projecting them into future years is explained. Next, the scenarios are defined, and analysis equations and indicators clarified. This process was completed with the use of some key assumptions, all of which are explained at length in Appendix A.

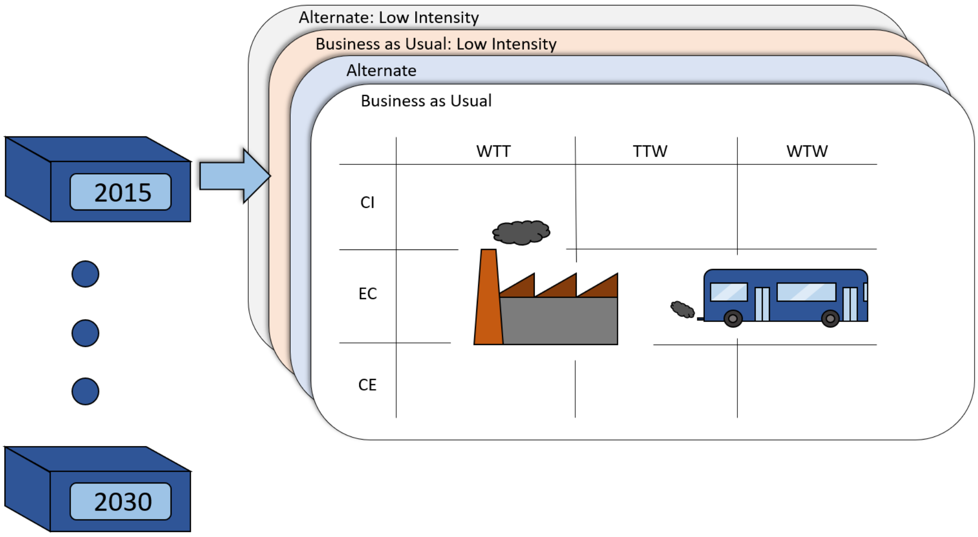


Figure 2.1: Illustration of Compiled Data

The objective is to analyze the performance of the bus fleet from the past, present and future. With 2015 taken as the base year, projections were made for the four scenarios in each year until 2030. Figure 2.1 illustrates this graphically: each box represents a year, in which there are four cards. The four cards each represent a scenario, and for each scenario there are 9 values. These values correspond to a WTT, TTW and WTW data point for all 3 indicators. The result is 1 data point each year for every cell on each card, all of which are plotted to observe the change over time, which can be seen in the Results and Discussion chapter.

2.1 Well-to-Wheel Analysis

With each type of bus accounted for, the overall Well-to-Wheel impact was calculated for three main factors:

Carbon Intensity (CI) in gCO_2e/kWh - defined as the intensity of greenhouse gas emissions per kilowatt-hour consumed, either by the supply chain or bus itself. This expresses emissions in terms of fuel energy content.

Energy Consumption (EC) in *kWh/km* - defined as the number of kilowatt hours consumed per kilometer traveled either along the fuel supply chain or by the bus itself. This expresses energy content in terms of a reference distance.

Carbon Emissions (CE) in gCO_2e/km - defined as the greenhouse gases emitted per kilometer traveled either along the supply chain or by the bus itself. This expresses emissions in terms of a reference distance.

These three indicators were used as they provide a solid basis from which to draw conclusions about the trends of the fleet. A decrease in local Carbon Intensity coupled with an increase in upstream Intensity is reflective of higher electromobility, and can provide the municipality with a good idea of how their local decarbonization efforts are affecting the country's overall emissions.

The fourth category needed to assemble the data has been called the Energy Expended, or EE. This is an upstream only (WTT) property expressed in kWh/kWh, and refers to the amount of energy that was expended in order to generate the fuel as a ratio of energy expended in fuel production to energy contained in the fuel.

The analysis consists of two components and splits the footprint of the vehicle into those occurring up the supply chain from the bus, namely Well-to-Tank, and those that occur within the bus itself during combustion, namely Tank-to-Wheel.

Wherever possible, data was collected directly via research sources. When this was not possible, equations from (Torchio and Santarelli 2010), listed below, were used to obtain an appropriate estimation.

$$CE_{WTT} = CI_{WTT} * EC_{TTW} \tag{2.1}$$

$$EC_{WTT} = EE_{WTT} * EC_{TTW} \tag{2.2}$$

$$XX_{WTW} = XX_{WTT} + XX_{TTW} \tag{2.3}$$

2.1.1 Carbon Intensity

Consistent use of data from the report by Nylund and Koponen (2012) was made in order to obtain reliable intensity numbers that fit with the JEC study. The report provided robust data on diesel buses, sugarcane based ethanol buses, FAME (100% RME) biodiesel buses, CNG buses and organic waste based biogas. LNG powered buses used in Warsaw required slightly more research, as the fuel was not included. The JEC WTW study by Edwards, Hass, Larivé, Lonza, Mass, Rickeard, et al. (2014) and a study by Wurster et al. (2011) provided the WTT and TTW numbers, respectively, with the latter, it should be noted, being carried out in a Euro VI engine in a heavy duty vehicle and not a transit bus. This was however the most representative data available and was deemed appropriate. As for the HVO powered PHEB, numbers were sourced from the Swedish Energy Agency (2016), since it is only used in Sweden. Results are shown in figure 2.2. Hybrid buses share the same values as their non-hybrid counterparts, as the increased efficiency of the vehicle is not accounted for in this parameter.

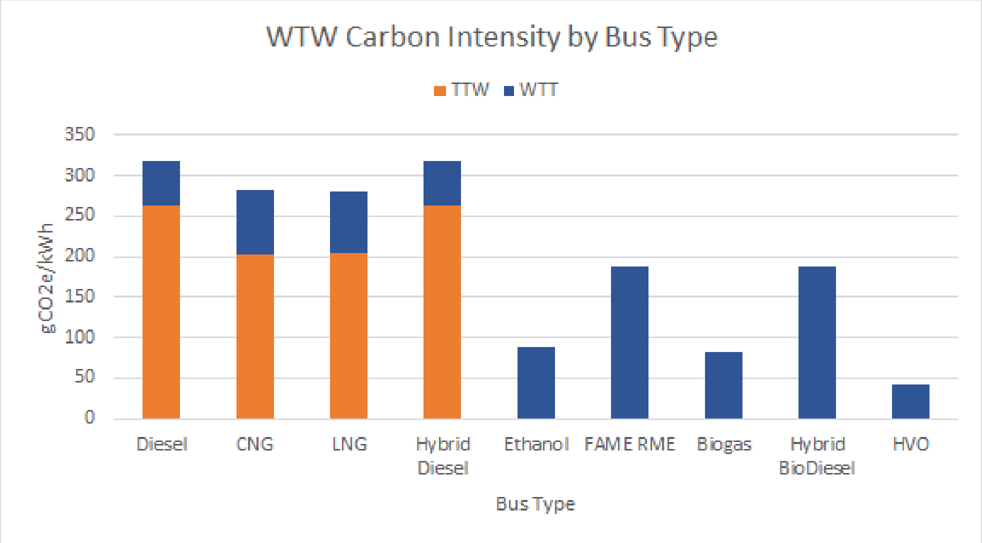


Figure 2.2: Carbon Intensity WTW Breakdown by Bus Type

According to the JEC methodology, combustion of biofuels is neglected, as it is assumed that the GHG absorbed in the growth of the fuel stock offsets that of its combustion (Nylund and Koponen 2012). For this reason, quite a few TTW values are reported as zero, both for this indicator and for the Carbon Emissions one.

2.1.2 Carbon Emissions

Data for this section was acquired much in the same way as in the Intensity section. The majority was found in the report by Nylund and Koponen (2012), or in the case of hybrid drivetrains, calculated from it, with an assumption of 27% WTW carbon savings for hybrids versus their non hybridized counterparts (Nylund and Koponen 2012, p. 280). The diesel based hybrid drivetrain is given in full and the bio-diesel based hybrid is assumed to be similar, with the biggest difference being that tailpipe emissions from the biofuel are ultimately not included. LNG was calculated from a report by Vermeulen et al. (2017) titled *Emissions testing of two Euro VI LNG heavy-duty vehicles in the Netherlands : tank-to-wheel emissions*, which stated that on average, TTW LNG emissions were roughly 3-6% less than those of diesel based engines. This claim was substantiated by DENA (2014). For WTT CE, equation 2.1 was used. The numbers are tabulated below in figure 2.3.

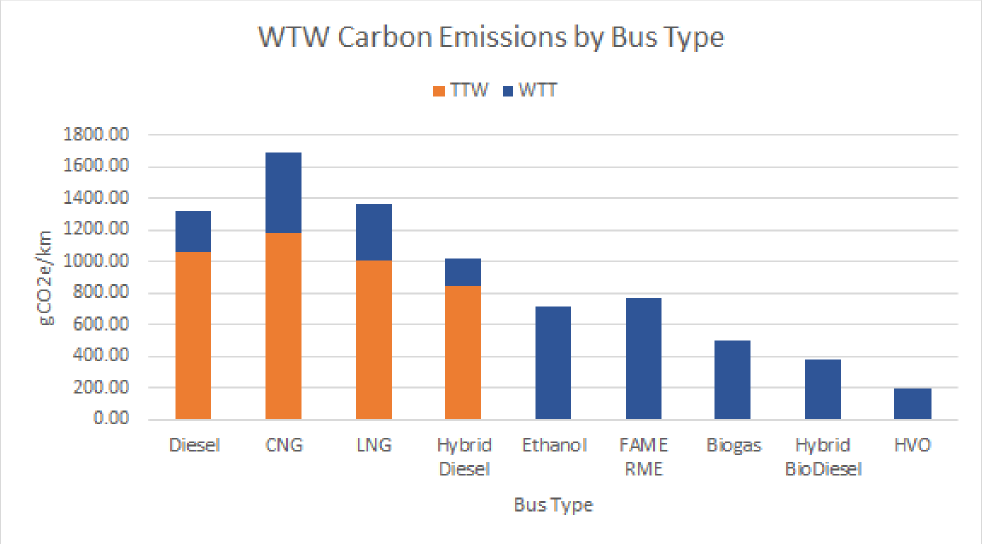


Figure 2.3: Carbon Emissions WTW Breakdown by Bus Type

2.1.3 Energy Consumption

Energy consumption was once again largely sourced from Nylund and Koponen (2012), with WTT hybrid consumption being assumed the same as its non hybrid counterparts. Results are shown in figure 2.4. LNG WTT was calculated via equation 2.2 and TTW via equation 2.3.

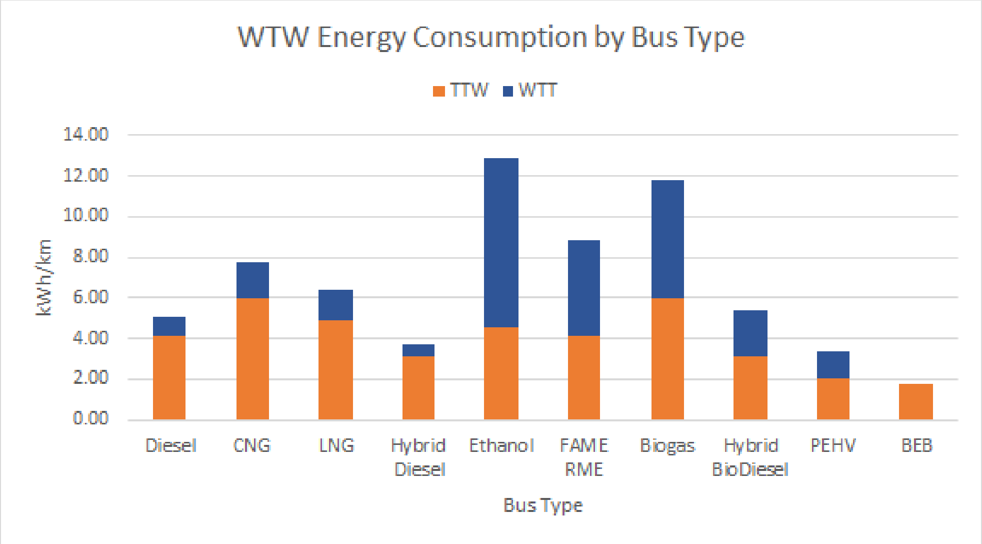


Figure 2.4: Energy Consumption WTW Breakdown by Bus Type

In this category, the PHEB and BEB are also included, as their energy consumption is not dependent on an energy mix. The PHEB values are taken from a recent study concerning public transit buses in Brazil (Dreier et al. 2018). As this type of bus is fairly new, studies are limited and thus this was the most reliable data that could be found. Finally, the BEB has no upstream energy consumption, and thus only had a TTW value, which is sourced from Zhou et al. (2016).

2.1.4 PHEB and BEB

For the Plug in Hybrid Bus, used with HVO fuel in Stockholm and Diesel fuel in Warsaw, a 'best-case scenario' was used stemming from the ZeEUS project in Stockholm, where 86% of the time electricity was used and the remaining 24% of the time fuel was consumed (ZeEUS - Zero Emission Bus System 2017), according to the equation:

$$CI_{WTT,PHEB} = 0.86 * CI_{Nat} + 0.24 * CI_{WTT,Fuel} \tag{2.4}$$

Where $\mathrm{CI_{Nat}}$ refers to the country's national carbon intensity, $\mathrm{CI_{Fuel,WTT}}$ is the upstream carbon intensity of the fuel being used, which is HVO for Stockholm and Diesel for Warsaw. For TTW values, the same equation is used, but with TTW values instead:

$$CI_{TTW,PHEB} = 0.24 * CI_{TTW,Diesel} \tag{2.5}$$

The equation is only for diesel, as following JEC methodology, biodiesel fuel is considered to have zero tailpipe emissions. It also reflects the main benefit of the electric functionality, in that carbon is only released when the engine is being used. The WTW emissions of the bus are then simply the addition of these two factors:

$$CI_{WTW,PHEB} = CI_{WTT,PHEB} + CI_{TTW,PHEB} \tag{2.6}$$

For the PHEB Carbon Emissions, the last factor is changed from CI to CE and the first term is multiplied by the energy consumption of the bus motor, as estimated in Jungmeier (2017) in order to yield the correct units:

$$CE_{WTT,PHEB} = 0.86 * CI_{Nat} * EC_{PHEBMotor} + 0.24 * CE_{WTT,Fuel} \tag{2.7}$$

The TTW Emissions are similar to Intensity, in that only that part which includes fossil fuel consumption is counted towards tailpipe emissions:

$$CE_{TTW,PHEB} = 0.24 * CE_{TTW,Diesel} \tag{2.8}$$

WTW total is thus:

$$CE_{WTW,PHEB} = CE_{WTT,PHEB} + CE_{TTW,PHEB} \tag{2.9}$$

For Energy Consumption of PHEBs, the upstream consumption is assumed to consist only of the energy consumed in transporting the fuel, and the electric portion does not factor in:

$$EC_{WTT,PHEB} = 0.24 * EC_{WTT,Fuel} \tag{2.10}$$

The local energy consumption then accounts for the TTW consumption of the bus engine burning the fuel of choice, along with the energy consumption of the electric motor, weighted the same as before:

$$EC_{TTW,PHEB} = 0.86 * EC_{PHEBMotor} + 0.24 * EC_{TTW,Fuel} \tag{2.11}$$

This yields a WTW EC of:

$$EC_{WTW,PHEB} = EC_{WTT,PHEB} + EC_{TTW,PHEB} \tag{2.12}$$

Concerning the electric bus, carbon intensity and emissions are directly related to the reported national mix, and there are no TTW emissions, so WTT and WTW factors are the same. Equations are then:

$$CI_{WTW,BEB} = CI_{Nat} \tag{2.13}$$

Thus the BEB Carbon Intensity directly corresponds to that of the nation's energy mix. For Carbon Emissions:

$$CE_{WTW,BEB} = CI_{Nat} * EC_{BEB} \tag{2.14}$$

Where CE_{BEB} is the energy consumption of the BEB.

2.2 National Carbon Intensities

2.2.1 Past Years

Two bus types in the study make use of electricity taken straight from the grid: The Battery Electric Bus (BEB) and the PHEB. While they do not have any tailpipe (TTW) emissions, they take their upstream emissions in part or completely from the carbon intensity of the national energy mix. The BEB, using only grid electricity, can have its emissions calculated solely from the national carbon intensity, as in the WTW model emissions from vehicle construction are neglected. In the case of the PHEB, the aforementioned ratio is used for carbon emissions both upstream and from the tank to the wheels. As outlined in the Literature Review, IEA data (IEA, 2018) was used to find the respective national Carbon Intensities from previous years in gCO_2/kWh, which was assumed to be representative of each city's energy mix. It can thus be noted that the lower the national carbon intensity, the lower the overall emissions from electric buses

2.2.2 Future Years

Future national carbon intensities were also needed to make proper projections of fleet consumption and emissions. The IEA does not provide future intensity projections, but the European Commission does, at 5 year intervals until 2050 (European Commission 2014). To check that these projections were appropriate for use, the Past IEA values obtained from 2000-2015 were compared with those of the EU Commission values from the same time period. A correlation of 0.999 was found for Spain, 0.982 for Sweden and 0.981 for Poland. With such strong correlations, the EU Commission projections were deemed appropriate to base IEA extrapolations upon. Since the the EU Commission only gave estimates each 5 years, the years between intervals were filled in linearly. Below the data for Sweden is exemplified; data for the other two countries can be found in Appendix B figures B.1-B.4. The dark orange represents the data used in this study, presented at 5 year intervals. The dark blue represents the data given by the EU Commission. The light blue is the EU Commission projections, and upon finding a good correlation between the dark colors, the light orange are the projections that were used in this study.

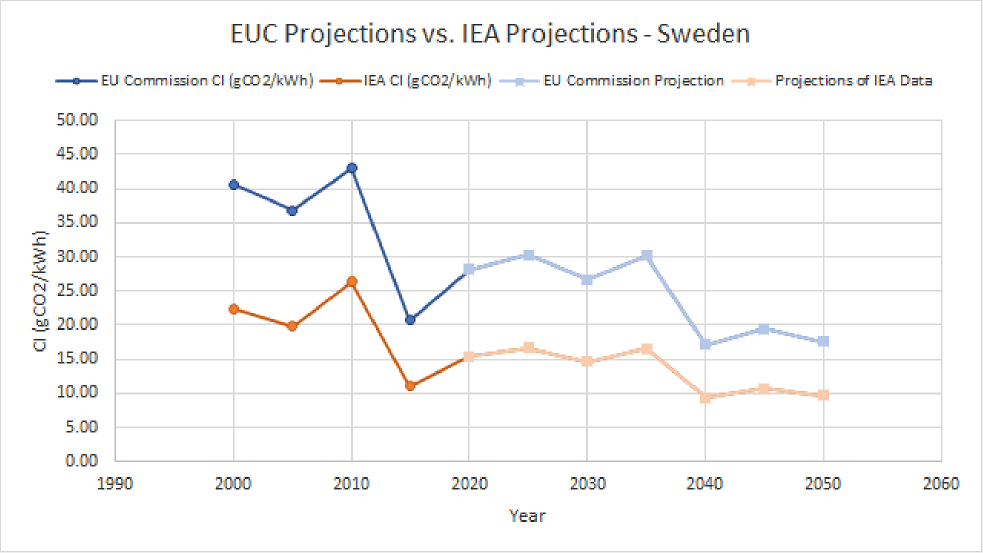


Figure 2.5: Comparison of National CI Projections

Below is an example of what the data utilized for Sweden looks like. The dark orange line corresponds to that of the above graph, but with each individual year accounted for. The projections follow the same rule, with a linear fill between each 5 year prediction.

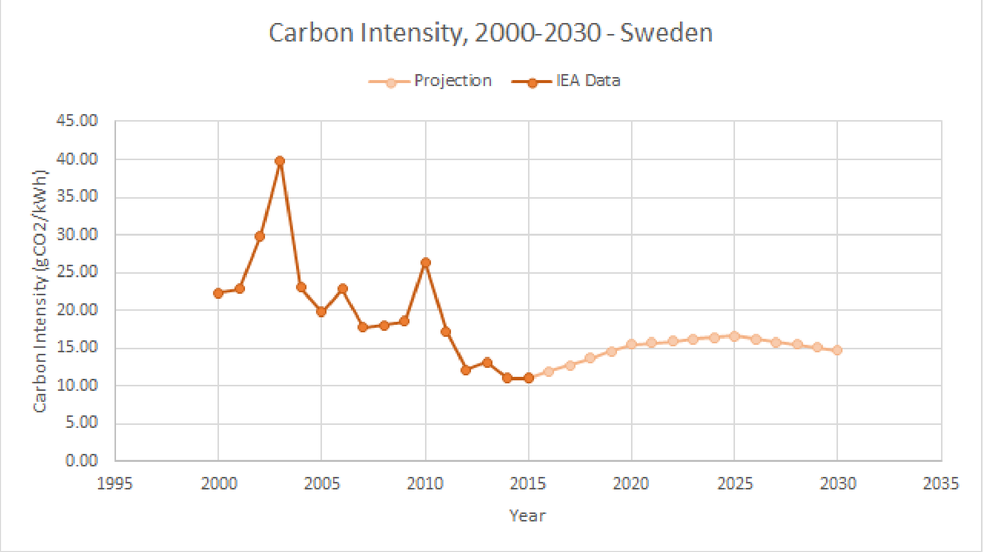


Figure 2.6: Swedish CI Projection

2.3 Scenarios

A total of four scenarios were examined in the study, namely Business as Usual (BAU), Alternative, BAU Low Emission and Alternate Low Emission. Business as usual and alternative are described below, where the main change is the focus of bus fleet development until 2030. The low emission scenarios take the same two scenarios, but assume additionally that the national energy mixes are 20% lower than their projected values for each year.

2.3.1 BAU Scenario

A central part of the study involved extrapolating data until 2030 to examine the possible effects of future public bus fleet investments. It was thus necessary to find estimates for both the national energy mixes and the bus fleets for each year until 2030. The BAU scenario considers that all standing orders and planned changes to bus fleets for the period of study are carried out according to schedule, but no further changes are made. In the case of Stockholm, a varying degree of electrification was projected. The lower boundary was used for the BAU Scenario, and the upper boundary for the Alternate Scenario

2.3.2 Alternate Scenario

The alternate scenario is an expansion upon the BAU scenario, using the same energy mix projections, but augmenting bus fleet changes, drawing from trends and policies to show a more aggressive iteration of the BAU scenario, with increased electrification and a quicker phasing out of diesel powered buses.

2.3.3 Low Intensity Scenarios

In order to offer a further bit of comparison, the energy mix projections until 2030 were reduced by a further 20% each year, and this extrapolation was used as a sub scenario for both the BAU and Alternate scenarios. This effectively models what the future outlook would be if national grid carbon intensity is to decrease more efficiently than planned in the next 12 years.

2.4 Modeling Future Bus Fleets

Of the 9 data point needed per scenario, all WTT and TTW values were calculated and WTW were represented as the sum of the two. The meanings of each data point are described in the next section, and the equations that were derived to make calculations are clarified in the section after.

2.4.1 Indicators

The results were determined for each scenario as they pertain to each of the 3 key indicators, CI, CE and EC, and for each part of the analysis, WTT, TTW and WTW. This gave a total of 9 trends per scenario that could be traced from the first year of available bus data until 2030. These indicators are listed below, along with the implications of their potential changes.

Table 2.1: Indicator descriptions

Indicator	WTT	TTW	WTW
CI (gCO2e/kWh)	Increase or decrease in the emission intensity of the fuel supply chain	Tailpipe emissions per unit energy consumed by vehicle	Total carbon intensity
EC (kWh/km)	Energy efficiency of the supply chain	Energy consumed per kilometer by vehicle	Total energy consumption
CE (gCO2e/km)	Emissions per km traveled along supply chain	Tailpipe emissions per unit distance by vehicle	Total carbon emissions

2.4.2 Analysis Equations

The analysis was carried out by iterating the following equations for each of the 9 trends for each year. Equations are outlined as follows:

$$CE_{XTX,aF,y} = \frac{\sum_{B=1}^{NT}(CE_{XTX,B,y} * NUM_{B,y})}{NUM_{F,y}} \tag{2.15}$$

Where NT refers to the number of bus types used by the city, and the subscript *B* refers to each individual bus type, while the subscript *F* refers to all bus types in the fleet. *XTX* in this case means any one of the 3 WTW phases, as the equation is the same for all. *NUM* refers to the number of buses per type or number in the whole fleet, depending on the subscript that accompanies it. Also important to note is that the previously derived equations for BEB and PHEB Carbon Emissions are included in the above summation. Following this notation, the fleet averages for the other two indicators are as follows:

$$EC_{XTX,aF,y} = \frac{\sum_{B=1}^{NT}(EC_{XTX,B,y} * NUM_{B,y})}{NUM_{F,y}} \tag{2.16}$$

$$CI_{XTX,aF,y} = \frac{\sum_{B=1}^{NT}(CI_{XTX,B,y} * NUM_{B,y})}{NUM_{F,y}} \tag{2.17}$$

Chapter 3

Results and Discussion

The Results and Discussion section presents the outcome of the constructed analysis. WTW trends are illustrated over the interval 2015-2030, and percent changes from start to finish are provided. Each city is presented individually, with treatment given to each of the 3 indicators one by one. For each city, a description of how the scenarios were constructed is provided. Comments on progress and possible abnormalities are included as well. The figures used to present the results consist of four stacked columns per year, each in two different shades of the same color. Each column represents a scenario, with the dark color the upstream (WTT) and the lighter color the local (TTW) portion of the analysis, respectively. After the individual analyses, the final section comments on how the projections align with Smart City projects and the sustainable development goals.

3.1 Barcelona

3.1.1 Background

The business as usual scenario for Barcelona is based on a report found concerning TMB's investment in electromobility (Transports Metropolitans de Barcelona 2017c). The report gives an ambitious and detailed outlook on the desired future of the bus fleet until 2029, shown in figure 4.1. Perhaps the most striking of these goals is to purchase only electric buses from 2025 onward, combined with a cease in hybrid purchases after 2022.

The Alternate scenario offers a more intensified version of the BAU scenario. Electric buses are implemented in higher numbers, and diesel is fully phased out by 2029. The move away from hybrid and CNG are also more pronounced. This leads to a slight difference in bus fleet size between the 2 scenarios, but as the difference is only 15 buses and the results are weighted averages, this has minimal effects. The fleet composition by year for both setups is given in figures 3.1 and 3.2.

The 'Low Intensity' or LI scenarios are sub-scenarios in which the same bus data and predictions as in the BAU and Alternate scenarios is taken, and each projected year's energy mix in Spain is reduced a further 20% to reflect a higher efficiency in decarbonization.

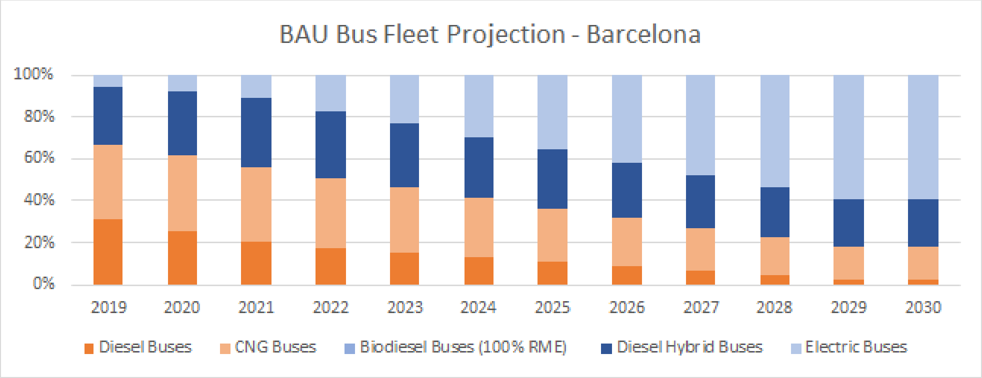


Figure 3.1: Barcelona Bus Fleet by Year - BAU

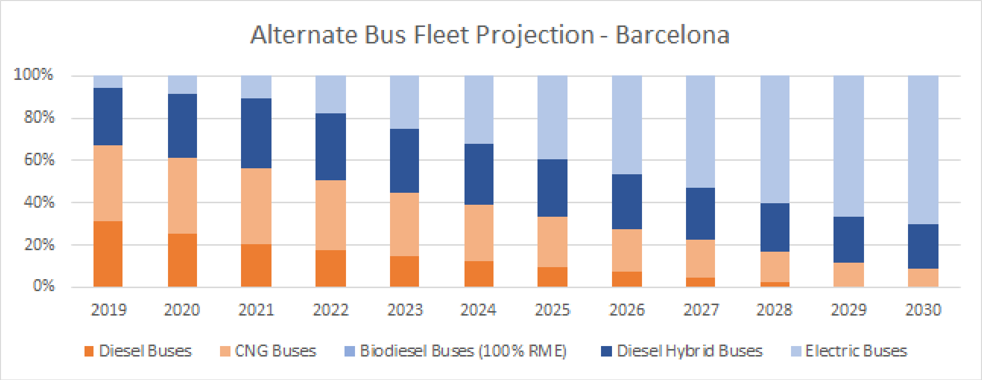


Figure 3.2: Barcelona Bus Fleet by Year - Alternate

3.1.2 Carbon Intensity

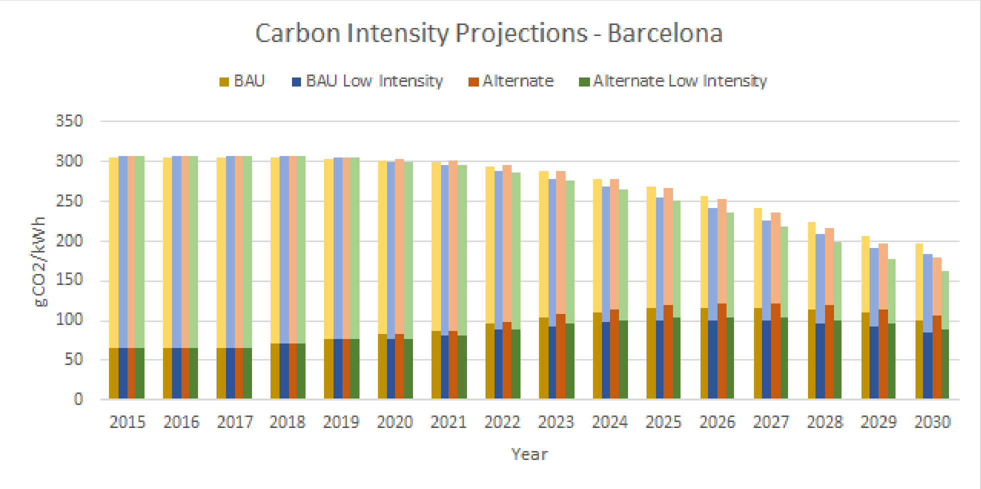


Figure 3.3: Barcelona CI Projections, 2015-2030

Projections for the BAU WTW Carbon Intensity show an overall decrease of 35% by 2030. It can however be seen in the figure 3.3 that upstream intensity rises, with an increase of 53%. This can be expected, since the intensity of the grid used for electric buses is much higher than those of the diesel and CNG bus fuels it is replacing. In the Low Intensity Scenario, the upstream increase falls from 53% to just 30%. A direct result of increased national grid decarbonization, this helps alleviate unwanted upstream GHG emissions from electric bus usage.

In the Alternate scenario, the progress of the BAU scenario is intensified, leading to an overall improvement. Figure 3.3 also shows an increase in upstream CI with respect to the BAU scenario, but the local CI drops 41% compared to the BAU, leading to an overall drop in WTW carbon intensity. The Alternate Low Intensity scenario shows its main benefits in the upstream area, where the increase is projected to be some 50% less than in the alternate scenario compared to the base year. This, along with the BAU Low Intensity Scenario show the strong upstream effects of a clean grid paired with electrification of buses. Should Barcelona begin to power these buses with a certain degree of locally generated renewable electricity, it could begin to see these kinds of improvements.

3.1.3 Carbon Emissions

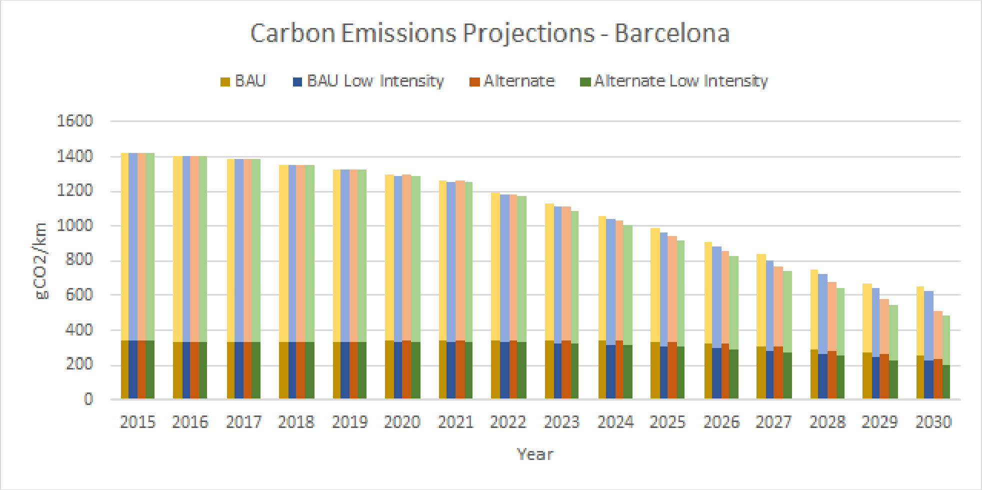


Figure 3.4: Barcelona CE Projections, 2015-2030

Carbon Emissions are projected to drop for all scenarios to 2030, both upstream and local. In the BAU Scenario, WTW emissions are projected to drop 54%, meaning a stark decrease in emissions per kilometer. Considering the Low Intensity variant of the BAU Scenario, a similar effect is seen as that of the CI section, where upstream emissions benefit from the lower national carbon intensity, and fall 33% compared with the 26% witnessed in the BAU.

The alternate scenario shows an improvement upon the BAU scenario, with WTW emissions dropping 64% and improvements in both upstream and local decarbonization, dropping here by 32% and 74% respectively. The Low Intensity projection shows the same local emissions drop of 74%, but the upstream emissions improve to drop by 41% with respect to the base year.

3.1.4 Energy Consumption

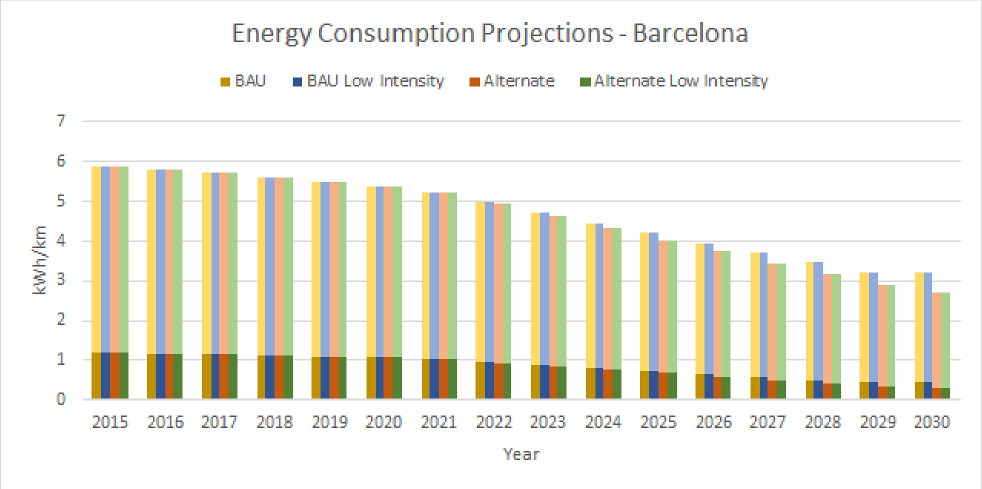


Figure 3.5: Barcelona EC Projections, 2015-2030

From figure 3.5, it can be seen that for energy consumption, the sub scenarios are not projected to make any difference. This is due to the nature of the indicator. The energy consumption upstream has to do with the efficiency of the extraction and transportation of the fuel, and locally depends on the drive train of the bus itself. An improvement in national carbon intensity will not have any bearing on the energy consumption of the fleet. That being said, the makeup of the fleet indeed has an effect, and the push for BEB integration in Barcelona shows and upstream energy consumption decrease of 63%, as less fuel transport is needed overall, and a downstream decrease of 41% due to the efficient drive trains of the electric buses.

The alternate scenarios show further improvements due to the heavier electrification and eradication of diesel buses. Upstream consumption here drops 76% and local consumption by 48%.

3.1.5 Barcelona Comments

The BAU scenario begins to show one of the key concerns of this thesis, which is how cities will handle the discrepancy between upstream WTT and local TTW emissions. Overall WTW CI emissions show a projected drop,meaning the increase in upstream Intensity is more than offset by its local component. Thus, Barcelona may be observed as decarbonizing effectively, and can indeed say that citywide emissions are decreasing, but it is important to examine the effects that this may have on upstream emissions. The city would also do well to explore alternative generation technologies, perhaps even locally for the electric fleet. The transit authority has had solar cells installed since 2013 and a CHP unit since 2014 for self consumption (Departament De Medi 2014, p. 46), so they could look to expand this for electric bus power . The city also makes a strong use of hybrid bus technology, which has proved a useful alternative to purely diesel models and has helped reduce emissions since the biofuel phase out. The expansion of these hybrids until their replacement by BEBs is an interesting approach that may bring large emission benefits locally.

3.2 Stockholm

3.2.1 Background

For Stockholm, the construction of the BAU scenario reflects the low end estimation of 2030 electrification. 35% of buses are electrified (Johansson et al. 2013, p. 542), replacing earlier ethanol, biogas and bio-diesel buses. Both hybrids remain the same, despite high likelihood that they will increase in number, as no standing orders were noted.

The alternate scenario reflects an aggressive approach to electro- and hybrid mobility. Electric buses are implemented to the high estimate of 83% as outlined in (Johansson et al. 2013, p. 542). Bio-diesel PHEBs and Bio-diesel Hybrids are also expanded based on claims of large efficiency gains and low payback times from (Johansson et al. 2013, p. 407-408). Again, all biofuels are phased out to fit the remaining percentages, assuming a constant fleet size. Below, the projected fleet compositions for both scenarios are shown.

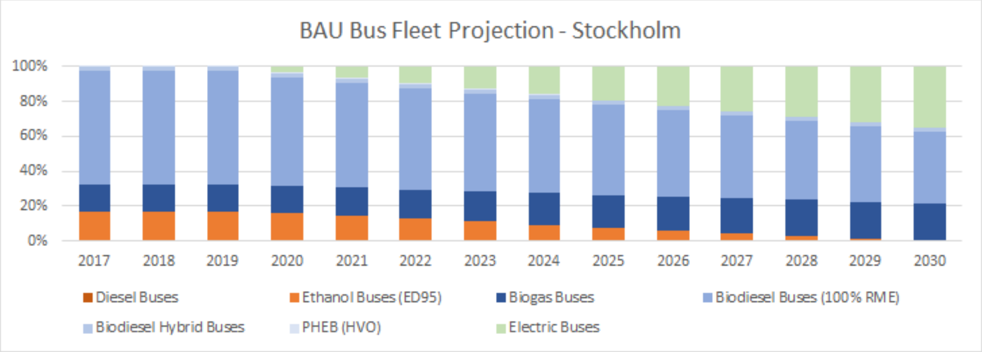


Figure 3.6: Stockholm Bus Fleet by Year - BAU

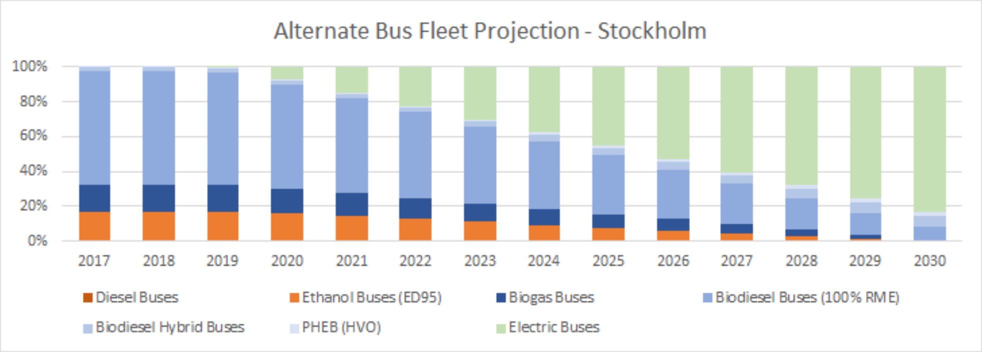


Figure 3.7: Stockholm Bus Fleet by Year - Alternate

3.2.2 Carbon Intensity

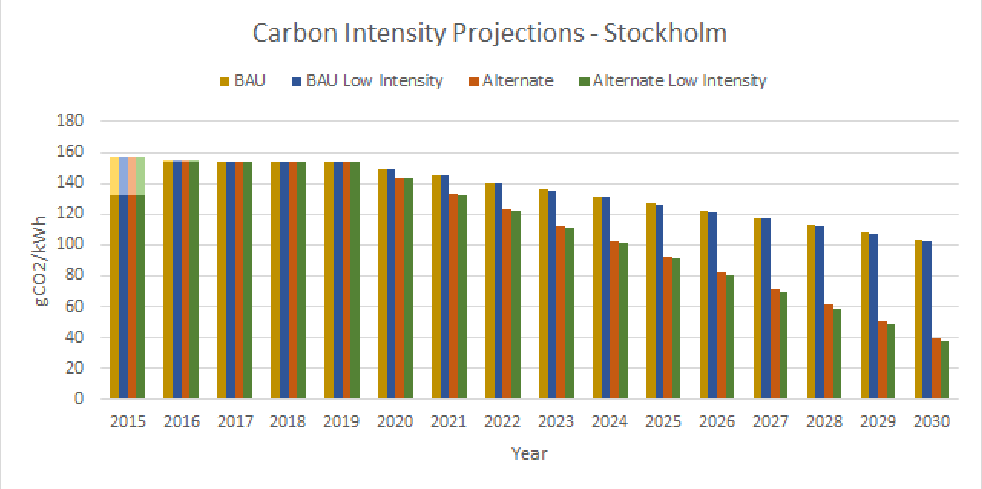


Figure 3.8: Stockholm CI Projections, 2015-2030

Throughout the analysis, WTW Carbon Intensity realizes a reduction of 34%, with the upstream portion decreasing by 21% and downstream by 100%. This last statistic is however a bit misleading because as explained, the JEC model only accounts for tailpipe emissions from fossil fuel sources. In the case of Stockholm, these sources disappeared once the last diesel bus was phased out at the beginning of 2017 (Lönnqvist 2017, p. 17). The integration of a large number of biofuel buses in 2016 shifts carbon intensity from down to upstream. The low intensity BAU scenario remains virtually unchanged from the standard BAU scenario, since Sweden already has a national carbon intensity below 20 gCO_2/kWh. Changes noted are an additional 1% decrease in upstream intensity.

In the Alternate Scenario, the projected decrease in upstream intensity doubles, with the same predicted decrease of 100% in the local intensity. Low Intensity Alternate Scenario presents similar effects to that of the Low Intensity BAU, offering a slight improvement in upstream emissions.

3.2.3 Carbon Emissions

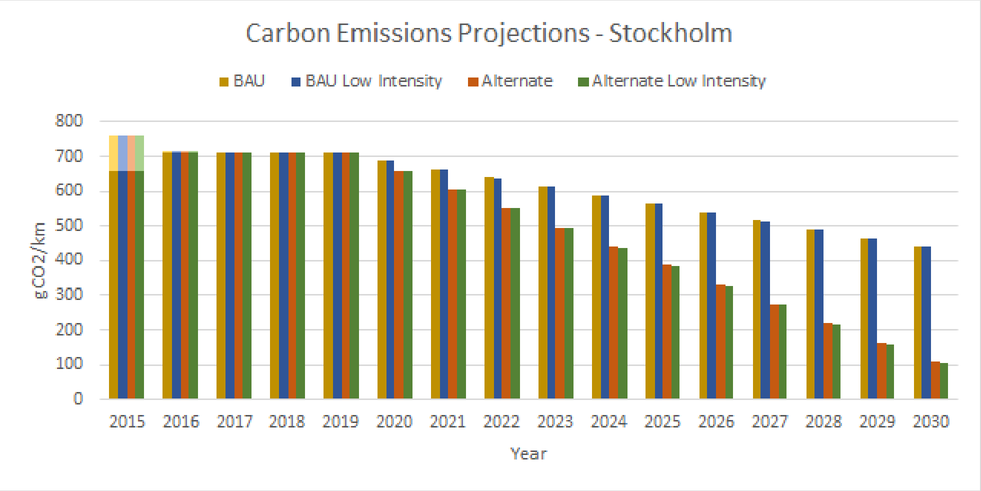


Figure 3.9: Stockholm CE Projections, 2015-2030

In the BAU Scenario, Carbon Emissions project a WTW decrease of about 42%, with a 33% decrease in upstream emissions and again a 100% decrease in local emissions due to the discontinuation of fuels that are counted for TTW emissions. The Low Intensity BAU Scenario once again does not show a substantial change, but emissions fall an extra 0.5% in the upstream part of the analysis.

The Alternate Scenario, reflecting a much heavier investment in electrification, results in a much stronger reduction in upstream carbon emissions, namely 83%. Together with 100% reduction in local emissions, this makes an 86% WTW CI reduction. The Alternate Low Intensity Scenario improves upon this, but only slightly.

3.2.4 Energy Consumption

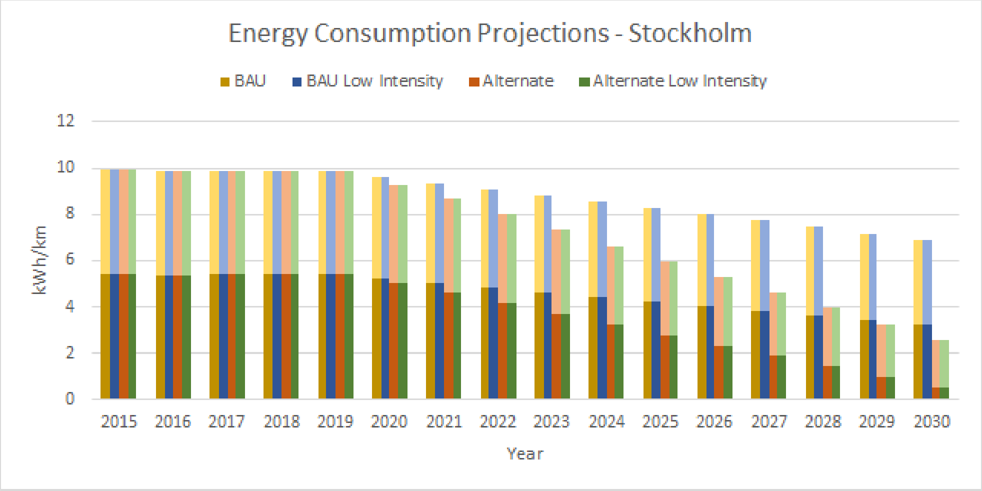


Figure 3.10: Stockholm EC Projections, 2015-2030

The WTW Energy Consumption is projected to drop across all scenarios, and as was the case with Barcelona, Low Intensity Scenarios do not differ from the normal ones. The BAU Scenario shows a WTW decrease of 30%, with upstream Energy Consumption falling 40% and local Consumption falling 18%. This decrease in upstream EC can mean the methods of fuel delivery are growing more efficient, or that there is less fuel that needs to be delivered, since electrification has increased. In this case, it is the latter.

The alternate scenario again gives much stronger results, with a WTW reduction of 74%, and upstream consumption dropping 90% to just 0.56 kWh/km for the fleet. Local energy consumption is by 2030 the major part of WTW EC, but will have fallen 54% itself over the 2015-2030 interval.

3.2.5 Stockholm Comments

Stockholm shows the clear advantage of already having very low national Carbon Intensity, and a relatively clean bus fleet. With the 2017 phase out of the last diesel powered buses, both TTW emission indicators drop to zero. This is a positive achievement for the city, and in the wake of the successful ZeEUS project, the expectation is that the city turns its focus to electrification in order to further reduce energy consumption, along with noise pollution (Xylia et al. 2017).

3.3 Warsaw

3.3.1 Background

The construction of the scenarios for Warsaw was based on press releases and already planned purchase orders for buses. The BAU assumes the orders of CNG and electric buses are completed on schedule, and they are assumed to replace an equal number of diesel buses. Upon completing these orders, no further adjustments are made, as no further future plans were uncovered. The alternate scenario reflects a heavier investment in low carbon bus solutions, namely electric buses and PHEBs. CNG and LNG numbers remain the same as BAU, and diesel continues to decrease proportionally to increases in other types.

These projections are represented graphically in figures 3.11 and 3.12.

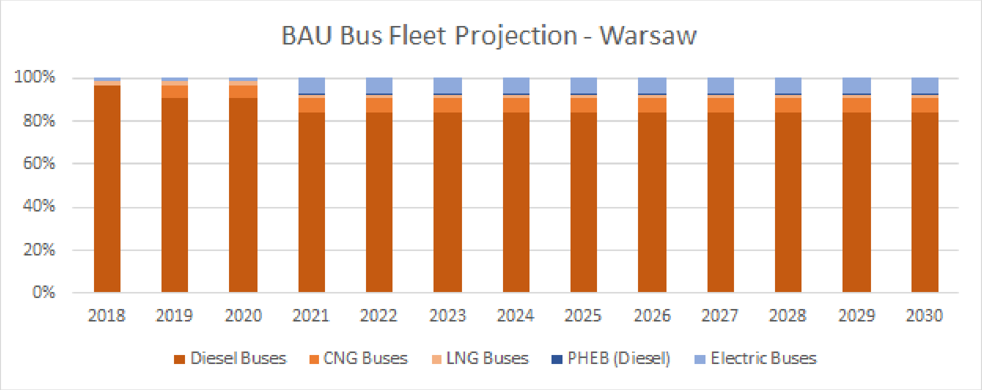


Figure 3.11: Warsaw Bus Fleet by Year - BAU

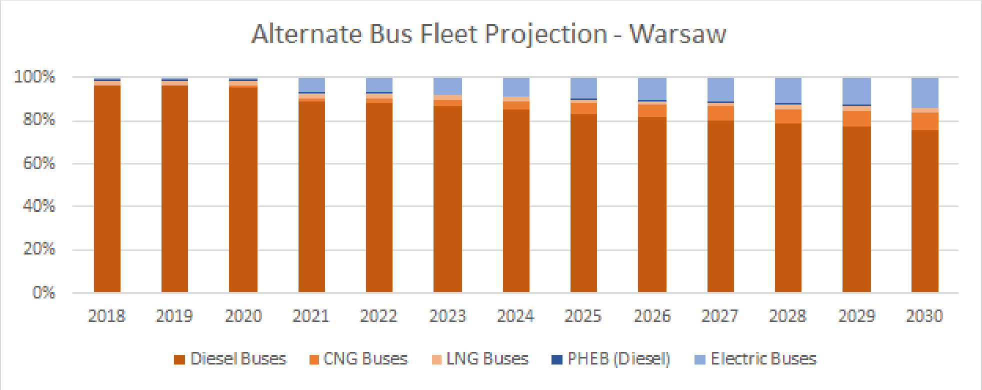


Figure 3.12: Warsaw Bus Fleet by Year - Alternate

3.3.2 Carbon Intensity

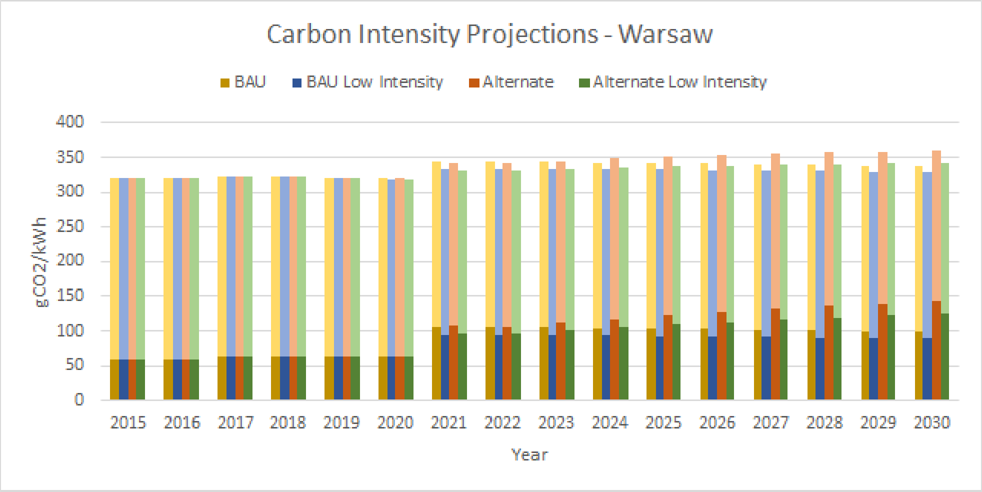


Figure 3.13: Warsaw CI Projections, 2015-2030

For BAU conditions, the local Carbon Intensity of the bus fleet is projected to fall by 8%, but an upstream increase of 56% is projected as well. As mentioned, this is to be expected when investing in electromobility. However, due to Poland's relatively high national Carbon Intensity, an overall increase in Intensity is observed, meaning that local improvements in this scenario do not "cover" the upstream increases and a net negative carbon savings of -5% is noted. The Low Intensity scenario still does not project overall savings, but the increase here has fallen to just -2%, whilst maintaining the local decrease of 8%.

The Alternate Scenario provides the least desirable outlook for bus fleet decarbonization in Warsaw, as Carbon Intensity shows only a local improvement. Upstream Intensity and WTW Intensity both nearly triple compared to their BAU counterparts. The Low Intensity Alternate Scenario shows improvements over the standard Alternate. WTW Intensity, while still projecting overall growth, has reduced from 12% in the Alternate to just 6% in the Low Intensity setting. This begins to show the limitations associated with a higher national carbon intensity when paired with investment in electromobility.

3.3.3 Carbon Emissions

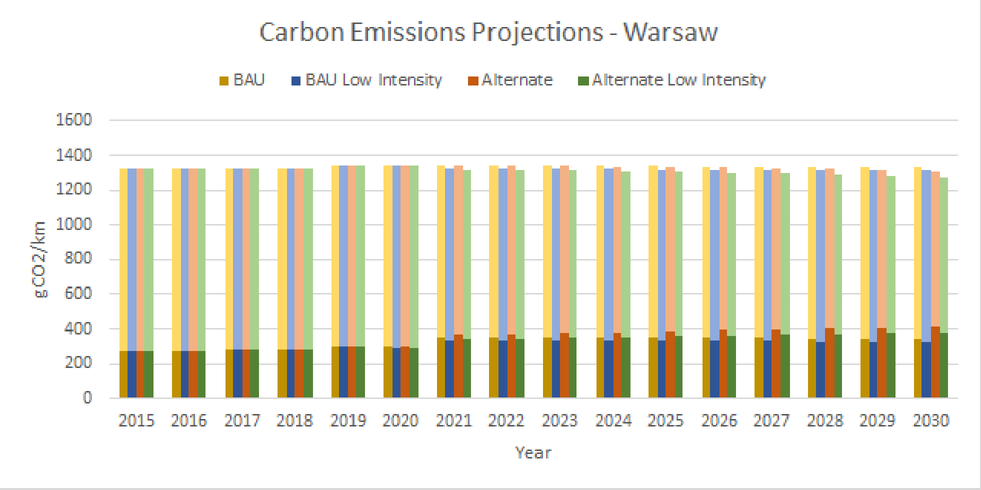


Figure 3.14: Warsaw CE Projections, 2015-2030

Emissions follow a similar trend to Intensity, with a local decrease of 6% projected, but again an upstream increase, here of 23%, is expected. This adds up to a -0.5% net decrease. The Low Intensity scenario provides a more positive outlook for the city, with WTW Emissions dropping by 0.8% in 2030, meaning that the increase in WTT Carbon Emissions has fallen enough to be covered by the decrease in TTW Emissions.

The alternate scenario continues to show improvements in local Emission reduction, with a 14% decrease projected. However, upstream emissions continue to increase, here rising by 48%. Local improvements are still enough to cover the upstream increase, and overall improvement in fleet Carbon Emissions sits at 1% less than the base year. The Low Intensity Scenario improves upon this by reducing the upstream increase to just 35%, meaning the overall improvement improves to 4%.

3.3.4 Energy Consumption

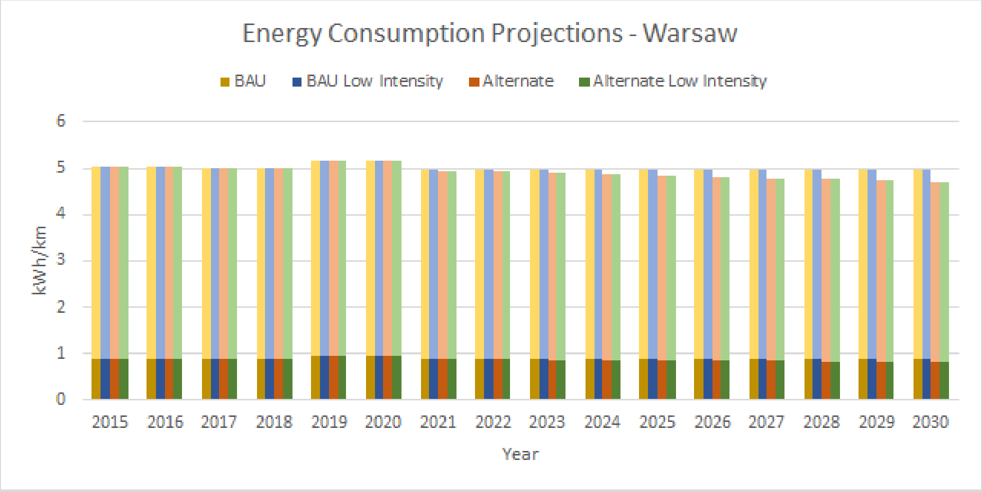


Figure 3.15: Warsaw EC Projections, 2015-2030

The Energy Consumption projected for the BAU and BAU Low Intensity Scenarios shows an overall improvement of just under 1%, with a small increase upstream and a small decrease locally.

The Alternate Scenarios show more favorable results, with a 6% improvement overall, achieved by an 8% upstream decrease and a 6% local decrease. However, even with these results, it can be shown in figure 3.15 that there is not much projected overall change in energy consumption in the current scenarios.

3.3.5 Warsaw Comments

It should be noted that the Carbon Intensity of Poland's national grid is notably higher than that of Spain and especially that of Sweden. Currently, none of the Warsaw scenarios are able to predict an overall WTW decrease in Carbon Intensity of the bus fleet to 2030. This highlights a potential problem with heavy electromobility investment in the nation, as it puts more stress on the national Carbon Intensity. Overall WTW Carbon Emissions do not show much more of an improvement, as in most scenarios they barely break even. Local gains are made, but at the sacrifice of upstream losses. Highlighting this is one of the central objectives of this thesis; identifying how electromobility carries different consequences for different nations. This raises the larger question as to whether the investment in electromobility is really an improvement in the Polish context. If decarbonization trends continue, it can be beneficial; figure 3.13 shows the Intensities all leveling off or beginning to decrease by 2030, but upstream gains will take longer to realize than in the other cities considered. The obvious recommendation is an intensified effort to reduce the national carbon intensity, but seeing that the country has long been dependent on fossil fuels (IEA 2017a), other, more locally manageable strategies may serve the city better in the near future.

Regarding the current situtation, Poland recently made changes to help meet its 15% renewable energy goal for 2020 (Reuters Staff 2018), but also approved plans to maintain lignite mining capacity (Newbury 2018). In light of this, perhaps increased local generation from cleaner sources may help bring upstream GHGs down for the Warsaw bus fleet. The city has also made efforts to reduce particulate emissions in its investment in CNG and LNG buses, noteworthy improvements which are not individually reflected in this study.

3.4 Sustainable Development Concerns

All three cities have shown interest in embracing smart city projects and addressing sustainable development. Their efforts to develop low carbon bus fleets show this dedication, but increases in upstream emissions from Barcelona and Warsaw bring the concern of scope into the discussion. A decrease in local emissions is, without a doubt a positive result. But attention must also be paid to the larger supply chain, and the environmental stresses the city is placing upon it that may not be accounted for within the city's system boundaries. This is a known issue, with Hammond and O'Grady (2014) reporting that in the case of the UK, these 'fugitive' emissions are unaccounted for by some energy conglomerates. Even the case of biofuels, which in this study are assumed to be offset by the carbon absorbed during their growth, may show drastic changes depending on the conditions in which they are grown. According to Chilvers and Jeswani (2017, p. 43), if deforestation is part of the method of bioethanol production, upstream carbon emissions can increase by 60%.

This presents a major concern for the sustainable development of these cities. A truly 'Smart City' must make every attempt to adhere to sustainable development, such as the goals put forth by the UN (UNDP 2015). However, Ahvenniemi et al. (2017) concludes that numerous smart city frameworks fail to follow the initial goal of increased sustainability. Also noted are the general lack of environmental and energy consumption indicators, and how these are at odds with the generally strong decarbonization goals set out by the United Nations and the European Commission.

Ahvenniemi et al. (2017) also suggests that the role of new Smart City technologies should be a means for sustainable development, and not simply introduced because it is new. There is evidence that this may work if structured properly; a 2018 article by Zawieska and Pieriegud (2018) projects that proper integration of smart mobility methods across the transport system of Poland could bring large GHG reductions, with hybrid and electric buses quoted as responsible for a 10-30% reduction alone. The study also notes that these reductions are best achieved with the simultaneous decarbonization of electricity generation technologies (Zawieska and Pieriegud 2018, p. 48), a statement that is in line with the results shown for Warsaw in this thesis.

Chapter 4

Conclusion

The conclusion section revisits the research questions individually and provides answers to them based on the body of the paper. A section for future work is also included, which addresses plans and suggestions for the cities moving forward.

How large are the potential effects of low emission bus models on current emissions and energy consumption, both locally and up the supply chain?

The results suggest that electrification of public bus fleets can make for some very strong GHG reductions and savings in energy consumption, but this is not a solution which can be employed in blanket fashion across the EU just yet. Additionally, the three cities face different challenges and have different goals, and for this reason it is important that their projected decarbonization success should be compared to their own historical performance and objectives, and not those of the other cities. While high levels of electrification seem to be the end goal for all 3 cities, the intermediate steps are every bit as important to ensure GHG reductions in the near future. Biogas has reduced Stockholm's emissions drastically in the absence of electric units, a role that hybrids are playing in Barcelona, and to a lesser degree CNG and LNG in Poland, aimed at bringing down regulated emissions.

Different socioeconomic and geographic conditions, among others, also yield some solutions non-viable. This was observed in Barcelona removing their bio fuelled buses when the corresponding subsidy ended. Alternatively, Poland has large deposits of coal, and thus generates most of its electricity with it, while Sweden opts for hydropower, which is more readily available in the area, and consequently carries with it substantially less emissions (IEA

2017a). Direct comparison between cities is tough for these reasons, but each can learn from the experiences of the others.

Barcelona is projected to see reductions in its WTW analysis, with definitive reductions in CI, EC and CE for the fleet to 2030. However, as mentioned, most of these reductions are focused locally, and upstream CE even reports an increase.

Stockholm, having largely eradicated local bus emissions, is looking ahead to reduce energy consumption and upstream emissions and is targeting improved electromobility to do so (Xylia et al. 2017). There is also an effort to employ more local, renewable energy sources which would bring upstream emissions down even further. Successful implementation of these ambitions could serve as a guideline for other cities public transit decarbonization efforts.

Warsaw is an interesting case, as it experiences the highest upstream and downstream emissions, but in the immediate future appears to be investing most heavily in electric buses. This is a good move for local emissions, as their alternatives - diesel, CNG and LNG are all high GHG emission models. However, unless upstream GHG Intensity drops severely, there is no projection of an overall WTW emission improvement in the bus fleet. This case shows the importance of reducing national CI in tandem with electrification, or employing an intermediate low carbon bus solution via biofuels or hybrid models.

How do public transit decarbonization strategies fit into the current trend of smart and sustainable cities?

The decarbonization of public transit and adoption of new technologies is in theory directly aligned with the promotion of Smart Cities and sustainable development. However, this study has shown that this is not necessarily a guarantee, and it might be in the best interest of the city to reevaluate their framework to place a heavier emphasis on metrics such as energy consumption and GHG emissions along the entire supply chain. Implementing policies with these goals in mind can help make Smart City projects more effective, and avoid the premature large scale introduction of technologies (i.e. Electromobility) that may shift emissions in lieu of reducing them.

It is also important to note that approaching decarbonization from a public transit standpoint gives the city direct influence over the efforts, since they are in charge of the transit authorities, They can thus guide implementation of smart and electromobility, along with controlling supply chain emissions, which would be harder to regulate if approaching decarbonization from the building sector and would, for example, require a more indirect approach involving proper regulations on private building companies.

Implications for Sustainable Development

As electromobility becomes more prominent, cities must also think about physical logistics. The ZeEUS study showed each city having a degree of difficulty locating, obtaining the necessary permits for and ensuring grid stability for the charging infrastructure needed (UITP 2018a; UITP 2018b; UITP 2015). In a recent study by Xylia et al. (2017), the focus is on where to begin electrification, and how the initial routes to be electrified can shape the outcome of the city's efforts. Electrifying routes near major transit hubs may provide the benefit of increased usage and proximity to electricity supply for trains. The study is however careful to note that electromobility is still in its infancy and thus uncertainties are to be expected.

Regarding Smart Cities, it is important that sustainability be upheld as a key facet of smart city development. Embracing emerging transport technologies that match the city goals for GHG and energy reduction can aid in this process. Cities must also work to structure policies that concern both the best interest of the city and the nation as a whole. Doing so can set the proper course for deep decarbonization all along the supply chain.

Future Work and Thesis Limitations

As mentioned, the thesis is limited by the assumptions listed in Appendix A. Future work would include further development of the model in order to reduce assumptions needed and thus increase accuracy of the estimates. More specific information on bus sizes and regional differences in emissions may be easiest to find by contacting the municipalities in question to find out if they have done any local emissions testing. They may also be able to provide insight on their local electricity mix, allowing for use of this over the national mix for the study.

As time goes on, scenarios may need to be adopted to reflect future developments, and the study can be expanded to include cost estimates of various scenarios. This could mean future scenarios include a cost optimization and emissions optimization variant. Accounting for different available technologies as well could provide insight as to the most cost effective and environmentally friendly investments over time, and help cities decide when to switch investment from one bus type to another.

The expansion of the study may also include more cities, since the model itself is applicable to any city, given the proper bus data is available. It can also easily accommodate emerging bus types, as long as the emissions data is available.

Bibliography

[AB 10] AB Stockholms Lokaltrafik. *Annual Report 2010*. Tech. rep. Stockholm: AB Stockholms Lokaltrafik, 2010, p. 92.

[AB 11] AB Stockholms Lokaltrafik. "Annual Report 2011". In: (2011).

[AB 14] AB Stockholms Lokaltrafik. *Annual Report 2013*. Tech. rep. Stockholm: AB Stockholms Lokaltrafik, 2014, p. 63.

[Ahv+17] Hannele Ahvenniemi et al. "What are the differences between sustainable and smart cities?" In: *Cities* 60 (2017), pp. 234–245. ISSN: 02642751. DOI: `10.1016/j.cities.2016.09.009`. URL: `http://dx.doi.org/10.1016/j.cities.2016.09.009`.

[Aju11] Ajuntament de Barcelona. "The energy, climate change and air quality plan of Barcelona (PECQ 2011-2020)". In: (2011), pp. 1–178. URL: `http://www.energy-cities.eu/db/Barcelona%7B%5C_%7DSEAP%7B%5C_%7D2011%7B%5C_%7Den.pdf`.

[Aju12] Ajuntament de Barcelona. "Barcelona's Commitment to the Climate". In: (2012). URL: `http://ajuntament.barcelona.cat/ecologiaurbana/sites/default/files/Barcelona%20Commitement%20to%20Climate.pdf`.

[Aju14] Ajuntament de Barcelona. "Urban Mobility Plan of Barcelona". In: (2014), p. 102. URL: `http://prod-mobilitat.s3.amazonaws.com/PMU%7B%5C_%7DSintesi%7B%5C_%7DAngles.pdf`.

[AL11] Alex Anas and Robin Lindsey. “Reducing urban road transportation externalities: Road pricing in theory and in practice”. In: *Review of Environmental Economics and Policy* 5.1 (2011), pp. 66–88. ISSN: 17506816. DOI: 10.1093/reep/req019.

[Are17] Area Metropolitant de Barcelona. *L’AMB redueix emissions de CO2 - Àrea metropolitana de Barcelona*. 2017. URL: http://www.amb.cat/ca/web/medi-ambient/actualitat/noticies/detall/-/noticia/l-amb-redueix-emissions-de-co2/6660690/11818?%7B%5C_%7DNoticiaSearchListPortlet%7B%5C_%7DWAR%7B%5C_%7DAMBSearchPortletportlet%7B%5C_%7DpageNum=1%7B%5C&%7D%7B%5C_%7DNoticiaSearchListPortlet%7B%5C_%7DWAR%7B%5C_%7DAMBSearchPortletportlet%7B%5C_%7Dformat=%7B%5C&%7D%7B%5C_%7DNoticia (visited on 08/19/2018).

[BDi10] City of Warsaw - BDiK. “The Transportation System of Warsaw: Sustainable Development Strategy up to the year 2015 and successive years”. In: (2010). URL: http://www.transport.um.warszawa.pl/sites/default/files/STRATEGIA%7B%5C_%7Dsynteza%20ENG.pdf.

[Bou+14] Jacky Bourgeois et al. “Conversations with my washing machine: an in-the-wild study of demand-shifting with self-generated energy”. In: *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp ’14 Adjunct* (2014), pp. 459–470. DOI: 10.1145/2632048.2632106. URL: http://dl.acm.org/citation.cfm?doid=2632048.2632106%7B%5C%%7D5Cnhttp://oro.open.ac.uk/40465/.

[CCH16] Carl K Chang, Lorenzo Chiari, and David Hutchison. “Inclusive Smart Cities”. In: (2016). URL: http://eu-smartcities.eu/sites/default/files/2017-09/EIP-SCC%20Manifesto%20on%20Citizen%20Engagement%20%7B%5C%%7D26%20Inclusive%20Smart%20Cities%7B%5C_%7D0.pdf.

[CDP16] CDP Open Data Portal. *2016 - Citywide Emissions, Map | CDP Open Data Portal*. 2016. URL: `https://data.cdp.net/Cities/2016-Citywide-Emissions-Map/iqbu-zjaj/data` (visited on 08/19/2018).

[Cit12] City of Stockholm. “Stockholm: A Sustainably Growing City”. In: (2012), p. 48. URL: `http://international.stockholm.se/Politics-and-organisation/A-sustainable-city/`.

[Cit17] City of Boston. *BOS:311 APP*. 2017. (Visited on 08/21/2018).

[CJ17] Andrew Chilvers and Harish Jeswani. *Sustainability of liquid biofuels*. 2017, pp. 1–96. ISBN: 978-1-909327-34-4. URL: `www.raeng.org.uk/biofuels%7B%5C%%7D0Awww.raeng.org.uk/biofuels`.

[CV17] Leslie Carter and Jenson Varghese. “Electric Bus Technology”. In: *Transport Research Report* March (2017), p. 57. URL: `http://www.mrcagney.com/uploads/documents/MRC%7B%5C_%7DElectric%7B%5C_%7DBus%7B%5C_%7DReport%7B%5C_%7D%7B%5C_%7D02082017.pdf`.

[DDD11] Bruno Declercq, Erik Delarue, and William D’haeseleer. “Impact of the economic recession on the European power sector’s CO2 emissions”. In: *Energy Policy* 39.3 (2011), pp. 1677–1686. ISSN: 03014215. DOI: `10.1016/j.enpol.2010.12.043`. URL: `http://dx.doi.org/10.1016/j.enpol.2010.12.043`.

[DEE18] DEEDS. *DEEDS – DialoguE on European Decarbonisation Strategies*. 2018. URL: `https://deeds.eu/` (visited on 08/20/2018).

[DEN14] DENA. “LNG in Germany : Liquefied Natural Gas and Renewable Methane in Heavy-Duty Road Transport”. In: (2014), pp. 1–2.

[Dep14] Departament De Medi. “4rt seguiment del Pla Director de Sostenibilitat Ambiental de TMB”. In: (2014), p. 71.

[Dre+18] Dennis Dreier et al. "Well-to-Wheel analysis of fossil energy use and greenhouse gas emissions for conventional, hybrid-electric and plug-in hybrid-electric city buses in the BRT system in Curitiba, Brazil". In: *Transportation Research Part D: Transport and Environment* 58.December 2017 (2018), pp. 122–138. ISSN: 13619209. DOI: `10.1016/j.trd.2017.10.015`. URL: `https://doi.org/10.1016/j.trd.2017.10.015`.

[Edw+14a] Robert Edwards, Heinz Hass, Jean-François Larivé, Laura Lonza, Heiko Mass, and David Rickeard. *WELL-TO-WHEELS Report Version 4.a JEC WELL-TO-WHEELS ANALYSIS WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT*. 2014, p. 98. ISBN: 9789279338878. DOI: `10.2790/95533`.

[Edw+14b] Robert Edwards, Heinz Hass, Jean-François Larivé, Laura Lonza, Heiko Mass, David Rickeard, et al. *Well-to-Wheels analysis of future automotive fuels and powertrains in the European context WELL-TO-TANK (WTT) Report. Version 4.* 2014, pp. 1–133. ISBN: 9789279338885. DOI: `10.2790/95629`.

[EIT18] EIT InnoEnergy. *MSc Energy for Smart Cities : InnoEnergy - pioneering change in sustainable energy*. 2018. URL: `http://www.innoenergy.com/education/master-school/our-master-programmes/msc-energy-for-smart-cities/` (visited on 08/20/2018).

[Eli08] Jonas Eliasson. "Lessons from the Stockholm congestion charging trial". In: *Transport Policy* 15.6 (2008), pp. 395–404. ISSN: 0967070X. DOI: `10.1016/j.tranpol.2008.12.004`.

[Eur09] European Parliament. "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009". In: *Official Journal of the European Union* 140.16 (2009), pp. 16–62. ISSN: 02870827. DOI: `10.3000/17252555.L_2009.140.eng`. arXiv: `534`.

[Eur14] European Commission. “EU Reference Scenario 2016 Presentation”. In: *Energy, transport and GHG emissions - Trends to 2050* (2014), p. 220. DOI: `10.2833/9127`. URL: `https://ec.europa.eu/energy/sites/ener/files/documents/ref2016%7B%5C_%7Dreport%7B%5C_%7Dfinal-web.pdf`.

[Eur17] European Investment Bank. *ELENA Completed Project Factsheet Energy Efficient Bus Network for Barcelona (ELECTROBUS)*. Tech. rep. 2017, pp. 1–2.

[Eur18] European Commission Regional Policy Newsroom. *130 new electric buses for Warsaw thanks to EU Cohesion policy - Regional Policy - European Commission*. 2018. URL: `http://ec.europa.eu/regional%7B%5C_%7Dpolicy/en/newsroom%20/news/2018/01/18-01-2018-130-new-electric-buses-for-warsaw-thanks-to-eu-cohesion-policy` (visited on 08/19/2018).

[HO14] Geoffrey P Hammond and Áine O’Grady. “The implications of upstream emissions from the power sector”. In: *Proceedings of the Institution of Civil Engineers - Energy* 167.1 (2014), pp. 9–19. ISSN: 17514223. DOI: `http://dx.doi.org/10.1680/ener.13.00006`. URL: `http://www.icevirtuallibrary.com/doi/full/10.1680/ener.13.00006`.

[IEA17a] IEA. *CO2 Emissions from Fuel Combustion - 2017*. Tech. rep. 2017, p. 529. URL: `www.iea.org`.

[IEA17b] IEA. “CO2 Emissions from Fuel Combustion 2017 - Highlights”. In: *International Energy Agency* 1 (2017), pp. 1–162. DOI: `10.1787/co2_fuel-2017-en`. URL: `https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf`.

[IEA18] IEA. *Indicators for CO2 Emissions*. 2018. URL: `https://doi-org.focus.lib.kth.se/10.1787/data-00433-en` (visited on 08/19/2018).

[Inf13] Infrastructure Department of The City of Warsaw. *Sustainable Energy Action Plan For Warsaw In The Perspective Of 2020: Synthesis*. 2013. ISBN: 9788363269241. URL: `http://bip.warszawa.pl/NR/rdonlyres/2B9032C5-3260-43F5-BF96-D75BF3FB3861/974080/20131231%7B%5C_%7DSEAP%7B%5C_%7Dsynteza%7B%5C_%7DEN.pdf`.

[JEC16a] JEC. *Welcome to the JEC website - European Commission*. 2016. URL: `https://ec.europa.eu/jrc/en/jec` (visited on 08/19/2018).

[JEC16b] JEC. *Well-to-Wheels Analyses - European Commission*. 2016. URL: `https://ec.europa.eu/jrc/en/jec/activities/wtw` (visited on 08/19/2018).

[Joh+13] T.B. Johansson et al. *Fossilfrihet på väg*. 2013. ISBN: 9789138240557.

[Jun17] Gerfried Jungmeier. "IEA HEV Task 33 "Battery Electric Busses"". In: *International Conference on Electric Mobility and Public Transport* (2017).

[Lat+15] Juhani Latvakoski et al. "Simulation-Based Approach for Studying the Balancing of Local Smart Grids with Electric Vehicle Batteries". In: *Systems* 3.3 (2015), pp. 81–108. ISSN: 2079-8954. DOI: `10.3390/systems3030081`. URL: `http://www.mdpi.com/2079-8954/3/3/81/`.

[LN14] Örjan Lönngren and Lova André Nilson. *Roadmap for a fossil fuel-free Stockholm 2050*. Tech. rep. 1. 2014, p. 3.

[Lön17] Tomas Lönnqvist. "Biogas in Swedish transport – a policy-driven systemic transition". PhD thesis. KTH - Royal Institute of Technology, 2017, p. 90. ISBN: 9789177293897. URL: `https://www.diva-portal.org/smash/get/diva2:1093408/FULLTEXT01.pdf`.

[Maa15] Helen Maalinn. "Sustainable public transports via use of biogas". In: September 2014 (2015).

[Mah+16] Moataz Mahmoud et al. "Electric buses: A review of alternative powertrains". In: *Renewable and Sustainable Energy Reviews* 62 (2016), pp. 673–684. ISSN: 18790690. DOI: `10.1016/j.rser.2016.05.019`.

[New18] Charles Newbury. *Poland approves lignite strategy | S&P Global Platts*. 2018. URL: `https://www.spglobal.com/platts/en/market-insights/latest-news/coal/060518-poland-approves-lignite-strategy` (visited on 08/22/2018).

[NGV18] NGV Global News. *MAN to Supply 110 Lion's City CNG Buses to Warsaw in 2019 | NGV Global*. 2018. URL: `http://www.ngvglobal.com/blog/man-to-supply-110-lions-city-cng-buses-to-warsaw-in-2019-0720` (visited on 08/19/2018).

[NK12] Nils-Olof Nylund and P Koponen. *Fuel and technology alternatives for buses*. 2012, pp. 1–15. ISBN: VTT Technology 46.

[Ols15] Michał Olszewski. *Polish strategies for decarbonization*. 2015. URL: `https://pl.boell.org/en/2015/08/26/polish-strategies-decarbonization` (visited on 08/19/2018).

[Pub18] Public Transit Authority of the capital city of Warsaw. *ZTM Warszawa Homepage*. 2018. URL: `http://www.ztm.waw.pl/?l=2` (visited on 08/19/2018).

[Reu18] Reuters Staff. *Polish parliament approves changes to green energy law | Reuters*. 2018. URL: `https://www.reuters.com/article/us-poland-energy/polish-parliament-approves-changes-to-green-energy-law-idUSKBN1JP1JV` (visited on 08/22/2018).

[Sek] Sekab Biofuels and Chemicals AB. "Ethanol - here and now". In: (). URL: `www.sekab.com`.

[Sto17a] Stockholm County Council. "Environmental report TN 2015-1526-25TN". In: 1.44 (2017), pp. 1–44.

[Sto17b] Stockholms Stad. *Smart and Connected City - City of Stockholm*. 2017. URL: `https://international.stockholm.se/governance/smart-and-connected-city/` (visited on 08/21/2018).

[Swe04] Swedish Energy Agency. *Energy in Sweden 2004*. Tech. rep. Eskilstuna: Swedish Energy Agency, 2004, p. 59.

[Swe16] Swedish Energy Agency. *Drivmedel och biobränslen 2015. Mängder, komponenter och ursprung rapporterade i enlighet med drivmedelslagen och hållbarhetslagen. ER 2016:12*. Tech. rep. 2016, pp. 1–46.

[The18] The World Bank Group. *Climate Change Knowledge Portal*. 2018. URL: `http://sdwebx.worldbank.org/climateportal/index.cfm?page=downscaled%7B%5C_%7Ddata%7B%5C_%7Ddownload%7B%5C&%7Dmenu=historical` (visited on 08/19/2018).

[Tra11] Centre d'Innovació del Transport. *Projectes Innovadors en el Sector del Transport i la Mobilitat*. Tech. rep. 2011. URL: `http://www.think-med.es/wp-content/uploads/group-documents/5/1357554892-ICEX2011TurismoMarruecos.pdf`.

[Tra14] Transports Metropolitans de Barcelona. *Resum de gestió 2013*. Tech. rep. 2014.

[Tra16] Transports Metropolitans de Barcelona. *2015 Management Report*. Tech. rep. August. 2016, p. 96.

[Tra17a] Transports Metropolitans de Barcelona. "2016 Management Report". In: July (2017).

[Tra17b] Transports Metropolitans de Barcelona. *Dades bàsiques/Basic data 2017*. Tech. rep. 2017, p. 2. URL: `https://www.tmb.cat/es/home`.

[Tra17c] Transports Metropolitans de Barcelona. "INNOVATION: How will we finance?: TMB USE CASE". In: (2017).

[Tra18] Transports Metropolitans de Barcelona. *Dades bàsiques/Basic data 2018*. Tech. rep. 2018, p. 2.

[TS10] Marco F. Torchio and Massimo G. Santarelli. "Energy, environmental and economic comparison of different powertrain/fuel options using well-to-wheels assessment, energy and external costs - European market analysis". In: *Energy* 35.10 (2010), pp. 4156–4171. ISSN: 03605442. DOI: `10.1016/j.energy.2010.06.037`. URL: `http://dx.doi.org/10.1016/j.energy.2010.06.037`.

[UIT14] UITP. *ZeEUS - Zero Emission Urban Bus Systems - Homepage*. 2014. URL: `http://www.uitp.org/zeeus-zero-emission-urban-bus-systems` (visited on 08/19/2018).

[UIT15] UITP. “WARSAW (PL)”. In: (2015), p. 2. URL: `http://zeeus.eu/uploads/publications/documents/zeeus-city-sheet-warsaw-en-final.pdf`.

[UIT18a] UITP. “Barcelona (ES)”. In: (2018), p. 2. URL: `http://zeeus.eu/uploads/publications/documents/zeeus-city-sheet-barcelona-en-final.pdf`.

[UIT18b] UITP. “STOCKHOLM (SE)”. In: (2018), p. 2. URL: `http://zeeus.eu/uploads/publications/documents/zeeus-city-sheet-stockholm-en-final-final.pdf`.

[UND15] UNDP. “Sustainable Development Goals”. In: *Undp* (2015), p. 24. ISSN: 1098-6596. DOI: `10.1017/CBO9781107415324.004`. arXiv: `arXiv:1011.1669v3`. URL: `http://www.undp.org/content/dam/undp/library/corporate/brochure/SDGs%7B%5C_%7DBooklet%7B%5C_%7DWeb%7B%5C_%7DEn.pdf`.

[Uni02] United States EPA. “Clean Alternative Fuels: Compressed Natural Gas”. In: EPA420-F-00-033 (2002), pp. 1–2.

[Ver+17] Robin Vermeulen et al. *Emissions testing of two Euro VI LNG heavy-duty vehicles in the Netherlands : tank-to-wheel emissions*. Tech. rep. Den Haag: TNO, 2017, p. 39.

[Wur+11] R. Wurster et al. “LNG as an alternative fuel for the operation of ships and heavy-duty vehicles”. In: March 2014 (2011), pp. 1–94.

[Xyl+17] Maria Xylia et al. “Locating charging infrastructure for electric buses in Stockholm”. In: *Transportation Research Part C: Emerging Technologies* 78 (2017), pp. 183–200. ISSN: 0968090X. DOI: `10.1016/j.trc.2017.03.005`. URL: `http://dx.doi.org/10.1016/j.trc.2017.03.005`.

[Xyl18] Maria Xylia. “Towards electrified public bus transport: The case of Stockholm”. Doctoral Thesis. KTH Royal Institute of Technology, 2018, p. 55. ISBN: 9789177297420.

[Zar17] Zarzaąd Transportu Miejskiego w Warszawie. *Informator Statystyczny 2017*. Tech. rep. Warsaw, 2017.

[ZeE14] ZeEUS - Zero Emission Bus System. *Demonstrations*. 2014. URL: `http://zeeus.eu/demonstrations-activities/demonstrations` (visited on 08/19/2018).

[ZeE17] ZeEUS - Zero Emission Bus System. *ZeEUS Demonstration in Stockholm – what have we learnt about plug-in hybrid buses? – ZeEUS – Zero Emission Urban Bus System*. 2017. URL: `http://zeeus.eu/news/zeeus-demonstration-in-stockholm` (visited on 08/20/2018).

[Zho+16] Boya Zhou et al. “Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions”. In: *Energy* 96 (2016), pp. 603–613. ISSN: 03605442. DOI: `10.1016/j.energy.2015.12.041`.

[ZM16] Jiucai Zhang and Tony Markel. “Charge management optimization for future TOU rates”. In: *World Electric Vehicle Journal* 8.2 (2016), pp. 521–530. ISSN: 20326653. URL: `https://www.nrel.gov/docs/fy16osti/66121.pdf`.

[ZP18] Jakub Zawieska and Jana Pieriegud. “Smart city as a tool for sustainable mobility and transport decarbonisation”. In: *Transport Policy* 63.November 2017 (2018), pp. 39–50. ISSN: 1879310X. DOI: `10.1016/j.tranpol.2017.11.004`. URL: `https://doi.org/10.1016/j.tranpol.2017.11.004`.

Appendix A

Key Assumptions

A.1 Assumptions

While constructing the study, a series of assumptions were made in order to reduce the number of variables present. These are listed and briefly described below.

Bus Engines

All but engines were assumed to be the EEV model that was used in the VTT Technical Research Center of Finland report, with the exception of those for which EEV based data could not be found, namely the LNG and PHEV. The euro standard was introduced in 1992 and has set limits on particulate emissions of passenger and heavy duty vehicles in every year since. New engine models have continually been released in correspondence to these stricter limits CITE. The standard does not define limits for CO_2 emissions specifically, but given efforts to reduce CO_2 emissions, engines have become more efficient, and thus the assumption is introduced in order to keep constant emission factors throughout the study. This means this study may slightly over or underestimate emissions depending on actual units used by the fleets in the past and future. Additionally, the hybrid configuration used in this study in all cases is parallel. City reports did not distinguish which type was being used, and the literature suggested that there were only minor statistical differences between the two (Nylund, N.-O., Koponen, P., 2012, Appendix 7/2).

N2O, CH4 Emissions Included as GHGs

Following the JEC methodology, smaller particulate emissions are included in the CO_2 emissions with equivalence factors of 296 for N2O and 23 for CH4, respectively (Nylund, N.-O., Koponen, P., 2012, pp. 77). All factors that refer to life cycle emissions in which these particulate emissions are accounted for are labeled as CO_2e for grams of CO_2 equivalent. This, combined with the study's specific focus on CO_2 emissions and energy consumption, mean that the current and future effects of particulate emissions are not addressed in as much depth. It is however worth noting that decreasing particulate emissions are also a significant objective of many municipalities. The aforementioned Euro engine standards contribute to this, as does the large investment in CNG buses by many cities, which show minimal decrease in CO_2 emissions, but a large decrease in particulate emissions (United States EPA, 2002).

No Distinction for Articulated Bus

All three cities included in this study make use of both single and articulated bus types (Transports Metropolitans de Barcelona 2018; Stockholm County Council 2017; Zarzaąd Transportu Miejskiego w Warszawie 2017). Being different sizes, consumption factors for these types is different. However, for the sake of simplicity and to make best use of the available resources, all buses included in the study are assumed to be singular. When various data was available, that which most closely represented a standard 12m bus was chosen. This will most likely introduce a slight underestimation factor into the results.

Standard Emission Factors

It is highly likely that the data obtained is subject to change across the three cities included, and even within cities, changes throughout seasons, bus routes and time of day are also likely to be noted. Since this study seeks to aggregate average data across many years, this was deemed necessary to simplify. All cities are analyzed according to the same emission data. While this may ignore regional differences, it ensures consistency across the three cities represented.

Assumed National Carbon Intensity

The data for national carbon intensities was used in all cases to represent the local intensity. This may not be 100% accurate in reality, but the consistency of available IEA data was chosen, especially considering that no complete sources of local carbon intensity could be found. Moving forward, this may come into play more, as cities may invest in their own cleaner generation technologies to power local services. Stockholm, for example, has considered this as they work to become fossil free by 2050 (Lönngren and Nilson 2014, p. 25).

Appendix B

National Carbon Intensity Projections

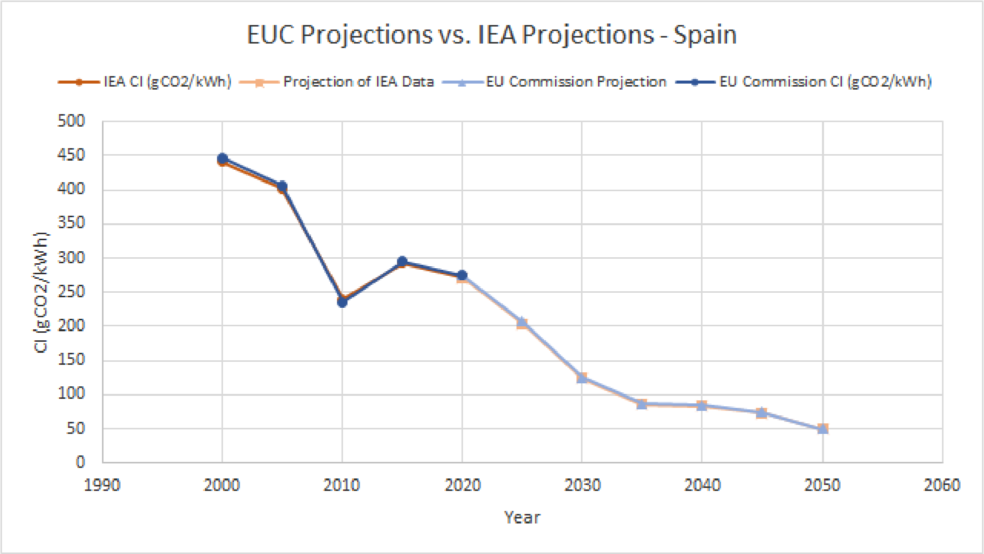


Figure B.1: Spanish Carbon Intensity Comparison of Projections

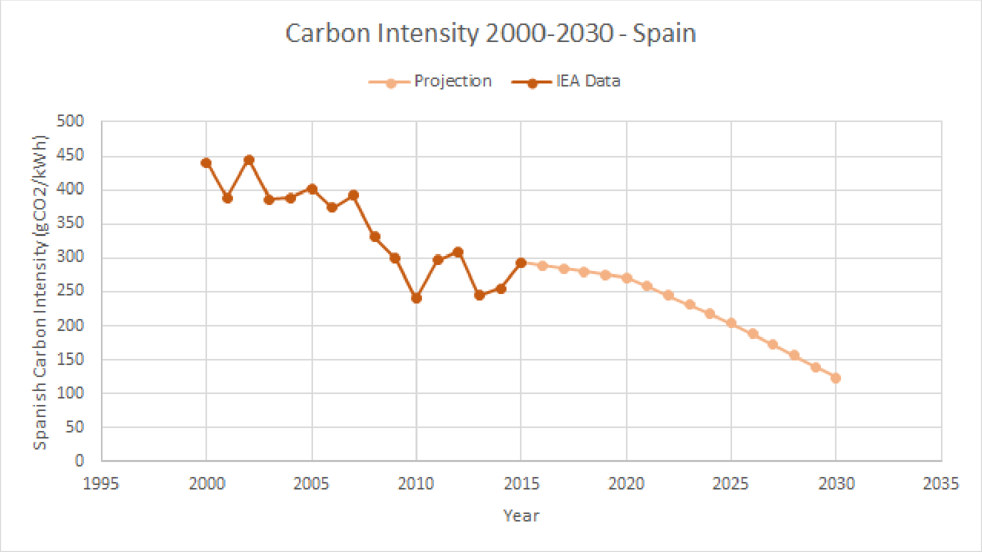


Figure B.2: Spanish Carbon Intensity - Projected

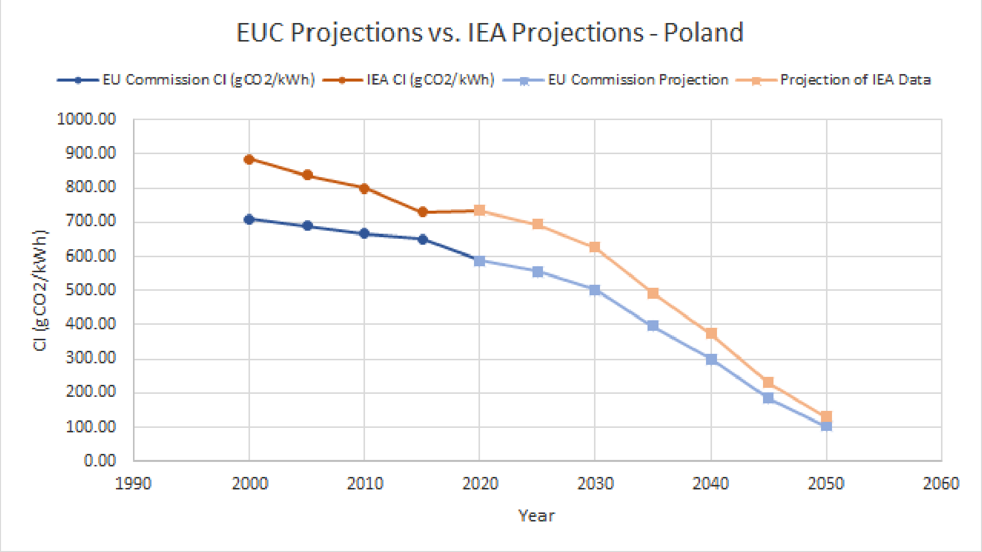


Figure B.3: Polish Carbon Intensity Comparison of Projections

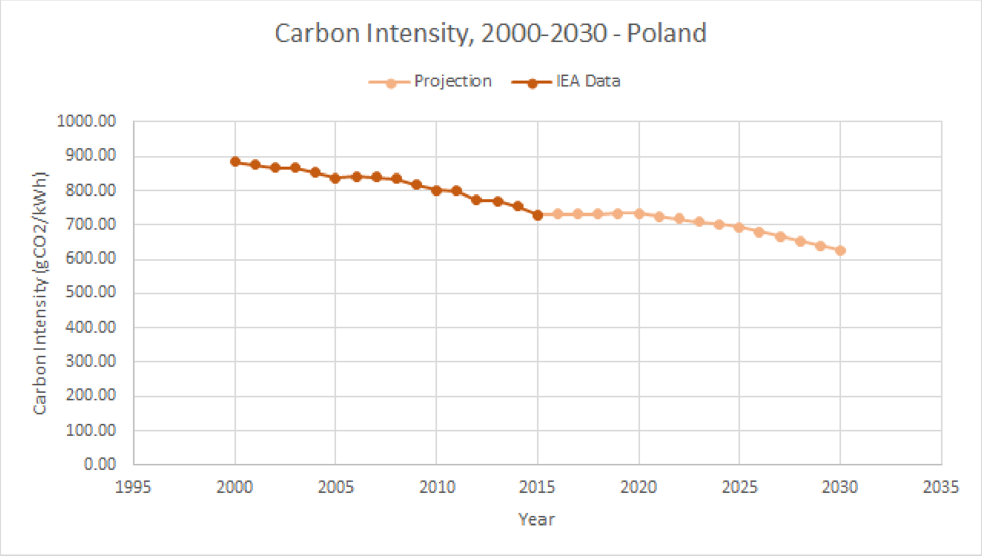


Figure B.4: Polish Carbon Intensity - Projected

Appendix C

City Results - Alternate Graphs

C.1 Barcelona

C.1.1 Carbon Emissions

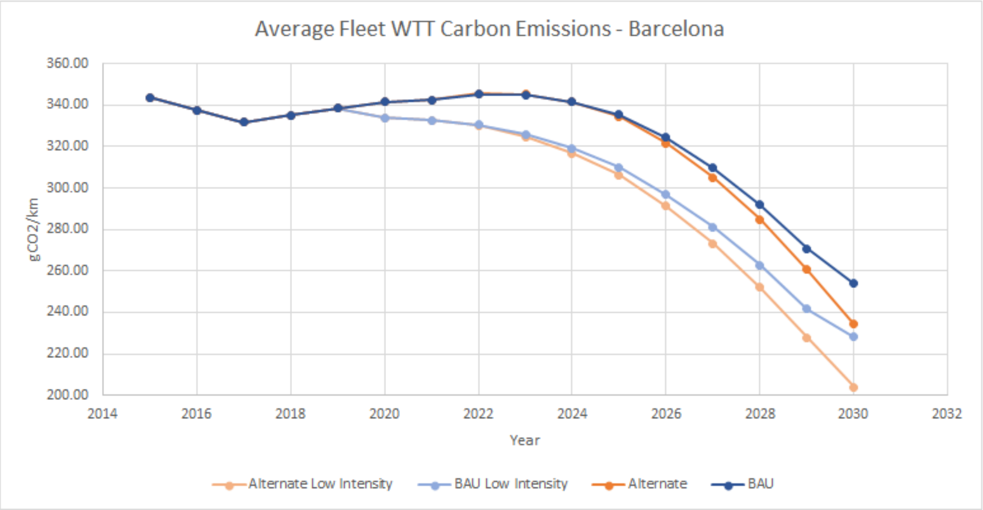


Figure C.1: Barcelona WTT CE - Projected

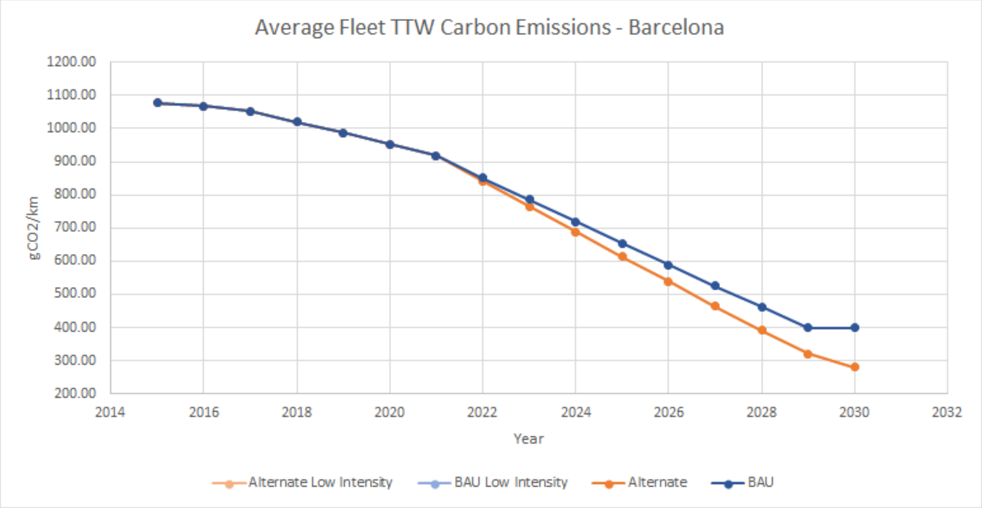


Figure C.2: Barcelona TTW CE - Projected

C.1.2 Energy Consumption

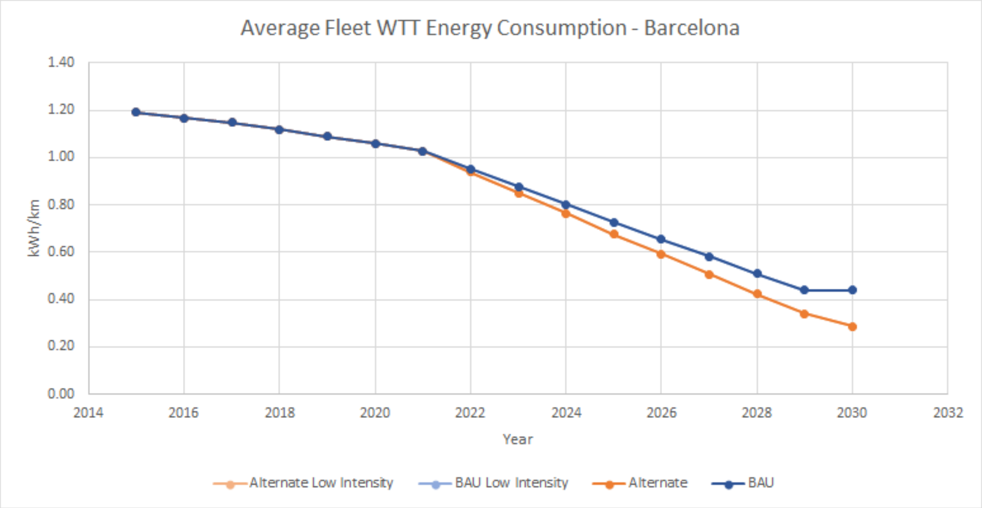


Figure C.3: Barcelona WTT EC - Projected

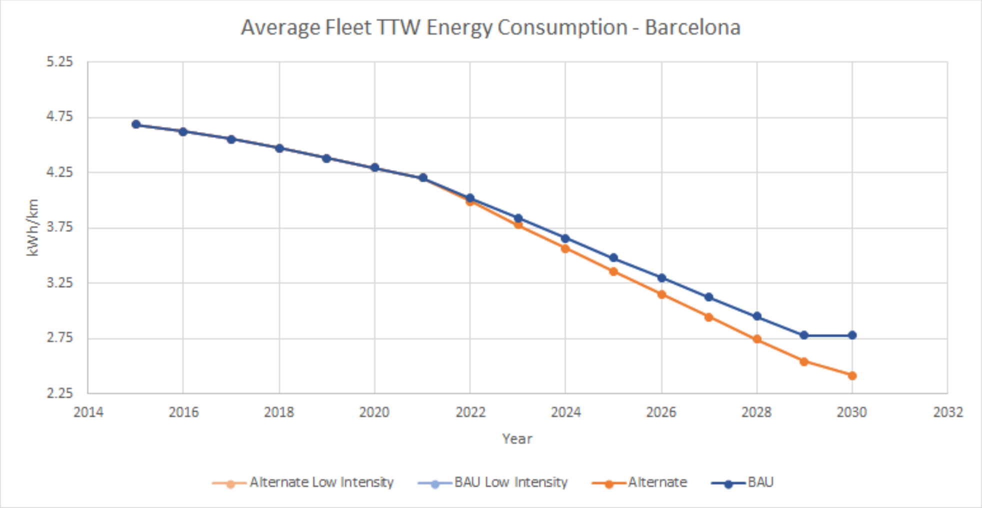


Figure C.4: Barcelona TTW EC - Projected

C.1.3 Carbon Intensity

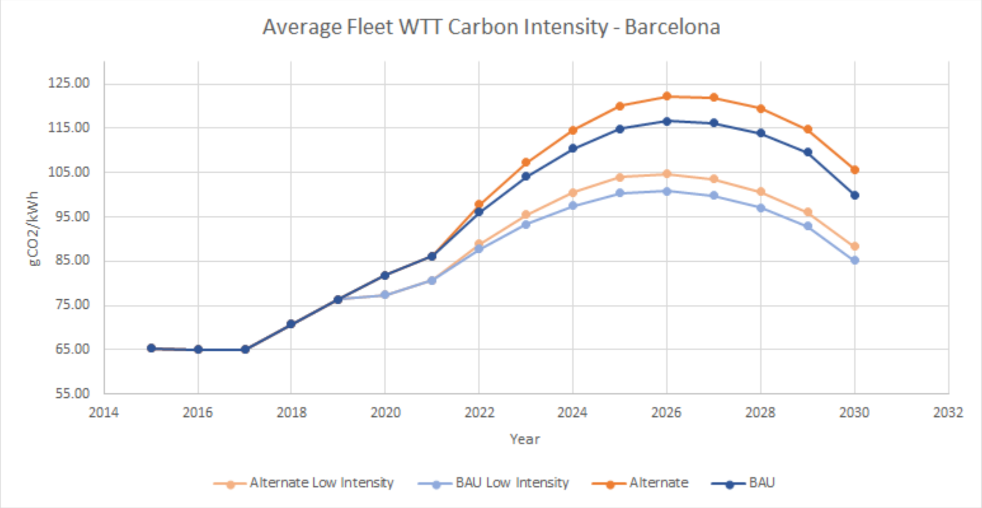


Figure C.5: Barcelona WTT CI - Projected

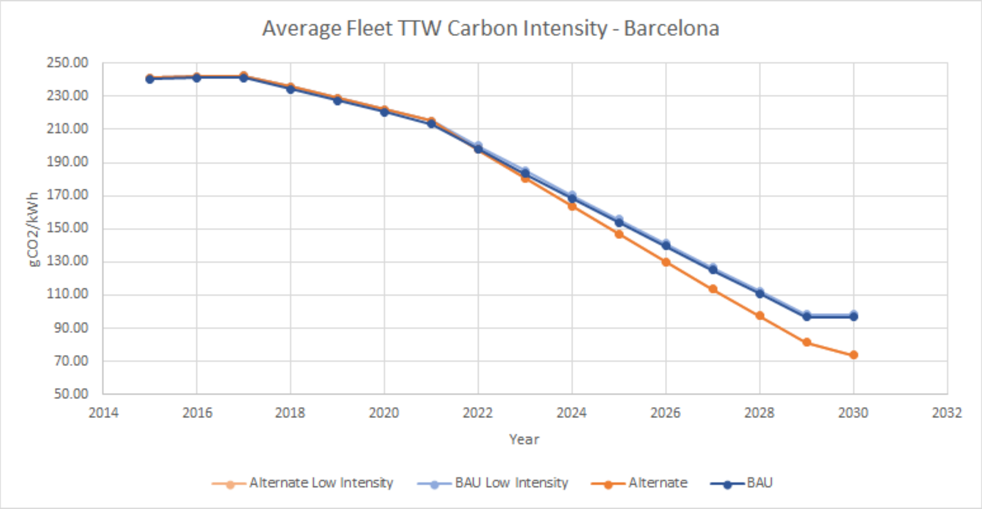


Figure C.6: Barcelona TTW CI - Projected

C.2 Stockholm

C.2.1 Carbon Emissions

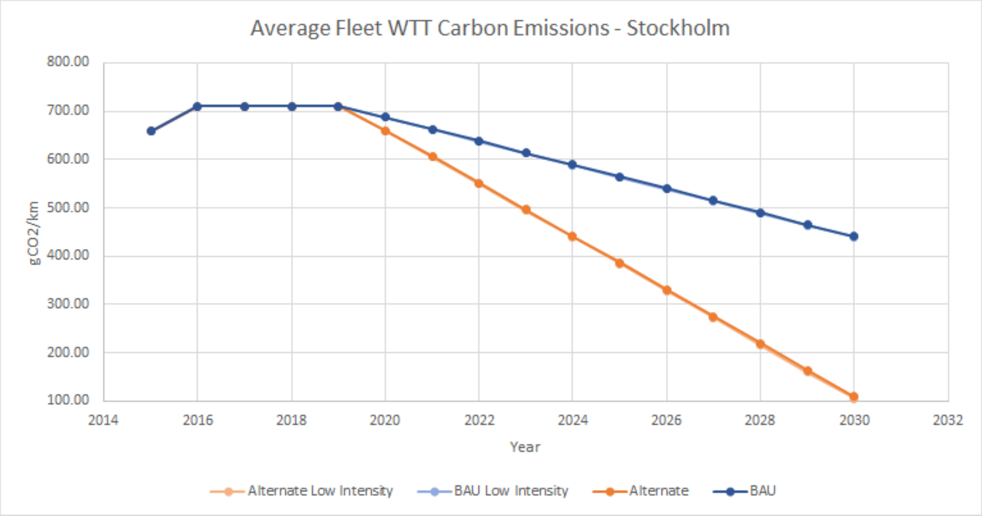


Figure C.7: Stockholm WTT CE - Projected

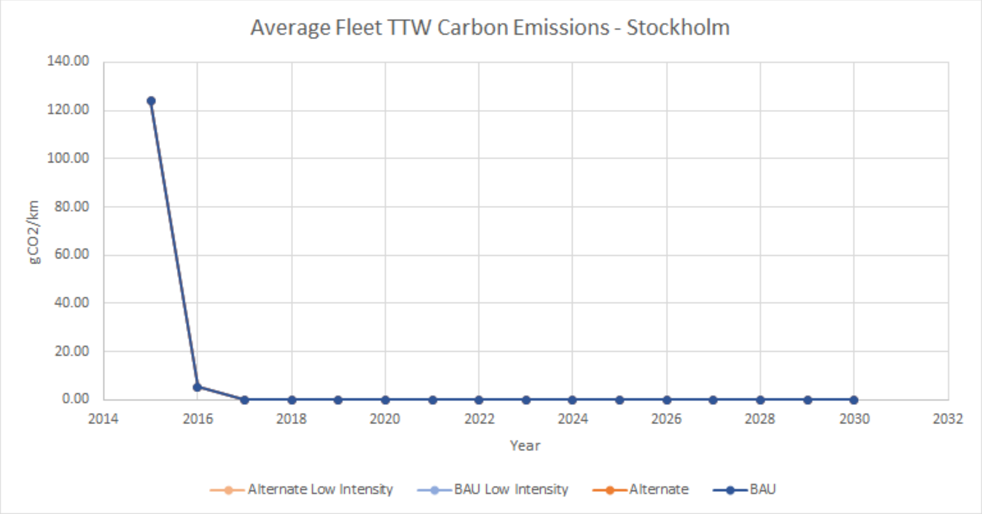


Figure C.8: Stockholm TTW CE - Projected

C.2.2 Energy Consumption

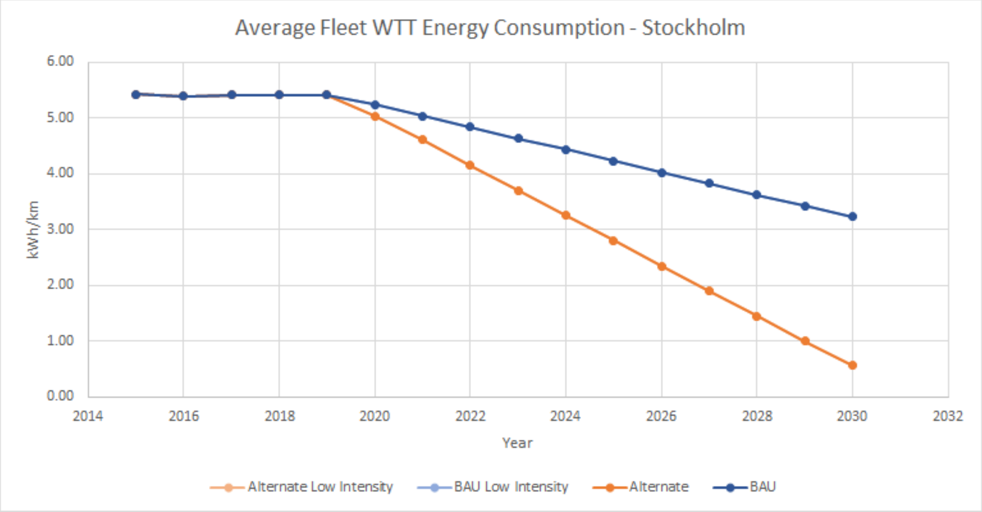


Figure C.9: Stockholm WTT EC - Projected

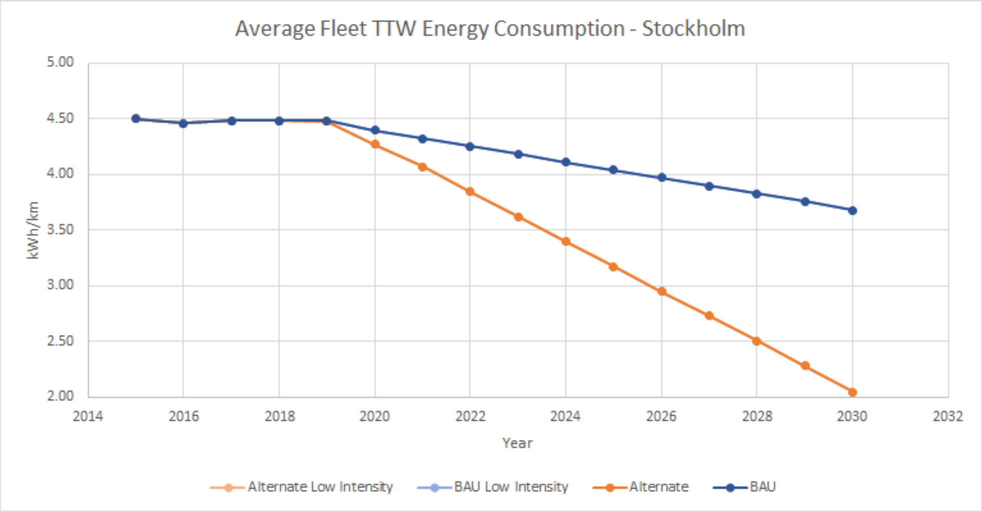


Figure C.10: Stockholm TTW EC - Projected

C.2.3 Carbon Intensity

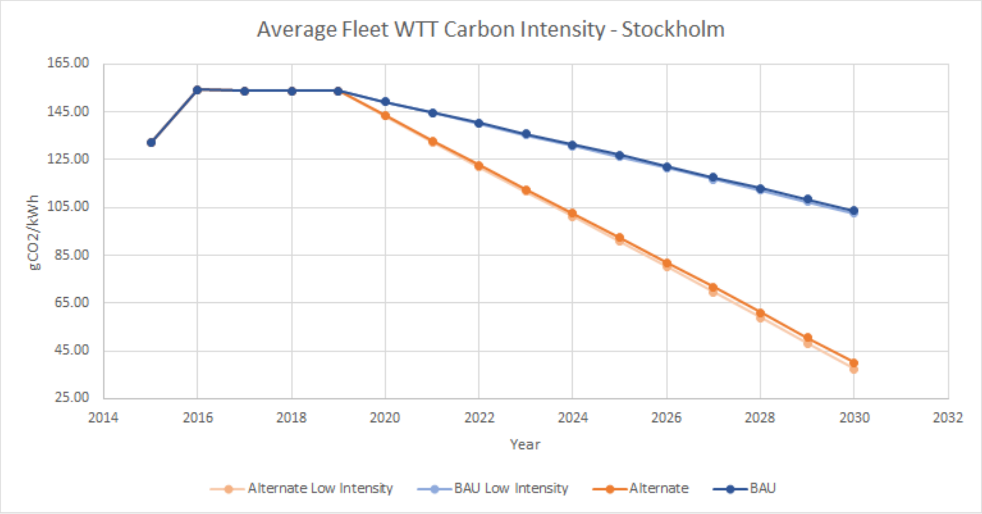


Figure C.11: Stockholm WTT CI - Projected

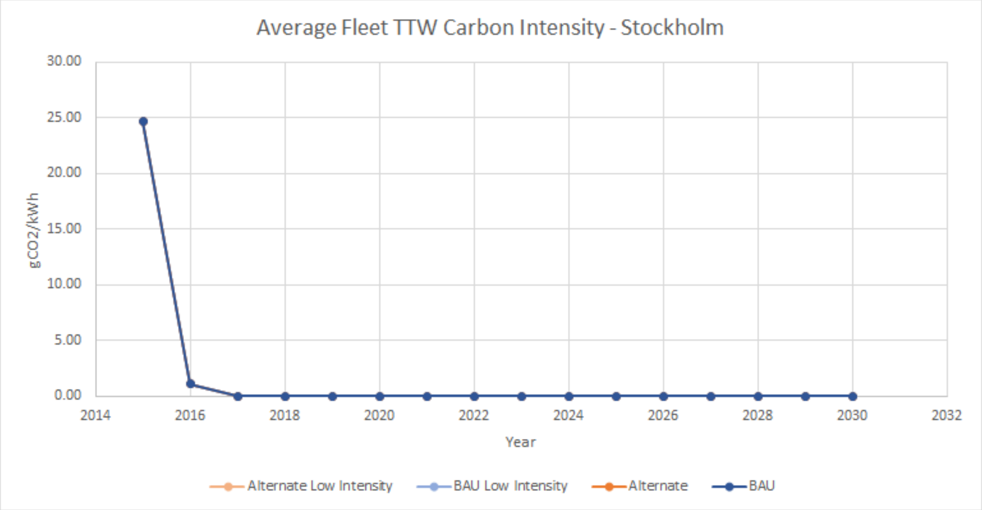


Figure C.12: Stockholm TTW CI - Projected

C.3 Warsaw

C.3.1 Carbon Emissions

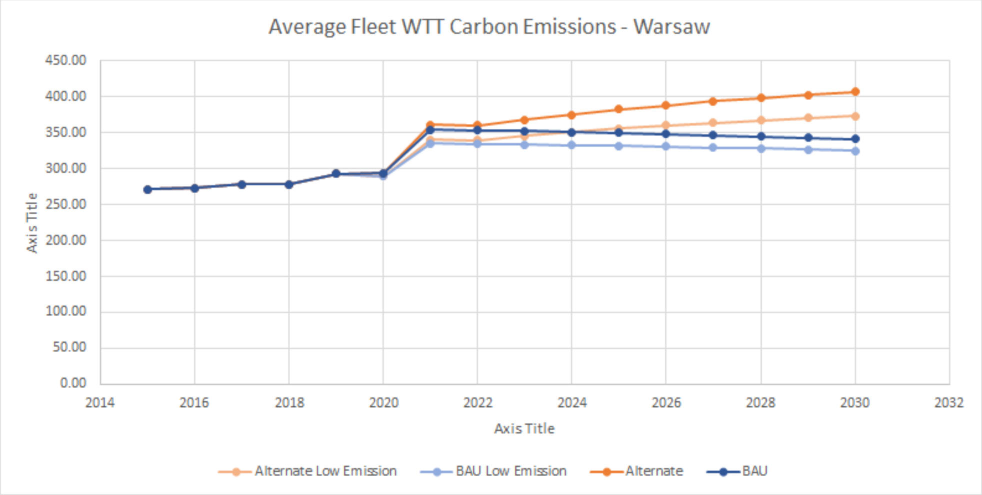


Figure C.13: Warsaw WTT CE - Projected

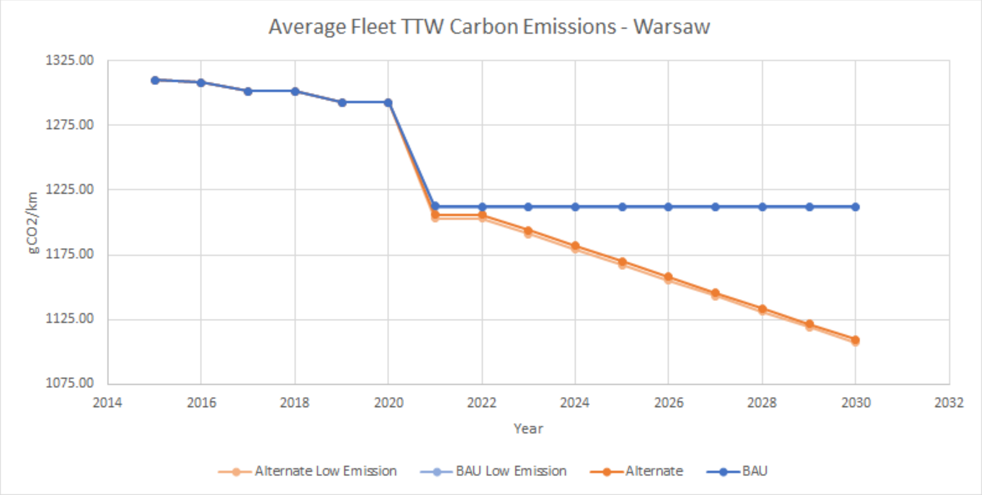


Figure C.14: Warsaw TTW CE - Projected

C.3.2 Energy Consumption

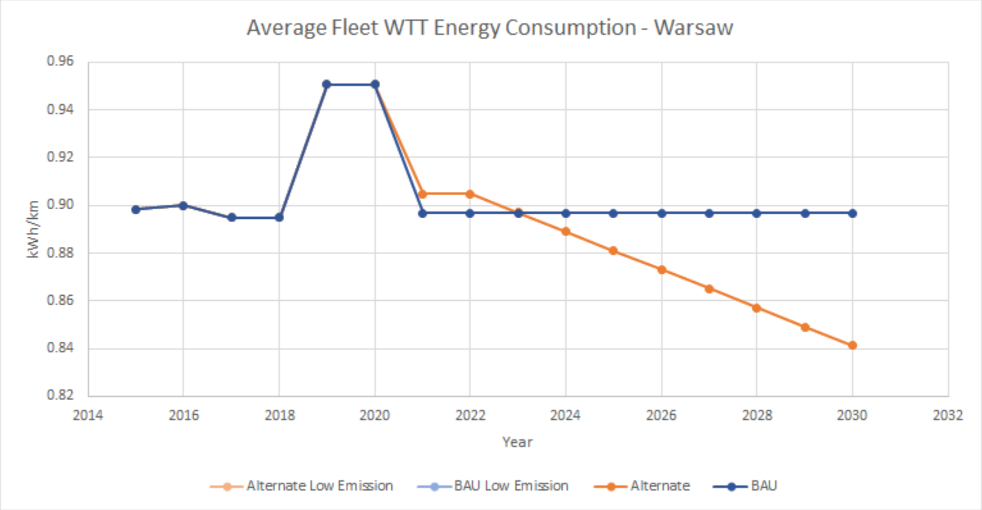


Figure C.15: Warsaw WTT EC - Projected

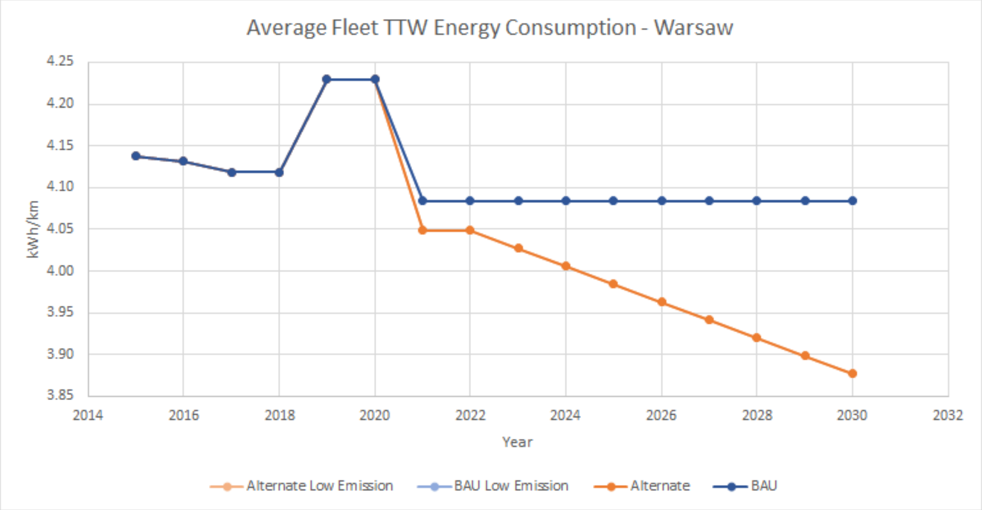


Figure C.16: Warsaw TTW EC - Projected

C.3.3 Carbon Intensity

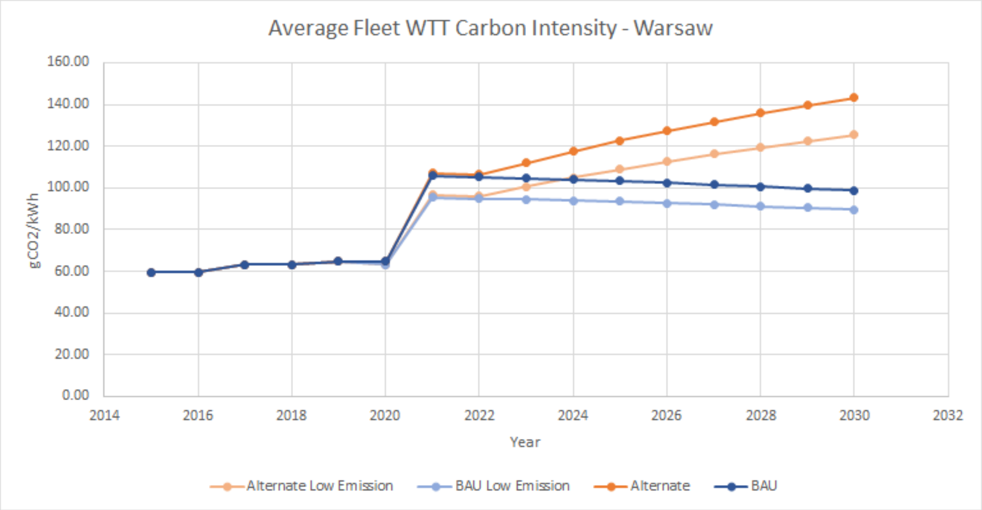


Figure C.17: Warsaw WTT CI - Projected

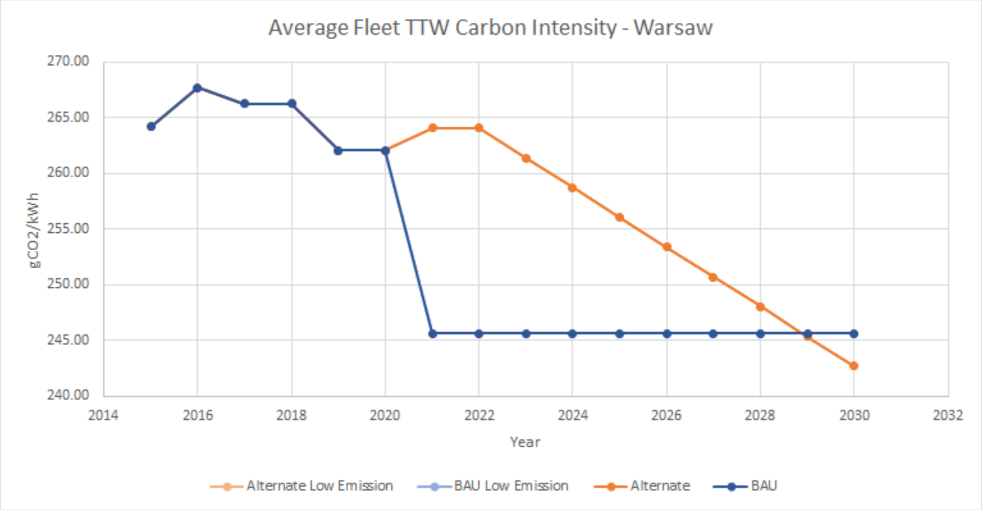
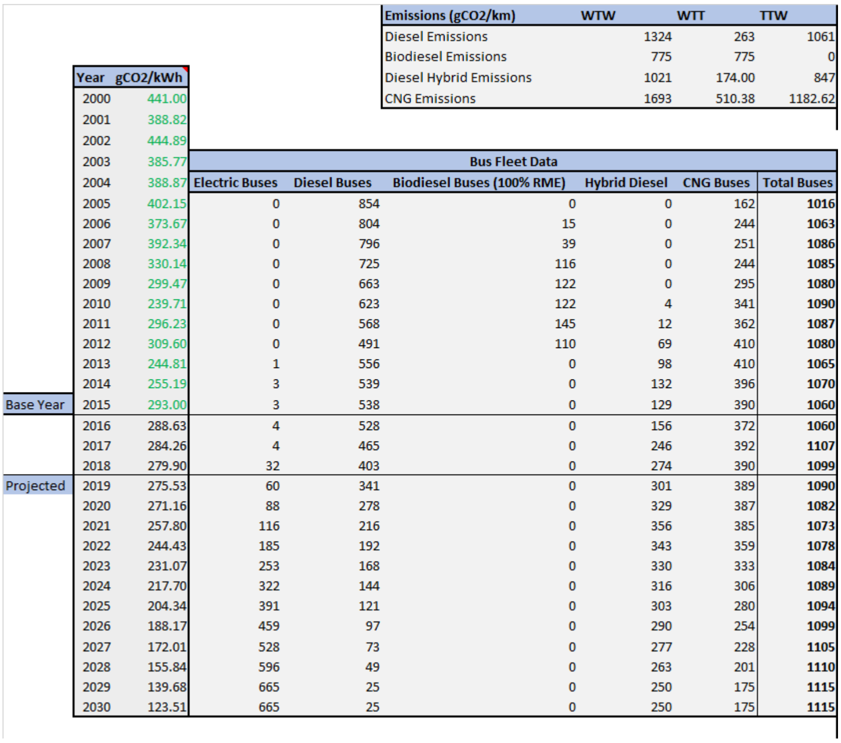


Figure C.18: Warsaw TTW CI - Projected

Appendix D

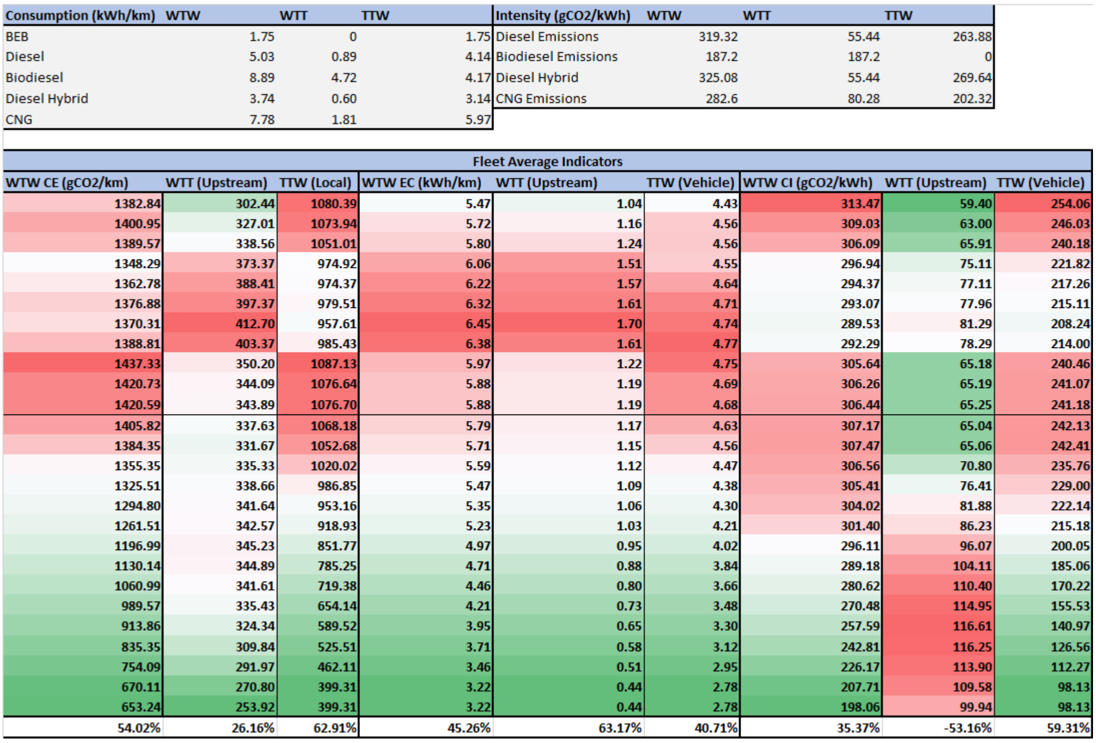
Excel Work



Emissions (gCO2/km)	WTW	WTT	TTW
Diesel Emissions	1324	263	1061
Biodiesel Emissions	775	775	0
Diesel Hybrid Emissions	1021	174.00	847
CNG Emissions	1693	510.38	1182.62

			Bus Fleet Data					
	Year	gCO2/kWh	Electric Buses	Diesel Buses	Biodiesel Buses (100% RME)	Hybrid Diesel	CNG Buses	Total Buses
	2000	441.00						
	2001	388.82						
	2002	444.89						
	2003	385.77						
	2004	388.87						
	2005	402.15	0	854	0	0	162	**1016**
	2006	373.67	0	804	15	0	244	**1063**
	2007	392.34	0	796	39	0	251	**1086**
	2008	330.14	0	725	116	0	244	**1085**
	2009	299.47	0	663	122	0	295	**1080**
	2010	239.71	0	623	122	4	341	**1090**
	2011	296.23	0	568	145	12	362	**1087**
	2012	309.60	0	491	110	69	410	**1080**
	2013	244.81	1	556	0	98	410	**1065**
	2014	255.19	3	539	0	132	396	**1070**
Base Year	2015	293.00	3	538	0	129	390	**1060**
	2016	288.63	4	528	0	156	372	**1060**
	2017	284.26	4	465	0	246	392	**1107**
	2018	279.90	32	403	0	274	390	**1099**
Projected	2019	275.53	60	341	0	301	389	**1090**
	2020	271.16	88	278	0	329	387	**1082**
	2021	257.80	116	216	0	356	385	**1073**
	2022	244.43	185	192	0	343	359	**1078**
	2023	231.07	253	168	0	330	333	**1084**
	2024	217.70	322	144	0	316	306	**1089**
	2025	204.34	391	121	0	303	280	**1094**
	2026	188.17	459	97	0	290	254	**1099**
	2027	172.01	528	73	0	277	228	**1105**
	2028	155.84	596	49	0	263	201	**1110**
	2029	139.68	665	25	0	250	175	**1115**
	2030	123.51	665	25	0	250	175	**1115**

Figure D.1: Barcelona BAU Excel Sheet - Left Side



Consumption (kWh/km)	WTW	WTT	TTW
BEB	1.75	0	1.75
Diesel	5.03	0.89	4.14
Biodiesel	8.89	4.72	4.17
Diesel Hybrid	3.74	0.60	3.14
CNG	7.78	1.81	5.97

Intensity (gCO2/kWh)	WTW	WTT	TTW
Diesel Emissions	319.32	55.44	263.88
Biodiesel Emissions	187.2	187.2	0
Diesel Hybrid	325.08	55.44	269.64
CNG Emissions	282.6	80.28	202.32

Fleet Average Indicators								
WTW CE (gCO2/km)	WTT (Upstream)	TTW (Local)	WTW EC (kWh/km)	WTT (Upstream)	TTW (Vehicle)	WTW CI (gCO2/kWh)	WTT (Upstream)	TTW (Vehicle)
1382.84	302.44	1080.39	5.47	1.04	4.43	313.47	59.40	254.06
1400.95	327.01	1073.94	5.72	1.16	4.56	309.03	63.00	246.03
1389.57	338.56	1051.01	5.80	1.24	4.56	306.09	65.91	240.18
1348.29	373.37	974.92	6.06	1.51	4.55	296.94	75.11	221.82
1362.78	388.41	974.37	6.22	1.57	4.64	294.37	77.11	217.26
1376.88	397.37	979.51	6.32	1.61	4.71	293.07	77.96	215.11
1370.31	412.70	957.61	6.45	1.70	4.74	289.53	81.29	208.24
1388.81	403.37	985.43	6.38	1.61	4.77	292.29	78.29	214.00
1437.33	350.20	1087.13	5.97	1.22	4.75	305.64	65.18	240.46
1420.73	344.09	1076.64	5.88	1.19	4.69	306.26	65.19	241.07
1420.59	343.89	1076.70	5.88	1.19	4.68	306.44	65.25	241.18
1405.82	337.63	1068.18	5.79	1.17	4.63	307.17	65.04	242.13
1384.35	331.67	1052.68	5.71	1.15	4.56	307.47	65.06	242.41
1355.35	335.33	1020.02	5.59	1.12	4.47	306.56	70.80	235.76
1325.51	338.66	986.85	5.47	1.09	4.38	305.41	76.41	229.00
1294.80	341.64	953.16	5.35	1.06	4.30	304.02	81.88	222.14
1261.51	342.57	918.93	5.23	1.03	4.21	301.40	86.23	215.18
1196.99	345.23	851.77	4.97	0.95	4.02	296.11	96.07	200.05
1130.14	344.89	785.25	4.71	0.88	3.84	289.18	104.11	185.06
1060.99	341.61	719.38	4.46	0.80	3.66	280.62	110.40	170.22
989.57	335.43	654.14	4.21	0.73	3.48	270.48	114.95	155.53
913.86	324.34	589.52	3.95	0.65	3.30	257.59	116.61	140.97
835.35	309.84	525.51	3.71	0.58	3.12	242.81	116.25	126.56
754.09	291.97	462.11	3.46	0.51	2.95	226.17	113.90	112.27
670.11	270.80	399.31	3.22	0.44	2.78	207.71	109.58	98.13
653.24	253.92	399.31	3.22	0.44	2.78	198.06	99.94	98.13
54.02%	26.16%	62.91%	45.26%	63.17%	40.71%	35.37%	-53.16%	59.31%

Figure D.2: Barcelona BAU Excel Sheet - Right Side