THE COST-EFFECTIVENESS ANALYSIS OF TRANSITION FROM BRT SYSTEM TO BI-ARTICULATED TROLLEYBUS SYSTEM IN ISTANBUL

by
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ABSTRACT

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Air pollution in Istanbul, which has reached the highest level of recent years, and high operational costs of diesel buses which are heavily dependent on imported fuel are of great concern. This thesis aims to investigate whether the trolleybus investment is viable in terms of economic, environmental and social aspects, if diesel buses operating on the Bus Rapid Transit (BRT) line of Istanbul, which annually make approximately 70 million kilometers, were replaced by trolleybuses. In addition to financial assessment of the investment, the following questions are examined: What will be the marginal cost of reduction in CO2, CO, NOx, THC, and PM? Which potential environmental life-cycle (LC) impacts from diesel fuel and electricity consumed during vehicle operation will be created? Life-Cycle Analysis is an extensive analysis technique to examine how products or processes affect the environment, by considering all the inputs and outputs throughout their life-cycle. The marginal cost assessment shows that trolleybus results in net saving of EUR 97.8 Million in terms of Net Present Value of cash outflows discounted at 10.5%. Moreover, in 2018 electricity generation conditions, global warming potential will be decreased by 35%, acidification potential will be grown by 1.9, eutrophication potential and photochemical oxidants creation potential will be 11.7 times and 2.7 times more, respectively. There is always a trade-off between separate LC impact categories and scenario analysis shows that the environmental LC impacts improve as the electricity grid mix becomes more renewable-oriented. Therefore, LC impact intended to be reduced should be considered for transition to trolleybus.

ÖZET

İSTANBUL'DA METROBÜS SİSTEMİNDEN ÇİFT KÖRÜKLÜ TROLEYBÜS SİSTEMİNE GEÇİLMESİNİN MALİYET ETKİNLİĞİ ANALİZİ

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Anahtar Kelimeler: Troleybüs, Metrobüs, Sürdürülebilir Toplu Ulaşım, Maliyet Etkinliği, Enerji Kaynaklarının Yaşam Döngüsü Etkisi

İstanbul'da son yılların en yüksek seviyesine ulaşan hava kirliliği ve yoğun olarak ithal yakıta bağımlı olan dizel otobüslerin işletme maliyetlerinin yüksek olması endişe uyandırmaktadır. Bu tez, yılda yaklaşık 70 milyon km yol kat eden İstanbul Metrobüs hattında çalışan dizel otobüslerin troleybüslerle değiştirilmesi durumunda, troleybüs yatırımının ekonomik, çevresel ve sosyal yönden uygun olup olmadığını araştırmayı amaçlamaktadır. Yatırımın finansal değerlendirmesine ek olarak, aşağıdaki sorular incelenmiştir: CO2, CO, NOx, THC ve PM'deki marjinal azaltma maliyeti ne kadar olacaktır? Aracın çalışması sırasında tüketilen elektriğin ve dizel yakıtın potansiyel çevresel yaşam döngüsü etkisi ne olacaktır? Yaşam Döngüsü Analizi, ürünlerin veya süreçlerin yaşam döngüleri boyunca tüm girdi ve çıktılarını dikkate alarak, çevreyi nasıl etkilediğini incelemek için kapsamlı bir analiz tekniğidir. Marjinal maliyet değerlendirmesi, troleybüsün nakit çıkışının % 10,5 oranında indirgenmiş Net Bugünkü Değeri açısından 97,8 Milyon Euro net tasarruf sağladığını göstermektedir. Ayrıca, 2018 elektrik üretim koşullarında, küresel ısınma potansiyeli % 35 oranında azalacak, asitlenme potansiyeli 1,9 artacak, ötrofikasyon potansiyeli ve fotokimyasal oksidan oluşturma potansiyeli sırasıyla 11,7 ve 2,7 katına çıkacaktır. Her zaman, ayrı yaşam döngüsü etkisi kategorileri arasında bir dengeleme vardır ve senaryo analizi, elektrik ağı karışımı daha yenilenebilir hale geldikçe çevresel yaşam döngüsü etkilerinin iyileştiğini göstermektedir. Bu yüzden, troleybüse geçişte, azaltılması amaçlanan yaşam döngüsü etkisi dikkate alınmalıdır.

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To my beloved family and fiancé,

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LIST OF ABBREVIATIONS

AP: Acidification Potential 15
BRT: Bus Rapid Transit 17
C_2H_4: Ethylene 45
CO: Carbon Monoxide 6
CO_2: Carbon Dioxide 6
COD: Chemical Oxygen Demand 44
DB: Diesel Bus 13
EP: Eutrophication Potential 15
eq.: Equivalent 44
EV: Electric Vehicle 6
GWP: Global Warming Potential 15
THC: Total Hydrocarbons 6
ICE: Internal Combustion Engine 3
IETT: Istanbul Electricity, Tramway and Tunnel General Management 44
LC: Life-Cycle 6
LCA: Life-Cycle Analysis 12
LPG: Liquefied Petroleum Gas 3
NMVOCs: Non-Methane Volatile Organic Compounds 23
NO_2: Nitrogen Dioxide 40
NO_x: Nitrogen Oxides 6
NPV: Net Present Value 11
OCLS: Overhead Contact Lines System 24
PM: Particulate Matters 6
PO_4: Phosphate 44
POCP: Photochemical Oxidants Creation Potential 15
PV: Present Value 11
SCR: Selective Catalyst Reduction 41

SO_2: Sulfur Dioxide 21
TB: Trolleybus 13
µg: micrograms 21
µm: micrometers 41
m^3: Cubic Meter 33
L: Liter 33
m: Meter 19
t: Metric tons 55

1. INTRODUCTION

According to the UN definition, sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations 1987). Cambridge dictionary defines sustainability as "The idea that goods and services should be produced in ways that do not use resources that cannot be replaced and that do not damage the environment.". In the light of those definitions, integrating sustainability into public transportation should enhance three concepts of sustainability, which are economic, environmental and social sustainability.
We are trying to meet the infinite demands of the human with finite sources resulting in an irreversible damage to the environment. The effects of irresponsible acts can obviously be seen in especially highly dense urban areas. Policymakers should immediately take charge to create more livable cities in the future. A regular citizen might not be well informed about the consequences of their acts; however, policymakers are generally aware of what the possible outcomes of the policies are, and which mitigating actions can be taken against them. In the sustainability aspect, policymakers bare the majority of the burden to perform urgent actions and create awareness among citizens.

With no objection to the fact that individual actions create a considerable impact on the environment, a change in the way that society lives undeniably results in a greater outcome. Sustainable public transport is a reliable instrument to achieve sustainability in environmental, economic and social aspects. Fully electric or hybrid buses have not been widely used until now, trolleybuses have a long history. The first trolleybus was built by Werner von Siemens in 1882. Even if it has been more than 135 years passed after its first use, they have never disappeared, in contrast, their usage has increased during World War I and II with meticulous attention to fuel economy. In addition, their popularity has increased all over the world, in recent years. Currently, 40 thousand trolleybuses are operating in 370 cities of 47 countries (UITP 2014).

In order to attract citizens towards public transport, a quiet, clean, comfortable and environmentally friendly solution should be agreed on. As studies and many policy applications all over the world suggest that building more roads does not solve the traffic issue, it substantially contributes to the problem of traffic congestion by giving the pave for more cars on the streets. The vicious circle of car-oriented unsustainable transport development can be solved by transport demand management, which includes push and pull measures. The push component which is "Pushing people out of their cars" is not within the scope of this research, the pull component that is "Pulling people into public transport" is the main essence of it.

Ownership of cars has been increasing along with the improved welfare of the people. For example, in contrast to high automobile and fuel prices and the widening application of paid parking in Turkey, car ownership is still increasing. It shows us that a significant rise in counterincentives to drive the personal automobiles do not push the people out of their cars unless a viable alternative is presented to people by policymakers.

In order to achieve sustainability in transport, in addition to production and spreading out of fuel-efficient vehicles or vehicles with alternative fuels, such behavioral changes are required as ecological driving and searching for the ways to increase occupancy levels for cars[1]. Those would result in higher efficiency but rebound effects[2] may be produced as well, which means that when people have more efficient cars, they may drive more. (Banister 2008). Thus, sustainability, energy efficiency and encouragement of public transport rather than that of personal automobiles gave the pave for this research interest.

Sustainable urban transport contributes to the development of a city in economic and social aspects while ensuring environmental preservation. Integrating sustainability to

[1] According to EEA's definition, car occupancy rate is evaluated by the number of passengers per vehicle, which means higher the occupancy rate, the higher the efficiency of mass passenger transit.
[2] The rebound effect is the phenomenon that increased energy efficiency and lower energy costs to consumer result in higher consumption.

transportation largely affects the growth of not only the transportation sector but also the environmental protection and welfare of inhabitants. Trolleybus which is one of the fully electric vehicles utilized in public transportation can be an effective economical solution to the emissions and pollutants in the air. Trolleybus can be a part of the solution to Istanbul's pollution problem and high dependency on imported fuel while resulting in a more sustainable future of transport with energy efficiency, lower levels of noise and vibration. Diesel buses operating on the BRT line of İstanbul, where diesel buses annually make around 70 Million km, can be converted to Trolleybuses, hence less damage to environment and more cost efficient operation can be achieved.

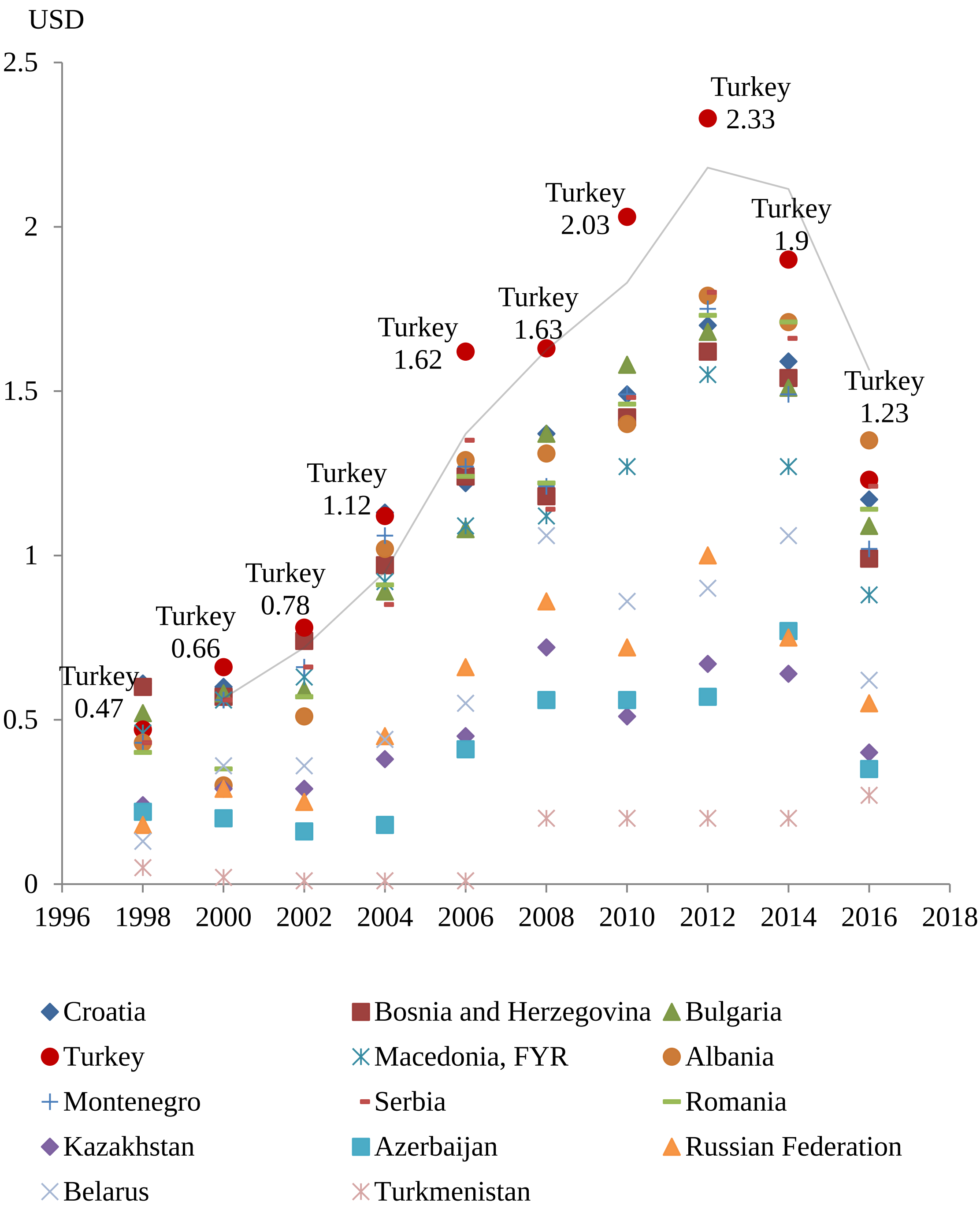
In Turkey, 78.4% of road motor vehicles fueled by gasoline and diesel, 21.2% of them fueled by liquefied petroleum gas (LPG)[3], which shows that the transport sector is largely dominated by internal combustion engines (ICE). The dependence on petroleum to that extent affects transportation costs and policies. Moreover, Turkey is also suffering from frequent and high fluctuations in currency exchange rates because petroleum is imported from other countries. However, electricity is produced domestically and is not affected by exchange rate volatility. Moreover, competition in the electricity market in Turkey has been enhanced since 2011, which leads electricity prices to stay at the competitive level.

Oil prices in Turkey have been set by the market since 2005. Wholesale prices for oil and electricity are cost-based but retail prices remain regulated through the Energy Market Regulatory Authority (EMRA)-approved uniform national retail tariff. The tariff is therefore not reflective of cost differences between various distribution regions. Retail electricity prices remained fixed between 2002 and 2007 despite rising generation costs. Starting in 2008, prices have then been adjusted quarterly to take into account input prices, inflation, and exchange rates. Prices for gasoline and diesel fuel in Turkey are among the highest in the world owing to high excise taxes on fuel. According to Merriam Webster definition, excise tax is put as an indirect taxation on the production, sale or use of specific products and goods. Excise taxes are identical for both commercial and non-commercial users (OECD 2016). As Figure 1.1 suggests, Turkey is the leading country with highest diesel pump prices in years between 1998 and 2016. In

[3] Unknown includes the motor vehicles that the type of fuel field in the license is filled incorrectly or left blank and electric vehicles. (TUIK)

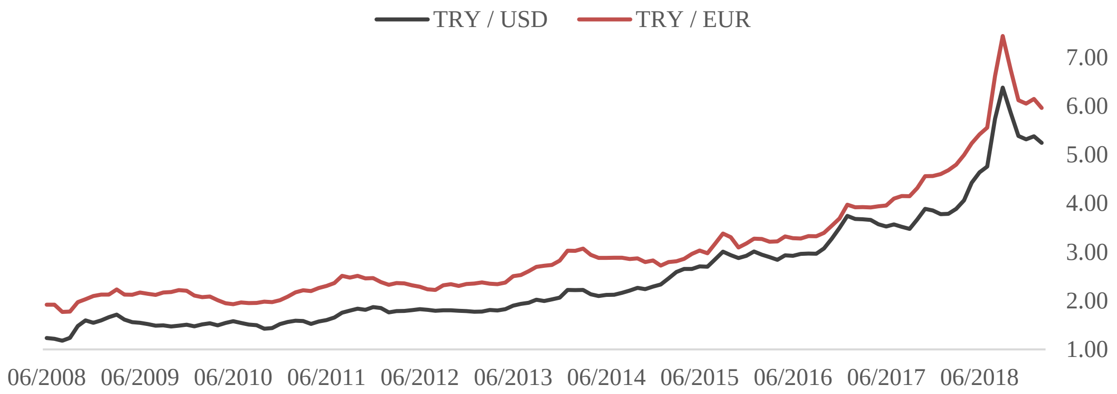
order to show the diesel fuel prices trend in Turkey across the years, a moving average has been added to the graph as a gray line. Note that prices are in US dollars.

Figure 1.1 Diesel pump price in US Dollars in upper-middle income countries between 1998 and 2016. The figure was made by the author using Worldbank data.



In the last few years, since US Dollar has substantially gained value over Turkish Lira, Turkey has been adversely affected by currency fluctuations in recent years, remarkably by economic crisis we are going through at the moment. In Figure 1.2, 10 year US Dollar and Euro selling rate on monthly basis is provided since imports are made based on Central Bank of Republic of Turkey (TCMB) selling rate.

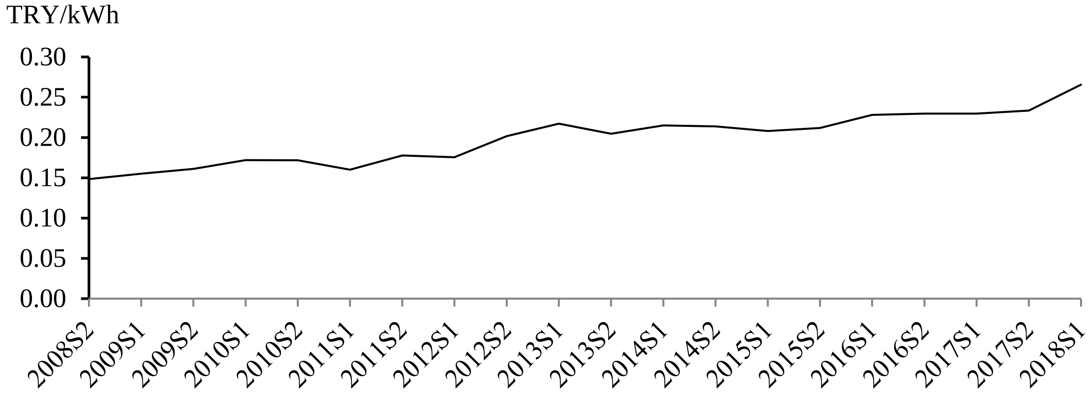
Figure 1.2 US Dollar and Euro selling rate against Turkish Lira between 06/2008 and 02/2019. The figure was made by the author using TCMB data.



Historical electricity prices for non-household consumers in Band IG, who have annual consumption over 150,000 Megawatt-hours (MWh)[4], including all taxes and levies, shows that unit electricity cost is much lower compared to diesel and the fluctuations are minor in Turkey. According to Figure 1.3, prices have ranged from 15 Kurus/kWh (0.15 TRY) to 27 Kurus/kWh (0.27 TRY) between 2008 and 2018. Thus, in order to decrease dependency on diesel fuel of fluctuating and high price, the use of electricity in transportation must be utilized.

[4] A megawatt hour (Mwh) is equal to 1,000 Kilowatt-hours (Kwh). The consumption cluster is determined according to the electricity consumption of future trolleybuses.

Figure 1.3 Unit electricity price for non-household consumers. The figure was made by the author using Eurostat data.



Besides the economic impact of energy use by traditional diesel buses, air pollution created by those buses is of great significance. According to (Mock 2016), it is predicted that Carbon Dioxide (CO_2) emissions resulting from road transport is going to be almost doubled in Turkey by 2030, which strongly implies doubled fuel consumption. Despite the fact that simply 10% of the vehicles in Turkey consist of heavy duty vehicles, more than half of the CO_2 emissions and fuel consumption stem from those vehicles. Moreover, the quality of the air is gradually deteriorating for the megacity of Istanbul and some preventive measures should be taken against it. The main emissions and pollutants created by the traffic are CO_2, Carbon Monoxide (CO), Nitrogen Oxides (NO_x, where x=1,2,…), Total Hydrocarbons (THC), Particulate matters (PM), and black smoke. The exhaust emissions are not the only airborne substances; over the life-cycle of diesel production and usage, various impacts on soil, water, and air are created in global, regional and local level.

Trolleybus is an effective solution to economically costly operation of one of the most commonly used public transport mode in Istanbul and it will help mitigating the contribution of public transport to air pollution. At the same time, trolleybus ensures less noisy, less vibrated operation and high energy efficiency.

The reason for choosing trolleybus in this study instead of Electric Vehicles (EVs) is the fact that available EVs on the market, even with the highest battery range, are not able to complete full distance of diesel buses currently operating on the BRT line. According to (Sevim 2017), the metrobuses operate in three kinds of mode of operation: first one is ‘usual mode’ in which buses operate for 16 hours non-stop and after the completion of 8 hours shift, another driver takes over the bus from the bus stops on the route for another 8 hours of shift. Second mode is ‘peak-hours mode’ in which buses are driven for 4 hours each in the morning and evening peak-hours by one driver, which sums up to 8 hours per day. Third one is ‘bus-to-terminal peak-hours mode’ in which buses operate for 16 hours and after the completion of 8 hours shift, first driver brings the bus to the bus terminal, then another driver takes over the bus from the terminal. According to the BRT operation plan of 2017, number of buses operating on usual mode, peak-hours mode and bus-to-terminal mode are 258, 199, and 42, respectively. With average speed of 35 km per hour (Sevim 2017), buses operating in ‘usual mode’ make distance of 560 km and those buses make up more than half of the all BRT fleet. The buses operating in ‘bus-to-terminal mode’ and ‘peak-hours mode’ are driven for 280 km and 140 km per shift.

Naumann and Vogelpohl under CACTUS project, states that currently available e-buses on the market have ranges of 72-288 kilometers. Those e-buses have passenger capacity of nearly half or less than half of the passenger capacity of currently operating metrobuses. SILEO E-buses have 25 m length and passenger capacity of maximum 210 passengers, and they are able to cover a range of up-to 300 km with a single charge in 6-10 hours (Sileo GmbH). The range depends on the road characteristics, weather, driving cycle, use of coolers/heaters etc. Experiences also show that batteries may preserve only 80% of its initial capacity (Grütter and AG 2015). Jungmeier states that there is a trade-off between battery capacity and charging power or charging time (Jungmeier 2017). Excess demand on the BRT line requires potential e-buses to have either high ranges or fast charging times.

In the light of information provided above, in “usual mode”, number of e-buses to be purchased, and drivers, should be at least doubled to have 6-10 hours of charging break to complete 560 km. E-buses with a range of up-to 600 km are not available on the market. Expensive, heavy and big batteries are needed for high ranges (up to 300 km), which also strictly limits the passenger capacity. Fast charging solutions or battery change in the bus stops during journeys can be applied, however those are too costly to the beneficiary, and necessitate detailed and optimized planning of charging cycle of the buses. Under Hybrid & Electric Vehicle Technology Collaboration Programme, Jungmeier also found that a 12 m e-bus system cost 20% higher than a diesel bus system over 12 years (Jungmeier 2017).

If the number of EVs is increased or if the back-up batteries are purchased to meet the excess demand on the BRT line, it results in considerable vehicle and battery costs. Moreover, as stated above, more drivers will be needed for additional EVs, which is an extra operational cost item for the bus operator. Hence, in the current EV technology and market conditions, EVs cannot be preferred over trolleybuses to be implemented on the BRT line. With the help of decreasing EV purchase prices, battery costs, increasing range of batteries, the advancement of fast charging solutions, and possible weight allowance given to the EV producers by the policy-makers, EVs for the BRT line can be feasible in the future. Therefore, alternative EV usage in the public transport in Istanbul is left to be investigated in a future work.

In the second and third sections of this thesis, literature review and methodology of the research are given. The fourth section provides a background information on current BRT system and how BRT system meets huge demand on the main arteries of Istanbul; historical and current usage of trolleybuses; and deteriorating air quality in Istanbul. In section five, investment analysis based on three main categories is presented which are as follows: *i)* costs and benefits of trolleybus system, and its pros and cons compared to other transport modes with a holistic and qualitative approach, *ii)* The main monetary assumptions about the economic analysis, and *iii)* Information about the emissions and pollutants, and the life-cycle impact categories for the energy sources subject to the analysis. In section 6, results of monetary cost efficiency are firstly presented via NPV and PV calculation of cash-outflows with three separate discount rates. Secondly, the marginal cost of emission reductions by switching to trolleybus system is given. Third, life-cycle impacts of energy sources with different electricity generation scenarios are investigated. Lastly, potential use of pure electric buses for future studies is discussed. Section 7 concludes that conversion to trolleybus system from diesel buses on the BRT line of Istanbul is recommended in order to reach sustainability in every aspect, economic, environmental and social, in the metropolitan city of Turkey.

2. LITERATURE REVIEW

There is a large body of literature investigating comparison of public transport systems such as trolleybuses, diesel engine, compressed natural gas (CNG), hybrid engine and fully electrical buses. While the focus of some studies is the comparison of different transport modes in terms of energy efficiency and costs, the others concentrate on total investment cost by applying cost-benefit analysis. Those researches are generally carried out for different cities and towns all over the world. However, in order to estimate total investment costs, a city-specific analysis is required since infrastructure and operational costs depend on various conditions such as road characteristics, climate, and economic, social and regulatory environment, etc.

For Turkey, the comparison of the trolleybus system with other transport modes was made in three studies. However, switching from the BRT system to trolleybus system in Istanbul has been studied in two articles. Çakır and Akbayır examined the current Metrobus system, and discussed the effects of integration of electric vehicles or trolleybuses into the existing BRT system in a general framework (Çakır and Akbayır 2017). They also mentioned the environmental effects using unit emissions (g/km) from the literature for different bus types which are fueled by separate sources. Regarding initial investment and operational costs of electrical buses and trolleybuses, the unit figures from the literature were roughly given in the article. They found that by electrification of Metrobus system, fuel costs and negative impacts of current buses to the environment could be decreased. Moreover, they pointed out that there needs to be more detailed investigation since only the general framework about trolleybuses has been given in the study.

Ayaz, et al. compares the currently operating BRT system in Istanbul with a possible Trolleybus system regarding CO_2 emissions and energy costs of both modes (Ayaz, et al. 2011). They conducted a simulation by running Matlab/Simulink, and their results suggest that the operation of trolleybuses over the Metrobus line instead of diesel buses is highly economical in terms of fuel costs. Regarding emissions, the reduction in the CO_2 emissions was concluded.

Under a project called TROLLEY Project which has been implemented all over the Europe, "WP4: Increased Public Transport Efficiency with Trolleybuses" makes a comparison of financial and economic efficiency between bus and trolleybus systems in Poland by making a cost-benefit analysis of the operational and investment costs of trolleybuses and diesel buses. This work package finds a breakeven point for a number of required passengers to make trolleybus investment viable. However, like in any other cost-benefit analysis, it necessitates the valuation of emissions, so human life, which is avoided in this thesis due to ethical concerns. Moreover, calculation of a breakeven point for Istanbul's BRT system is not necessary for three reasons. First, demand for Metrobus line is already high and hardly satisfied. Second, since Poland and Turkey have different characteristics, the breakeven point found along this project does not necessarily correspond to Istanbul facts. Third, the required investment amount, the trolleybus system's environmental effects, its marginal effect on emission reductions and life-cycle impacts of the energy sources of trolleybuses and diesel buses in Turkish electricity grid mix are the main focus of this research.

In conclusion, in the literature it has been asserted that trolleybus system is more energy cost efficient, environmental-friendly and have less investment costs compared to railway systems. Moreover, switching from BRT system to trolleybus is supported. However, there is no in-depth investment analysis carried out for conversion of BRT system in Istanbul in terms of life-cycle impacts of the vehicle power sources, an estimation of total amount of investment, marginal cost calculation, and a comparison of possible benefits and costs of Trolleybus with other alternatives by a holistic approach.

In this study, the initial investment and operational costs of trolleybuses and diesel buses were compared using literature data and energy figures from Trolleybus operation in Malatya, Turkey. The current operational plan, i.e. the supply of metrobuses, was calculated for each line in order to find required number of trolleybuses and distance travelled. Total life-cycle impacts, which will be potentially created by the electricity and diesel fuel used during trolleybus and diesel bus operation, were estimated by using life-cycle emission data from Turkish electricity production and Chinese diesel production and usage. Moreover, marginal cost of emissions reduction was calculated by dividing differential net present value of life-cycle cash outflows of each system by the potential decrease in emissions, while it was assumed that emissions are created by fully natural gas sourced electricity generation and by the diesel exhaust. The investment analysis considers environmental, monetary and social aspects for the qualitative and quantitative comparison of each system without assigning monetary values, in order to abstain from flaws of cost-benefit analysis which monetizes priceless aspects.

3. METHODOLOGY

For the comparison of trolleybus and diesel buses utilization on the BRT line, an investment analysis is made by comparing NPVs of lifetime costs and present value of future cash outflows. In the NPV calculation, only cash outflows are considered since inflows are assumed to be equal with the same number of passengers. The costs items which are equal for both systems are not included in the analysis as well.

In order to make the environmental impact analysis, two different methodologies are used: Cost-Effectiveness Analysis (CEA) and Life-Cycle Analysis (LCA). After giving brief information on these two approaches, the difference between them is discussed in this section.

Cost-Effectiveness Analysis (CEA) is a useful tool to compare the cost of policies or projects with their calculated effects. CEA has not been frequently used in the transport sector. However, it is commonly used in investment assessments in the social sector. It has been believed that the effects of transport policies or projects are mainly economic, not social, and those impacts can be monetized. However, transport investments have social consequences which do not have a price, such as contribution to sustainability and welfare increase. Nowadays, with increased attention to environmental protection and human welfare, CEA has begun to be used more commonly. (The World Bank 2005)

CEA avoids most of the drawbacks of Cost-Benefit Analysis (CBA) by trying to solve cost minimization issues while, at the same time, carefully refraining from problems of factors without a price. Benefits are less likely to have monetary values than costs which tend to incur sooner. Assume that an action is taken for the environment protection. Costs of those actions would be realized today, however, benefits of this preservation of the environment would occur in the future. Therefore, discounting problems are either excluded or diminished in CEA. It is an essential tool for the execution of a model, not for establishing a goal. (Ackerman 2008)

The reason to prefer CEA is over CBA needs some explanation and clarification. Cost-Benefit Analysis (CBA) is a public policy evaluation method through weighing social benefits against social costs by monetizing the non-monetary effects. It suggests that a social policy should be implemented if the foreseen benefits of the policy exceed the costs of it (E.Boardman 2015). Present value of costs and benefits are compared with their future value, including value of a human life or environment. If social harm is irreversible, like in environmental policies, then application of conventional CBA is not suitable and ethical. Our attitude towards environment determines the future of us and next generations, the irreversible consequences of our acts will come up in the long-run. (Rose-Ackerman 2011)

CEA determines the costs of an investment and associates these costs to some certain measures of investment effectiveness. Therefore, I carried out an cost-effectiveness analysis to assess the marginal cost or saving of transition to trolleybus per one kg deduction in harmful gas emissions such as Carbon Monoxide (CO), Carbon dioxide (CO_2), Nitrogen oxides (NO_x, where x=1,2,…), Total hydrocarbons (THC), Particulate matters (PM). Volatile organic compounds and black smoke are also important factors impacting human health; however, due to lack of data, they are not taken into consideration in this analysis.

The cost-effectiveness analysis was grounded on The World Health Organization (WHO) Guidelines (World Health Organization 2003). Interventions taken by decision-makers can be accurately assessed by CEA against the case of “doing nothing”, thereby providing decision-makers with information on what could be achieved if they could start again to build the Trolleybus system. The Incremental Cost-Effectiveness Ratio (ICER) is calculated according to the following formula:

$$\text{ICER}=\frac{C_{TB}-C_{DB}}{E_{TB}-E_{DB}} \tag{1}$$

where C_{TB} is the Net Present Value (NPV) of the cash outflows from the trolleybuses over the project reference period, C_{DB} is the cash outflows from the diesel buses over the project reference period, E_{TB} is the amount of the emissions and pollutants from the trolleybuses over the project reference period, E_{DB} is the amount of the emissions and pollutants from the diesel buses over the project reference period.

NPV was calculated as follows:

$$NPV=\sum_{t=1}^{t}\frac{C_t}{(1+r)^t}-C_0 \qquad (2)$$

where C_t is the net cash outflow during t, C_0 is the initial investment, r is the discount rate, t is the time periods which cover the project reference period.

The costs and benefits for the society have been taken into consideration as a whole because all members of the relevant society must be regarded in a social policy analysis. Moreover, the gas emissions are not treated as “externalities” like in the most of the conventional economic analyses, specifically like in cost-benefit analyses. Since we are living on the same earth, not outside of it, we and next generations get harmed by any deterioration in nature and we are rewarded by every favorable treatment we give to the world.

Conventional economics considers the environmental impact to be an ‘externality’, something outside its concern. Environmental economists are trying to bring these adverse impacts back within the discipline; for example, they calculate the unit monetary cost of a specific disease to the state by making logical assumptions for the total number of people suffering from that disease and then they measure the total monetary cost of those to the state. Another example is the Shadow pricing method to measure how much people are concerned about global warming or noise (Cato 2009). However, struggling for monetizing everything, especially the things without a price, is not useful. That’s why, the monetary costs of environmental effects, which would be calculated through healthcare costs to the state, are not assigned to the emissions in this research. Human health does not have a price.

Life-cycle emissions are used for the impact assessment of diesel fuel and electricity which are consumed during vehicle operation. LCA is an extensive analysis technique to examine how much a product, process or project has an impact on the environment, by considering all the inputs and outputs throughout the project/product/process life-cycle; from beginning of its life until its final use or disposal. The LCA allows decision-makers to act being aware of all the environmental impacts of a project.

In order to capture the life-cycle impacts of power sources of trolleybus and diesel bus systems, the environmental life-cycle impacts of electricity and diesel are considered starting from their production until their final use in this study, without inclusion of life-cycle emissions of other items such as vehicle, batteries, stations, etc. For the Turkish electricity generation, Atilgan and Azapagic conducted the life-cycle assessment based on 'cradle to grave analysis', which consists of extraction, processing, and transportation of the raw materials and fuels, construction and removal of the facility. The supply of electricity to final consumer, including transmission, distribution and use was excluded from the scope of the study (Atilgan and Azapagic 2016). For diesel life-cycle impacts, the study of (Li, et al. 2013) has been used in this thesis, which covers the emissions created during diesel fuel production and diesel engine operation. The impacts are categorized into four: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Oxidants Creation Potential (POCP), which are the common impact categories with the same equivalent units in both studies.

4. BACKGROUND INFORMATION

In this section, brief information on the current BRT system in Istanbul, history of Trolleybus and its current usage, and air quality and signals from the environment in Istanbul are given.

4.1. Current BRT System

Turkey's population is about 80 million according to address-based population registration system's 2016 data; Istanbul hosts 18.5% of whole country's population with 15 million people whereas it only makes up 0.7% of the total area of Turkey. Naturally, for this city to handle that much of non-proportional crowd there needs to be careful city planning and urban transportation, which should be sustainable.

To see the necessity of sustainable urban transportation that regards the environment, in Table 4.1, population and car ownership figures of Istanbul as of 2007 until 2018 are provided: the population density, car ownership values, and the number of automobiles per 1000 individuals, which is a direct and true measure of car ownership. Except for year 2018, the population of Istanbul increases steadily since 2007, however car ownership rate grows more than the increasing population where the most of the population consists of highly mobile age group. Moreover, as (Mock 2016) suggests that in Turkey, approximately 50% of all the new cars initially registered in Istanbul. This figure depicts the urgent necessity of an environmentally friendly solution to Istanbul's pollution problem.

Table 4.1 The population and car ownership figures in Istanbul. The figure was made by the author using TUIK data.

Years	Population (Pop.)	Pop. Density (per km^2)	Pop. Growth	Number of Cars	Car Ownership Rate*	Car Ownership Growth Rate
2018	14,804,116	2711	-1.50%	2,644,411	179	-4.56%
2017	15,029,231	2752	1.52%	2,813,027	187	4.78%
2016	14,804,116	2711	1.00%	2,644,411	179	6.26%
2015	14,657,434	2684	1.95%	2,463,995	168	6.26%
2014	14,377,018	2633	1.53%	2,274,368	158	4.37%
2013	14,160,467	2593	2.21%	2,146,257	152	4.49%
2012	13,854,740	2537	1.69%	2,009,777	145	3.59%
2011	13,624,240	2495	2.78%	1,907,782	140	1.89%
2010	13,255,685	2427	2.64%	1,821,694	137	-0.02%
2009	12,915,158	2365	1.72%	1,775,335	137	-0.76%
2008	12,697,164	2325	0.98%	1,758,745	139	1.75%
2007	12,573,836	2302		1,711,773	136	

*Car Ownership Rate is the number of cars per 1000 individuals.

As a solution for Istanbul’s traffic and pollution problem, İstanbul Metropolitan Municipality has started Bus Rapid Transit (BRT) system called Metrobus in 2007. BRT is a high-quality bus transport mode by providing the public with cost-effective and fast services at high passenger capacities. The dedicated busways and stations placed in the center of the road, fast operations at frequent intervals, and off-board fare collection are the main characteristics of BRT system (Institute for Transportation and Development Policy 2014). BRT System has been widely used throughout the world due to its various advantages including its implementation with a moderate cost and a shorter period. It is now benefited in 170 cities by carrying approximately 33.4 Million passengers per day (BRT Data).

The Metrobus system was initiated by IETT to reduce the heavy traffic on the arteries and to introduce comfortable and fast transportation mode. In September 2007, Metrobus began its first operation in Topkapi-Avcilar line which has 18.5 km of length. In the second phase, the existing route has been extended to Zincirlikuyu in September 2008, which constitutes Avcilar-Zincirlikuyu line. With the completion of third phase which is the extension of the Avcilar-Zincirlikuyu line to Sogutlucesme in March 2009, the shortest road connection between European and Asian sides of Istanbul has been finalized. In the last phase of Metrobus project, the route has been extended to Beylikduzu thereby forming of 52 km-long Sogutlucesme-Beylikduzu line in 2012

(IETT History). Currently, Metrobus operates along 52 km with 499 busses. Although (IETT 2017) states that there officially exist 593 buses assigned to BRT line, according to (Sevim 2017) only 499 of them are currently operating.

BRT systems provide economically sustainable results such as a decline in time cost for passengers using public transportation and automobile drivers. According to (International Energy Agency 2002), while average bus speeds are from 5 to 15 km per hour depending on traffic, resulting in a travel of 100-300 km/day, in BRT systems the speeds range from 20 to 25 kilometers per hour with a travel of up to 500 km/day. However, Istanbul's BRT system is one of the fastest all over the world with the average speed of 30-40 kilometers per hour (IETT). Moreover, the usual busses often have 20 minute or longer wait time between journeys, in Metrobus system, it is typically 10 minutes or less between buses; in peak times more than 2 buses per minute. The larger carrying capacity of Metrobus than usual busses helps to meet excess demand in congested areas and peak hours while CO emission and other emissions detrimental to human health decline, which achieves environmental sustainability.

The social impacts of BRT system can be categorized as encountering less traffic density, providing equal opportunity for those who cannot afford to buy an automobile, regarding handicapped people due to low floor feature in all busses, less number of traffic accidents due to special way.

According to IETT, annual ridership of the current BRT system is 340 million passengers. Thus, when the BRT system in Istanbul is transformed into more efficient and more sustainable system in a way that it results in less noise, less vibration, less emission of gasses, number of people who are going to be impacted is substantial. In order to achieve greater efficiency and sustainability in public transportation, “Trolleybus” is the most convenient public transport system to be applied on the Metrobus path. The emissions from Metrobuses can be decreased by switching to a trolleybus system, which is the electrification of the current system. Even if the current buses have Euro IV/V or hybrid engines, the emissions resulting from those 7/24 operating buses should definitely be examined. The environmental effect can be minimized by shifting to 100% continuous electric system.

The increase in the rate of private car ownership and the need for mobility in the city, and trying to meet these needs with bus systems causes the rise of traffic intensity and accordingly the increase of greenhouse gas emissions and the decrease of the quality of life. The first objective to be considered in the solution of transportation problems in the city should be "to ensure the mobility of people, not that of the vehicles"[5]. Metrobus is an environmentally sensitive transportation system established to reduce the traffic intensity in the main arteries and to enable the passengers to travel faster, more comfortable and more economically without being caught in the traffic. However, the current passenger experiences do not exhibit comfort, especially in peak hours. There needs to be more passenger capacity in the buses to be able to allocate peak demand, with less noise, emission, and vibration.

4.2. Trolleybus System

According to Encyclopedia Britannica's definition, Trolleybus is a vehicle operating on the roads on rubber tires, which gets its required energy from electricity supplied by two overhead wires via trolley poles. It's basically a bus electrified by overhead wires.
First trolleybus in the history was a horse carriage with two electric motors, operating via overhead wire. It was built by Werner von Siemens and named as 'Elektromote'. Elektromote successfully completed its 540 meter test ride in 1882 in a suburb of Berlin. The small and eight wheeled vehicle could reach the speed of 12 km per hour on average via overhead wire. However, operation of the trolley was ceased due to poor road conditions for the non-rubber wheels and predominant usage of electric streetcars, running on metal wheels along the rails. Then, it was forgotten until the beginning of 1900s.

With the contribution of the improvement of trolley by Max Schiemann, around 1900, Trolleys became popular in the international level as of 1920s, especially in UK. The conversion of trams to trolleybuses in Nechells route gave the pave for trolleybus expansion. The conversions from trams to trolleybuses were made due to increasing urban congestion, while people were blaming the trams for the worsening traffic. The

[5] (Ilıcalı, Camkesen, Kızıltaş, & Ergin, 2011)

advantages of trolleybuses were appealing for the bus operators and passengers, and for the environment. Their low maintenance costs and longer lifetime were well appreciated by the operators, while passengers enjoyed trolleybuses' quiet, almost zero vibration and high capacity features. At the same time, no local pollution was created by the trolleybuses.

The production of large diesel buses resulted in the decrease in demand for trolleybuses with the current of modernization around 1960s. Trolleybus routes were started to be closed down and replaced by diesel buses in UK. There were several reasons for the abandonment of trolleybuses. The inflexibility and high purchase prices of the trolleybuses compared to diesel buses affected the demand for them. Moreover, they had higher maintenance costs due to limited availability of spare parts which were more expensive. Trolleybuses ended up at a similar fate in other countries as happened in UK (Brunton 1992).

Now, around 40,000 trolleybuses are currently operating in approximately 370 cities and 47 different countries. They have been always widely used in the public transport of Eastern Europe and Russia; they are getting more and more popular all over the world. The urgent need for environmental friendly transport solution directs developed economies to improve and utilize the trolleybus system more (UITP 2014).

Figure 4.1 The world's first trolleybus by Werner von Siemens[6]

[6] "On the road – with electric power: From the trolleybus to the eHighway" https://new.siemens.com/global/en/company/about/history/news/on-the-road-with-electric-power.html

4.3. Air Quality in Istanbul

In Istanbul, air pollution has reached the highest level of recent years, particularly in the districts of Yenibosna, Kadıköy, and Esenyurt, which are Metrobus operating regions. The rate of air pollution has increased due to the effects of transportation, the use of coal and urban transformation. The amount of PM_{10} and $PM_{2.5}$ has been increasing because the urban transformation process inherently has certain environmental impacts which are neglected by the policymakers and the required measures are not taken in the city planning.

The WHO and the EU clearly point out the necessity of measuring and evaluating pollutants such as Sulfur dioxide, nitrogen oxides, particulate matter, carbon Monoxide, carbon dioxide, hydrocarbons. There are other pollutants and greenhouse gas emissions such as benzene, cadmium, lead, arsenic, nickel, and ozone which need to be assessed.

Table 4.2 WHO guidelines for PM emissions limit values (WHO 2005)

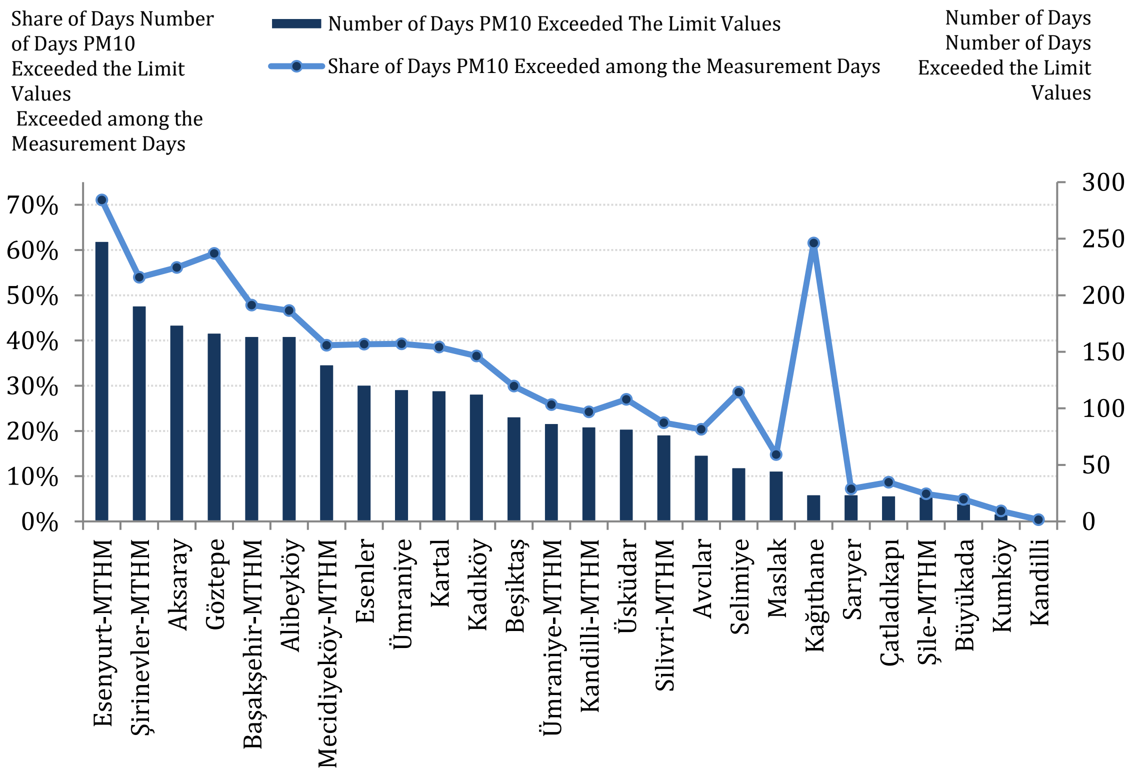
	Annual Mean	24-Hour Mean
Fine Particulate Matter ($PM_{2.5}$)	10 (μg/m³)	25 (μg/m³)
Coarse Particulate Matter (PM_{10})	20 (μg/m³)	50 (μg/m³)

The limit values for PM_{10} concentration is set by WHO as shown in the table above. Moreover, the EU (Directive 2008/EC/) has determined PM_{10} limit values in two ways. First, the limit value of 50 micrograms per cubic meter ($\mu g/m^3$) for daily mean PM_{10} concentration should not exceed 35 times per year. Second, annual mean PM_{10} concentration value should not exceed 40 $\mu g/m^3$.

According to 2017 Air Quality Report of Chamber of Environmental Engineers, the first criterion of WHO could not be met in Istanbul, except for few neighborhoods (Büyükada, Çatladıkapı, Kağıthane, Kandilli, Kumköy, Sarıyer, Şile-MTHM). However, since the number of days in which emissions are measured changes across years, the figures do not demonstrate clear results. For example, when average PM_{10} values had exceeded 800 $\mu g/m^3$ in Kağıthane station in Istanbul, there was no air quality measurement thereafter. Furthermore, in Figure 4.2 which was prepared using

(Chamber of Environmental Engineers (TMMOB CMO) 2017) data, the number of days in which PM_{10} has exceeded daily concentration limit values (50 µg/m^3) in 2017 has been provided. It can be obviously seen that the share of days PM_{10} exceeded the limit values among the days that PM_{10} was measured is very high for certain locations such as Esenyurt, Şirinevler, Aksaray. In Kağıthane, while number of days PM_{10} exceeded the limits was low, the share of days PM_{10} exceeded the limits among the days on which measurement was made is extremely high, which gives a sign about the fact that measurement was ceased. Immediate measures should be taken until the negative health effects of those emissions are experienced in the vulnerable part of society.

Figure 4.2 The number of days PM_{10} exceeded the limit values and the share of days PM_{10} exceeded the limit values among measurement days in 2017. The figure was made by the author.



Determining the sources and levels of those air pollutants related to transportation is significant in the development of İstanbul air quality. Thus, starting from 2006, with the partnership of Dokuz Eylül University and Istanbul Metropolitan Municipality, an EU project of air quality management was implemented (EU; Dokuz Eylul University 2009). The goal of the project is the identification of emissions in the city of Istanbul by using local emissions sources. Those sources were classified as industrial, transport and household related sources. Emissions of CO, SO_2, NO_x, PM_{10}, and non-methane volatile organic compounds (NMVOCs) arising from above-mentioned sources were determined.

According to the data obtained in this project, traffic is the highest contributor of NO_x and CO emissions in the air, with the shares of 89% and 68%, respectively while being responsible for 20% of PM_{10} emissions in the air. Traffic is also responsible for 1% of the SO_2 emissions whereas the industry is the highest contributor with 83%. SO_2 emission impact of current diesel buses is low and negligible due to low-sulfur diesel and SCR usage in engines. Therefore, this emission is not covered in this study.

The population growth, not caring for the forests and nature, focusing on the construction of buildings as a main economic activity, non-fully utilization of public transportation and rising ownership of personal cars are fundamental causes of air pollution in Istanbul Metropolitan City.

Although the future diesel buses will generate less emissions than today, with improving engine stages such as Euro V, Euro VI; the conventional buses will never be able to achieve renewable powered electric vehicles, regardless of the engine fuel type; diesel, bio-diesel or natural gas. Trolleybuses predominantly powered by renewables are the bright future of sustainable public transport.

5. THE INVESTMENT ANALYSIS

The key question being intended to be answered by economic evaluation here is whether the trolleybus project is worthwhile from an overall social point of view. In this respect, primary effects and financial costs will be regarded in order to carry out a Cost-effectiveness analysis for trolleybuses in comparison with the current fleet of Metrobus. The primary effects involve reduced vehicle operating costs thanks to less consumption of fuel and lubricants, less frequent vehicle maintenance, less tire wear, lower levels of depreciation due to longer lifetime, changes in road maintenance costs and environmental effects.

The costs are split into three categories: trolleybus system investment cost, operating costs and cost of financing the project. Trolleybus investment costs consist of three major items. First is overhead contact lines system (OCLS) which includes overhead wire, poles, masts, switches, support points, arms, insulators, clamps, brackets, push terminals, light signaling, ropes, suspenders, suspensions etc. The installation cost of OCLS is also covered under this cost-item. Second cost item is the power supply system, which is made of power substations and its cabling. The third one is vehicle purchase which will recur at the end of the vehicles' lifetime. Operating costs consist of energy costs, network maintenance of trolleybuses, maintenance of vehicles, drivers' wages and Auxiliary Power Unit (APU) reinvestment for trolleybus. Cost of financing project is embedded in the calculations via discounting.

Terms of contract in this kind of transport projects which necessitates huge investment are determined via bids between beneficiary and contractor. For instance, OCLS can be constructed either by the contractor or the beneficiary which is Directorate of IETT. Network maintenance can also be carried out by the contractor or operator/beneficiary depending on the terms of the contract. Due to the impossibility to foresee every aspect of necessary investments before the project begins and the need for many experts in this field, the analysis requires a more simplistic, holistic approach with certain assumptions.

Installation of OCLS, substation costs, power supply in the depot, network maintenance cost, vehicle purchase, reinvestment of battery are the main cost items, which are the differential costs. The cost of existing facilities such as the cost of terminals, road construction, stops and depots where vehicles can be stored, maintained and overhauled are ignored since they are already installed.

At the first step, the Net Present Values (NPV) of lifetime costs of trolleybus and diesel bus systems, including operational costs, were estimated. Secondly, the life-cycle emission impacts from the energy sources of diesel buses and trolleybuses over their lifespan were calculated. At the final step, both systems are compared in economic and environmental aspects.

A zero-emission scenario hasn't been investigated in this research. There are no zero emission energy sources in reality because no power supply is totally zero emission through their life-cycle. However, if the lifecycle costs are not regarded, in the case of renewables use in electricity production, zero-emission can be achieved.

5.1. A Qualitative Approach to Costs & Benefits of Double Articulated Trolleybuses and Its Feasibility on BRT Line

Compared to 100% electric buses and diesel engine buses, trolleybuses have several advantages over other alternative transport means in terms of environmental friendliness, fuel economy, operational costs, and so on.

Regarding environmental advantages of trolleybuses over diesel/compressed natural gas engine buses, firstly, trolleybuses generate lower levels of emissions depending on the electricity production resource. Since trolleybuses are more compatible with renewable energy sources, in case of their use in the electricity production, zero emissions can be achieved. Moreover, trolleybuses have a constant level of emission among their lifetime whereas diesel buses emit more as they age.

Trolleybuses have higher energy efficiency than diesel buses thanks to electrical system and they can achieve energy saving via regenerative braking system; 25% of the energy consumption of trolleybuses can be recuperated. (Rail&Bus Consultants GmbH; Verkehrs-Consult Leipzig 2013)

In order to show that energy efficiency of trolleybuses is twice as much as diesel buses, Table 5.1 is provided below. As it is stated on the next section, one trolleybus consumes 3 kWh of electricity per km and diesel bus consumes 0.561 L of fuel. However, 1 kWh is equal to 3.6 MJ and 1 L diesel is equal to 38.6 MJ, which makes up energy consumption per km 10.8 MJ and 21.66 MJ for trolleybus and diesel bus, respectively. Moreover, thanks to the energy efficiency and low unit costs of electricity, energy cost of trolleybuses per km is about one third of diesel fuel cost per km, where diesel costs 2.86 TRY per km, and electricity costs 0.81 TRY per km.

Table 5.1 Energy assumptions and consumption per km

	Consumption per km	Megajoule per unit of fuel	Consumption per km
Electricity (kWh)	3.00	3.6	10.8
Diesel (L)	0.561	38.6	21.6546

One of the operational advantages of trolleybuses over traditional buses is a lower maintenance cost due to less wear of brake lining and wheels, and electrical system. Thanks to the direct propulsion, no need for transmission units in trolleybuses. On average, 20 years of a trolleybus lifetime is a considerable advantage over 12 years of the life-span of diesel buses. The longer lifetime is particularly important in Turkey since the vehicle purchase is a main cost item. Higher passenger capacity of trolleybuses gives superiority to existing Metrobuses.

The multiple axle systems of trolleybuses allows for minimized or zero friction between the tire and the road under winter conditions. The less noise and minimized vibration in trolleybuses increases the comfort level of both drivers and passengers. Not only for comfort but also for the physiological health of drivers and passengers, exposure to a constant and regular vibration and noise might result in muscular disorders and hearing loss, respectively (Lewis & Johnson 2012; Mondal, Dey, & Kumar 2014).

There are several advantages of trolleybuses over 100% electric buses; firstly, no peak electricity demand problem would occur thanks to the continuous electrical connection via OCLS (CALSTART 2014). Possible solutions to peak demand problem requires great planning of BRT operation, the purchase of extra electric buses in order to keep them as back-up in the bus depot, which is highly avoided by municipalities due to high capital costs. Secondly, the issue of running out of battery is solved. On Istanbul's BRT Line, which has a great demand, EVs necessitate either having extra e-buses in the fleet, or extra batteries on the stops, or wireless charging technology. The utilization of pure electric buses on the BRT line has not been investigated in this thesis since they require certain conditions, high investment, and technological improvements to be viable for BRT system in Istanbul with high demand and long operation time.

Another transport mode which can be compared with trolleybuses is trams. One of the advantages of trolleybus system over trams is the lower infrastructure and initial investment cost required by the trolleybuses and they have less operating costs. In terms of operational viability, when the slope of the road is steeper than 6%, rail systems can create problems. However, trolleybus systems are more applicable in the areas where the upward slope is up to 18% (Bozankaya GmbH n.d.). Moreover, they can successfully operate on slopes in excess of 20% (IEEE 2010). In the Metrobus line, the upward slopes of more than 6% degree and The Bosphorus Bridge, where electric infrastructure cannot be set up, make tramway system infeasible. Moreover, trolleybus is not affected by factors such as excess supply on electricity transformers, intra-transformer ring systems and power failure issues which might be experienced in the rail systems. In contrast to trams, in emergency cases, the generator and battery system of the trolleybus systems begin to run and a certain distance is covered. Trolleybus provides sustainability and persistence in public transportation as it has the redundancy mechanism both in the line and electrical supply system.

Moreover, the political advantage of the trolleybus system is its fast implementation. Dedicated lines in existing BRT structure in Istanbul increase the viability of trolleybus project implementation with only short interruption on the trips and daily journeys during installation and operation.

The energy supply of trolleybuses must be provided by two trolley poles which are continuously contacted with two contact conductors (+ and -) where the necessary voltage for the operation is determined by the electrical demand on the system. (Zavada, Zavada, and Miloš 2010) suggests that the poles are approximately 6 meters long, which enables trolleybus to have a lateral movement up to 4.5 meters. Over the Metrobus line, grid overhead wires can also be used in the case of need for more flexible movement. However, since the current BRT system has simply one dedicated line per way, there is no need for freedom of movement except for the return of the buses to bus garage/depot. In that case, auxiliary battery can be utilized rather than constructing the overhead contact line system covering the way to bus depot.

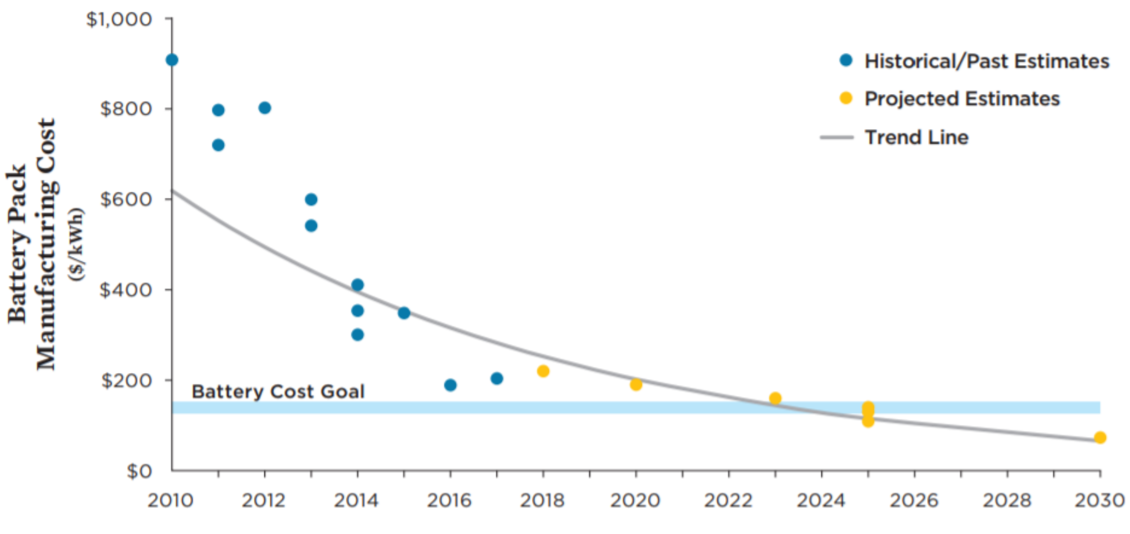
Despite the numerous advantages trolleybus system mentioned above, they also possess some perceived and real shortcomings compared to alternative systems. The first disadvantage of trolleybus system is about the lack of vehicle flexibility. The vehicles have a narrow range of motion and cannot be utilized if they are desired to be scheduled in another route without catenary system. However, their range of movement does not raise any issue since the vehicles use their dedicated lane without getting into usual traffic, and they are able to laterally move up to 4.5 meters. If the re-routing of the vehicles is needed, this type of inflexibility might be identified as a disadvantage.

High initial investment cost of trolleybus system is one of the major barriers against wide implementation of it. The purchase price of trolleybuses is two times higher than that of buses, which is mainly caused by the small orders of trolleybuses, whereas the conventional diesel buses are produced and ordered in bulk due to their common use. If the demand for trolleybuses increases in other cities or countries, and their production requires less customization, their price would decrease in the future. However, the longer lifetime of trolleybuses, which ranges from 15-22 years, than lifetime of diesel buses, which is 10-12 years on average, compensates high investment costs (Zavada, Zavada and Miloš 2010).

Another important shortcoming of trolleybus system is probable delays in case of poles' disconnection from wires (de-wiring), or electricity supply failure. The de-wiring generally stems from excessing the maximum allowed speed at intersections, poor maintenance of the OCLS and equipment on the trolleybuses, and improper or insufficient staff training. Electricity supply failures can be combatted with APUs on the trolleybuses and electricity generators. If trolleybuses were not a reliable transport system, they would not be used in 360 cities in the world.

A need for auxiliary power unit (APU) replacement in every 5-6 years depending on the battery charging cycle (Parametrix; LTK Engineering Services 2011) is perceived to be a disadvantage due to high cost of batteries as APU. However, decreasing battery costs in the last years promises the expansion of trolleybus systems as the literature suggests (Björn and Måns 2015, McKinsey 2012, BCG 2018). In Figure 5.1.1, it is estimated that the increasing electric vehicle manufacturing will enable battery cost reduction, hence EVs will be able to compete with conventional fossil fuel vehicles (Union of Concerned Scientists 2017).

Figure 5.1 Decreasing battery production costs[7]



Unaesthetic view due to overhead wires is the last and the least important disadvantage of the trolleybuses. With surpassing economic and environmental advantages of the trolleybuses compared to other means of transport, they are utilized even in many historical cities in the world without aesthetic concerns.

[7] Union of Concerned Scientists, Electric Vehicle Battery: Materials, Cost, Lifespan. https://www.ucsusa.org/clean-vehicles/electric-vehicles/electric-cars-battery-life-materials-cost

In terms of feasibility, the overhead wires should be established approximately at a height of six meters. Trolley wires can be built in 4.9 meters above the ground (Atkins China Limited 2001). Over the BRT line, there is no barrier for the construction of OCLS and trolleybus system is the most suitable transit mode.

In Table 5.2, the summary of the advantages and disadvantages of trolleybuses over diesel buses, electric buses and trams is presented.

Table 5.2 Advantages and disadvantages of trolleybuses compared to diesel buses, electric buses and trams

Compared to	**Advantages**	**Disadvantages**
Diesel Buses	▪ Environmental-Friendly ▪ A constant level of emission ▪ Lower energy costs ▪ Lower maintenance costs ▪ Higher energy efficiency and energy saving ▪ Higher passenger capacity ▪ Less noise and vibration ▪ Less noise and vibration ▪ Longer lifetime	▪ A narrow range of motion ▪ Inflexibility ▪ Unaesthetic view ▪ De-wiring ▪ Higher capital costs ▪ APU costs
Electric Buses	▪ No peak demand problem ▪ No running out of battery issue ▪ Higher passenger capacity thanks to small APU ▪ Less battery replacement costs	▪ A narrow range of motion ▪ Unaesthetic view ▪ De-wiring
Trams	▪ Lower infrastructure and initial investment cost ▪ Less operating costs ▪ Able to climb upward slopes up to 18%-20% ▪ Fast implementation	▪ Less passenger capacity ▪ Less efficient in meeting huge demand, if trams are feasible

5.2. A Quantitative Analysis of Double Articulated Trolleybuses and Its Feasibility on BRT Line

For the estimation of investment costs for both systems, certain assumptions are required. The costs which are not differentiating for diesel bus and trolleybus are not taken into account since they cancel out each other. For the sake of convenience, the assumptions are categorized into four: *i)* Assumptions on vehicles, *ii)* Assumptions on operational costs including energy, maintenance and replacement items, driver costs, *iii)* Assumptions on infrastructure, and *iv)* Project related assumptions. All the prices adjusted to 2018 prices and calculations are made in 2018 Euros with no inflation after 2018 in order to see economic analysis results in real terms. The assumptions are categorized and presented in Appendix Tables 1, 2, 3, and 4.

When assumptions on vehicles are taken into consideration, one of the main cost items for investment is the number of required bi-articulated trolleybuses. The number of trolleybuses is calculated regarding existing supply for current BRT system (Sevim 2017), its 7/24 working operation plan, passenger capacity of buses and average speed. There are 6 routes in total, and vehicles are allocated as buses operating non-stop for 16 hours, buses operating for 16 hours and stopping at the terminal after 8 hours, and buses operating for 8 hours spending 4 hours in peak periods in the morning and evening. The average speed of 35 km/hr is taken constant for each route. In my calculations, 421 double articulated trolleybuses (24 m) are required to meet expected demand to carry 750,000 daily numbers of passengers whereas 499 metrobuses (18m) are currently operating on the line. The reason for the difference between number of required vehicles is that bi-articulated trolleybuses have a passenger capacity of 221 (Bozankaya GmbH n.d.), whereas current diesel buses can carry 171 passengers on average. The capacity of current diesel buses is determined by taking weighted average of passenger capacity of buses in-operation (See Appendix Table 5). No change in the current operation plan is assumed for the trolleybuses, since the determination of the operation plan is out of scope of this research. The number of trolleybuses required and distance travelled for each route are calculated as follows:

$$t_{b_i} = \frac{d_i}{v} \times 60 \qquad (3)$$

where t_{b_i} is the duration of one-way journey of a bus on the route i in minutes, d_i is one-way distance on the route i in kilometers, and v is the average speed of a diesel bus (km/hr) which is 35 km/hr.

$$j_{b_i} = \text{CEILING}\left(\frac{t_{b_i} \times h_{b_i} \times 60}{d_{b_i}}, 1\right) \qquad (4)$$

where j_{b_i} is the number of daily journeys that a bus makes on the route i, t_{b_i} is the duration of one-way journey of a bus on the route i in minutes, d_i is one-way distance on the route i in kilometers, 1 is the significance for rounding up j_{b_i} to nearest 1, and h_{b_i} is the daily operational hours of a bus on the route i, i.e. 8 hours operating and 16 hours operating buses.

$$J_{b_i}=j_{b_i}\times n_{b_i} \tag{5}$$

where J_{b_i} is the total number of daily journeys by diesel buses on the route i, j_{b_i} is the number of daily journeys that a bus makes on the route I, and n_{b_i} is the number of buses operating on the route i.

$$J_{t_i}=\text{CEILING}\left(\frac{J_{b_i}\times c_b}{c_t},1\right) \tag{6}$$

where J_{t_i} = is the total number of daily journeys by trolleybuses on the route i, J_{b_i} is the total number of daily journeys by diesel buses, c_b is the capacity of a diesel bus, c_t is the capacity of a bi-articulated trolleybus, and 1 is the significance for rounding up J_{t_i} to nearest 1.

$$n_{t_i}=\text{CEILING}\left(\left[\frac{J_{t_i}\times t_{t_i}}{60}\times\frac{s16_i}{16}\right]+\left[\frac{J_{t_i}\times t_{t_i}}{60}\times\frac{s8_i}{8}\right],1\right) \tag{7}$$

where n_{t_i} is the number of required trolleybuses on the route i, J_{t_i} is the total number of daily journeys by trolleybuses on the route i, t_{t_i} the duration of one-way journey of a bus on the route i in minutes, $s16_i$ is the share of number of vehicles operating 16 hours on the route i, $s8_i$ is the share of number of vehicles operating 8 hours on the route i, and 1 is the significance for rounding up j_i to nearest 1.

Purchasing cost of a diesel bus was 250,000 EUR in 2014 according to an articulated diesel bus bid (No 2014/92378) initiated by IETT Head of Procurement Department. The price of a trolleybus (24m) is 750,000 EUR in 2014, which is inflated from 2014 to 2018 using 0.85% compound annual growth rate and it is found to be 775,827 EUR, as approximated from (Hedekoglu 2015) and (Rail&Bus Consultants GmbH; Verkehrs-Consult Leipzig 2013) and the fact that the market prices range from 700,000-800,000 EUR. Lastly, the lifetime of trolleybuses is taken as 20 years, whereas the lifetime of diesel buses is assumed as 12 years after a literature review. The prices adjusted to 2018 prices according to below formula:

$$P_{2018} = P_o(1+i)^{(2018-Y_o)} \tag{8}$$

where P_{2018} is 2018 price of an item, P_o is the origination price, Y_o is the origination year, and i is the compound annual growth rate.

Regarding assumptions on operation of the vehicles, Directorate of IETT purchases fuel with 13.5% discount on unit pump prices.[8] In year 2018, the pump price of diesel is 5.88 TL per liter (L) for Istanbul European side-central on average.[9] When 13.5% discount was applied to this price, diesel unit cost per liter was found as 5.09 TL. Average fuel consumption of a Metrobus is 0.561 L/km.[10] By taking all into account, the energy consumption of a Metrobus is computed as 2.85 TL per km or 0.503 EUR per km using 5.6729 EUR/TRY rate.

Electricity consumption of bi-articulated trolleybuses is assumed to be 3.0 kWh per km (Malatya Metropolitan Municipality 2016). Average electricity consumption of Trolleybuses operating in Malatya in 2015 and 2016 is used in this analysis since the trolleybuses assumed to be used in this research and trolleybuses in Malatya are identical. Literature about energy consumption data of bi-articulated buses (24m) in other countries for comparison is not available. For cross-check, according to an interview with a Trambus Project responsible, which was carried out in Malatya, it is stated that 24m trolleybuses consume electricity amount of 2.5-3.0 kWh per km on average. To be on the safe side, the electricity consumption is taken as 3 kWh/km. The cost of electricity, which is 0.27 TL per kWh, is based on the first half of 2018 Eurostat data which applies for non-household consumers in Band IG, who have annual consumption over 150,000 Megawatt-hours (MWh) in Turkey, including all taxes and

[8] (Sevim 2017)
[9] https://www.opet.com.tr/gecmis-tarihli-akaryakit-fiyatlari#istanbul
[10] (Sevim 2017)

levies. Thus, the energy consumption of a bi-articulated trolleybus is estimated as 0.81 TL per km or 0.164 EUR per km using 4.949 EUR/TRY rate for the H1-2018.

One of the operational costs is maintenance cost of vehicles. Despite the fact that trolleybuses have lower maintenance costs than diesel buses, longer lifetime of trolleybuses leads to higher maintenance costs in the final years of their life. Thus, it is assumed to be maintenance costs will be the same for both systems through their life-span.

Besides vehicle maintenance costs, a differential cost item for trolleybus is yearly network maintenance cost, which is taken as 25,000 EUR in 2014 prices and inflated to 25,861 EUR in 2018 prices.

Replacement costs constitute a part of operational costs for trolleybuses. Auxiliary Power Unit (APU) is a necessary power unit in a trolleybus in order to continue driving for up to certain distance in case of trolleybuses to be detached from the traction line. APU can be a battery, a diesel engine, or a supercapacitor. APUs are assumed to be a battery which helps the trolleybus to cover the distance from bus terminal to depot in two directions and the distance over the Bosphorus Bridge on which overhead wires are not applicable. The batteries can be charged dynamically through energy recuperation during deceleration, through the poles during regular overhead contact line operation or through a plug-in to the electrical grid when parked (UITP 2015). The available APUs on the market are sufficient to drive 15 km per charge without wire connection with 5 years of lifetime. Prediction of daily off-wire distance driven by trolleybuses determined possible charging cycles of future trolleybuses. The lifetime of batteries was calculated by the assumption of 3000 charging cycles (tbus.org.uk)[11] and one APU costs $80,000 in 2011 US Dollars. The price is adjusted to 2018 US Dollars using 1.63% compound annual growth rate (average CPI between 2011 and 2018 in US) and then converted to Euros using 1.1764 EUR/USD rate. The cost of one APU is found as 76,151 EUR in 2018. They are only needed 5 years after the first purchase and the replacement of trolleybuses, in other words, there is no additional APU cost for years between 1-5 and 21-25 since APU cost is already embedded in the trolleybus purchase price.

[11] http://www.tbus.org.uk/leipzig.htm

As far as assumptions on infrastructure are concerned, there are no market prices for overhead contact line system, and the system cost is highly dependable on the local conditions and bid/contract between the parties. Therefore, the infrastructure cost of Trambus project in Malatya is taken as a reference price which allows for nearest approximation. According to (Hedekoglu 2015), total infrastructure cost per km is 850,000 EUR consisting of overhead contact line system including catenary masts, wires, communication systems, etc. and substations. This price is in 2014 Euros, it is inflated to 2018 price using 0.85% compound annual growth rate (average CPI between 2014 and 2018 in Euro Area).

In the literature, the overhead contact line system is assumed to have 50 years of lifetime. However, there are many examples around the world that trolleybus infrastructure is still being used after 50 years without complete renewal.

Small, single unit substations are necessary power units in certain points to supply the necessary power to overhead contact line. The number of required substations should be established as a function of the expected load on the line. However, since the calculation of expected load is out of the scope of this research, the literature data is used, which is the normal distance between substations is 2-3 kilometers (UITP 2015). Installation of one substation in every 2.5 km for two-way direction is assumed, as applied in Trambus Project. Furthermore, one substation costs 325,000 EUR in 2014 prices implying the cost of 130,000 EUR (trolley-project) per km in two-way for 52 km of the route, which is inflated from 2014 to 2018 using 0.85% compound annual growth rate and it is found to be 134,477 EUR. The lifetime of substations is taken as 30 years thereby no residual value exists at the end of project reference period.

With respect to project related assumptions, Directorate IETT is assumed to be responsible for OCLS construction and network maintenance. Moreover, all the calculations are made for two-directions of the 52 km BRT line. In case of the application of overhead wires is not possible over the Bosphorus Bridge, sectional overhead wire can be constructed. Project reference period is 30 years and it is assumed that trolleybuses will start to operate in 2022 with the initial investment realized in 2021.

Constant annual mileage, in other words stable demand, is assumed due to the fact that it necessitates strong assumptions about critical cost items such as percentage increase in distance traveled per day, unforeseen future purchase price of additional buses and trolleybuses, the question of whether available number of buses is sufficient to meet increasing demand by only appointing more drivers per bus.

Annual mileage is 71,638,080 kilometers by current diesel buses, which is estimated according to the number of operating buses in each line (Sevim 2017) and aligns with the numbers stated in IETT reports. Trolleybuses are expected to cover a distance of 55,459,520 kilometers per year thanks to the higher capacity of bi-articulation. The estimations are made according to below formula:

$$\text{Annual Mileage by Diesel Buses}= \sum_{i=1}^{n}\left[J_{b_i}\times d_i\right] \times W \tag{9}$$

$$\text{Annual Mileage by Diesel Buses}= \sum_{i=1}^{n}\left[J_{t_i}\times d_i\right] \times W \tag{10}$$

where J_{b_i} is the total number of daily journeys by diesel buses, J_{t_i} is the total number of daily journeys by trolleybuses, d_i is one-way distance on the route i in kilometers, W is the number of supply days in a year, and n is the number of routes.

The average speed of 35 km/h (Sevim 2017), which determined the number of journeys per day is an important input in the analysis. Supply days are taken as 320 working days because, in 2018, 251 days are working days, and for non-working days it is assumed to be 60% of the weekday supply of metrobuses, which sums up to 320.

Following Exchange Rates are used for 2018: EUR/TL = 5.6729; $/TL = 4.8221; EUR/$ = 1.17 64

NPV of cash outflows from trolleybuses and diesel buses over 30 years is estimated according to formula below, which was also presented in Section 3.

$$\text{NPV}= \sum_{t=1}^{t}\frac{C_t}{(1+r)^t}\text{-}C_0 \tag{11}$$

where r is the discount factor for the future cash flows to be discounted. A sensitivity analysis is carried out with different discount factors, which do not change the resulting efficient system but have a considerable impact on the NPVs and the difference between them. As suggested by (Uzunkaya & Uzunkaya 2012), average discount rates to be used in investment analyses should be between 9% and 11.9%. Therefore, the less costly system has been examined by applying discount factors of 9%, 10.5%, and 12%.

Table 5.3 Project timeline

2018	2019 2020	2021	2022-2051
Base Year for Prices	Project Feasibility Studies and Settlements	Initial Investment	Operation & Cash Outflows

For trolleybus system, overall construction cost of trolleybus infrastructure is added as initial investment in 2021. From 2022 until 2027, the summation of trolleybus purchase cost divided by its lifetime, yearly network maintenance, fuel costs, and cost of drivers is given as negative cash outflows. Starting from 2027 until 2042, APU cost, on which straight line depreciation is applied, is added to cash outflows. The reason for adding APU cost until 2042 is the fact that the lifetime of trolleybuses ends in 2042 and new trolleybuses are purchased including their APUs inside. Between 2042 and 2047, APU cost is excluded; however in 2047 APU cost is entered as a cost item in the cash outflows. In the final year of the project reference period, 2051, network residual value is added as positive cash inflow.

For diesel bus system, constant cash outflows are foreseen over 30 years, constituting purchasing cost of diesel buses, diesel fuel costs, and cost of drivers. All assumptions behind the NPV and cash-outflow calculations are presented in Appendix Table 6.

5.3. Approach to The Marginal Cost of Emission Reduction Calculations and Comparison of Life-cycle Emissions and Pollutants from Diesel Bus and Trolleybus

In this section, firstly, general information on the emissions and pollutants released during diesel combustion, and electricity generation is given for diesel buses and trolleybuses. Then, the environmental life-cycle (LC) impacts of each energy source during their life-cycle, including electricity and diesel production, are considered since there is no such energy source which produces zero-emission. Therefore, electricity is not regarded as ‘Zero-Emission” energy source in this study.

Main emissions created by the diesel combustion and during electricity production subject to this study are Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Oxides (NO_x, where x=1,2,...), Total Hydrocarbons (THC) and Particulate Matters (PM). The resulting emissions from Trolleybus are due to life-cycle emissions of electricity production from natural gas. The reason for choosing natural gas as the main source of electricity generation is the fact that electricity supply is mostly sourced by natural gas in Marmara Region (Marmara Energy Forum 2007). For the sake of simplicity, other sources are not regarded in the emission calculation for Istanbul. The only data about emissions created during electricity production in Turkey (Atilgan & Azapagic 2015) is used. For the electricity production, reference emissions are the life-cycle emissions from natural gas utilization, however, the reference emissions for diesel bus emissions are not life-cycle.

The reference values for diesel bus emissions are taken from EMBARQ study by (Cooper, Arioli, Carrigan, & Jain 2012). Mean values for D15 + SCR engines with fuel consumption of 0.525 lt/km are used. Then, those values are adjusted to fuel consumption of metrobuses, which is 0.561 lt/km. D15 stands for diesel with 15 ppm and lower sulfur content while SCR represents diesel bus engine equipped with selective catalytic reduction engine. The reason for choosing D15 + SCR is the fact that the producers of currently operating metrobuses have been using SCR in the production of internal combustion engines and the buses are fueled by the low-sulfur diesel.

Since natural gas is the cleanest fossil fuel, total emissions and pollutants from trolleybus operation were re-estimated by using literature data for CO, CO_2, NO_x, THC and PM stemming from hydropower, geothermal, and wind (Köne and Büke 2007) and 2018 electricity mix (please refer to Appendix Table 8) in order to abstain from a bias. Since CO and PM data for renewables is not available in LCA literature, they were taken as zero. For emission and pollutant data of coal and lignite, tha data from (Atilgan and Azapagic 2015) was used. The results of the calculations are presented as a benchmark in the cost effectiveness analysis and to understand environmental impact of the fossil fuels on the electricity generation.

The final emission and pollutant values per km used in the marginal cost analysis are presented in Table 5.4 below, and unit emissions used in marginal cost calculation as directly taken from source studies are presented in Appendix Table 7.

Table 5.4 Emission and pollutant values per km used in the marginal cost calculation

Vehicle Type / Emission	CO	THC	NO_x	PM	CO_2
Diesel Bus (g/km)*	4.172	0.015	7.322	0.060	1,170.770
Trolleybus (g/km)[a]	0.810	0.060**	1.230	0.009***	1,092.000
Trolleybus (g/km)[b]	0.723	0.165**	1.806	0.714	1,405.698

* the data for fuel consumption of 0.525 lt/km, adapted to 0.561 lt/km

** only CH4 (methane)

*** only PM2.5

[a] When powered by electricity from only natural gas

[b] When powered by electricity from 2018 grid mix

The second environmental analysis is the life-cycle emission impact analysis for both electricity and diesel. LC impacts are categorized into four in the scope of this research: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Oxidants Creation Potential (POCP). They are analyzed with different electricity grid mix scenarios. There are other LC impacts which are not included in this thesis but included in environmental life-cycle analysis of electricity generation in Turkey (Atilgan & Azapagic 2016). It is due to discrepancy between equivalent units and use of different LC impact analysis software in diesel LCA (Li, et al. 2013). Below, information about emissions and LC impact categories are presented.

Carbon Dioxide (CO_2)

CO_2 emissions lead to increases in CO_2 concentrations in the climate system that will remain in the atmosphere for thousands of years. Source of 23% of the EU's total emissions of carbon dioxide is road transport (EEA 2016). CO_2 is the most fundamental greenhouse gas responsible for global warming. Heavy-duty vehicles such as trucks and buses are responsible for approximately 25% of CO_2 emissions from road transportation in the EU and for about 6% of total EU emissions (European Commission n.d.). It is both local and GHG pollutant.

Carbon Monoxide (CO)

Carbon Monoxide, which is a local pollutant, arises from incomplete fuel combustion and vehicle emissions. CO oxidizes to CO_2 in the existence of oxygen at combustion temperatures but it can also be frozen without oxygen in the air as happens in vehicles where exhaust gases rapidly cool.

Excessive levels of CO are not generally observed outdoors but people with certain types of heart diseases are susceptible to CO emissions in the air. Even if CO does not have direct and significant health effects due to low levels of concentration in outdoors, it has significant indirect impacts on global warming.

CO indirectly contributes the global warming potential as a result of producing a reaction with Hydroxyl Radical (OH) in the lowest part of the atmosphere while strictly increasing the amount of OH. Therefore, CO is a key factor in climate change by chemically changing methane, ozone, and carbon dioxide concentrations (Daniel and Solomon 1998). CO emissions can also lead to 'ozone' formation which a significant greenhouse gas contributing to global warming.

Nitrogen Oxides (NO_x)

NO_x stem from fuel combustion such as transport and industrial plants. Road transport accounts for more than 30% of NO_x emissions in the EU (EEA 2016). NO_x composes of nitrogen Monoxide (NO) and nitrogen dioxide (NO_2), where the former constitutes the majority of NO_x emissions. NO_x also contributes to the 'ozone' formation and particulate matter emissions resulting in acid rains. They are both local and GHG pollutant like CO_2.

Nitrogen oxide can be turned into NO_2 by oxidization where NO_2 is also another pollutant. NO_2 is a respiratory element and regular exposure to raised levels can result in increased observation of acute respiratory disease in children and more vulnerability to respiratory infections in adults (Blumberg, Walsh and Pera 2003).

Selective Catalyst Reduction (SCR) technologies are known for their nitrogen oxides (NO_x) mitigation. However, NO_x emissions created by Euro V diesel buses, diesel hybrid and other buses fueled by fossil fuels in China are given crucial importance in policy-making. It is because reduction in NO_x emissions from Euro IV diesel buses with SCR systems is not sufficient. Moreover, Euro V diesel buses perform better at decreasing NO_x emissions than Euro IV buses do, but they are still above the limit values by 180% (Zhang, et al. 2014).

Total Hydrocarbons (THC)

Total hydrocarbons (THC) covers a wide range of chemicals such as non-methane hydrocarbons (NMHC) and methane (CH_4) which is the most prevalent hydrocarbon in the atmosphere. In diesel, CH_4 levels are lower compared to natural gas. Certain reactive hydrocarbons or non-methane hydrocarbons (NMHC) can react with oxides of nitrogen when it is exposed to sunlight; as a result, they form ozone. At different concentrations depending on the hydrocarbon characteristics, health effects may be observed since plenty of hydrocarbons are either toxic or carcinogenic (The Alberta Capital Airshed; Blumberg, Walsh, & Pera 2003). However, Methane (CH_4), unlike reactive hydrocarbons, does not significantly contribute to ozone formation due to its non-reactive feature (UNFCCC 2004). Main impacts of ozone on human health are eye irritation, damage in the lungs and the exacerbation of respiratory problems (EEA 2016).

Particulate Matters (PM)

Particulate matter is an umbrella definition for suspended solid particles and liquid droplets in the air and it is a local pollutant. Particulate matter includes anything from complex acid mixtures and heavy hydrocarbons to a dust grain (Blumberg, Walsh and Pera 2003). PM is categorized according to the size measured by the aerodynamic diameter. Fine particles less than 10 micrometers (μm) in aerodynamic diameter cause the greatest problems. PM_{10} is inhalable particles which are less than 10 μm in diameter. $PM_{2.5}$ is respirable particles and it includes particles less than 2.5 μm in diameter (fine, ultrafine, nanoparticles). Separate emission factors result in different particle sizes where finer particles are created by traffic and fuel burning. Approximately 12 % of the EU's primary $PM_{2.5}$ emissions arise from road transport (EEA 2016). PM emissions primarily result in health problems in cardiovascular and respiratory systems. All population is affected, but susceptibility to the pollution may vary with health or age (WHO 2005). Children and older people and people who have heart or lung diseases are the most vulnerable individuals to exposure to particle pollution.

According to (EPA 2003), health problems arising from long-term exposures to high particle levels are decreased lung function, the development of chronic bronchitis and premature death. Health effects for short-term exposure are irregular heartbeat, severe asthma, acute bronchitis, respiratory symptoms such as coughing or difficulty in breathing and nonfatal heart attacks in people with heart disease and aggravated lung disease.

Most of the PM inhaled can be eliminated by mucus and cilia, but a major fraction of $PM_{2.5}$ cannot be prevented. They remain in the human lungs and are responsible for 96% of particles there. $PM_{2.5}$ cannot only penetrate into lung's exchange region but also further run through the respiratory barrier and go into the circulatory system. In the final stage, it spreads to the whole body.

Moreover, The $PM_{2.5}$ can readily produce a reaction with certain toxic compounds, such as transition metals and polycyclic aromatic hydrocarbons (PAHs which are caused by vehicle exhaust and emissions from fossil fuels) due to its specific surface (Song, Li and Mao 2018). PM can also damage and stain historical stone artifacts such as statues and monuments (EPA). On the next section, WHO Guideline values for PM are depicted.

The environmental impacts of the diesel production and combustion, which are referred as usage impacts, are taken from the study carried out by (Li et al. 2013). According to this study, the diesel production impacts are based on Chinese Core Life Cycle Database and diesel combustion impacts are taken from Ecoinvent 2.0. The average fuel efficiency of 25 L per 100 km is taken. Despite the fact that the national life-cycle emission inventories should be regarded in life-cycle emission analyses, Turkey does not have a national emission inventory for the diesel usage in Turkey. Emissions created during combustion of diesel in heavy-duty vehicles highly differ; depending on altitude, climate, driving cycle, vehicle age, and so on. The reference fuel consumption is also higher than current diesel buses' fuel consumption. However, the LC sources I benefited in this thesis provide a good understanding of diesel and electricity effects from life-cycle perspective.

For the environmental LC impacts of electricity production in Turkey, (Atilgan and Azapagic 2016), which is the only LCA for the calculation of impacts from Turkish electricity grid mix, is used. In that study, the LCA is carried out based on 2010 electricity grid mix in Turkey, which consists of coal (9%), lignite (17%), natural gas (47%), hydropower (25%), onshore wind (1%) and geothermal (0.3%). Other fuel sources (1.2%) such as fuel oil, solar energy, LNG and biomass are disregarded in the calculations of LC impacts. The LCA is made regarding 'cradle to grave analysis', which consists of extraction, processing, and transportation of the raw materials and fuels, construction and removal of the facility. The supply of electricity to final consumer, including transmission, distribution and use is excluded from the scope of the study. When the source emissions from the study were applied to this thesis, 2018 grid mix was regarded since it is more up-to-date.

One of the reasons for choosing the above-mentioned four impact categories is that they are estimated in the life-cycle perspective by applying the same boundaries and expressed in the same equivalent factors. In other words, in the assessment of each impact category, identical processes should be taken into consideration with being stated in terms of same figures. Moreover, the reliability of the sources is high since the studies include a data comparison with literature. Below, brief information on impact categories is given.

Global Warming Potential (GWP)

As EPA suggests, Global Warming Potential (GWP) enables analysts and policy-makers to make the comparison of the global warming effects of various gases, thereby, to make decisions across projects or sectors by setting an upper limit for emissions. It estimates how much energy one ton of a gas emissions will absorb over a pre-defined period, usually 100 years for GWP, relative to one ton of CO_2 emissions. The higher the GWP value, the more that a specific gas warms the Planet in comparison with CO_2 over that period of time. The gases responsible for GWP are CO_2, CH_4, N2O and fluorinated gases; and GWP is indicated in CO_2 equivalents. According to 2016 US data, approximately 28.5% of greenhouse gas emissions stemmed from transportation while

28.4% of them came from electricity production since 68% of world's electricity is generated from fossil fuels.

CO_2 is the most fundamental greenhouse gas responsible for global warming. CO_2 emissions lead to increases in CO_2 concentrations in the climate system that will remain in the atmosphere for thousands of years. Heavy-duty vehicles such as trucks and buses are responsible for approximately 25% of CO_2 emissions from road transportation in the EU and for about 6% of total EU emissions (European Commission).

Acidification Potential (AP)

Acidification Potential (AP) is described as the potential acidifying effect of substances which are emitted to atmosphere and then return to the surface of the Earth. It accounts for various damages on soil, groundwater, surface waters, organisms, ecosystems, and materials; specifically, acidification of waters, decimation of fish stocks, acid rains, and forest decline. AP is measured in SO_2 equivalents and the main sources of AP are NO_x, SO_2, NH3, H2S, and HCL and the interaction between them. The effect range of the acidification potential is on both regional and local level. Chief sources of AP are fuel combustion for transport and electricity generation, and agriculture.

Eutrophication Potential (EP)

Eutrophication Potential (EP), namely Nutrient Enrichment, can be defined as over-fertilization of soil and water and results in escalated biomass production and less biodiversity. As a consequence of EP, vascular plants vanish or become vulnerable to diseases due to Algae growth in aquatic ecosystems. Secondly, the dissolution of dead algae results in the decrease in the number of aquatic animals which require more oxygen, thereby decrease in biodiversity. EP is indicated in PO_4-equivalents (Phosphate-eq.). The main sources of EP are NH4, NO_x, PO_4, P, and Chemical Oxygen Demand (COD). The effect of EP is on both local and regional level.

Photochemical Oxidants Creation Potential (POCP)

Photochemical Oxidants Creation Potential (POCP) can be identified as the chemical reaction of airborne substances with sunlight which produces other substances especially ozone. Therefore, ground-level ozone (so-called bad ozone) concentration increases which leads to damage in ecosystems, flora and human health. Major impacts of POCP on human health are eye irritation, decreased lung function, severe asthma, and respiratory symptoms. Children, elders and people who spend most of their time in outdoors are more susceptible to diseases caused by increase in ozone. POCP can also be referred as Smog Creation Potential and its impact range is on local level. Main sources of POCP are fuel combustion in vehicles, industrial processes, and energy production.

Table 5.5 The summary of life-cycle emission impacts

Impact Category	Contributors	Short Description	Indicator	Impact Level
Global Warming Potential (GWP)	CO_2, CH_4, NO_x, CO	Various emissions with global warming impact	Kg/T CO_2-eq	Global
Acidification potential (AP)	NO_x, SO_2, NH3, H2S, HCL	The acidifying effect of substances and their acid formation potential	Kg/T SO_2-eq	Regional, Local
Eutrophication potential (EP)	NH4, NO_x, PO_4, P, COD	Potential of the emissions to change the amount of nutrients (phosphorus and nitrogen) present in the inland waterways	Kg/T PO_4-eq	Regional, Local
Photochemical oxidants creation potential (POCP)	NO_x, VOCs, CO, CH_4, sunlight	A measure for estimating airborne substances' potential in the formation of atmospheric oxidants especially ozone	Kg/T C_2H_4-eq	Local

Lastly, a scenario analysis has been carried out for electricity generation in 2023, 2030, and 2050 with different cases (A, B, C, and D). 2018 Grid Mix is used as a base scenario, by taking weighted averages of impacts. For 2050 assumptions, I benefited from (Atilgan and Azapagic 2017) which investigated LC impacts from future Turkish electricity production up to 2050. For grid mix information for the scenario assumptions, please refer to Appendix Table 8. Here, the main focus is to understand how much sources of electricity generation contribute the life-cycle emission impacts, not making an exact estimation on the impacts.

6. RESULTS AND DISCUSSION

The results of economic analysis and environmental life-cycle analysis of the investment in a possible double-articulated trolleybus system and current BRT system are presented in this section. The economic performance of each system is examined via NPV and cash outflows with different discounting scenarios. Henceforth, lifetime costs will refer to monetary costs of diesel buses and trolleybuses over 30 years. The environmental life-cycle analysis is carried out for fuels by considering different electricity grid mixes in each scenario. A summary on the results is given in sections below**.**

6.1. Monetary Cost Efficiency

In this section, Net Present Value (NPV) is used as a proxy to see the less costly system over the project life-cycle. The NPVs are calculated as negative NPVs since no cash inflow is included in the calculation. The reason is that the ticket income is same for each investment and only differential items, basically cash outflows, are considered. Therefore, in the selection of the system with lower life-cycle costs, the system with higher NPV should be chosen. Straight Line Depreciation is applied to vehicle and network infrastructure investment of diesel buses and trolleybuses with a discount rate of 9%, 10.5% and 12% in order to reflect different cases. Moreover, results below represent “municipality” point of view because both systems’ total costs to the municipality are estimated, including taxes and levies. Since excise and value-added taxes are high on diesel but not on electricity, and the lifetime costs are mainly driven by the energy costs; the NPV results were recalculated by applying fuel prices exempt from tax and levies in order to understand the “state” point of view. The analysis results for “municipality” side are taken as the main outcome of the financial assessment due to the fact that the municipality is the actual beneficiary, not state. The results of the calculations from “state” standpoint are shown just after the main results. The figures for Present Value (PV) of Cash Outflows are also depicted in Appendix Tables 9, 10, 11, 12, 13, and 14 to see the results on pre-defined time basis over the project life from both “municipality” and “state” point of view.

6.1.1. Scenario 1: NPV and PV of Cash Outflow Discounted with 9% Rate

As it can be seen in Table 6.1, when we look at Net Present Value (NPV) of investments which is discounted with 9%, the NPV of EUR -549.9 Million is foreseen for the Trolleybus system whereas the NPV of EUR -665.6 Million is predicted for the diesel bus system. Trolleybus results in a saving of EUR 115.7 Million or a decrease by 17.4% of the diesel bus lifetime costs.

Table 6.1 NPV of lifetime costs with 9% discount

NPV of Lifetime Costs	EUR	USD	TRY
Trolleybus	-549,906,092	-646,930,232	-3,119,562,270
Bus	-665,593,620	-783,029,395	-3,775,846,048
Lifetime Cost Change By	**-115,687,528**	**-136,099,164**	**-656,283,778**

As stated in section 6.1, the result above represents the “municipality” point of view. In order to mirror the “state” point of view, unit energy prices were recalculated as 0.245 EUR/km for diesel by making 51.2% tax deduction[12] from 0.503 EUR/km; 0.133 EUR/km for electricity by making 18.5% tax deduction[13] from 0.164 EUR/km. NPV of lifetime cost of trolleybus system slightly increases to EUR -532.6 Million from -549.9 Million, however NPV of diesel bus lifetime cost dramatically rises to EUR -476.2 Million from -665.6 Million. As Table 6.2 suggests, trolleybus results in a cost of EUR 56.5 Million, or an increase by 11.9% of the diesel bus lifetime costs. Hence, from the standpoint of “state”, the final efficient system becomes reversed compared to the

[12] (OECD 2018)
[13] (Eurostat database: Electricity prices for non-household consumers - bi-annual data, S1-2018)

outcome of the estimations with tax-included energy prices.

Table 6.2 NPV of lifetime costs with 9% discount, from the state point of view

NPV of Lifetime Costs	EUR	USD	TRY
Trolleybus	-532,636,788	-626,613,972	-3,021,595,232
Bus	-476,151,058	-560,162,032	-2,701,157,335
Lifetime Cost Change By	**+56,485,730**	**+66,451,940**	**+320,437,898**

In Figure 6.1, present value of cash outflows over the project reference period of 30 years shows that as of first year, trolleybus system achieves lower cash outflow than diesel buses, which is due to substantially lower energy costs of trolleybuses. The interpretation of PV of cash outflow figure below can be made in that way: higher the line, higher the cash outflows, which means that current BRT system is less cost advantageous than trolleybus system. Besides lower unit energy costs, the shorter distance traveled by trolleybus thanks to their high capacity is another factor in lower operational costs. Non-discounted and discounted cash outflows at 9% rate year by year are presented in Appendix Table 9.

Figure 6.1 PV of cash outflows discounted with 9% rate over 30 years

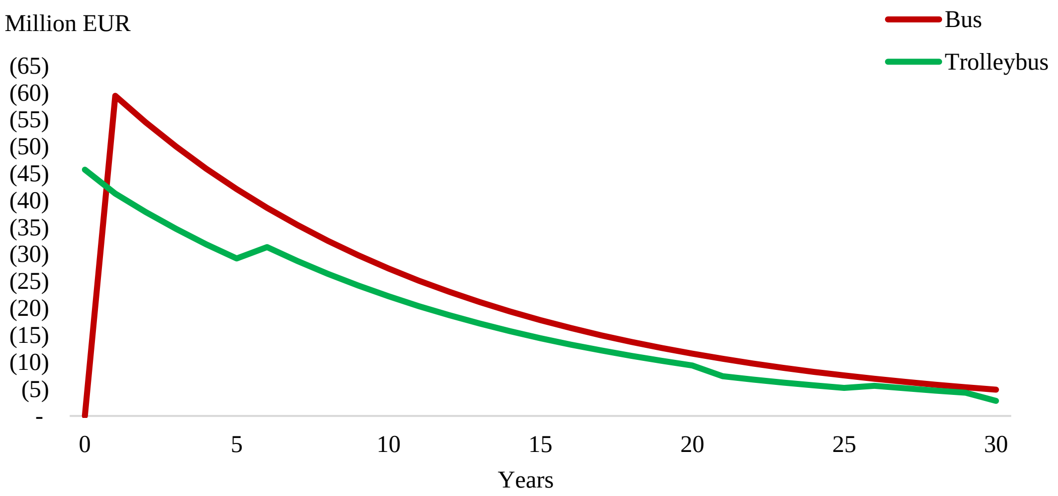
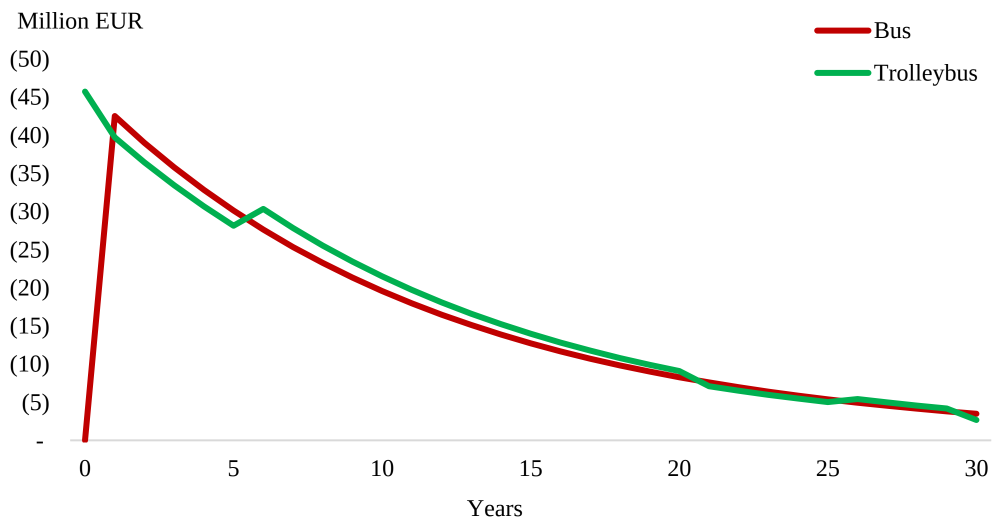


Figure 6.2 is reproduced from Figure 6.1, in order to reflect the “state” standpoint. It shows that as of first year, trolleybus system achieves lower cash outflow than diesel buses, however starting from year 6 until year 21, trolleybus becomes less cost advantageous. Between year 21 and year 25, trolleybus system starts to have lower cash

outflows than diesel bus system, however, cash outflows is higher for trolleybus as of year 26. At the end of the project reference period, which is year 30, PV of cash outflows from trolleybus system is lower than that of diesel bus system due to subtraction of network residual value. From the "state" point of view, non-discounted and discounted cash outflows at 9% rate year by year are presented in Appendix Table 10.

Figure 6.2 PV of cash outflows discounted with 9% rate over 30 years, from the state point of view



6.1.2. Scenario 2: NPV and PV of Cash Outflow Discounted with 10.5% Rate

In Table 6.3, Net Present Value (NPV) of investments which is discounted with 10.5% is shown. The NPV of the Trolleybus system life-cycle costs is EUR -488.4 Million, while the NPV of diesel bus system is EUR -586.2 Million. Compared to 9% discount rate, a lower saving of EUR 97.8 Million, in other words cost decrease by 16.7% of the diesel bus lifetime costs can be achieved by switching to trolleybus system.

Table 6.3 NPV of lifetime costs with 10.5% discount

NPV of Lifetime Costs	EUR	USD	TRY
Trolleybus	-488,353,413	-574,517,342	-2,770,380,075
Bus	-586,151,674	-689,570,899	-3,325,179,833
Lifetime Cost Change By	**-97,798,262**	**-115,053,557**	**-554,799,758**

From the standpoint of "state", NPV of lifetime cost of trolleybus system slightly increases to EUR -473.2 Million from -488.4 Million, whereas NPV of diesel bus lifetime cost sharply rises to EUR -419.3 Million from -586.2 Million, in which trolleybus results in a cost of EUR 53.8 Million, or an increase by 12.8% of the diesel bus lifetime costs. Therefore, compared to the outcome of the estimations with tax-included energy prices, trolleybus system brings lifetime costs rather than savings, as it can be seen in Table 6.4 below.

Table 6.4 NPV of lifetime costs with 10.5% discount, from the state point of view

NPV of Lifetime Costs	EUR	USD	TRY
Trolleybus	-473,145,286	-556,625,930	-2,684,105,895
Bus	-419,320,034	-493,303,876	-2,378,760,622
Lifetime Cost Change By	**+53,825,252**	**+63,322,053**	**+305,345,273**

In Figure 6.3, PV of cash outflows over 30 years shows that as of first year, trolleybus system still results in lower cash outflow than diesel. According to PV of cash outflow figure, since higher the line, higher the cash outflows, trolleybus system is more cost advantageous than the current BRT system. Besides above-mentioned explanations, discount factor does not affect resulting less costly system, it has an impact on the time that the gap between cash outflows of the systems gets narrower, and the NPV of the systems. Non-discounted and discounted cash outflows at 10.5% rate year by year are presented in Appendix Table 11.

Figure 6.3 PV of cash outflows discounted with 10.5% rate over 30 years

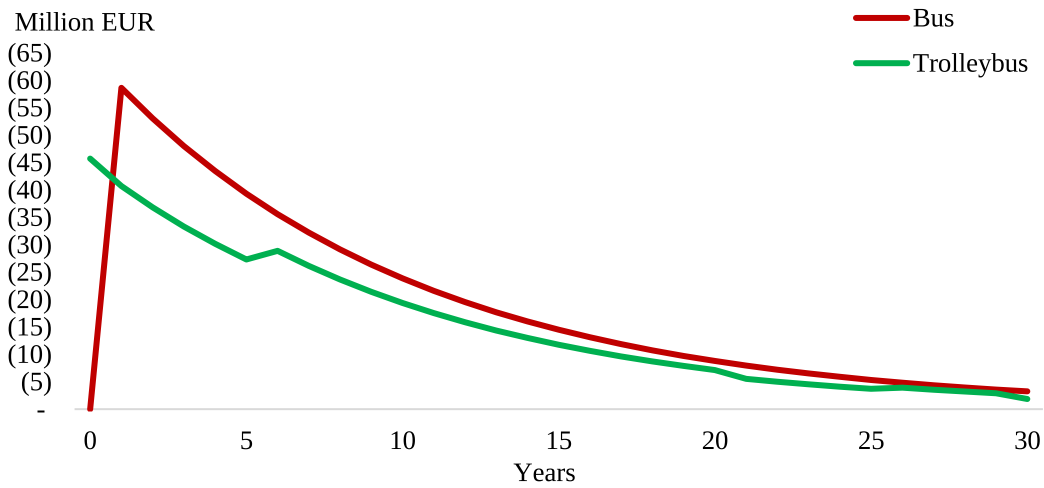
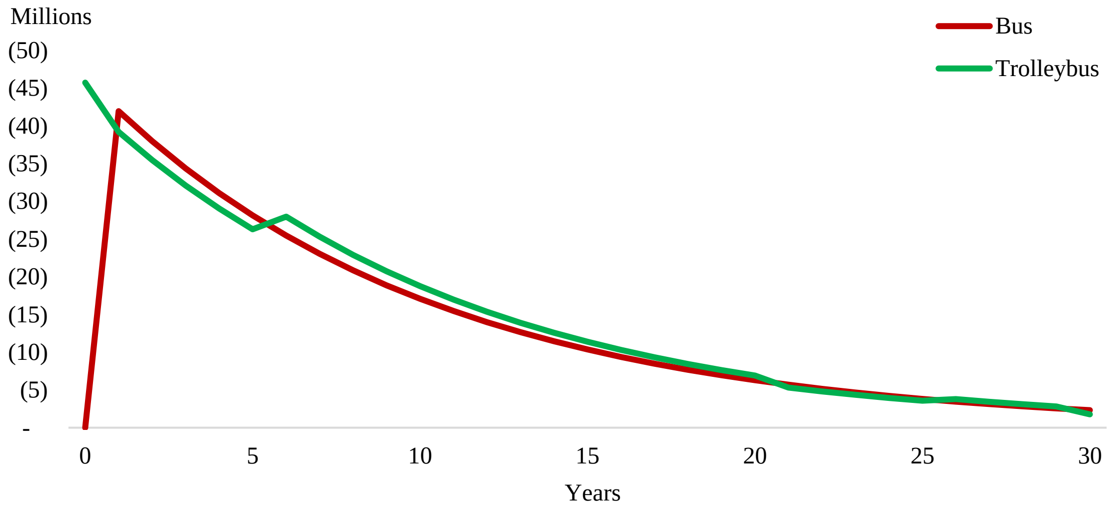


Figure 6.4 is depicted to reflect the “state” point of view. Like in Figure 6.2, similar trend can be observed for the PV of cash outflows. Figure 6.2 and Figure 6.4 only differ in terms of difference of lifetime costs due to higher discount rate, not in terms of the timeline that trolleybus cash outflows exceed the diesel bus costs. From the “state” point of view, non-discounted and discounted cash outflows at 10.5% rate year by year are presented in Appendix Table 12.

Figure 6.4 PV of cash outflows discounted with 10.5% rate over 30 years, from the state point of view



6.1.3. Scenario 3: NPV and PV of Cash Outflow Discounted with 12% Rate

Table 6.5 shows that when NPV of investments is discounted with 12% rate, the NPV of EUR -438.5 Million is resulted for the Trolleybus system, whereas the NPV of diesel bus system is EUR -521.9 Million. Compared to 10.5% discount rate, a lower saving of EUR 83.4 Million, in other words a decrease by 16.0% of the diesel bus lifetime costs can be achieved by switching to trolleybus system.

Table 6.5 NPV of lifetime costs with 12% discount

NPV of Lifetime Costs	EUR	USD	TRY
Trolleybus	-438,509,394	-515,878,961	-2,487,619,939
Bus	-521,866,810	-613,943,764	-2,960,498,224
Lifetime Cost Change By	**-83,357,416**	**-98,064,803**	**-472,878,285**

As far as "state" point of view is concerned, as demonstrated in Table 6.6, NPV of lifetime cost of trolleybus system shows a little increase to EUR -425.0 Million from -438.5 Million, whereas NPV of diesel bus lifetime cost substantially rises to EUR -373.3 Million from -521.9 Million, in which trolleybus results in a cost of EUR 51.6 Million, or an increase by 13.8% of the diesel bus lifetime costs. Hence, for the state, trolleybus system comes with less lifetime costs based on amount, however, higher lifetime costs based on the share of the diesel bus lifetime costs, in comparison with the results of lower discount rates.

Table 6.6 NPV of lifetime costs with 12% discount

NPV of Lifetime Costs	EUR	USD	TRY
Trolleybus	-424,969,184	-499,949,749	-2,410,807,686
Bus	-373,332,054	-439,201,885	-2,117,875,409
Lifetime Cost Change By	**+51,637,130**	**+60,747,864**	**+292,932,277**

Figure 6.5 shows that trolleybus system results in lower cash outflow than diesel buses do as of first year. As higher the PV of cash outflow line means higher the cash outflows, current BRT system is still less desirable than trolleybus system with 12% discount rate. In this case, cash outflows converge to each other sooner than in other discount rates. Non-discounted and discounted cash outflows at 12% rate year by year are presented in Appendix Table 13.

Figure 6.5 PV of cash outflows discounted with 12% rate over 30 years

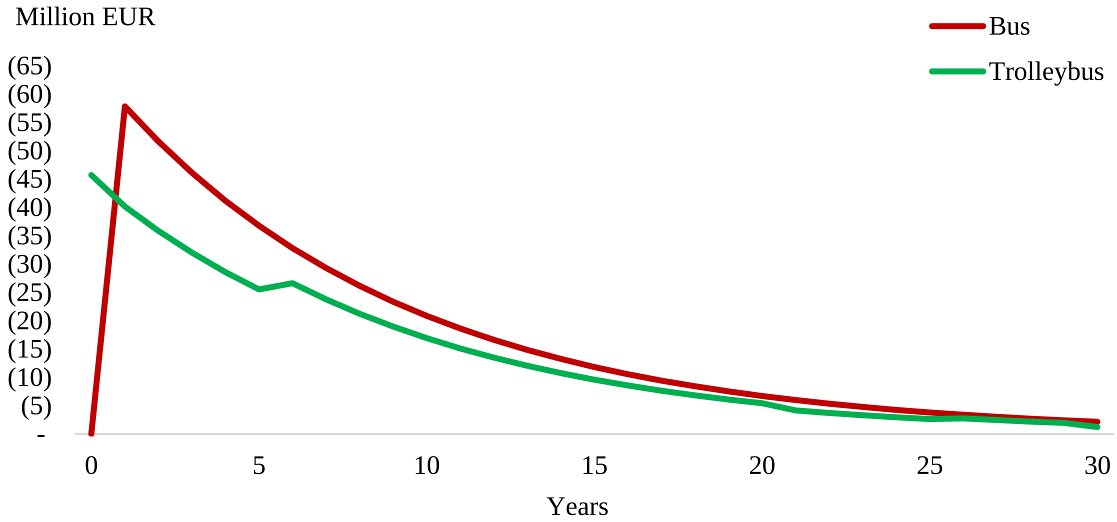
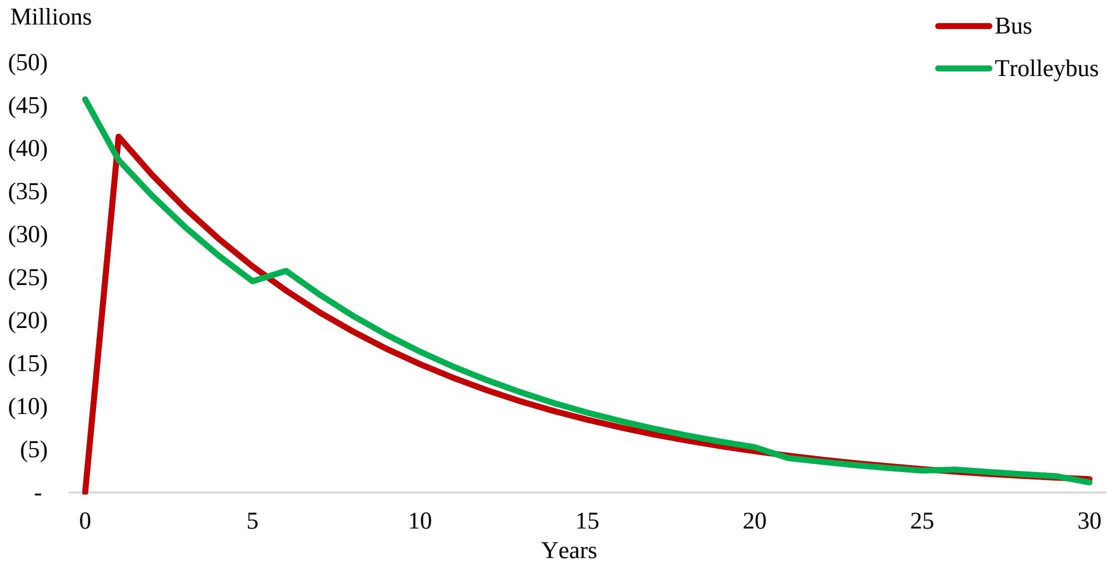


Figure 6.6 shows that similar picture can be observed for the PV of cash outflows of each system as in other discount rates, from the “state” point of view. Only the difference between PV of cash outflows falls, the year that one passes other does not change. Diesel bus system is the outperforming system in terms of PV of cash outflows for the state. From the “state” point of view, non-discounted and discounted cash outflows at 12% rate year by year are presented in Appendix Table 14.

Figure 6.6 PV of cash outflows discounted with 12% rate over 30 years, from the state point of view



It can be concluded that saving rates coming from switch to trolleybus system fall as the discount rate rises. The trolleybus surpasses diesel bus in any discount rate scenario even without environmental impact. From the “state” side, the outcome becomes reversed in each discount factor compared to the “municipality” standpoint, which implies that trolleybus system comes with net costs, rather than savings for the state, but it brings net savings for the municipality because excise and value-added taxes on diesel fuel are substantially higher than those taxes on electricity.

6.2. Marginal Cost of Emission and Pollutant Reductions

In section 6.2., the results of cost-effectiveness analysis for the assessment of marginal cost of transition to trolleybus per one kg deduction in harmful gas emissions and pollutants are presented. The emissions and pollutants subject to analysis are Carbon Monoxide (CO), Carbon dioxide (CO_2), Nitrogen oxides (NO_x), Total hydrocarbons (THC), Particulate matters (PM).

In the cost-effectiveness analysis, as stated in the previous sections, the emission and pollutant values from electricity production only sourced by natural gas are used (Atilgan and Azapagic 2015). For the electricity production, reference emissions are the life-cycle emissions, however, diesel bus emissions are only exhaust emissions, not life-cycle. The majority of life-cycle emissions of diesel fuel are produced during diesel engine combustion phase. Therefore, for this analysis, diesel extraction/production emissions are neglected. The reference values for diesel bus emissions are taken from EMBARQ study by (Cooper, Arioli, Carrigan, and Jain 2012). Mean values of D15 + SCR engines, which are obtained from meta-analysis, are used.

In Table 6.7, total annual emissions and pollutants created by diesel buses and trolleybuses, when electricity is generated from natural gas, are depicted in terms of kg-equivalent units. According to table, if trolleybuses are utilized in the BRT line instead of diesel buses, CO, NO_x and PM can be decreased by 85%, 87%, and 88% respectively. Expected fall in CO_2 emissions will be by 28% whereas THC produced by trolleybuses will be two times more than the THC created by diesel buses. By looking at those figures, it can be said that, a switch to trolleybus system, besides its economic advantage, will bring emission and pollutant reduction except for THC.

Table 6.7 Total annual emissions and pollutants created by diesel buses and trolleybuses in kg, if electricity generation is fully sourced by natural gas.

System	CO	THC	NO_x	PM	CO_2
Diesel Bus	298,853	1,072	524,523	4,287	83,871,686
Trolleybus	44,922	3,328	68,215	499	60,561,796
Change (kg)	**-253,931**	**+2,256**	**-456,308**	**-3,788**	**-23,309,890**

Regarding the information on the source of electricity production in Marmara Region, and due to lack of emission data for each electricity production source in Turkey, the source of electricity generation was taken as “only natural gas”. Since natural gas is the cleanest fossil fuel, total emissions and pollutants from trolleybus operation were re-estimated by using literature data for CO, CO_2, NO_x, THC and PM stemming from hydropower, geothermal, and wind (Köne and Büke 2007) and 2018 electricity mix (see Appendix Table 8) in order to abstain from a bias. Since CO and PM data for renewables is not available in LCA literature, they were taken as zero. For emission and pollutant data of coal and lignite, (Atilgan and Azapagic 2015) was used.

Results of the re-calculation show that all the emissions and pollutants except for CO are going to increase compared to “only natural gas” electricity generation. As shown in Table 6.8, if trolleybuses were utilized in the BRT line instead of diesel buses, CO and NO_x are expected to be decreased by 87% and 81%, respectively, whereas possible fall in CO_2 emissions will be by only 7%. In contrast, THC produced by trolleybuses will be 7.5 times more than the THC created by diesel buses. Moreover, the amount of PM is expected to be 8.2 times higher in the trolleybus case, when the 2018 grid mix is concerned. Change in environmental figures compared to figures of electricity sourced by 100% natural gas, is also stated on the table below. Hence, switch to trolleybus system will lead to a decrease in CO, CO_2, and NO_x but rise in THC and PM, which shows whether the electricity is produced from clean energy sources or not is of great significance.

Table 6.8 Total annual emissions and pollutants by diesel buses and trolleybuses in kg, regarding 2018 electricity mix

System	CO	THC	NO_x	PM	CO_2
Diesel Bus	298,853	1,072	524,523	4,287	83,871,686
Trolleybus	40,097	9,151	100,160	39,598	77,959,336
Change (kg)	**-258,756**	**+8,079**	**-424,363**	**+35,311**	**-5,912,350**
Change relative to NG* (kg)	**-4,825**	**+5,823**	**+31,945**	**+39,099**	**+17,397,541**

*NG stands for electricity from “only natural gas”

In Table 6.9, the annual figures of diesel bus and trolleybus, which is powered by fully natural gas, were multiplied by 30 and divided to 1000 in order to convert units from kg to metric tons for the 30 years of project reference period. 7,618 tons of CO and 699,297 tons of CO_2 will be eliminated over 30 years, if the trolleybus system starts to operate. 13,689 tons of NO_x and 114 tons of PM will be reduced thanks to electrification of the line. However, THC amount will increase by 68 tons.

Table 6.9 Total emissions and pollutants created by diesel buses and trolleybuses over 30 years in metric tons, if electricity generation is fully sourced by natural gas.

System	CO	THC	NO_x	PM	CO_2
Diesel Bus	8,966	32	15,736	129	2,516,151
Trolleybus	1,348	100	2,046	15	1,816,854
Change (t)	**-7,618**	**+68**	**-13,689**	**-114**	**-699,297**

The same calculation was applied to the annual figures of diesel bus and trolleybus system, which is powered by electricity regarding 2018 mix. According to Table 6.10, 7,763 tons of CO and 177,370 tons of CO_2 will be eliminated over 30 years, if the BRT fleet is converted to trolleybuses and the vehicles were powered by the electricity from 2018 mix. 12,731 tons of NO_x will be reduced thanks to electrification of the line. On the contrary, the amount of PM and THC is expected to rise by 1,059 tons and 242 tons, respectively. Change in figures compared to figures of electricity sourced by 100% natural gas, is also stated on the table below.

Table 6.10 Total emissions and pollutants created by diesel buses and trolleybuses over 30 years in metric tons, regarding 2018 electricity mix

System	CO	THC	NO_x	PM	CO_2
Diesel Bus	8,966	32	15,736	129	2,516,151
Trolleybus	1,203	275	3,005	1,188	2,338,780
Change (t)	**-7,763**	**+242**	**-12,731**	**+1,059**	**-177,370**
Change relative to NG* (t)	**-145**	**+175**	**-958**	**+1,173**	**+521,926**

To understand the cost effectiveness of the trolleybus system, the differential lifetime cost of trolleybus found in the section 6.1 is divided by the reduction in each emission and pollutant item. According to evaluation of the trolleybus project, like in various greenhouse gas abatement projects, trolleybus system brings net savings in all emissions and pollutants except for THC over the project period when the electricity is fully sourced by natural gas. Trolleybuses result in more THC release to the air than THC created by diesel buses. In other words, the differential lifetime cost of trolleybus system is negative rather than being positive independent of the GHG deduction.

Therefore, in both economic and environmental aspects, trolleybus system outperforms the current diesel buses as far as electricity production from natural gas is concerned. However, high initial capital cost and its financing are still important factors to evaluate the project feasibility and efficiency.

As far as emissions and pollutants from electricity mix in year 2018 are concerned, trolleybus system results in marginal savings in CO, CO_2, and NO_x, but costs for THC and PM over the project reference period due to the fact that the amount of THC and PM from electricity escalates when electricity is produced from dirty fossil fuels such as coal and lignite.

In Table 6.11 below, for each discount scenario, marginal savings and costs over 30 years of project reference period are shown. The numbers on the first line represent the results for "only natural gas" case, the bold numbers on the second line stand for the results for the electricity mix in 2018. The negative numbers correspond to savings from each emission and pollutant reduction; positive numbers represent costs for per kg emission and pollutant deduction. As the amount of emission and pollutant reduction increases, the marginal savings fall in terms of positive values because amount of reduction is placed in the denominator. For the same reason, as the deduction amount in emission and pollutant rises, the marginal costs increase in terms of positive values. Hence, across the marginal savings, lower the savings in terms of positive values (higher in terms of negative values), better the performance; across the marginal costs, higher the costs in terms of positive values (lower in terms of negative values), better the performance. Results are summarized below.

When the lifetime cost of switching to trolleybus system from diesel bus system was discounted at 9% rate, for "only natural gas" case, costs or savings of one kg abatement in emissions and pollutants subject to analysis were found as follows: saving of 15.19 EUR for CO, cost of 1,709.43 EUR for THC, saving of 8.45 EUR for NO_x, saving of 1,018.10 EUR for PM and saving of 0.17 EUR for CO_2. For electricity mix in 2018, costs or savings of one kg abatement in emissions and pollutants subject to analysis were found as follows: saving of 14.90 EUR for CO, cost of 477.31 EUR for THC, saving of 9.09 EUR for NO_x, cost of 109.21 EUR for PM and saving of 0.65 EUR for CO_2.

When the lifetime cost of switching to trolleybus system from diesel bus system was discounted at 10.5% rate, for “only natural gas” case, costs or savings of one kg abatement in emissions subject to analysis were found as follows: saving of 12.84 EUR for CO, cost of 1,445.10 EUR for THC, saving of 7.14 EUR for NO_x, saving of 860.67 EUR for PM and saving of 0.14 EUR for CO_2. For electricity mix in 2018, costs or savings of one kg abatement in emissions and pollutants subject to analysis were found as follows: saving of 12.60 EUR for CO, cost of 403.50 EUR for THC, saving of 7.68 EUR for NO_x, cost of 92.32 EUR for PM and saving of 0.55 EUR for CO_2.

When the lifetime cost of switching to trolleybus system from diesel bus system was discounted at 12% rate, for “only natural gas” case, costs or savings of one kg abatement in emissions subject to analysis were found as follows: saving of 10.94 EUR for CO, cost of 1,231.71 EUR for THC, saving of 6.09 EUR for NO_x, saving of 733.58 EUR for PM and saving of 0.12 EUR for CO_2. For electricity mix in 2018, costs or savings of one kg abatement in emissions and pollutants subject to analysis were found as follows: saving of 10.74 EUR for CO, cost of 343.92 EUR for THC, saving of 6.55 EUR for NO_x, cost of 78.69 EUR for PM and saving of 0.47 EUR for CO_2.

In brief, the table shows that firstly, switching to trolleybus system brings marginal savings for reduction in each emission except for THC in the case of electricity production from natural gas. Second, trolleybus system comes with marginal savings for reduction in CO, CO_2 and NO_x but costs for THC and PM in the case of electricity production from 2018 mix because it leads THC and PM to increase. Lastly, as the discount rate rises, marginal savings/costs decrease in terms of positive values because of the falling net present values of the each system. The Table 6.11 was replicated in terms of USD and TRY terms in Appendix Tables 15 and 16.

Table 6.11 Marginal differential cost of trolleybus system per kg emission reduction in EUR

Discount Rate	CO	THC	NO_x	PM	CO_2
9%	-15.19 **(-14.90)**	1,709.43 **(477.31)**	-8.45 **(-9.09)**	-1,018.10 **(109.21)**	-0.17 **(-0.65)**

10.5%	-12.84 **(-12.60)**	1,445.10 **(403.50)**	-7.14 **(-7.68)**	-860.67 **(92.32)**	-0.14 **(-0.55)**
12%	-10.94 **(-10.74)**	1,231.71 **(343.92)**	-6.09 **(-6.55)**	-733.58 **(78.69)**	-0.12 **(-0.47)**

6.3. Environmental Life-Cycle Impacts of Energy Sources with Different Electricity Generation Scenarios

In this section, from 6.3.1 to 6.3.7, four environmental impacts, GWP, AP, EP, and POCP, are analyzed with different electricity grid mix scenarios. There are other impacts which are not included in this thesis but included in environmental life-cycle analysis of electricity generation in Turkey (Atilgan and Azapagic 2016). It is due to discrepancy between equivalent units and use of different LC impact analysis software in diesel LCA (Li, et al. 2013). It can be said that when life-cycle impacts of processes are concerned, there is always a trade-off between different impact categories i.e. when GWP improves EP worsen as (Shaw, et al. 2011) suggests.

6.3.1. Base Scenario with Current Electricity Grid Mix in 2018

Currently in Turkey, fossil fuels make up 70% and hydropower constitutes 24% of the electricity generation. The share of wind and geothermal energy is 4% and 2%, respectively. In 2018, no nuclear power facility is installed. Since 2018 is the base scenario, trolleybus LC impacts using 2018 data are referred as “Trolleybus” in the graphs. There is no alternative scenario for diesel bus impacts; therefore it is referred as “Diesel Bus” in all the graphs.

By taking this information into consideration, LC impacts for the trolleybuses over 30 years are as follows: GWP is 2,770,491 t CO_2-eq., AP is 16,094 t SO_2-eq., EP is 11,269 t PO_4-eq. and POCP is 1,028 t C_2H_4-eq. 30 years of LC impacts for the diesel buses are GWP of 4,172,744 t CO_2-eq., AP of 5,609 t SO_2-eq., EP of 889 t PO_4-eq. and POCP of 280 t C_2H_4-eq.

If the conversion from diesel buses to trolleybuses is realized, global warming potential (GWP) will be decreased by 35%; acidification potential (AP) will be grown by 1.9, eutrophication potential (EP) and photochemical oxidants creation potential (POCP) will be 11.7 times and 2.7 times more, under the current electricity generation conditions, respectively.

6.3.2. 2023 Scenario based on Action Plan

This scenario is taken from National Action Plan 2023 for Renewable Energy in Turkey prepared by Republic of Turkey Ministry of Energy and Natural Resources. The share of energy source on the 2023 action plan is used in the calculation of weighted averages of impacts. The results for impacts of future electricity generation in 2023 show that GWP of 2,439,680 t CO_2-eq., AP of 14,319 t SO_2-eq., EP of 10,595 t PO_4-eq. and POCP of 887 t C_2H_4-eq. will be created in 30 years.

In this scenario, it can be seen that the impacts from electricity generation are lower compared to base scenario. If the electrification of current system is made, GWP will fall by 42%; AP will become 1.6 times larger, EP and POCP will be 10.9 times and 2.2 times more, under 2023 electricity generation conditions, respectively.

6.3.3. 2030 Scenario based on Author's Assumptions

I assume that, in 2030, Turkey will focus more on renewables by using its great potential for them and will decrease fossil fuel usage; with 50% share of fossil fuels and 30% share of hydropower. Remaining 15% and 5% of electricity generation will be based on wind and geothermal energy.
By taking potential 2030 grid mix into consideration, GWP will be 1,869,188 t CO_2-eq., AP will be 11,804 t SO_2-eq., EP will be 7,254 t PO_4-eq. and POCP will be 680 t C_2H_4-eq. in 30 years.

In 2030, the impacts from electricity are lower compared to 2023 scenario. If diesel buses are replaced with trolleybuses, GWP will shrink by more than half; AP will be 1.1 times larger, EP and POCP will be 7.2 times and 1.4 times more, respectively.

6.3.4. 2050 Scenario-A

As (Atilgan ve Azapagic 2017) suggests, the Scenario-A for 2050 assumes 69% fossil fuel use, 21.5% renewables and 9% nuclear power by making a projection regarding prevailing energy trends. For the period of 30 years, the calculated impacts are directly taken from BAU-2 case suggested in the study. Future electricity generation in the scenario 2050-A would lead to GWP of 2,046,456 t CO_2-eq., AP of 2,396 t SO_2-eq., EP of 4,592 t PO_4-eq. and POCP of 349 t C_2H_4-eq..

In 2050-A, electricity generation creates more GWP compared to 2030 scenario, due to higher fossil fuel usage. However, the other effects would be substantially weakened. If the trolleybus system starts to operate instead of diesel buses, GWP will shrink by more than half; AP will be 0.6 times less, EP and POCP will be 4.2 times and 0.2 times more, respectively.

6.3.5. 2050 Scenario-B

The Scenario-B for 2050 assumes 39% fossil fuel use, 56% renewables and 5% nuclear power regarding considerable amount of investment in renewables. For the period of 30 years, the calculated impacts are directly taken from A-4 case. Future electricity generation in the scenario 2050-B would lead to GWP of 1,098,098 t CO_2-eq., AP of 1,847 t SO_2-eq., EP of 2,745 t PO_4-eq. and POCP of 299 t C_2H_4-eq..

In 2050-B, trolleybuses would create less environmental impacts in comparison with 2050-A scenario, due to greater use of renewables in the electricity production. Compared to diesel buses, GWP will be decreased by 74%; AP will be 0.7 times less, EP and POCP will be 2.1 times and 0.1 times more, respectively.

6.3.6. 2050 Scenario-C

The Scenario-C for 2050 assumes 26% fossil fuel use, 69% renewables and 5% nuclear power with massive investment in renewables and carbon reduction technologies. For the period of 30 years, the calculated impacts are directly taken from B-4 case. Future electricity generation in the scenario 2050-C would lead to GWP of 598,963 t CO_2-eq., AP of 1,797 t SO_2-eq., EP of 1,248 t PO_4-eq. and POCP of 250 t C_2H_4-eq..

In 2050-C, trolleybuses would create less environmental impacts in comparison with 2050-B scenario, thanks to higher concentration of renewables in the electricity production. Compared to diesel buses, GWP will be decreased by 86%; AP will be 0.7 times less, EP will be 0.4 times larger, POCP will be shrunk 0.1 times.

6.3.7. 2050 Scenario-D

The Scenario-D for 2050 assumes 16% fossil fuel use, 79% renewables and 5% nuclear power with larger investment in renewables than Scenario-C. For the period of 30 years, the calculated impacts are directly taken from C-4 case. Future electricity generation in the scenario 2050-D would result in GWP of 299,481 t CO_2-eq., AP of 1,747 t SO_2-eq., EP of 299 t PO_4-eq. and POCP of 250 t C_2H_4-eq..

In 2050-D, the environmental impacts of trolleybuses are at minimum level in comparison with all the other scenarios. The electricity production is sourced by greater amount of renewables. Compared to diesel buses, GWP will be decreased by 93%; AP and EP will be shrunk by 0.7 times, and POCP will be 0.1 times less.

The summary of LC impacts of energy sources in diesel bus and trolleybus scenarios for 30 years, as stated in sections of 6.3, is provided in Table 6.12 below.

Table 6.12 Summary table of life-cycle impacts of energy sources in each scenario for 30 years.

	Impact Category			
	GWP	AP	EP	POCP
Scenarios / Unit	(t CO_2-eq)	(t SO_2-eq)	(t PO_4-eq)	(t C_2H_4-eq)
DB	4,172,744	5,609	889	280
TB	2,770,491	16,094	11,269	1,028
TB 2023	2,439,680	14,319	10,595	887
TB 2030	1,869,188	11,804	7,254	680
TB 2050-A	2,046,456	2,396	4,592	349
TB 2050-B	1,098,098	1,847	2,745	299
TB 2050-C	598,963	1,797	1,248	250
TB 2050-D	299,481	1,747	299	250

DB: Diesel Bus, TB: Trolleybus

The comparison between different scenarios on the basis of impact categories are summarized and presented in Appendix Figures 1, 2, 3 and 4.

6.4. Discussion on Potential Use of Electric Buses on the BRT Line

As stated in the Section 1. and Section 5.1, besides many advantages of trolleybuses over electric buses, upsides of electric buses are worth to mention and further study on the operation of e-buses on the BRT line can be carried out by the sustainable urban transport researchers and analysts in the future. EVs provide high flexibility in terms of utilization of buses on other routes, and the elimination of de-wiring problem. Moreover, they do not require infrastructure costs as trolleybuses do. With a meticulous planning of BRT fleet operation, issue of peak electricity demand can be solved for e-buses. For now, pure electric buses are not able to operate on the BRT line due to short range of motion, insufficient time for charging to meet high demand and limited passenger capacity. Several fast charging solutions could be utilized, such as battery change on the specific stops or depots, wireless charging, or additional purchase of electric buses to keep and charge them in the bus depot. However, municipalities in Turkey usually avoids high capital costs such as cost of e-buses, their batteries, which should be replaced every few years depending on the charging cycle, and wireless charging system, hence electric bus operation becomes unviable in current circumstances on the BRT line. EVs could be chosen as a transport mode in other routes with fewer commuters.

With the help of decreasing purchase prices of batteries and EVs due to mass production, and extending range of journeys, EVs promise an environmentally-friendly future for us and next generations. The maximum permissible weight is a barrier in increasing the passenger capacity due to extra weight of batteries; a weight allowance can be given to the e-bus producers by policymakers.

7. CONCLUSION AND POLICY RECOMMENDATIONS

In this thesis, the feasibility of replacement of diesel buses with trolleybus system on BRT line is addressed. In the economic analysis, trolleybus system economically outperforms current diesel buses operating in BRT line, based on certain assumptions such as assumptions on cost items, operational plan, energy, etc. The economic advantage of trolleybus comes from less costly operation due to high energy efficiency and low energy costs despite high initial investment. Three different discount rates are applied in the life-cycle cost analysis, and the resulting better system based on the comparison of NPVs has not changed. The higher the discount rate, the sooner the PV of cash outflows of two systems converges to each other. At the same time, the higher the discount rate, the less NPV difference between those in terms of both amount of lifetime costs and the smaller the ratio of this difference to diesel bus NPV.

For the calculation of environmental impacts of trolleybus and current BRT system, two different approaches were used. First, marginal cost of trolleybus system has been investigated by comparing emissions and pollutants from electricity production, which is fully natural gas sourced, and diesel production & combustion. According to calculations, trolleybus comes with marginal savings for the reduction in each emission except for THC. Trolleybuses release less CO, CO_2, PM, NO_x; and more THC than diesel buses do. The resulting marginal savings -not costs- are due to trolleybus system's less costly operation and more environmental friendly feature. Moreover, emissions and marginal costs are re-estimated regarding electricity production in 2018 mix. Besides higher THC of electricity, the amount of PM also increases when the current mix is included in the analysis. When the electricity is fully sourced by "only natural gas", the eliminated amount of CO_2 and NO_x is lower compared to emission and pollutant levels in the dirtier fossil fuel dominated current electricity mix. In that sense, marginal savings decrease or costs increase. Hence, it can be clearly stated that without renewable-based or clean source-based electricity generation, environmental sustainability cannot be achieved.

Second, life-cycle environmental impacts were benefited and examined within various electricity generation scenarios. If trolleybuses are powered by the electricity which is produced with the current electricity grid mix, the Global Warming Potential (GWP) of vehicles considerably falls, and it can be further decreased by switching to more renewable-oriented energy generation. If a decrease in GWP or GHG is targeted, then in the application of trolleybus, GWP or GHG impact should be considered. Lastly, since the impact level of GWP is on global level, GWP-focused decision making can be used. Regarding second environmental impact analyzed in this thesis, which is Acidification Potential (AP), trolleybus has higher figures than diesel bus, if AP is calculated considering 2018 electricity production mix. In 2050 scenarios, diesel bus AP can be more than halved compared to trolleybus AP thanks to renewables-oriented electricity grid mix in 2050. Electrification of BRT line leads to less AP if concentration of renewables increases in the grid mix.

The third environmental impact, Eutrophication Potential (EP), of electricity is multiple times of diesel bus EP level except for Scenario D in 2050. The electricity source with minimum EP requires highly renewable-oriented electricity production in Turkey, which seems not realistic in the near future. If the switch from diesel buses to trolleybuses is realized within the current conditions, increase in EP is inevitable due to trade-off between GWP and EP.

When Photochemical Oxidants Creation Potential (POCP), which is the last environmental impact, is considered, diesel is better option than electricity because the POCP of electricity is much higher than that of diesel, in current electricity grid mix. Fossil fuel dominated electricity generation results in worse POCP levels of electricity than diesel. In 2050 scenarios, the level of POCP from electricity generation gets closer to POCP level of diesel, even below in Scenarios C and D.

We should always keep in mind that, those environmental impacts stand for 'Potential' impacts and their calculation is not straightforward. Underestimation or overestimation of each impact is possible in the literature. Therefore, further analysis is required with a national diesel LC impact study using same equivalent units in order to allow us to compare the impact categories.

Before the project begins, public perception must be fully understood and necessary actions should be taken regarding the survey results. Since trolleybuses might be perceived as old-fashioned and low-tech in the public eye, their marketing should be well managed for their favorable promotion. One of the biggest mistakes would be imposing this transport mode without ensuring the positive public opinion.

As a result, achieving sustainable transport is not possible without renewable oriented electricity production. There is always a trade-off between separate LC impact categories. The publicity of electrification in transport as zero-emission can be misleading due to the fact that electricity generation is not costless to environment. The life-cycle emissions should be regarded in transport analyses. To do that, national life-cycle emission inventories should be compiled along with the support of Turkish state bodies and academia since the LC impacts are location specific. The development and implementation of a mutual LC impact calculation method would be highly beneficial.

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APPENDIX

Appendix Table 1 Number of vehicles, journeys and annual distance

	Number of Vehicles	**Annual Number of Journeys**	**Annual Distance Travelled**
Bus	499	2,242,560	71,638,080
Trolleybus	421	1,736,000	55,459,520

Appendix Table 2 Main assumptions on lifetimes of the main cost items

Item	Lifetime/Years
Network	50
Substation	30
Diesel Bus	12
Trolleybus	20
Auxiliary Battery (APU)	5

Appendix Table 3 Main assumptions on investment analysis

Base Year	2018
Discount rate	9-10.5-12%
Project Reference Period	30 Years
Network residual value (50 years	40%
Road Length (km	52
Substation interval (km	2.5

Appendix Table 4 Main assumptions on drivers and working days

Number of drivers per bus	798
Number of drivers per trolleybus	674
Number of drivers per vehicle	1.6
Hourly cost of one driver (TRY	45
Working hours per driver/day	8
Working days equivalent	320

Appendix Table 5 The current fleet of BRT system in Istanbul

Model Year	Brand	Emission Feature	Number of Buses	Passenger Capacity	Weight (kg)	Max Permissible Weight (kg)
2007	MERCEDES CAPACITY	EURO IV	50	193	18548	32000
2008	MERCEDES CAPACİTY	EURO V	100	193	18548	32000
2009	MERCEDES CAPACİTY	EURO V	99	193	18548	32000
2008	APTS PHİLEAS	EURO V	15	200	22640	36700
2009	APTS PHİLEAS	EURO V	34	200	22640	36700
2012	MERCEDES CONECTO G	EURO V	169	148	16868	29000
2015	MERCEDES CONECTO G	EURO V	126	148	16568	29000

Appendix Table 6 Life-cycle costs of diesel buses and bi-articulated trolleybuses and assumptions behind the calculations

	COST ITEM	Unit	Number of Units	Unit Cost (€)	Total Cost for Full Distance (€)	Number of Units	Unit Cost (€)	Total Cost for Full Distance (€)
	1. Capital Costs		**Trolleybus (24 m)**			**Diesel Bus (18 m)**		
	1.1 Network costs							
a	Overhead contact lines system	per km of road length	52	744,794	38,729,282	-	-	-
b	Electric power substations	per km of road length	52	134,477	6,992,787	-	-	-
c	Overall construction	per km of road length	52	879,271	45,722,070	-	-	-
	1.2. Vehicles							
d	Purchasing cost of vehicle	number of vehicles	421	775,827	387,137,659	499	258,609	129,045,886
	2. Operating Costs							
e	2.1. Yearly network maintenance	per km of road length	52	25,861	1,344,767	-	-	-
f	2.2. APU Replacement Cost	number of vehicles	421	76,151	37,999,256	-	-	-
g	2.3. Fuel Cost	per km driven	55,459,520	0.164	9,077,028	71,638,080	0.503	36,014,937
h	2.4. Cost of drivers	hourly	1,724,416	8.815	15,201,300	2,043,904	8.815	18,017,693

All the prices are in 2018 Euros

a. Inflated from 2014 price of 720,000 EUR using 0.85% compound annual growth rate
b. Inflated from 2014 price of 130,000 EUR using 0.85% compound annual growth rate
c. Inflated from 2014 price of 850,000 EUR using 0.85% compound annual growth rate
d. For Trolleybus, inflated from 2014 price of 750,000 EUR using 0.85% compound annual growth rate
For Diesel bus, inflated from 2014 price of 250,000 EUR using 0.85% compound annual growth rate
e. Inflated from 2014 price of 25,000 EUR using 0.85% compound annual growth rate
f. Inflated from 2011 price of 80,000 USD using 1.63% compound annual growth rate. Only needed 5 years after the first purchase and replacement of trolleybuses (No additional APU cost for years between 1-5 and 21-25)
g. For Trolleybus, 2018 electricity price of 0.055 EUR/kWh converted from 0.27 TRY/kWh using average EUR/TRY rate of 4.949 for the first half of 2018: The cost per km 0.164 EUR with the energy need of 3 kWh/km.
For Diesel bus, 2018 diesel price of 1.055 USD/liter converted from 5.09 TRY/liter using average USD/TRY rate of 4.822 for the year 2018: The cost per km 0.503 EUR with the energy need of 0.561 L/km.
h. Inflated from 2017 hourly cost of one driver, which is 45 TRY, using 11.15% compound annual growth rate for Turkey and using 5.6729 EUR/TRY rate.

Appendix Table 7 Unit emission and pollutant data used in marginal cost calculations

	CO	THC	NO_x	PM	CO_2
Diesel Bus (g/km)*	3.904	0.014	6.852	0.056	1095.64
Trolleybus (g/kWh)[a]	0.270	0.02**	0.41	0.003***	364
Trolleybus (g/kWh)[b]	0.241	0.055**	0.602	0.238	468.566

* the data for fuel consumption of 0.525 lt/km, adapted to 0.561 lt/km

** only CH4 (methane)

*** only PM2.5

[a] When powered by electricity from only natural gas

[b] When powered by electricity from 2018 grid mix

Appendix Table 8 Turkish electricity grid mix with different scenarios

Electricity Source	2018	2023	2030	2050-A	2050-B	2050-C	2050-D
Coal	19%	13%	10.0%				
Lignite	15%	15%	10.0%	69.50%	39.00%	26.00%	16.00%
Natural Gas	36%	36%	30.0%				
Large reservoir hydropower	10%	10%	12.00%				
Small reservoir hydropower	4%	3%	6.00%				
Run-of-river hydropower	10%	9%	12.00%	21.50%	56.00%	69.00%	79.00%
Onshore wind	4%	12%	15.00%				
Geothermal	2%	2%	5.00%				
Nuclear	0	0	0	9%	5%	5%	5%

Appendix Table 9 Non-discounted cash outflows and discounted cash outflows at 9% rate over 30 years from the "municipality" perspective

	Non-Discounted Cash Outflows		Discounted Cash Outflows @9%	
Year	Bus	Trolleybus	Bus	Trolleybus
2021	-	-45,722,070	-	-45,722,070
2022	-64,786,454	-44,979,978	-59,437,114	-41,266,035
2023	-64,786,454	-44,979,978	-54,529,463	-37,858,748
2024	-64,786,454	-44,979,978	-50,027,030	-34,732,796
2025	-64,786,454	-44,979,978	-45,896,358	-31,864,950
2026	-64,786,454	-44,979,978	-42,106,750	-29,233,900
2027	-64,786,454	-52,579,829	-38,630,046	-31,351,634
2028	-64,786,454	-52,579,829	-35,440,409	-28,762,967
2029	-64,786,454	-52,579,829	-32,514,137	-26,388,043
2030	-64,786,454	-52,579,829	-29,829,483	-24,209,214
2031	-64,786,454	-52,579,829	-27,366,499	-22,210,288

2032	-64,786,454	-52,579,829	-25,106,879	-20,376,411
2033	-64,786,454	-52,579,829	-23,033,834	-18,693,955
2034	-64,786,454	-52,579,829	-21,131,958	-17,150,418
2035	-64,786,454	-52,579,829	-19,387,117	-15,734,328
2036	-64,786,454	-52,579,829	-17,786,346	-14,435,163
2037	-64,786,454	-52,579,829	-16,317,749	-13,243,269
2038	-64,786,454	-52,579,829	-14,970,412	-12,149,788
2039	-64,786,454	-52,579,829	-13,734,323	-11,146,595
2040	-64,786,454	-52,579,829	-12,600,296	-10,226,234
2041	-64,786,454	-52,579,829	-11,559,905	-9,381,866
2042	-64,786,454	-44,979,978	-10,605,417	-7,363,135
2043	-64,786,454	-44,979,978	-9,729,741	-6,755,170
2044	-64,786,454	-44,979,978	-8,926,367	-6,197,404
2045	-64,786,454	-44,979,978	-8,189,328	-5,685,691
2046	-64,786,454	-44,979,978	-7,513,145	-5,216,231
2047	-64,786,454	-52,579,829	-6,892,793	-5,594,100
2048	-64,786,454	-52,579,829	-6,323,664	-5,132,202
2049	-64,786,454	-52,579,829	-5,801,526	-4,708,442
2050	-64,786,454	-52,579,829	-5,322,501	-4,319,672
2051	-64,786,454	-37,088,116	-4,883,029	-2,795,373

Appendix Table 10 Non-discounted cash outflows and discounted cash outflows at 9% rate over 30 years from the “state” perspective

	Non-Discounted Cash Outflows		Discounted Cash Outflows @9%	
Year	Bus	Trolleybus	Bus	Trolleybus
2021	-	-45,722,070	-	-45,722,070
2022	-46,346,807	-43,299,047	-42,520,006	-39,723,896
2023	-46,346,807	-43,299,047	-39,009,180	-36,443,942
2024	-46,346,807	-43,299,047	-35,788,238	-33,434,809
2025	-46,346,807	-43,299,047	-32,833,246	-30,674,137
2026	-46,346,807	-43,299,047	-30,122,244	-28,141,410
2027	-46,346,807	-50,898,898	-27,635,087	-30,349,350
2028	-46,346,807	-50,898,898	-25,353,290	-27,843,440
2029	-46,346,807	-50,898,898	-23,259,899	-25,544,441
2030	-46,346,807	-50,898,898	-21,339,357	-23,435,267
2031	-46,346,807	-50,898,898	-19,577,392	-21,500,245
2032	-46,346,807	-50,898,898	-17,960,910	-19,724,995
2033	-46,346,807	-50,898,898	-16,477,899	-18,096,326
2034	-46,346,807	-50,898,898	-15,117,339	-16,602,134
2035	-46,346,807	-50,898,898	-13,869,118	-15,231,315
2036	-46,346,807	-50,898,898	-12,723,962	-13,973,684
2037	-46,346,807	-50,898,898	-11,673,359	-12,819,893

2038	-46,346,807	-50,898,898	-10,709,504	-11,761,370
2039	-46,346,807	-50,898,898	-9,825,233	-10,790,248
2040	-46,346,807	-50,898,898	-9,013,975	-9,899,310
2041	-46,346,807	-50,898,898	-8,269,702	-9,081,936
2042	-46,346,807	-43,299,047	-7,586,883	-7,087,970
2043	-46,346,807	-43,299,047	-6,960,443	-6,502,725
2044	-46,346,807	-43,299,047	-6,385,727	-5,965,803
2045	-46,346,807	-43,299,047	-5,858,465	-5,473,213
2046	-46,346,807	-43,299,047	-5,374,739	-5,021,297
2047	-46,346,807	-50,898,898	-4,930,953	-5,415,262
2048	-46,346,807	-50,898,898	-4,523,810	-4,968,130
2049	-46,346,807	-50,898,898	-4,150,285	-4,557,917
2050	-46,346,807	-50,898,898	-3,807,601	-4,181,575
2051	-46,346,807	-35,407,185	-3,493,211	-2,668,680

Appendix Table 11 Non-discounted cash outflows and discounted cash outflows at 10.5% rate over 30 years from the “municipality” perspective

	Non-Discounted Cash Outflows		Discounted Cash Outflows @10.5%	
Year	Bus	Trolleybus	Bus	Trolleybus
2021	-	-45,722,070	-	-45,722,070
2022	-64,786,454	-44,979,978	-58,630,276	-40,705,863
2023	-64,786,454	-44,979,978	-53,059,073	-36,837,885
2024	-64,786,454	-44,979,978	-48,017,261	-33,337,452
2025	-64,786,454	-44,979,978	-43,454,534	-30,169,640
2026	-64,786,454	-44,979,978	-39,325,371	-27,302,842
2027	-64,786,454	-52,579,829	-35,588,571	-28,883,213
2028	-64,786,454	-52,579,829	-32,206,851	-26,138,654
2029	-64,786,454	-52,579,829	-29,146,472	-23,654,891
2030	-64,786,454	-52,579,829	-26,376,897	-21,407,141
2031	-64,786,454	-52,579,829	-23,870,495	-19,372,978
2032	-64,786,454	-52,579,829	-21,602,258	-17,532,107
2033	-64,786,454	-52,579,829	-19,549,555	-15,866,160
2034	-64,786,454	-52,579,829	-17,691,905	-14,358,516
2035	-64,786,454	-52,579,829	-16,010,774	-12,994,132
2036	-64,786,454	-52,579,829	-14,489,388	-11,759,396
2037	-64,786,454	-52,579,829	-13,112,568	-10,641,987
2038	-64,786,454	-52,579,829	-11,866,578	-9,630,757
2039	-64,786,454	-52,579,829	-10,738,984	-8,715,618
2040	-64,786,454	-52,579,829	-9,718,538	-7,887,437
2041	-64,786,454	-52,579,829	-8,795,057	-7,137,952
2042	-64,786,454	-44,979,978	-7,959,328	-5,526,007

2043	-64,786,454	-44,979,978	-7,203,011	-5,000,911
2044	-64,786,454	-44,979,978	-6,518,562	-4,525,711
2045	-64,786,454	-44,979,978	-5,899,151	-4,095,666
2046	-64,786,454	-44,979,978	-5,338,599	-3,706,485
2047	-64,786,454	-52,579,829	-4,831,311	-3,921,028
2048	-64,786,454	-52,579,829	-4,372,227	-3,548,442
2049	-64,786,454	-52,579,829	-3,956,767	-3,211,259
2050	-64,786,454	-52,579,829	-3,580,784	-2,906,117
2051	-64,786,454	-37,088,116	-3,240,529	-1,855,096

Appendix Table 12 Non-discounted cash outflows and discounted cash outflows at 10.5% rate over 30 years from the "state" perspective

	Non-Discounted Cash Outflows		Discounted Cash Outflows @10.5%	
Year	Bus	Trolleybus	Bus	Trolleybus
2021	-	-45,722,070	-	-45,722,070
2022	-46,346,807	-43,299,047	-41,942,811	-39,184,658
2023	-46,346,807	-43,299,047	-37,957,295	-35,461,229
2024	-46,346,807	-43,299,047	-34,350,494	-32,091,610
2025	-46,346,807	-43,299,047	-31,086,420	-29,042,181
2026	-46,346,807	-43,299,047	-28,132,506	-26,282,517
2027	-46,346,807	-50,898,898	-25,459,282	-27,959,842
2028	-46,346,807	-50,898,898	-23,040,074	-25,303,024
2029	-46,346,807	-50,898,898	-20,850,746	-22,898,665
2030	-46,346,807	-50,898,898	-18,869,453	-20,722,773
2031	-46,346,807	-50,898,898	-17,076,428	-18,753,641
2032	-46,346,807	-50,898,898	-15,453,781	-16,971,621
2033	-46,346,807	-50,898,898	-13,985,322	-15,358,933
2034	-46,346,807	-50,898,898	-12,656,400	-13,899,487
2035	-46,346,807	-50,898,898	-11,453,756	-12,578,721
2036	-46,346,807	-50,898,898	-10,365,390	-11,383,458
2037	-46,346,807	-50,898,898	-9,380,443	-10,301,772
2038	-46,346,807	-50,898,898	-8,489,089	-9,322,871
2039	-46,346,807	-50,898,898	-7,682,434	-8,436,987
2040	-46,346,807	-50,898,898	-6,952,429	-7,635,282
2041	-46,346,807	-50,898,898	-6,291,791	-6,909,758
2042	-46,346,807	-43,299,047	-5,693,928	-5,319,496
2043	-46,346,807	-43,299,047	-5,152,876	-4,814,024
2044	-46,346,807	-43,299,047	-4,663,236	-4,356,583
2045	-46,346,807	-43,299,047	-4,220,123	-3,942,609
2046	-46,346,807	-43,299,047	-3,819,116	-3,567,972
2047	-46,346,807	-50,898,898	-3,456,214	-3,795,676

2048	-46,346,807	-50,898,898	-3,127,795	-3,435,001
2049	-46,346,807	-50,898,898	-2,830,584	-3,108,598
2050	-46,346,807	-50,898,898	-2,561,614	-2,813,211
2051	-46,346,807	-35,407,185	-2,318,203	-1,771,018

Appendix Table 13 Non-discounted cash outflows and discounted cash outflows at 12% rate over 30 years from the "municipality" perspective

	Non-Discounted Cash Outflows		**Discounted Cash Outflows @12%**	
Year	**Bus**	**Trolleybus**	**Bus**	**Trolleybus**
2021	-	-45,722,070	-	-45,722,070
2022	-64,786,454	-44,979,978	-57,845,049	-40,160,695
2023	-64,786,454	-44,979,978	-51,647,365	-35,857,763
2024	-64,786,454	-44,979,978	-46,113,719	-32,015,860
2025	-64,786,454	-44,979,978	-41,172,963	-28,585,589
2026	-64,786,454	-44,979,978	-36,761,574	-25,522,848
2027	-64,786,454	-52,579,829	-32,822,834	-26,638,578
2028	-64,786,454	-52,579,829	-29,306,102	-23,784,445
2029	-64,786,454	-52,579,829	-26,166,162	-21,236,111
2030	-64,786,454	-52,579,829	-23,362,645	-18,960,814
2031	-64,786,454	-52,579,829	-20,859,504	-16,929,298
2032	-64,786,454	-52,579,829	-18,624,558	-15,115,444
2033	-64,786,454	-52,579,829	-16,629,069	-13,495,933
2034	-64,786,454	-52,579,829	-14,847,383	-12,049,940
2035	-64,786,454	-52,579,829	-13,256,592	-10,758,875
2036	-64,786,454	-52,579,829	-11,836,243	-9,606,138
2037	-64,786,454	-52,579,829	-10,568,074	-8,576,909
2038	-64,786,454	-52,579,829	-9,435,780	-7,657,955
2039	-64,786,454	-52,579,829	-8,424,804	-6,837,459
2040	-64,786,454	-52,579,829	-7,522,146	-6,104,875
2041	-64,786,454	-52,579,829	-6,716,202	-5,450,781
2042	-64,786,454	-44,979,978	-5,996,609	-4,163,329
2043	-64,786,454	-44,979,978	-5,354,115	-3,717,258
2044	-64,786,454	-44,979,978	-4,780,460	-3,318,981
2045	-64,786,454	-44,979,978	-4,268,268	-2,963,376
2046	-64,786,454	-44,979,978	-3,810,953	-2,645,871
2047	-64,786,454	-52,579,829	-3,402,637	-2,761,535
2048	-64,786,454	-52,579,829	-3,038,069	-2,465,656
2049	-64,786,454	-52,579,829	-2,712,561	-2,201,479
2050	-64,786,454	-52,579,829	-2,421,930	-1,965,606
2051	-64,786,454	-37,088,116	-2,162,437	-1,237,924

Appendix Table 14 Non-discounted cash outflows and discounted cash outflows at 12% rate over 30 years from the "state" perspective

	Non-Discounted Cash Outflows		Discounted Cash Outflows @12%	
Year	Bus	Trolleybus	Bus	Trolleybus
2021	-	-45,722,070	-	-45,722,070
2022	-64,786,454	-44,979,978	-57,845,049	-40,160,695
2023	-64,786,454	-44,979,978	-51,647,365	-35,857,763
2024	-64,786,454	-44,979,978	-46,113,719	-32,015,860
2025	-64,786,454	-44,979,978	-41,172,963	-28,585,589
2026	-64,786,454	-44,979,978	-36,761,574	-25,522,848
2027	-64,786,454	-52,579,829	-32,822,834	-26,638,578
2028	-64,786,454	-52,579,829	-29,306,102	-23,784,445
2029	-64,786,454	-52,579,829	-26,166,162	-21,236,111
2030	-64,786,454	-52,579,829	-23,362,645	-18,960,814
2031	-64,786,454	-52,579,829	-20,859,504	-16,929,298
2032	-64,786,454	-52,579,829	-18,624,558	-15,115,444
2033	-64,786,454	-52,579,829	-16,629,069	-13,495,933
2034	-64,786,454	-52,579,829	-14,847,383	-12,049,940
2035	-64,786,454	-52,579,829	-13,256,592	-10,758,875
2036	-64,786,454	-52,579,829	-11,836,243	-9,606,138
2037	-64,786,454	-52,579,829	-10,568,074	-8,576,909
2038	-64,786,454	-52,579,829	-9,435,780	-7,657,955
2039	-64,786,454	-52,579,829	-8,424,804	-6,837,459
2040	-64,786,454	-52,579,829	-7,522,146	-6,104,875
2041	-64,786,454	-52,579,829	-6,716,202	-5,450,781
2042	-64,786,454	-44,979,978	-5,996,609	-4,163,329
2043	-64,786,454	-44,979,978	-5,354,115	-3,717,258
2044	-64,786,454	-44,979,978	-4,780,460	-3,318,981
2045	-64,786,454	-44,979,978	-4,268,268	-2,963,376
2046	-64,786,454	-44,979,978	-3,810,953	-2,645,871
2047	-64,786,454	-52,579,829	-3,402,637	-2,761,535
2048	-64,786,454	-52,579,829	-3,038,069	-2,465,656
2049	-64,786,454	-52,579,829	-2,712,561	-2,201,479
2050	-64,786,454	-52,579,829	-2,421,930	-1,965,606
2051	-64,786,454	-37,088,116	-2,162,437	-1,237,924

Appendix Table 15 Marginal differential cost of trolleybus system per kg emission reduction in USD

Discount Rate / USD	CO	THC	NO_x	PM	CO_2
9%	-17.87 **(-17.53)**	2,011.04 **(561.53)**	-9.94 **(-10.69)**	-1,197.73 **(128.48)**	-0.19 **(0.77)**
10.50%	-15.10 **(-14.82)**	1,700.07 **(474.70)**	-8.40 **(-9.04)**	-1,012.52 **(108.61)**	-0.16 **(0.65)**
12%	-12.87 **(-12.63)**	1,449.03 **(404.60)**	-7.16 **(-7.70)**	-863.01 **(92.57)**	-0.14 **(0.55)**

Appendix Table 16 Marginal differential cost of trolleybus system per kg emission reduction in TRY

Discount Rate / TRY	CO	THC	NO_x	PM	CO_2
9%	-86.15 **(-84.54)**	9,697.44 **(2,707.74)**	-47.94 **(51.55)**	-5,775.59 **(619.52)**	-0.94 **(3.70)**
10.50%	-72.83 **(-71.47)**	8,197.88 **(2,289.03)**	-40.53 **(43.58)**	-4,882.49 **(523.72)**	-0.79 **(3.13)**
12%	-62.07 **(-60.92)**	6,987.39 **(1,951.03)**	-34.54 **(37.14)**	-4,161.54 **(446.39)**	-0.68 **(2.67)**

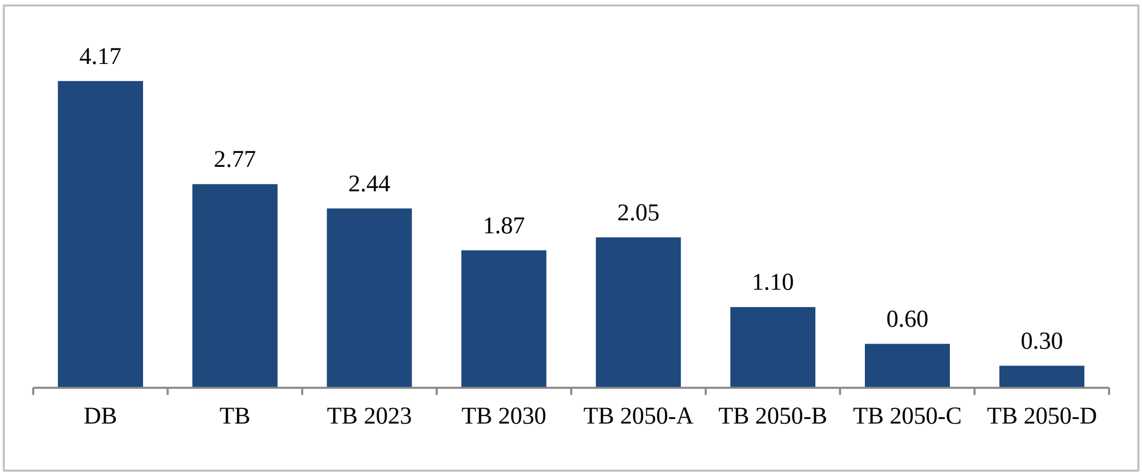
Appendix Table 17 Life-cycle impacts of energy sources of diesel buses and trolleybuses per km

Impact Category	Unit (per km)	Diesel Bus	Trolleybus	Trolleybus 2023	Trolleybus 2030	Trolleybus 2050-A	Trolleybus 2050-B	Trolleybus 2050-C	Trolleybus 2050-D
Global warming potential (GWP)	(kg CO_2-eq)	1.94E+00	1.67E+00	1.47E+00	1.12E+00	1.23E+00	6.60E-01	3.60E-01	1.80E-01
Acidification potential (AP)	(kg SO_2-eq)	2.61E-03	9.67E-03	8.61E-03	7.09E-03	1.44E-03	1.11E-03	1.08E-03	1.05E-03
Eutrophication potential (EP)	(kg PO_4-eq)	4.14E-04	6.77E-03	6.37E-03	4.36E-03	2.76E-03	1.65E-03	7.50E-04	1.80E-04
Photochemical oxidants creation potential (POCP)	(kg C_2H_4-eq)	1.30E-04	6.18E-04	5.33E-04	4.09E-04	2.10E-04	1.80E-04	1.50E-04	1.50E-04

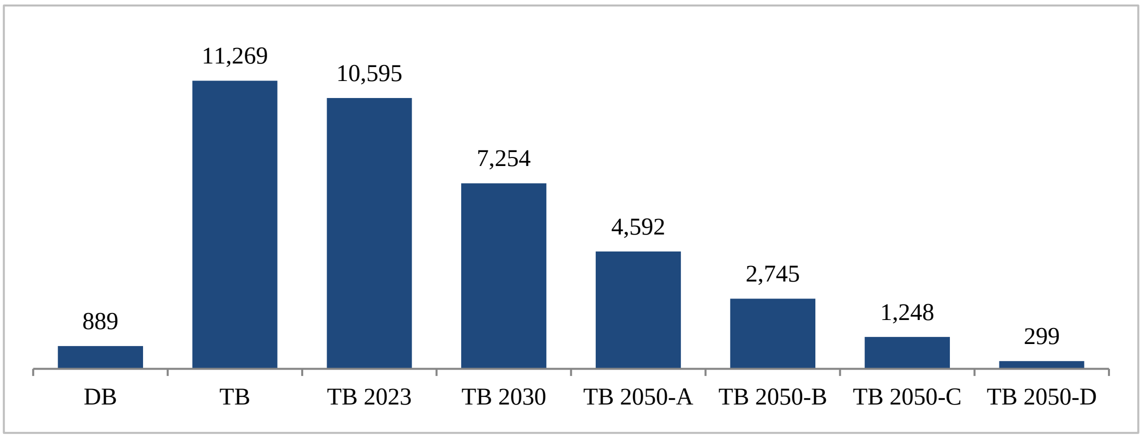
Appendix Table 18 Life-cycle impacts of energy sources of diesel buses and trolleybuses over the project reference period of 30 years

Impact Category	Unit (30 Years)	Diesel Bus	Trolleybus	Trolleybus 2023	Trolleybus 2030	Trolleybus 2050-A	Trolleybus 2050-B	Trolleybus 2050-C	Trolleybus 2050-D
Global warming potential (GWP)	(t CO_2-eq)	4,172,744	2,770,491	2,439,680	1,869,188	2,046,456	1,098,098	598,963	299,481
Acidification potential (AP)	(t SO_2-eq)	5,609	16,094	14,319	11,804	2,396	1,847	1,797	1,747
Eutrophication potential (EP)	(t PO_4-eq)	889	11,269	10,595	7,254	4,592	2,745	1,248	299
Photochemical oxidants creation potential (POCP)	(t C_2H_4-eq)	280	1,028	887	680	349	299	250	250

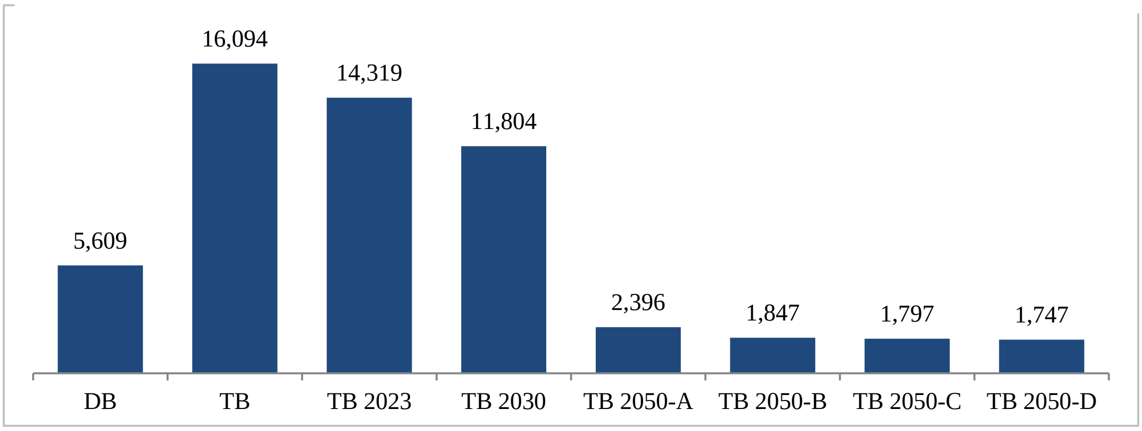
Appendix Figure 1 Comparison of GWP caused by diesel bus and different trolleybus scenarios in million tonnes CO_2-eq over 30 years



Appendix Figure 2 Comparison of EP caused by diesel bus and different trolleybus scenarios in tonnes PO_4-eq over 30 years



Appendix Figure 3 Comparison of AP caused by diesel bus and different trolleybus scenarios in tonnes SO_2-eq over 30 years



Appendix Figure 4 Comparison of POCP caused by diesel bus and different trolleybus scenarios in tonnes C_2H_4-eq over 30 years