

A Comparative Analysis of Waste to Energy Scenarios to Achieve Sustainable Smart Mobility in the Durban Aerotropolis

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Declaration

As the candidate's supervisor I agree to the submission of this dissertation

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I declare that

the work presented in this thesis is a product of my individual effort and that any data or information which has been obtained from external sources has been acknowledged. Literature used for research purposes has been referenced in text and included on the reference list.

..... 12 April 2021
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Prian Reddy Date

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Abstract

The aim of this dissertation was to develop a multi-criteria decision making tool which could assist Transport Engineers at the eThekweni Municipality to decide which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit system, by taking into consideration Operational, Environmental, Social, Financial and Technical Sustainability indicators.

The Transport, Reduction, Optimisation, Implementation, Scenario (T.R.O.I.S) model has been successfully developed using a Smart Fuel Scenario Assessment Matrix, Comparative Rank Analysis Scoring and Weighting factors to calculate an Average Weighted Score for each of the nine bus propulsion technologies which were identified during the Literature Review process in Chapter 2 of this dissertation. The Smart Fuel Scenario Assessment Matrix was developed by first identifying the CIVITAS Alternative Bus Fuel Framework (2016) as the most suitable inventory of Sustainability Indicators and Smart Fuel Scenarios, which was discovered during the Literature Review. This Framework of Sustainability Indicators and Smart Fuel Scenarios was modified and integrated into a Scenario Assessment Matrix, which enabled comparative analysis.

A Microsoft Excel Interface has been developed to provide a pleasant user interface to be used by Transport Engineers at the eThekweni Transport Authority to decide as to which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System which passes through Dube Tradeport and the King Shaka International Airport.

The recommendation of this dissertation was for the eThekweni Transport Authority to select an Electric Trolley Bus system for Line C8 of the Go! Durban Bus Rapid Transit System. This recommendation outcome was obtained by using the weighting factors developed from the SMART Sustainability Indicator Assessment Matrix to produce an example of what an output of the T.R.O.I.S model would look like. The tool has been designed to be flexible, in that the user can adjust the weighting factor for each of the eleven Sustainability Indicators in the matrix based on the needs and resources available at the eThekweni Transport Authority. The T.R.O.I.S model can be continuously updated using the latest data for the various Sustainability Indicators as well as the addition of new indicators in future iterations of the model.

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List of Abbreviations

BEV – Battery Electric Vehicle
BRT – Bus Rapid Transit
CNG – Compressed Natural Gas
FCEV – Fuel Cell Electric Vehicle
GHG – Greenhouse Gas
ICE – Internal Combustion Engine
NO _x – Nitrogen Oxides
PM ₁₀ – Particulate Matter 10 Microns or Less
SMART – Specific Measurable Achievable Relevant Time-bound
SWOT – Strengths Weaknesses Opportunities Threats
T.R.O.I.S – Transport Reduction Optimisation Implementation Scenario
TTW – Tank to Wheels
WTW – Well to Wheels
SUM – Sustainable Urban Mobility
SI – Sustainability Indicator
WWTW – Waste Water Treatment Works

Chapter 1: Research Overview

This section will attempt to introduce the dissertation by means of motivation, aims and objectives, as well as the structure of the research undertaken.

1.1. Introduction

The city of Durban aspires to become a Smart Aerotropolis, centred around the King Shaka International Airport and Dube Tradeport (Dube Tradeport, 2020). In order to achieve this, the eThekweni Municipality needs to adopt Smart City planning principles in combination with its Aerotropolis aspirations.

An Aerotropolis can be described as a city which depends on an international airport and a supporting integrated rapid transport network to provide high speed connectivity between suppliers, consumers and industry stakeholders. A multimodal, airport based, commercial core (i.e. Dube Tradeport) should be linked via integrated rapid transportation corridors to clusters of aviation-linked businesses and mixed-use commercial and residential developments. These components would then work in a symbiotic relationship based on their proximity and accessibility to the King Shaka International Airport (Kasarda, 2017).

The Go! Durban Bus Rapid Transit (BRT) System is currently being developed in the eThekweni Municipality to provide integrated rapid transportation corridors to improve mobility in the City of Durban. Line C8 of the Go! Durban BRT system is planned to link the Durban Central Business District (CBD), Umhlanga, the King Shaka International Airport (Dube Tradeport) and Tongaat in the north of the city. This integrated rapid transport corridor will pass through the Durban Aerotropolis which is being developed around the King Shaka International Airport and Dube Tradeport which consists of aviation-linked businesses and mixed use commercial and residential developments.

South Africa is a signatory to the Paris Climate Change Agreement which binds us to reduce our Greenhouse Gas (GHG) emissions to prevent the further warming of the global climate. Climate Change can pose a threat to human civilisation due to severe weather conditions such as drought, wildfires and coastal flooding due to rising sea levels. The South African Green Transport Strategy (2018 to 2050) and the eThekweni Climate Action Plan (CAP, 2018) both seek to reduce the amount of GHG emissions which are released by the transport industry in South Africa and eThekweni respectively.

Therefore, a sustainable solution is required to ensure the continued expansion of the Go! Durban Bus Rapid Transit System, whilst reducing the Greenhouse Gas Emissions released by the BRT system through the use of low emission propulsion technologies.

1.2. Motivation

The motivation of this research is to assist the eThekweni Municipality in deciding, which is the best low emission propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit system. This requires the development of a multi-criteria decision making tool, which can inform Transport Engineers in the eThekweni Transport Authority of the best bus propulsion technology with regards to the Operational, Environmental, Social, Financial and Technical Sustainability of the Go! Durban Bus Rapid Transit system.

The motivation of this research with regards to reducing the operational GHG emissions of the Go! Durban Bus Rapid Transit system is mandated by South Africa's commitment to the Paris Climate Change Agreement, the South African Green Transport Strategy (2018 to 2050) and the eThekweni Climate Action Plan (CAP) (2018). There is a lack of information regarding the different types of bus propulsion technologies which can be employed for Line C8 of the Go! Durban Bus Rapid Transit system. In addition, the Operational, Environmental, Social, Financial and Technical Sustainability of each option is not well understood. This means that Transport Engineers are not able to make an informed decision regarding the choice of bus propulsion technology.

This research aims to further reduce the Well to Wheels (WTW) Greenhouse Gas (GHG) emissions of the Go! Durban Bus Rapid Transit Fleet on Line C8 by proposing that green energy sources be used to power the various bus propulsion technologies which will be investigated by literature review. It is hypothesised that the proposed new wastewater treatment works that is planned for Dube Tradeport, can produce sufficient surplus biogas and therefore energy to power a portion of the Go! Durban BRT buses which will operate on Line C8 which runs through Dube Tradeport and the Durban Aerotropolis.

Wastewater demand modelling according to the 2050 masterplan of the Dube Tradeport, was conducted by the author in 2017 (Reddy, 2017) and has been explored in the case study in Chapter 4 of this thesis using data from the existing Sequencing Batch reactor Wastewater Treatment Plant provided by Veolia Water in 2017. This case study discusses the wastewater quantity and quality which can be expected over the medium

to long term at Dube Tradeport which will be used as input criteria for the Biogas modelling that was conducted using the BioWATT Assessment Tool (BioWATT, 2016).

1.3. Research Question, Aims and Objectives

1.3.1 Research Question

How can Operational, Environmental, Social, Financial and Technical Sustainability Indicators be used to develop a multi-criteria decision making tool to assist Transport Engineers at the eThekweni Municipality, to decide which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System?

1.3.2 Research Aim

The aim of this research is to develop a multi-criteria decision making tool which can assist Transport Engineers at the eThekweni Municipality to decide which bus propulsion technology to select for Line C8 of the Go! Durban BRT system, by taking into consideration Operational, Environmental, Social, Financial and Technical Sustainability Indicators.

1.3.3 Research Objectives

The objectives of this dissertation consists of the following:

- Biogas modelling for a proposed new wastewater treatment works at Dube Tradeport to determine how many BRT buses could be fuelled per day.
- Development of a Smart Fuel Scenario Assessment Matrix to determine a comparative scenario Rank Analysis Score.
- Development of a SMART Sustainability Indicator Assessment Matrix and to determine a weighting factor for each Sustainability Indicator in the Matrix.
- Development of a Multi-criteria decision making tool to enable Transport Engineers at the eThekweni Municipality to decide as to which bus propulsion technology to select for the Line C8 of the Go! Durban BRT system.

1.4. Methodological approach

The figure below explains the methodological approach which was taken during the development of this dissertation. A critical analysis of Smart Fuel alternatives for the Go! Durban BRT system and wastewater management strategies for Dube Tradeport was conducted by literature review. Secondly, Smart Fuel scenarios and sustainability indicators were identified and collated by literature review.

This data was then analysed using a Smart Fuel Scenario and Sustainability Indicator assessment matrix respectively. This was then followed by the development of a Smart Fuel Scenario, Comparative Rank Analysis Scoring which when used in conjunction with a SMART indicator weighting factor, led to the development of the T.R.O.I.S decision making tool.

The Smart Fuel Scenario Assessment Matrix was developed by first identifying the CIVITAS Alternative Bus Fuel Framework (2016) as the most suitable inventory of Sustainability Indicators and Smart Fuel Scenarios, which was discovered during the Literature Review. This Framework of Sustainability Indicators and Smart Fuel Scenarios was modified and integrated into a Scenario Assessment Matrix, which enabled comparative analysis.

The T.R.O.I.S Multi-Criteria Decision Making Tool can be calibrated based on the objectives of the eThekweni Municipality or other local authorities to develop a weighted average Sustainability Indicator Score per Smart Fuel Scenario. This model output can then be used by Transport Engineers at the eThekweni Municipality, to determine which bus propulsion technology to select for Line C8 of the Go! Durban BRT system. Figure 1 below shows a graphical representation of the methodology:

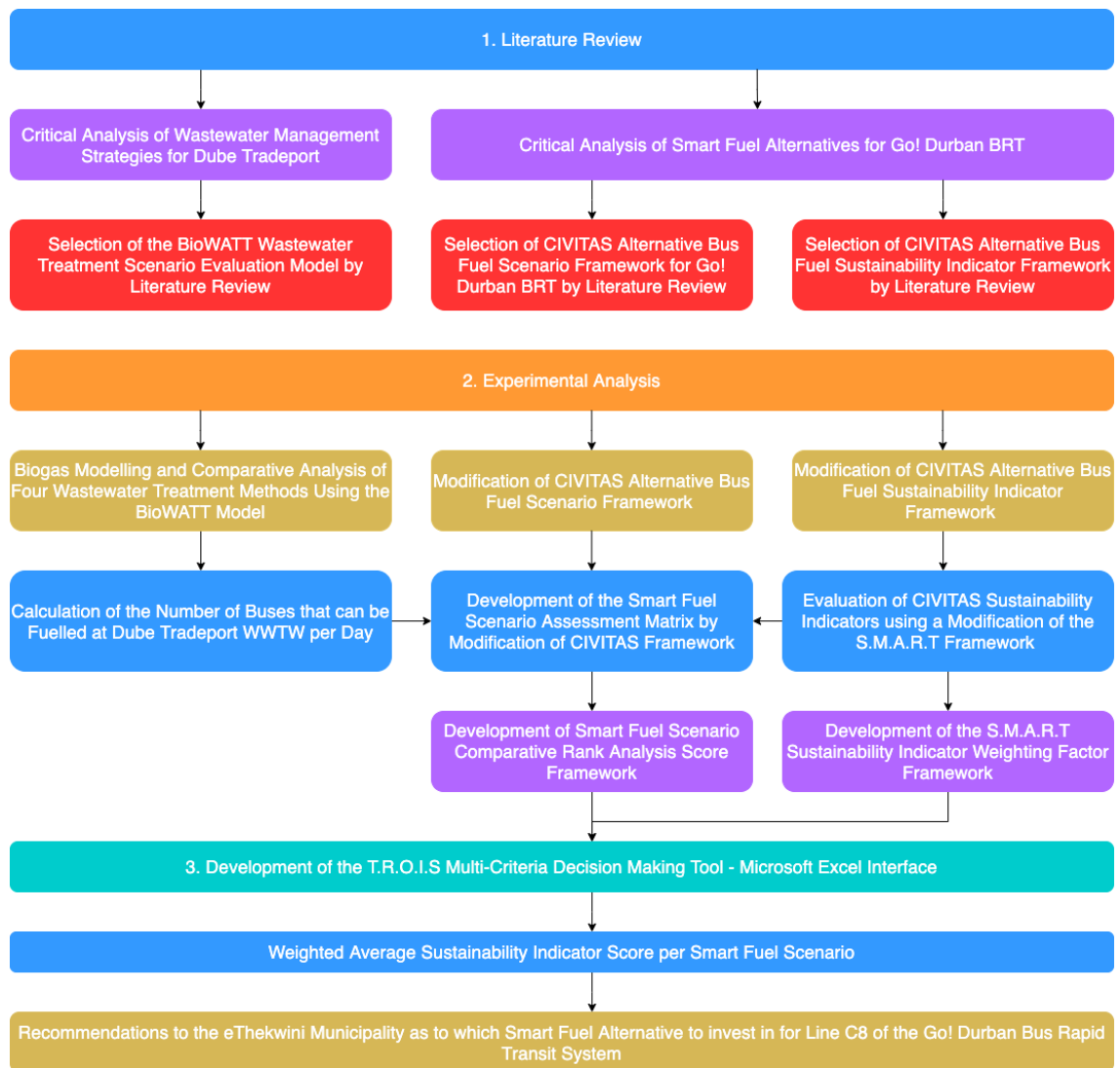


Figure 1: Showing Methodological Approach of this dissertation

1.5. Research Framework

Figure 2 below shows the Research Framework which was used to develop this dissertation: The Research Framework consists of an Introductory Chapter, Literature Review, Methodology, Case study, Results and Discussion and lastly a Chapter on Recommendations and Conclusions to the eThekweni Municipality regarding which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System, which passes through King Shaka International Airport and the Dube Tradeport precinct. A more detailed breakdown of each Chapter is presented in the flow chart in Figure 2 below:

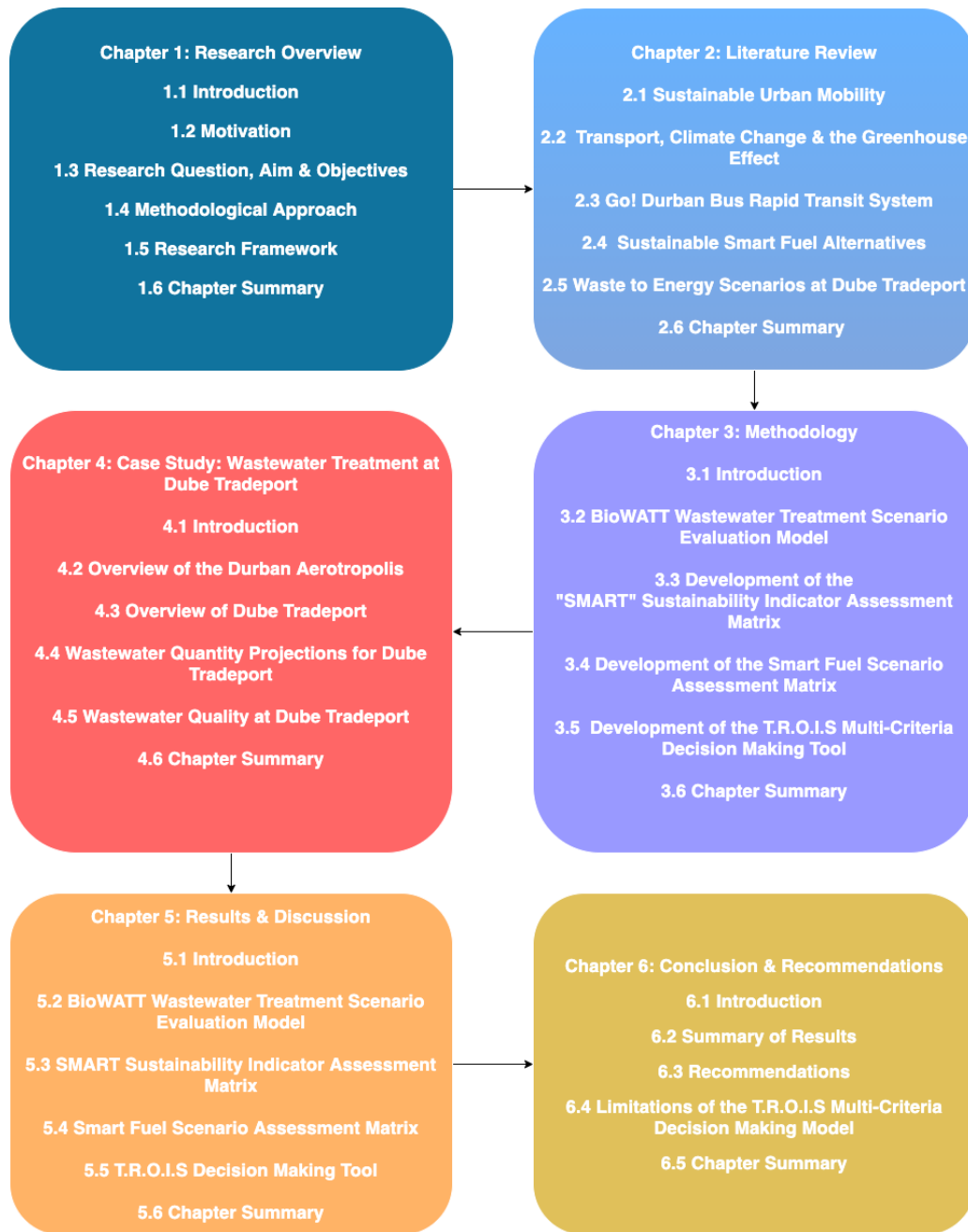


Figure 2 Showing Research Framework used to develop this dissertation

1.6. Chapter Summary

Thus concludes Chapter 1: Research Overview consisting of the Aim, Objectives, Methodology and Research Framework.

Chapter 2: Literature Review

This section consists of a critical analysis of Sustainable Urban Mobility in the context of the Durban Aerotropolis. The historical relationship between Transport, Climate Change and the Greenhouse Effect has been explored using a Top Down approach involving Global Agreements to reduce GHG emissions via the Paris Climate Change Agreement, National Policy as per the South African Green Transport Strategy and the eThekweni Municipality's Climate Action Plan. Thereafter the scope of the Go! Durban BRT system was investigated to develop a context for further analysis. Sustainable bus fuel technologies were then evaluated for Line C8 of the Go! Durban BRT system. Waste to Energy Technologies, which could possibly be applied to convert organic waste that is produced in Dube Tradeport into a source of sustainable fuel for buses, has also been investigated in Chapter 2.

2.1 Sustainable Urban Mobility

Sustainable Urban Mobility is the ability of a city to provide non-declining physical accessibility over time to its inhabitants. The provision of this service is dependent on the city's ability to use natural, man-made and human resources in a sustainable manner which does not inhibit the ability of future generations to meet their mobility needs. Sustainability of the mobility system itself in terms of operational efficiency must be partnered with a low carbon footprint in terms of operational greenhouse gas emissions (Jeon and Amekudzi, 2005).

The ultimate goal is to achieve seamless physical mobility within a city for all inhabitants irrespective of their socio-economic background. An efficient, safe and reliable urban mobility network provides an opportunity for socio-economic transformation by increasing access to educational facilities, government services and jobs. A well designed public transportation network, will increase the ability of marginalised communities to participate in the formal economy, leading to higher economic growth (Benoit Lefevre, 2016).

The use of the Sustainable Urban Mobility principle in the context of the Smart City, has led to the evolution of the term Smart Mobility. Chun and Lee (2015) have defined smart mobility as a comprehensive future traffic service that makes use of smart technology to improve efficiency and performance.

Smart mobility uses intelligent traffic systems to move people and goods quickly and efficiently using mass public transit systems. These systems must have a low environmental impact with reduced levels of greenhouse gas emissions and energy consumption. The use of smart technology should follow an integrated approach, ranging from design to construction and maintenance.

Non-motorised transport such as cycling should also play an important role, with the provision of a network of safe and continuous cycle lanes. Park and ride facilities, which avoid the congestion of the inner city should also be provided. The design of a smart mobility system should place emphasis on the sustainability of the feeder system itself rather than only focusing on the main trunk line. The binding principle of smart mobility is that it cannot be considered smart if it is not sustainable.

2.2 Transport, Climate Change and the Greenhouse Effect

The Sun provides a source of heat and light which warms the Earth's climate. This is achieved via the radiation of energy at very short wavelengths. This occurs most frequently in the visible and or near-visible components of the light spectrum. Approximately, one-third of the solar energy that radiates from the Sun, reaches the outer layer of the Earth's atmosphere and is reflected directly back into space. The remaining two-thirds of solar energy that is radiated by the Sun, towards the Earth is absorbed by the land surface and, to a lesser extent, by the Earth's atmosphere (IPCC, 2020).

The Earth in turn radiates the same amount of energy back into space to maintain an energy balance. The Earth is much colder than the Sun, therefore it radiates energy at much longer wavelengths, which are primarily in the infrared part of the light spectrum. A large amount of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This process is known as the Greenhouse Effect (IPCC, 2020).

The Greenhouse Effect behaves in a similar manner to how the glass walls of a greenhouse reduces the airflow and increases the temperature of the air inside. The Earth's greenhouse effect undergoes this process to warm the surface of the planet, which in turn maintains life on Earth. The average temperature at the Earth's surface without the natural process of the greenhouse effect, would be below the freezing point of water. Although this process is necessary to sustain life on Earth, human activities,

primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural Greenhouse Effect, which has led to global warming and Climate Change (IPCC, 2020).

There are many types of gases which contribute to the Greenhouse Effect and are ranked in terms of Global Warming Potentials. “Nitrogen (comprising 78% of the dry atmosphere) and oxygen (comprising 21%), exert almost no greenhouse effect. Water vapour is the most important greenhouse gas, followed by carbon dioxide (CO₂). Methane, nitrous oxide, ozone and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect” (IPCC, 2020).

If current GHG emissions are left unchecked, uncontrolled global warming could lead to rapid Climate Change which can have unintended negative consequences such as rising sea levels, extreme weather patterns and water and food insecurity. The Figure 3 below shows the Greenhouse Effect, which is caused by the emission of Greenhouse Gases into the atmosphere, through the burning of fossil fuels:

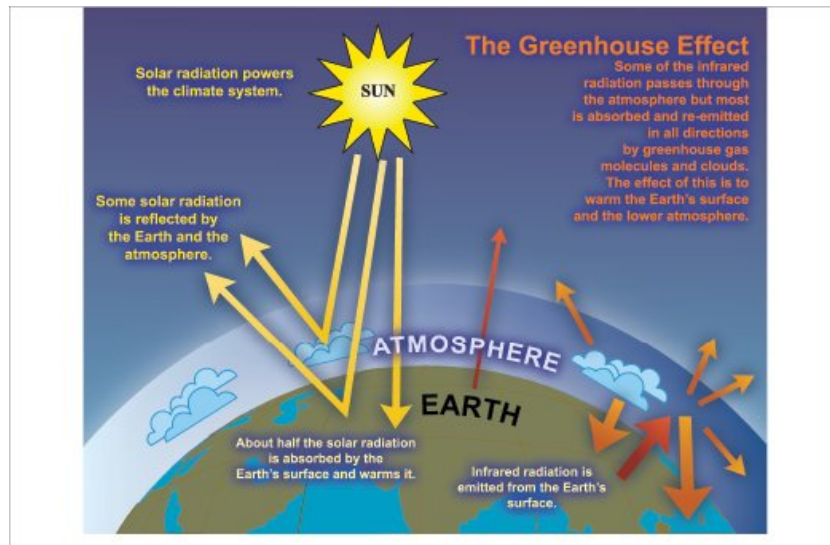


Figure 3 Showing Greenhouse Effect caused by the release of GHG emissions into the atmosphere through the burning of fossil fuels (IPCC, 2020)

The National Aeronautics and Space Administration (NASA), has been measuring the change in global surface temperature relative to 1951 to 1980 average temperatures. The Graph below produced by NASA's Goddard Institute for Space Studies shows that the global surface temperature has been steadily increasing relative to 1951 to 1980 average temperatures.

The Figure 4 below shows the change in global surface temperature relative to 1951 to 1980 average temperatures (NASA, 2020).

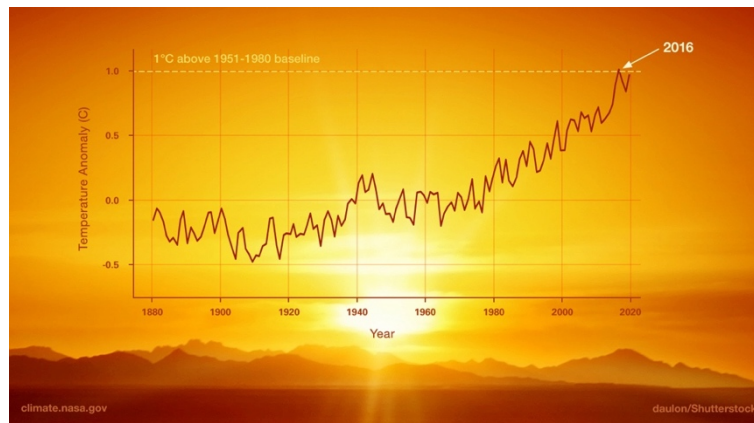


Figure 4 Showing the change in global surface temperature relative to 1951-1980 average temperatures (Source: NASA's Goddard Institute for Space Studies, 2020)

Emissions from the transport sector in South Africa account for almost 10.8% of the country's total Greenhouse Gas (GHG) Emissions. Apart from the direct emissions due to the combustion of fuels, there are indirect emissions from the production, refining and transportation of fuels (National Department of Transport, 2018).

Road transport has been identified as the primary source of transport-related CO₂ emissions in South Africa, contributing 91.2% of total transport GHG emissions. The heavy reliance of the sector on fossil fuels contributes significantly to total GHG emissions for the country (Green Transport Strategy for South Africa, 2018).

The Figure 5 below shows the GHG emissions from the transport sector in South Africa between 2000 and 2050, taking into account existing and currently planned policies.

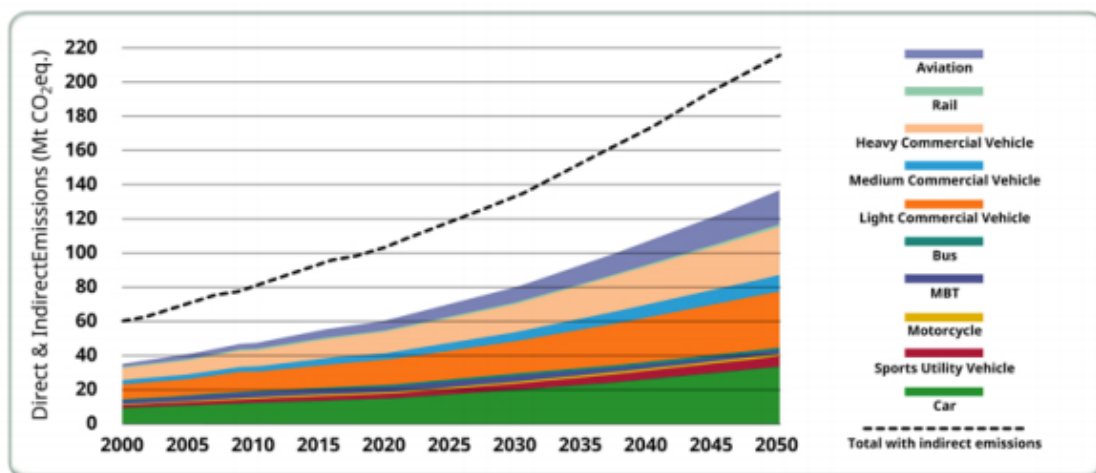


Figure 5 Showing GHG emissions from the transport sector with existing measures (South Africa's GHG Mitigation Potential Analysis, DEA, 2018)

In 2009, South Africa pledged to reduce greenhouse gas (GHG) emissions by 34% by 2020 and 42% by 2025 below business as usual forecasts. This target has been maintained in the White Paper on National Climate Change Response Policy and the National Development Plan. To achieve this pledge, South Africa's Nationally Determined Contribution (NDC) when joining the Paris Climate Change Agreement, commits the country to limiting its GHG emissions to peak at a range between 398 and 614 Mt CO₂eq for the period 2025 - 2030.

The Figure 6 below shows an analysis of South Africa's pledge to emission reduction targets based on the Department of Environmental Affairs figures for historical and projected GHG emissions:

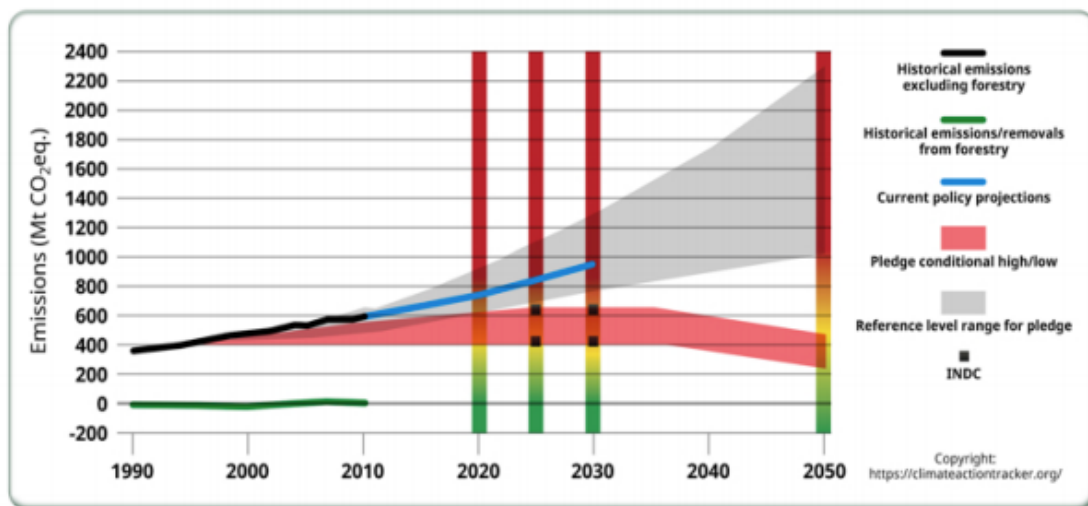


Figure 6 Showing Analysis of South Africa's pledge to emission reduction targets based on the Department of Environmental Affairs figures for historical and projected GHG emissions (Green Transport Strategy for South Africa, 2018)

The Paris Agreement is a legally binding international treaty on climate change, which was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016 (UN, 2020). The objective of the Paris Climate Change agreement is to limit global warming to below 2 degrees Celsius, but preferably below 1.5 degrees Celsius, compared to pre-industrial levels.

According to South Africa's Greenhouse Gas Mitigation Potential Analysis Mitigation Report (2014), potential mitigation measures have been identified for implementation within the transport sector to reduce emissions and contribute towards South Africa's GHG reduction targets by 2050.

These mitigation measures include implementing a modal shift from private car use to shared public transport, a reduction in the demand for travel by implementing traffic demand management measures in urban areas, the introduction of more efficient vehicle technologies and transport operations and the promotion of alternative low-carbon fuels.

The Figure 7 below shows how the total cost of ownership of various alternative low carbon fuel type technologies, decreases over time compared to hybrid and traditional fossil fuels (Green Transport Strategy for South Africa, 2018).

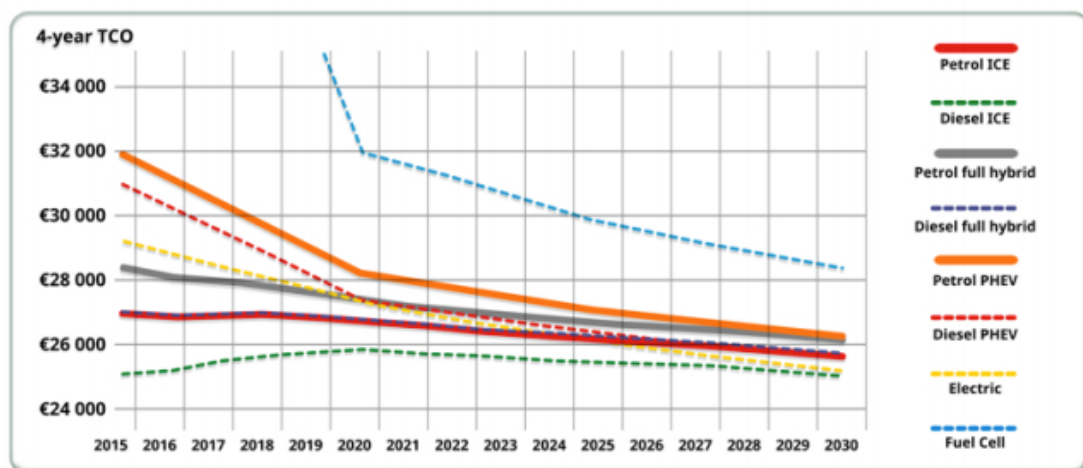


Figure 7 Showing the change in the Total Cost of Ownership for various alternative fuel type technologies over time (Green Transport Strategy for South Africa, 2018)

According to the Green Transport Strategy for South Africa (2018 to 2050) published by the Department of Transport in 2018, the long term vision is to achieve the following: “The replacement of fossil fuels by vehicle technologies with low or zero tailpipe emissions, such as electric and fuel cell vehicles, will be far advanced and, coupled with a significantly lower national electricity grid emissions factor due to a large scale switch to renewable energy improvements this will lead to a dramatic reduction in the carbon intensity of motorised transport”.

Secondly, “All waste collection vehicles and a portion of municipal buses not already replaced by electric vehicles will be retrofitted to enable propulsion with a combination of biogas and biofuels produced from domestic, commercial and agricultural waste”. These two goals of the Green Transport Strategy for South Africa (2018) provides a mandate for the eThekweni Municipality to select alternative low carbon fuels for the Go! Durban Bus Rapid Transit system to achieve the emissions reduction goals as outlined in this strategy by 2050.

In 2015, the eThekweni Municipality's total city-wide GHG emissions were 20,8 million tonnes CO₂ equivalents. eThekweni's GHG emissions are dominated by manufacturing at 41% of emissions, followed by the transport sector at 30% of emissions.

The City is highly dependent on fossil fuels, with approximately 46% of emissions originating from electricity use. This is due to Eskom's high dependence on coal powered power stations. Other dominant fossil fuels in the eThekweni Municipality include diesel and petrol. Diesel consumption is particularly high due to high volumes of freight traffic from the port of Durban (eThekweni Climate Action Plan, 2019).

The Figure 8 below shows a summary of the GHG emission inventory for the eThekweni Municipality in 2015.

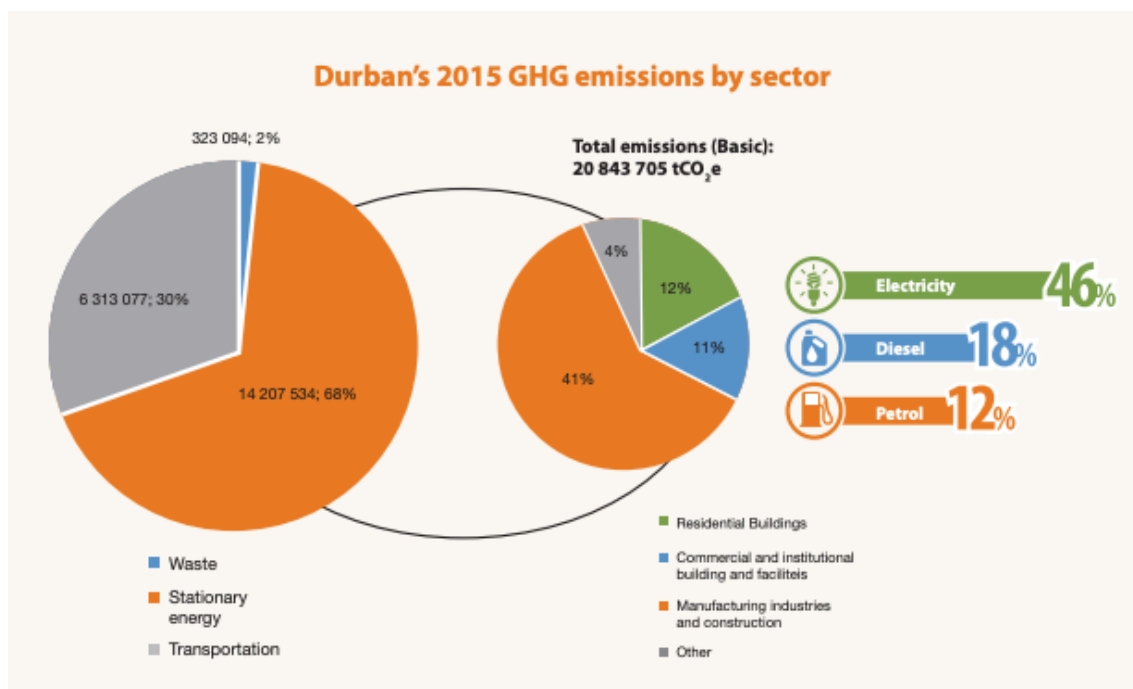


Figure 8 Showing: Summary of the eThekweni Municipality GHG Inventory (eThekweni Municipality, 2015)

According to the eThekweni Climate Action Plan, which was published in 2019, a Business As Usual (BAU) scenario was developed based on economic and population growth projections for the eThekweni Municipality. If the City continues to grow with no climate mitigation measures, emissions will more than double, from 21MtCO₂ e in 2015 to 46MtCO₂ e in 2050. During the same period, emissions per person will increase from 6tCO₂ e per person to 10tCO₂ e per person, as the economy and income per person increases (eThekweni Climate Action Plan, 2019).

The eThekweni Municipality developed a second scenario which attempts to assist the City of Durban to achieve carbon neutrality, based on an ambitious 1.5°C global warming temperature change scenario. This scenario attempts to meet the requirements of the Paris Climate Change Agreement with bold actions that will result in an over 80% reduction in GHG emissions using 2015 as a base year from 21.2MtCO₂ e in 2015 to 3.7MtCO₂ e in 2050.

This suggests a decline in GHG emissions per person from 5.95tCO₂ e in 2015 to 0.89tCO₂ e in 2050 (eThekweni Climate Action Plan, 2019). The Figure 9 below shows the two scenarios as outlined in the eThekweni Climate Action Plan (2019) with a Business As Usual scenario as well as an ambitious emission reduction scenario which attempts to meet the requirements of the Paris Climate Change Agreement.

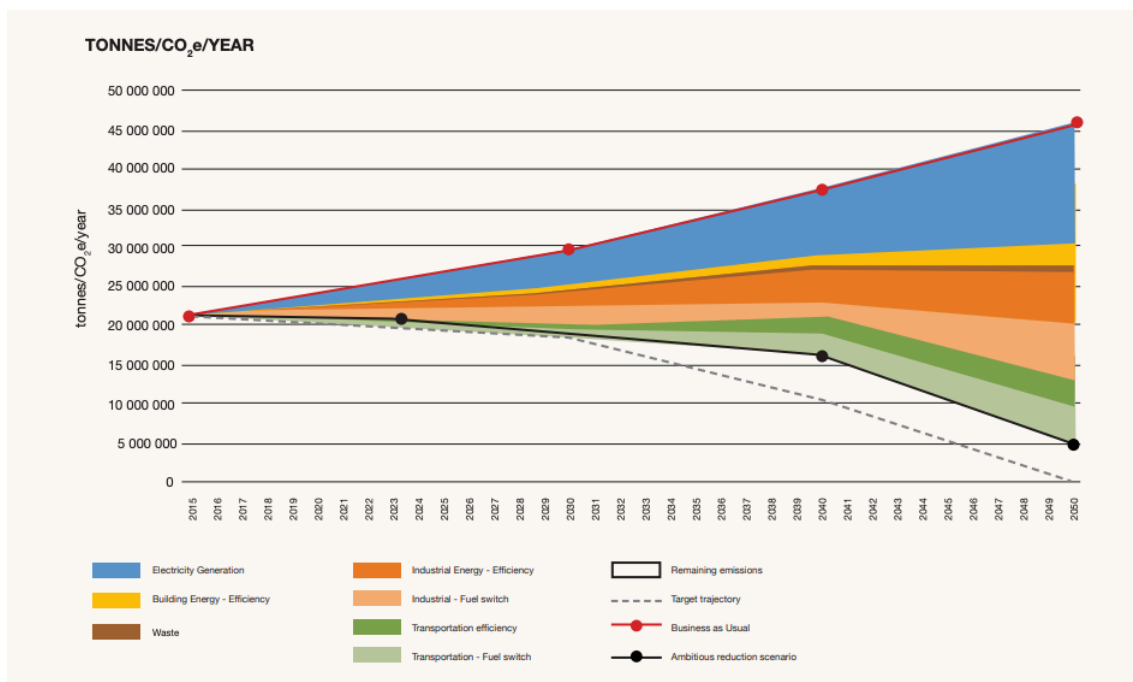


Figure 9 Showing: the GHG emission reduction scenarios for the eThekweni Municipality (eThekweni CAP, 2019)

The priority sectors for the reduction of GHG emissions in the eThekweni Municipality are electricity, transport and industrial stationary energy respectively. These priority sectors as outlined in the eThekweni Climate Action Plan (CAP) 2018 are summarised in the infographic shown in the Figure 10 below:

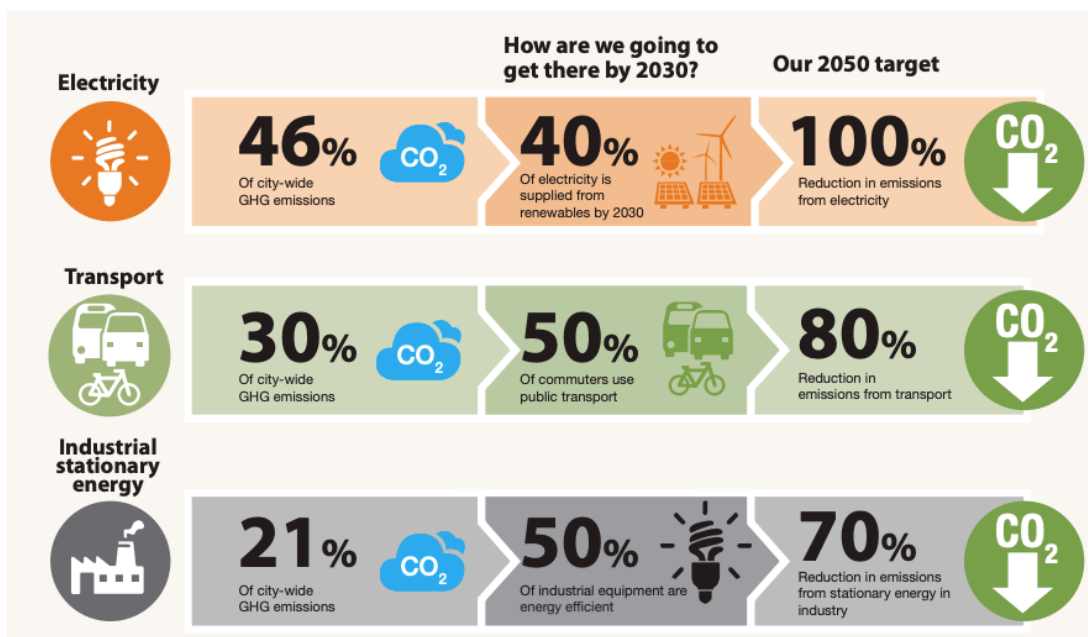


Figure 10 Showing: the priority sectors for the reduction of GHG emissions in the eThekweni Municipality (eThekweni CAP, 2019)

The Figure 10 above shows that the transport sector currently contributes towards 30% of GHG emissions in the eThekweni Municipality. The City of Durban aims to ensure that 50% of commuters use public transport as their main mode of travel by 2030 to assist in the reduction in GHG emissions attributed to private car usage. Private cars currently contribute towards 54% of passenger transport in the eThekweni Municipality, therefore this target is within reach once the Go! Durban BRT system has been fully implemented. The Go! Durban Masterplan is presented in detail in the following section.

Almost 46% of residents in the eThekweni Municipality use a combination of public and non-motorised transport (NMT), in the form of minibus taxis, buses, rail, walking and cycling. There are approximately 200 bus operators and 110 taxi associations who provide transport services to residents. The legacy of apartheid planning and urban sprawl, results in most residents having to travel far distances and spending a lot of time and a high percentage of their income on transport (eThekweni Municipality, 2019)

Non-motorised trips (NMT) in the eThekweni Municipality are dominated by walking, with almost 32% of households (41% of low-income households) conducting at least one walking trip on a typical travel day. Walking is the common mode of transport for last mile journeys and the movement of people from public transport hubs to their final destination. Cycling in the eThekweni Municipality makes up a very small component of

commuter trips (0.05%) and is mostly a recreational activity rather than a major mode of transport (eThekwini Climate Action Plan, 2019).

The second target of the eThekwini Climate Action Plan (2019) is the reduction of the amount of GHG emissions produced by the transport sector in the eThekwini Municipality by approximately 80% and is anticipated to be achieved by the year 2050. The implementation and expansion of the Go! Durban Integrated Rapid Public Transport Network (IRPTN) with a strong focus on Transit Oriented Development (TOD) aims to reduce the number of private vehicles on the road and reduce the need to travel by ensuring that more people live closer to where they work and access services.

The Implementation of travel demand measures anticipates the reduction in existing private car trips by 50% by 2050. The provision and maintenance of high quality active mobility and non-motorised transport (NMT) systems will attempt to increase the use of NMT to 30% by 2050. The final goal is the facilitation of a switch of all vehicles to low-carbon options by 2050 (eThekwini Climate Action Plan, 2019).

The eThekwini Municipality's Climate Action Plan (2019) sets out ambitious targets to transform the city's fleet to low emission vehicles, focusing on electric vehicles and hybrids. The long-term goal is to shift all vehicles across the City to zero-emission vehicles, with the understanding that this transition will be an incremental process over time.

The eThekwini Municipality has limited authority over private vehicles, which account for the majority of transport emissions. Transforming private vehicles to zero emission alternatives requires engagement with National Government regarding supporting legislation and tax incentives as well as private sector support for the construction of supporting infrastructure.

The eThekwini Municipality is however able to ensure that it meets some portion of the goal of reducing transport related GHG emissions by 2050 by procuring low or zero emission buses to service the new Go! Durban Bus Rapid Transit (BRT) System. The following section aims to understand the operational context of the proposed new Go! Durban BRT system which is in the process of being implemented, before alternative fuel options can be investigated for possible implementation.

2.3 Go! Durban Bus Rapid Transit System

The Go! Durban bus rapid transit system which is being developed in the eThekweni Municipality, seeks recommendations regarding the feasibility of implementing sustainable smart fuel alternatives for the C8 line which passes through Dube Tradeport (eThekweni Municipality, 2020). This is in line with the sustainability ethos of the Durban Aerotropolis, which has incorporated environmental, social and economic sustainability principles into the development masterplan (Dube Tradeport, 2020).

A Bus Rapid Transit System (BRT) is a highly specialised bus system, which aims to provide a high-quality, rapid, mass transport system (Institute for Transportation and Development Policy, 2007). The system is characterised by a number of features, although not all of these are necessarily present in every implementation due to budget and or policy constraints (ITDP and GIZ, 2014). These features include grade separation which is the provision of separate and dedicated BRT lanes so that buses do not become impeded by traffic congestion (Institute for Transportation and Development Policy, 2007). This improves travel time and attracts more commuters away from private vehicle usage for their daily commute between work and home.

A BRT system also requires larger buses, allowing for the movement of a greater number of passengers (ITDP, 2007). There is also an emphasis on the need to provide a high quality of service, including high levels of maintenance, ease of boarding, quality stations with passenger facilities including toilets and good security both on the bus and at the stations (ITDP, 2007; EMBARQ). Bus services should be frequent, with low wait-times (ITDP, 2007). Other features that should be included are: electronic fare collection, modal integration, including integrated ticketing, allowing passengers to easily transfer between modes, integration with pedestrian, cycling and other transport routes (ITDP, 2007).

There are numerous benefits to BRT systems such as a reduction in the number of vehicles on the road (Institute for Transportation and Development Policy, 2007): one BRT bus can replace almost three buses or ten taxis and therefore can significantly reduce the number of vehicles in the road during peak hours (ITDP and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2014).

BRT buses have lower operating and capital costs per passenger. The dedicated right of way lanes ensure that BRT buses are less likely to be delayed by peak-hour congestion and can offer commuters faster travel times (EMBARQ, 2013). Increased

efficiencies due to scaling of the system across the city and increased passenger uptake, will result in further reduced Greenhouse Gas Emissions and decreased congestion on the roads.

Fewer private vehicles on the roads , dedicated public transport lanes for the BRT system and improved training for drivers will decrease the number of accidents and fatalities which happen every year. BRT stations allow for faster passenger loading so that buses can move more people in a given time period, than a greater number of smaller vehicles would be able to do (EMBARQ, 2013).

The National Transport Survey of 2013 (StatsSA, 2014) provides data regarding commuting patterns in the eThekweni Municipality. Over half of the city's commuters use public transport to travel to work (54%). Almost 41% of commuters use minibus taxi (MBT) transport, followed by 36% using private vehicles (either passengers, or drivers). Almost 7% of commuters use the bus, 5% use the train and 11% of commuters walk all the way to work.

The eThekweni Municipality designed the Go! Durban BRT system to provide an integrated rapid public transport network that would ensure that 85% of the city's population would have access to scheduled public transport services (eThekweni, 2014). The Go! Durban strategy involved the planning and design of a public transport network system that incorporated and integrated all modes of transport – including non-motorised transport (eThekweni, 2014).

The Go! Durban system has retained rail as one of the main transport modes, in addition to BRT, along the corridors it serves and where the passenger numbers supported rail as the desired transport mode (eThekweni, 2014). This was the design process behind the case for the north-south rail corridor which was constructed to link Bridge City in the north to Umlazi in the south.

Go! Durban represents an integrated strategy with a network of nine public transport corridors (eThekweni, 2014). This comprises an integrated package of rail and rapid bus trunk routes with dedicated rights-of-way, feeder and complimentary services infrastructure. Construction is currently underway on the first phase, which was due to be completed by 2018 (eThekweni, 2014).

The Figure 11 below shows the Go! Durban Bus Rapid Transit Masterplan with the nine main trunk corridors of the system. The focus of this research is the C8 line which connects the Durban Central Business District to Umhlanga, the King Shaka International Airport and Tongaat which is shown in purple in the figure below.

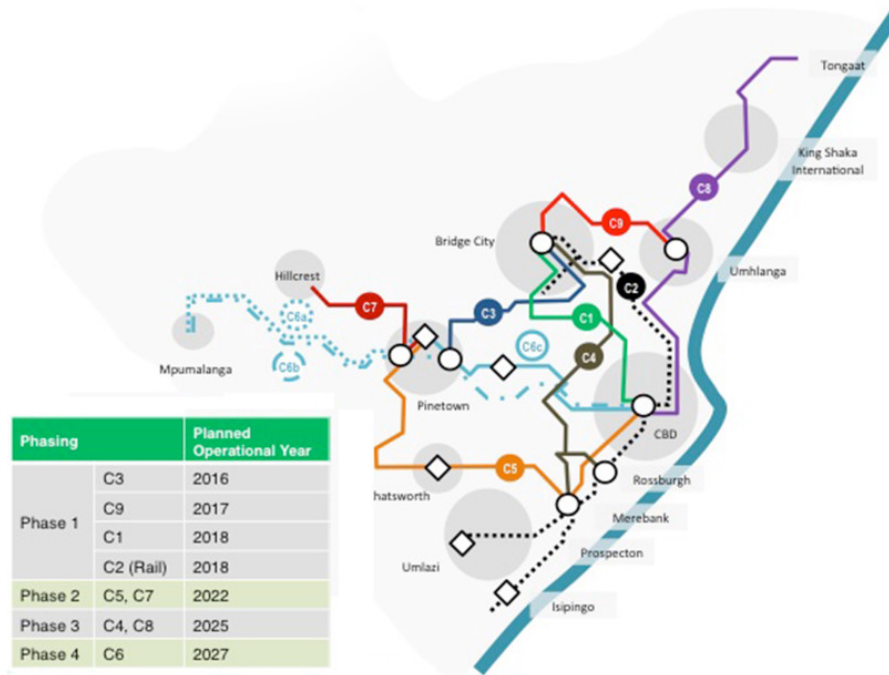


Figure 11 Showing: the Go! Durban BRT Masterplan (eThekweni, 2020)

This context was chosen due to the sustainable development ambitions of the Dube Tradeport and greater Durban Aerotropolis which is being developed around the King Shaka International Airport. This links strongly with the ambitions of the eThekweni Municipality with regards to reducing the Tank to Wheels (TTW) GHG emissions of the City’s public transport vehicle fleet as outlined in the eThekweni Climate Action Plan (2018).

2.4 Sustainable Smart Fuel Alternatives

There are four main energy carriers which are available for buses which could possibly be deployed at the Go! Durban BRT system. These include fossil fuels such as diesel (which the current status quo of the Durban Transport municipal bus system), bio fuels such as bioethanol, biodiesel or Compressed Natural Gas (Bio-CNG), battery electric buses and hydrogen fuel buses.

Different bus propulsion technologies exist and use either one of the above fuel options or a combination of energy carriers which are known as hybrid systems. The introduction of the EURO VI emission standards for diesel buses has also substantially improved the efficiency of diesel powered Internal Combustion Engine (ICE) buses which may prove to be a viable solution until battery electric and or hydrogen fuel cell systems are widely available in South Africa.

The Figure 12 below shows a summary of the different fuel alternatives which will be investigated by literature review:

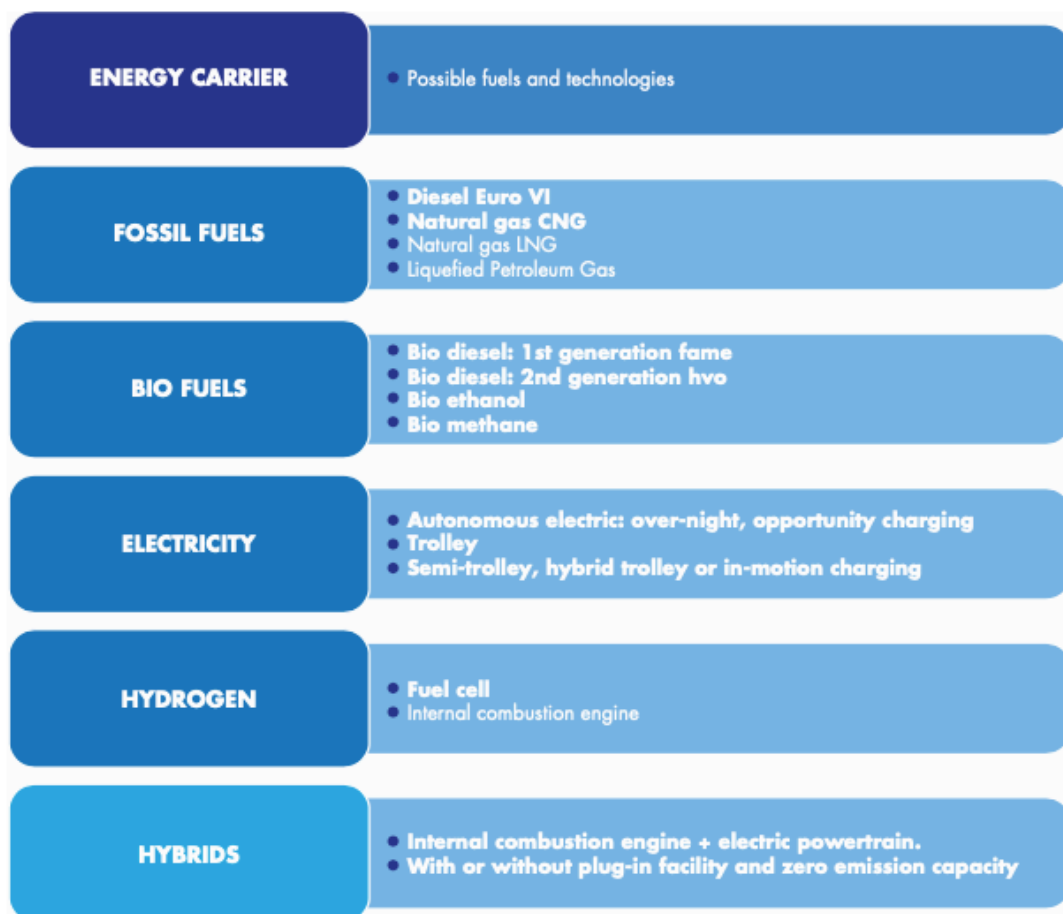


Figure 12 Showing a summary of bus fuel alternatives which will be investigated for the Go! Durban BRT system (CIVITAS, 2016)

Fossil fuels are concentrated organic compounds which are found in the Earth's crust. These compounds are formed from the organic remains of plants and animals that lived millions of years ago (Pedraza, 2019). Some well-known types of fossil fuels which are used as energy sources include coal, petroleum and natural gas. Fossil fuels are non-renewable energy resources, which means that dependency on these sources of energy could lead to energy insecurity in the future, should reserves run out.

The burning of fossil fuels to provide a source of energy for propulsion using internal combustion engine (ICE) vehicles, is a large global contributor towards GHG emissions which has led to a warming of the earth's climate due to the increase in the strength of the Greenhouse Effect in the Earth's atmosphere as explained in Section 2.2. Therefore, it is important for Transport Engineers to be able to make an informed decision regarding the choice of bus propulsion technology to select.

The following bus propulsion technologies are available in the form of fossil fuel based options: Regular diesel, Gas-to-liquids (GTL) diesel, Compressed natural gas (CNG), Liquid natural gas (LNG) and Liquid petroleum gas (LPG) (CIVITAS, 2016). The introduction of the new Euro VI standard for engines in 2014, has resulted in buses running Internal Combustion Engines (ICE) using regular diesel with increasingly clean standards with regards to local pollutant emissions. This is almost comparable in some cases to the buses running on alternative sources/powertrains. This is an important consideration for developing countries with limited budget and should be considered due to the limited production of zero emission buses in South Africa.

The Euro VI diesel ICE bus technology will be taken as the base case as part of a comparative analysis of sustainable fuel alternatives which could possibly be implemented on Line 8 of the Go! Durban Bus Rapid Transit (BRT) which passes through the Dube Tradeport and Durban Aerotropolis. Sustainable alternatives which will be considered in the analysis include, Euro VI Bio-Euro VI CNG buses, Battery Electric Buses

2.4.1 Euro VI diesel buses (Baseline Case)

Bus technology with a conventional diesel combustion engine, running on regular diesel fuel, fulfilling Euro VI emission standards (2014) will be used as a baseline for comparison purposes of potential fuel technology solutions for the Go! Durban Bus Rapid Transit system.

Diesel bus engines are well developed products with a relatively high efficiency of approximately 40%. Diesel combustion in the (ICE) engine takes place automatically due to the high temperature after compression of the air-fuel mixture and the low self-ignition temperature of diesel. Diesel is a relatively safe fuel because it does not evaporate easily. The quality of the fuel has improved drastically due to the decrease of

the content of sulphur and poly-aromatic hydrocarbons. This has led to a decrease of noxious emissions and application of particle filters and catalysts have become widely used as per Euro VI standards. The operational performance of a bus diesel ICE is shown in the Table 1 below:

Table 1 Showing: Operational Performance of a Euro VI diesel bus (CIVITAS, 2016)

Operational Performance	Diesel ICE (Euro VI)
Range	600-900km
Route Flexibility	High
Acceleration Performance	Good
Energy Consumption	4,1 kWh/km
Refuelling Frequency	Every 2nd day
Refuelling Time	5-10 min

Diesel fuel storage and dispensers are most often located at the bus operator depot to stream line the refuelling process. There is also a cost saving with regards to the bulk purchase of diesel and insourcing the refuelling process.

A diesel engine has a relatively high NO_x and PM emissions, however Euro VI engines are required to meet stringent pollutant emissions standards. Euro VI diesel engines are equipped with a particle filter and a NO_x reduction system. Table 2 below shows a comparison of GHG, NO_x and PM10 emission rates per km for the Euro V and Euro VI standards respectively.

Table 2 Showing a comparison of GHG, NO_x and PM10 emission rates per km for the Euro V and Euro VI standards respectively (CIVITAS, 2016)

Emissions	Unit	Euro V	Euro VI
GHG WTT	gCO ₂ e/km	1383	1317
NO _x TTW (direct)	g/km	3.5	0.5-1.1
PM10 TTW (direct)	g/km	0.1	0.015

Buses with a diesel powertrain emit a significant amount of noise which is caused by the combustion sound of a diesel engine. This noise emission has gradually reduced over time due to the application of advanced fuel injection systems and noise isolation techniques. External costs for noise of (diesel) buses are significant and fluctuate depending on the time of day (AEA, 2014). The noise emissions for a EURO VI diesel bus is a standing 80 dB with a pass by noise emission of 77 dB (CIVITAS, 2016).

A Euro VI diesel bus has an indicative purchase price of approximately 220,000.00 Euros per bus (CIVITAS, 2016) which is approximately R4,046,517.50 per bus using 2020 exchange rates. A Euro VI diesel bus, when equipped with emission reduction systems, effectively reduces NOx and PM emissions from the engine to very low values. The use of bio diesel or GTL fuel with a Euro VI diesel engine, would have limited effects on the tail pipe emissions. Further CO₂ reduction can be achieved by improving the efficiency of the drive line, tyres, auxiliaries and driving behaviour.

The long history of diesel (ICE) engines in the bus industry, means that the efficiency, maintenance and costs of diesel buses are predictable with a fuelling infrastructure that already exists. These buses can also easily be adapted to use biofuels such as bio-diesel. The main factor against the use of diesel as a fuel is the need for a long term, low emission renewable energy source. The Figure 13 below shows the layout of a typical diesel powertrain which is commonly used in most bus systems in South Africa (left) and a new Go! Durban bus (EURO V) which was purchased in 2019 (eThekweni, 2019).

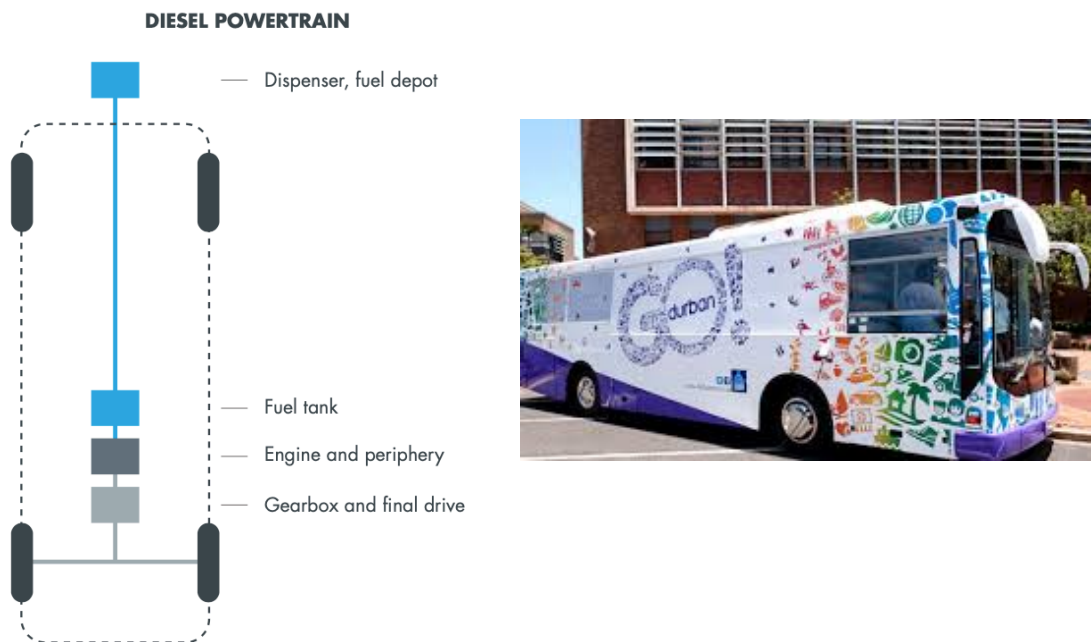


Figure 13 Showing: Euro VI Diesel bus powertrain layout (left CIVITAS, 2016) and new Go! Durban Euro V bus (right Go! Durban, 2018)

2.4.2 Euro VI Compressed Natural Gas (CNG) or Bio-CNG Buses

The compressed natural gas (CNG) engine is a mature bus technology with a conventional (otto, spark ignition) combustion engine which complies with Euro VI emission standards (as of 2014) and runs on either compressed natural gas, or bio-gas (upgraded bio-methane). The efficiency rate of this type of engine is lower in comparison to a Euro VI diesel engine.

The quality of regular natural gas (calorific value) varies according to the local gas supply and largely depends on the actual composition of the gas. The engine control is able to adapt to differences in quality. The lower efficiency of the CNG engine compared to a diesel engine, means that the natural gas engine will consume more energy per km.

Natural gas contains less energy per litre than diesel and must be compressed and stored in large tanks, which takes up space on a bus. Refuelling a CNG bus takes the same amount of time as diesel and approximately matches the operational performance of a traditional diesel bus. Operational performance indicators for a CNG Bus is shown in Table 3 below:

Table 3 Showing: Operational Performance of a Euro VI CNG Bus (CIVITAs, 2016)

Operational Performance	Bio-CNG ICE Bus
Range	350km to 400km
Route Flexibility	High
Energy Consumption	5,2 kWh/km
Refuelling Frequency	every 1 st or 2 nd day
Refuelling Time	Short refilling time: 5-10 min

Compressed natural gas (CNG) bus fleets require a specific refilling infrastructure (specialised compressor and buffer tank for fast refilling). The gas is supplied via a connection to an existing gas network or delivered at the local depot via truck.

A lower engine efficiency and lower CO₂ emissions of natural gas or biogas per unit of energy combined leads to comparable tank to wheels (TTW) CO₂ emissions as for diesel engine buses. The well to wheels (WTT) CO₂ emissions is dependent on the production and distribution of the gas as well. With the introduction of Euro VI diesel bus engines, with much cleaner emission standards, the difference in pollutant emissions between Euro VI diesel and Euro VI CNG engines have almost diminished in real terms.

Compressed natural gas (CNG) bus engines run stoichiometric, such that if the fuel-air mixture control is accurately maintained, a three-way catalyst can clean the exhaust gasses with high efficiency. Figure 14 below shows a typical CNG Bus and powertrain.



Figure 14 Showing: Euro VI CNG bus powertrain layout (left) (CIVITAS, 2016) and CNG Rea Vaya Bus Johannesburg (right) (Rea Vaya, 2020)

Compressed Natural gas (CNG) engine buses use a different combustion process which results in the emission of less noise than traditional diesel engine buses. The noise emissions for a CNG bus is around 78 dB (standing) and around 78 dB (passing by). The cost of purchasing a CNG bus is around 250,000.00 Euros per bus or R4,583,369.97 per bus (CIVITAS, 2016).

The purchase costs of CNG engine buses are higher than traditional diesel buses due to the large CNG tanks on the roof, a reinforced bus frame and added safety measures which are required. Where there is no CNG infrastructure available (gas lines, storage, compressor) additional capital expenditure costs will apply if this fuel technology is selected.

The main advantages of CNG buses as compared to diesel buses are the lower noise emissions. With the introduction of Euro VI diesel engine standards, the difference in air pollution emissions has been diminished. With regards to GHG emissions, CNG buses can be fuelled with biomethane to reduce WTW GHG emissions compared to diesel engine buses. This is due to the carbon neutral nature of bio-methane when the entire lifecycle of the fuel source is considered. The main disadvantages of CNG buses are the

safety concerns around the possibility of gas leakage and ignitability of CNG resulting in an increased risk of fire. As the use case of this fuel source is high volume public transport, issues of safety onboard the Go! Durban BRT bus fleet should also be considered.

2.4.3 Battery Electric Buses

Battery electric buses normally use a rechargeable battery to store energy on-board and the buses are charged statically. Buses driving on electricity are considered to be the cleanest technology that is currently available. Electric buses produce zero local emissions and have the largest positive impact on local air quality. Electric buses have a lower level of noise emissions than buses with combustion engines.

The well to wheel (WTW) GHG emissions of electricity-powered buses, is highly dependent on the energy source that is used to generate the electricity. In South Africa, using grid electricity to power electric buses does not decrease the negative impact of the GHG emissions as a result of Eskom's dependence on using coal to generate electricity.

The electric bus battery can be recharged slowly overnight or at large intervals at the main bus depot (overnight charging) or at higher frequencies along the bus line and at terminus (opportunity charging) (CIVITAS, 2016). Recharging an electric bus battery (especially with a slow charge) can sometimes take a long time.

This means that the employability of this bus technology (the hours available for daily duty) is not as high as for traditional diesel buses. This adds additional costs to the total cost of ownership (TCO), for the procurement of extra buses and bus drivers to make up for the slow charging times. Electric bus batteries are also expensive to procure and large batteries result in less passenger capacity due to the added weight.

Two main charging strategies are considered for battery electric buses: Opportunity charging electric buses aim to minimize the weight of the battery by regular recharging en route at bus stops. They have a small to medium battery capacity (typically 20-60 kWh). Overnight charging e-buses have a large battery capacity (typically 200-350 kWh) which is required to drive longer distances (150-250km) without recharging. The battery is usually charged from the grid at the depot over-night but can also be recharged during the day, for instance at central bus stations (CIVITAS, 2016)

The electric powertrain of a battery electric bus is efficient and suitable for stop and go operations. In addition, energy can be regenerated via electric braking. This leads to low energy tank to wheels (TTW) consumption compared to technologies which use internal combustion engines.

Opportunity charging buses: Short autonomy very dependent on capacity of the battery and actual energy use: <100 km, limited route flexibility, recharging needed multiple times a day, short recharging time: 5-10 min and energy consumption of around 1.4 kWh/km (CIVITAS, 2016) shown in Table 4 below:

Overnight charging buses: medium autonomy, very dependent on capacity of the battery and actual energy use: 100 - 250 km; higher route flexibility, recharging at the end of each day or during the day, long recharging times: more than 3 hours and energy consumption of around 1.6 kWh/km (CIVITAS, 2016), shown in Table 4 below:

For an overnight charged battery electric bus, the empty mass of the bus can be high due to the large and heavy battery. This negatively affects the total passenger capacity. For example a 2-axle 12m 300kWh electric bus can transport 70 passengers compared to about 100 persons for the 12m diesel engine version (CIVITAS, 2016). Both for opportunity and overnight-charging buses, charging times depend on the power of the charging station and the battery technology that is employed.

Table 4 Showing: Operational Performance of a Battery Electric Bus (CIVITAS, 2016)

Operational Performance	Opportunity Charging Battery Electric Bus	Overnight Charging Battery Electric Bus
Range	<100 km	100 - 250 km
Route Flexibility	Limited route flexibility	Higher route flexibility
Energy Consumption	1.4 kWh/km	1.6 kWh/km
Refuelling Frequency	Recharging needed multiple times a day	Recharging at the end of each day or during the day
Refuelling Time	5-10 min	More than 3 hours

The useful life of the bus chassis and powertrain, excluding the battery, is estimated to be around 12-15 years. The electric propulsion is expected to have a longer life than an internal combustion engine due to fewer moving parts and subsequently less maintenance being required. The useful life of a battery is expected to last shorter, however this depends largely on operating and charging conditions of the battery.

Figure 15 below shows the battery electric bus powertrain layout and a battery electric bus produced by Proterra:

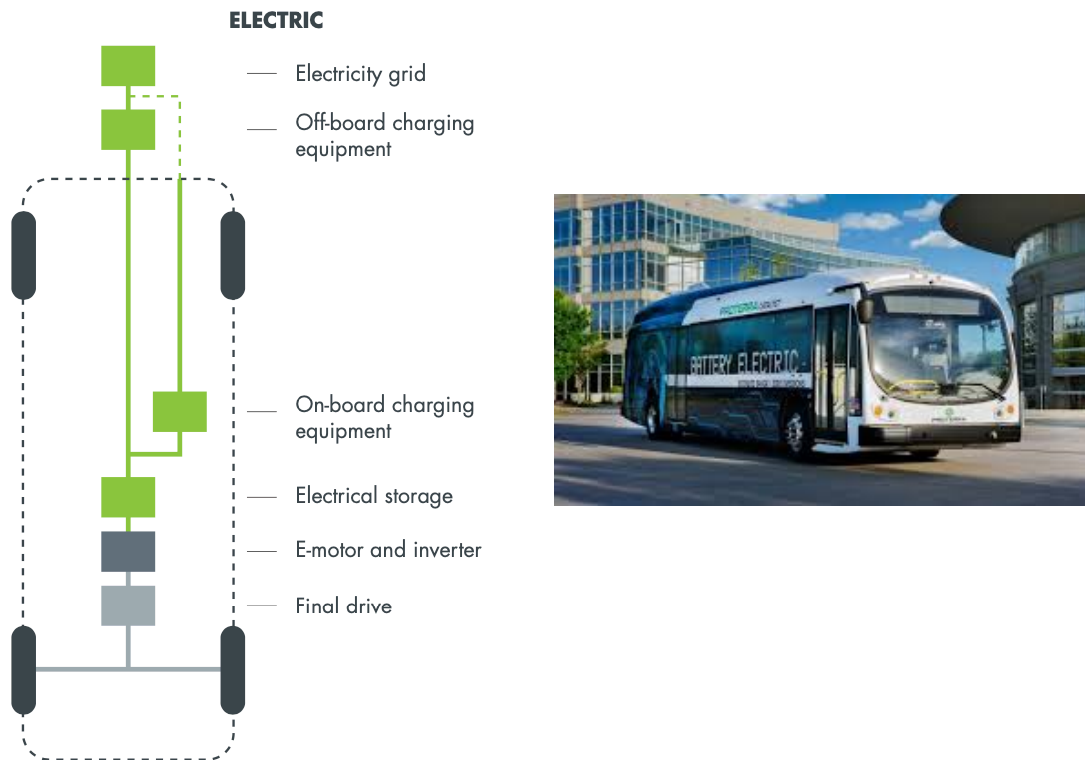


Figure 15 Showing: Battery electric bus powertrain layout (left) (CIVITAS, 2016) and Battery Electric Bus (Right) (Proterra, 2020)

Battery electric buses require a dedicated infrastructure, such as charging points within the bus depots and/or along the routes at bus stops. On-board charging equipment and charging points are mature products and are widely available. More recent innovations in charging technology include opportunity charging with a pantograph (conductive) or inductive are being researched with active pilots in Europe (CIVITAS, 2016).

As discussed earlier, Well to wheel (WTT) GHG emissions for battery electric buses depend largely on the energy production method that is employed. Local pollutant emissions and tank to wheels (TTW) GHG emissions are zero. With regards to noise emissions, battery electric buses have lower noise levels than standard diesel buses.

The cost of a battery electric bus is in the region of 320,000 to 500,000 Euros per bus. This amounts to around R5,866,713.56 to R9,166,739.95 per bus. Purchase prices of battery electric buses are largely dependent on the battery capacity of the bus. Battery

replacement costs are significant and largely depend on size (capacity) and ageing (CIVITAS, 2016).

Opportunity charging electric buses are considered viable in terms of projected costs. The main limitation is the reduction of the service flexibility and the impact of traffic irregularities on opportunity e-bus revenue service. These types of irregularities may result in a time shortage for opportunity charging due to a delayed service or in a situation when two or more e-buses (regular and delayed services) claim for space at a single charging point (CIVITAS, 2016).

Establishing a reliable system of opportunity charged e-buses requires charging standardisation, embedding such a system into a more complex urban mobility scheme, with measures such as dedicated bus lanes, traffic light preferences for urban transit, IT tools for e-bus scheduling and online control. Opportunity battery electric bus systems and Smart Mobility theory is closely linked (CIVITAS, 2016).

Overnight charging electric buses are not expected to meet average daily autonomy requirements nor carry a sufficient number of passengers due to the weight of the batteries for intensive bus lines. Therefore, this type is considered not suitable for whole day operation on frequent bus lines with a high degree of passenger occupancy. The technology is suitable for shorter daily operations and low demand bus lines (CIVITAS, 2016).

The main advantages of battery electric buses are they are one of the cleanest technologies available given the local zero emission of pollutants and lower noise emissions. Electricity can be produced from sustainable sources to reduce well to wheels GHG emissions. The main disadvantages of battery electric vehicles are the high purchase price and the large investment in charging infrastructure that is required across the operations of a City Bus Rapid Transit (BRT) system.

2.4.4 Electric Trolley Buses

Electric trolley buses are considered a very mature technology. These types of buses are often dominantly electricity-powered buses, using overhead wiring infrastructure as an external electricity source. An APU (auxiliary power unit) is used to provide some autonomous operation (to overcome short distances without overhead wiring or to serve as limp-home). Older variants have generator sets on-board (CIVITAS, 2016), whilst newer versions have a battery to take over this functionality.

Electric trolley bus technologies, where the bus is fully connected to the power supply all along the network are most common versions of the system. Other variations include partly connected hybrid- or semi-trolley technologies using in-motion charging. Most versions have an auxiliary power unit (small engine) or electric battery available to cover short distances without overhead wiring for emergency reasons.

The operational performance of an electric trolley bus has the following characteristics. Range, is unlimited within the network providing constant electricity supply. Flexibility beyond the network is only possible using an auxiliary power unit or battery. This technology does not incorporate refuelling or recharging time in normal operation (except when auxiliary power unit battery needs to be recharged). Lastly, the powertrain is very energy-efficient where energy consumption is around 1,4 kWh/km (CIVITAS, 2016) as shown in Table 5 below:

Table 5 Showing: Operational Performance of a Trolley Electric Bus (CIVITAS, 2016)

Operational Performance	Opportunity Charging Trolley Electric Bus
Range	Range, is unlimited within the network providing constant electricity supply
Route Flexibility	Flexibility beyond the network is only possible using an auxiliary power unit or battery
Energy Consumption	1,4 kWh/km
Refuelling Frequency	n/a
Refuelling Time	n/a

The infrastructure required to run this bus technology is an expensive overhead wiring network (including transformers and high voltage connections). The pre-existence of an overhead wiring infrastructure in the host city makes a large difference in the Capex costs for the infrastructure that is required for this to be successfully implemented. WTT GHG emissions depend largely on the production method of the grid electricity supply. Local pollutant emissions and TTW GHG emissions are zero which is a strong factor favouring this form of electric bus system. The noise emissions for an electric trolley bus is much lower than the noise level of standard internal combustion diesel engine buses.

The purchase cost is approximately 400,000.00 - 450,000.00 Euros per trolleybus. This amounts to R7,333,391.96 to R8,250,065.95 per bus in South African Rands. Capital expenditure is especially high for a new trolley network due to the high costs of developing the required overhead infrastructure. Cities can benefit from an overhead electric infrastructure which may already be in place. This will therefore influence the

design of the trolley bus routes to attempt to save of the infrastructure costs that are required. (CIVITAS, 2016). Figure 16 below shows an electric trolley bus:

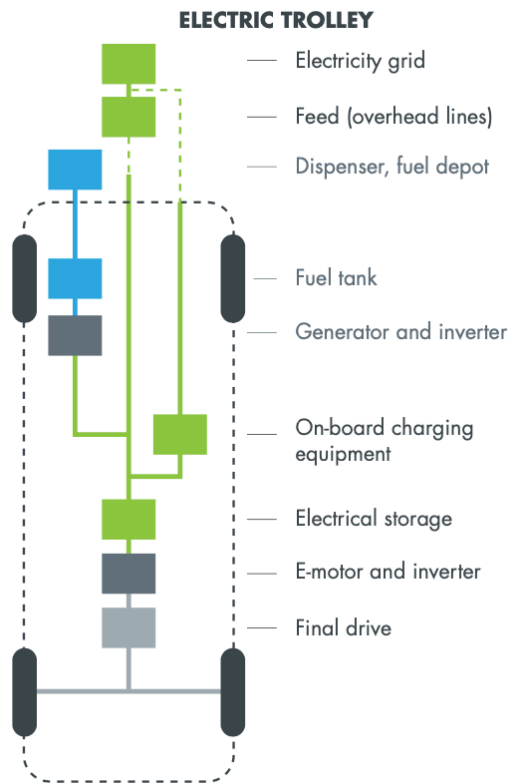


Figure 16 Showing: Electric trolley bus powertrain layout (left) and Electric Trolley Bus (Right) (Skoda, 2019)

The main advantages of trolley buses are that they are one of the cleanest technologies available given the local zero emission of pollutants and lower noise emissions. Electricity can be produced from sustainable sources such as solar to reduce the total well to wheels GHG emissions of the electric trolley bus system.

The main disadvantages of the electric trolley bus solution, is the requirement of overhead electricity lines. In addition, trolleybuses currently often cost double the price of a conventional diesel bus due to low production volumes, however if economy of scale is achieved, the price per vehicle may reduce over time.

The expected lifetime of a trolley bus is longer (about 20 years) than a typical diesel bus. When no infrastructure is available initial high capital expenditure (infrastructure) and operational expenditure (maintenance of infrastructure) are applicable (CIVITAS, 2016).

2.4.5 Hybrid Diesel – Electric Buses

A hybrid diesel-electric bus uses two sources of automotive power. The more common type: the hybrid electric vehicle (HEV) uses a combination of an internal combustion engine and an electric drive system (electric motor/generator and battery and/or capacitors). There are two types of hybrid diesel-electric buses which are available on the market, parallel hybrids and serial hybrids (CIVITAS, 2016).

Parallel hybrids have an internal combustion engine (e.g. diesel or CNG) and a coupled electric motor to assist the engine, to regenerate braking energy and to charge the battery. These types can be further categorised depending on how the power sources are balanced. Most often, the combustion engine is dominant, however no exclusive mode (electric only or internal combustion only) can be used so they are referred to as mild hybrids (CIVITAS, 2016).

Serial hybrids have an internal combustion engine that produces electricity to charge a battery and provide energy to power the electric motor(s) which in turn propel the bus. Most types can connect to the electricity grid to charge the battery (plug-in). Depending on the capacity of the battery they can offer a substantial zero-emission range.

Serial hybrids can be battery dominant, where they are often called 'plug-in hybrid electric' or extended range electric vehicle or range extended electric vehicle. Their counterparts are the serial hybrid types where the battery is small, these types often offer limited zero-emission range, however they have the benefit of regenerative braking energy. Instead of a generator set running on diesel, in principle, a Bio-CNG, bioethanol engine or a fuel cell stack can be used to charge the battery to further reduce well to wheel GHG emissions (CIVITAS, 2016).

The operational performance of a diesel-electric hybrid bus consists of the following : a range of approximately 600-900km, a high route flexibility, refilling is only needed after every 2nd day, short refilling times of 5min, energy consumption of around 3,3 kWh/km. The energy consumption for the hybrid diesel-electric bus depends on the overall system layout and the duty cycle. These Operational Indicators are shown in Table 6 below:

These buses will tend to be heavier and can take advantage of regenerative braking energy. The highest savings, of up to 30%, can be achieved in heavy congested urban stop and go traffic. The higher empty mass can also affect the passenger capacity of a diesel-electric hybrid bus. The infrastructure that is required, depends on the fuel of the

internal combustion engine. Plug-in types will also require a charging infrastructure in addition to refuelling for the internal combustion engine.

Table 6 Showing: Operational Performance of a Diesel- Electric Hybrid Bus (CIVITAs, 2016)

Operational Performance	Diesel-Electric Hybrid Bus
Range	600km - 900km
Route Flexibility	High route flexibility
Energy Consumption	3,3 kWh/km
Refuelling Frequency	After every 2nd day
Refuelling Time	Short refilling times of 5min

The Figure 17 below shows the powertrain layout of a diesel-electric bus and full view schematic:

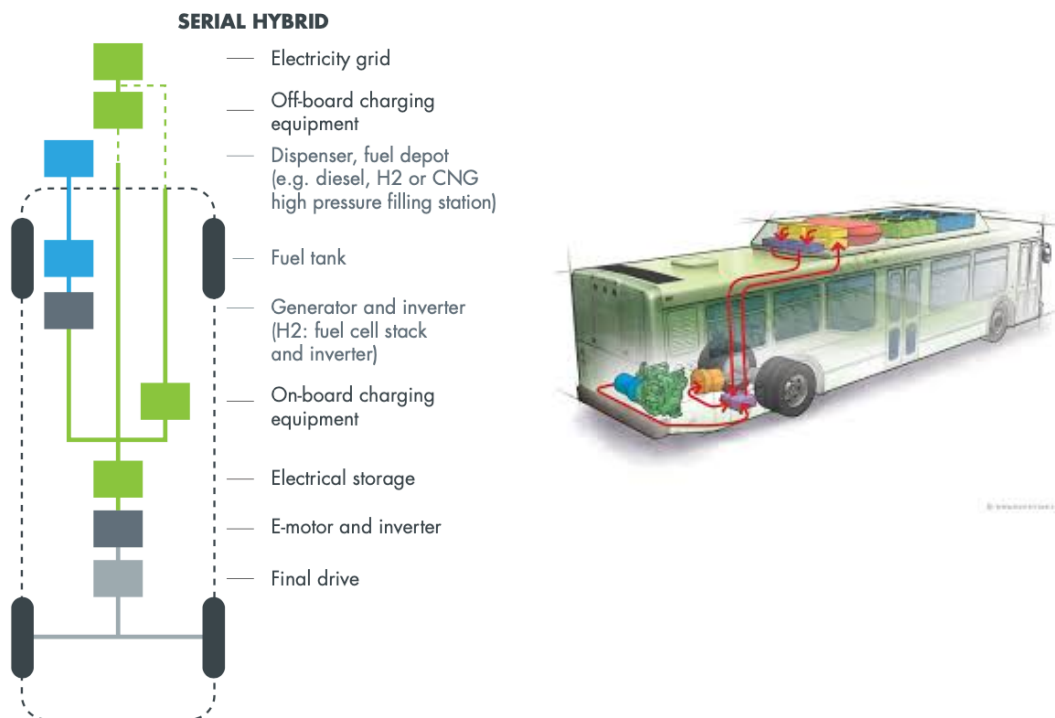


Figure 17 Showing: Diesel-Electric Hybrid powertrain layout (left) and Diesel-Electric Hybrid Bus (Right) (Struve, 2016)

Tank to wheel (TTW) GHG emissions are generally lower than the respective powertrains with a single motive power source, because of the lower energy consumption. The higher efficiency of the powertrain, results in lower local emissions. However, the exact effects for NOx rather depend on the duty cycle as the catalyst to reduce NOx may cool down when the engine is shut-off for long periods of time (CIVITAS, 2016).

Noise emissions are lower when a bus operates fully electric with emissions of standing: 69 dB; Passing-by 73 to 78 dB depending on the driving mode that is employed. The purchase price of a diesel-electric hybrid is approximately 220,000.00 - 300,000.00 Euros per bus. This is approximately R4,033,365.58 to R5,500,043.97 per bus in South African Rands. Due to the higher complexity and more components, hybrid buses are generally more expensive than a conventional diesel bus. This can be up to 50% more expensive than a traditional hybrid bus and depends on the level of hybridisation in the model.

Hybrids (especially serial hybrids) also offer the opportunity to undertake short distances in purely electric drive. A precondition is an electrification of the auxiliaries. This option is important where the bus route crosses a densely populated area or ancient city centre, where low levels of noise and local emissions are required to reduce local pollution.

The main advantages of a hybrid diesel electric bus is lower fuel and energy consumption in heavy urban traffic. The main disadvantages are more costly and probably heavier bus (a heavier bus will lead to a reduced number of passengers given the same amount of axles).

2.4.6 Hydrogen Fuel Cell Electric Buses

Hydrogen fuel cell buses are powered by fuel cells which convert the chemical energy of hydrogen into electricity and deliver electrical energy into the powertrain of an electric bus. Hydrogen is, stored and compressed in tanks on the roof of the bus with hydrogen refuelling facilities located at the bus depot. These buses produce no tank to wheels (TTW) greenhouse gases or air pollution in use, because water vapour is the only tailpipe emission. Hydrogen can be produced from a variety of sources including fossil fuel-based industrial processes and the electrolysis of water using renewable electricity (CIVITAS, 2016).

There are three types of bus technologies which run on hydrogen and that are available on the market: an internal combustion engine running on hydrogen gas, a serial hybrid hydrogen fuel cell with electric battery and drive, without or with a small battery (fuel cell dominant) and a serial hybrid hydrogen fuel cell with electric battery and drive (battery dominant) (CIVITAS, 2016).

The first option was tested by OEMs in Europe and was found to not be a feasible option for buses. The second option has already been used previously in many European cities,

but did not prove to be very efficient technology solution. The third option, which is a serial hybrid hydrogen fuel cell with electric battery and drive (battery dominant) has been found to be the most efficient hydrogen bus technology option (CIVITAS, 2016).

Hydrogen buses which contain fuels cells employ these cells to convert the chemical energy from the hydrogen into electricity for motive power. A PEM (Proton Exchange Membrane) type fuel cell is most commonly used in bus systems. A battery is used to buffer the energy produced by the fuel cell stack. In addition, a battery can also be used to store regenerated energy from braking. Large fuel storage tanks are needed and are typically placed on the roof to store the hydrogen under a very high pressure (350 or 700 bar) and a special infrastructure (filling station) is needed to fill the tanks to the required high pressures. Another option is to use an on-board reformer, however this will offer little or no GHG benefit (CIVITAS, 2016).

Hydrogen fuel can be produced offsite in several ways, either from steam reforming from natural gas (Grey Hydrogen), via renewably powered electrolysis (Green Hydrogen) and by the conversion of a hydrocarbon fuel such as methanol, ethanol, natural gas (Brown Hydrogen). This research will also investigate the production of hydrogen gas via the Hazer Process, which uses biogas or upgraded biomethane produced from a wastewater treatment plant at Dube Tradeport. The various types of hydrogen which can be produced by energy source is shown in the figure 18 below:

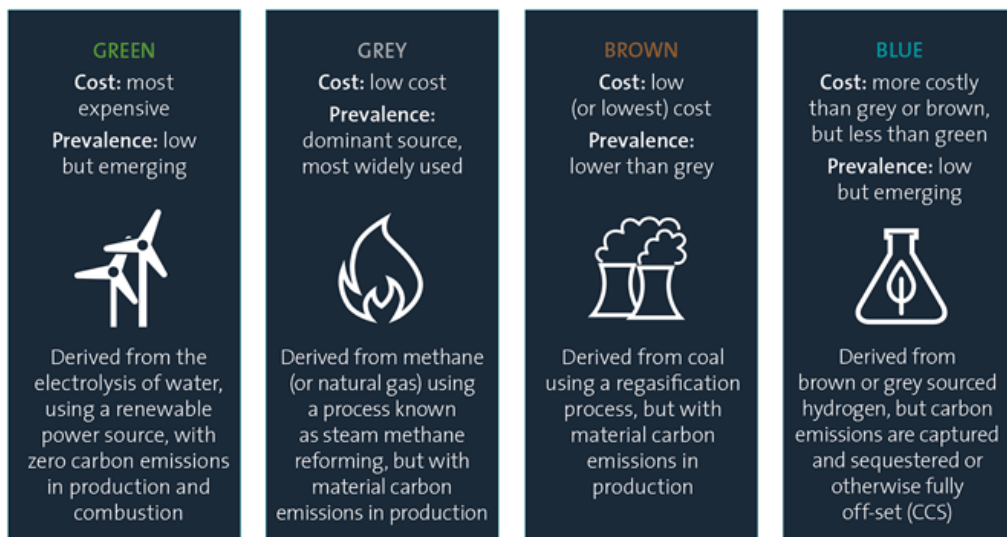


Figure 18 Showing: Different types of hydrogen which can be produced by energy source (Ashurst, 2020)

The energy use and GHG emission of the hydrogen fuel depends heavily on the production process that is chosen. The production of biogas using an anaerobic digester from organic waste such as wastewater sludge can produce a renewable and sustainable source of biogas which can be converted into pure hydrogen gas using the Hazer Process once the gas has passed through a water scrubbing process. This method of hydrogen production is still in the research and piloting phase, however it presents a green hydrogen production alternative to the current electrolysis via solar or wind power. This method of green hydrogen production is far more energy efficient than electrolysis and will be explored further under waste to energy scenarios for Dube Tradeport.

Using electricity to produce hydrogen via electrolysis (even if renewable energy is used) is seen as an inefficient process, because the electricity can also be stored directly into large lithium ion batteries at charging stations.

The operational performance of a hydrogen fuel cell bus consists of a range of between 200 – 400 km (range depends on tank size of hydrogen and the storage pressure). A higher pressure of 700 bar would increase the range at the same volume of the storage tanks. Hydrogen fuel cell buses have high route flexibility and refilling is required every day at the end of operation.

The hydrogen refilling time is relatively short at 10 minutes. The energy consumption rate of a hydrogen fuel cell bus is approximately 3,1 kWh/km. The higher empty mass of a hydrogen fuel cell bus, affects the passenger capacity. However, this can be solved by adding an extra axle if a high capacity is required. Operational indicators for a Hydrogen Fuel Cell Bus is shown in Table 7 below:

Table 7 Showing: Operational Performance of a Hydrogen Fuel Cell Bus (CIVITAS, 2016)

Operational Performance	Hydrogen Fuel Cell Electric Bus
Range	200 – 400 km
Route Flexibility	High route flexibility
Energy Consumption	3,1 kWh/km
Refuelling Frequency	Every day at the end of operation
Refuelling Time	10 minutes

The Figure 19 below shows the layout of a hydrogen fuel cell bus powertrain and hydrogen fuel cell bus prototype which has been developed by Toyota in 2020.

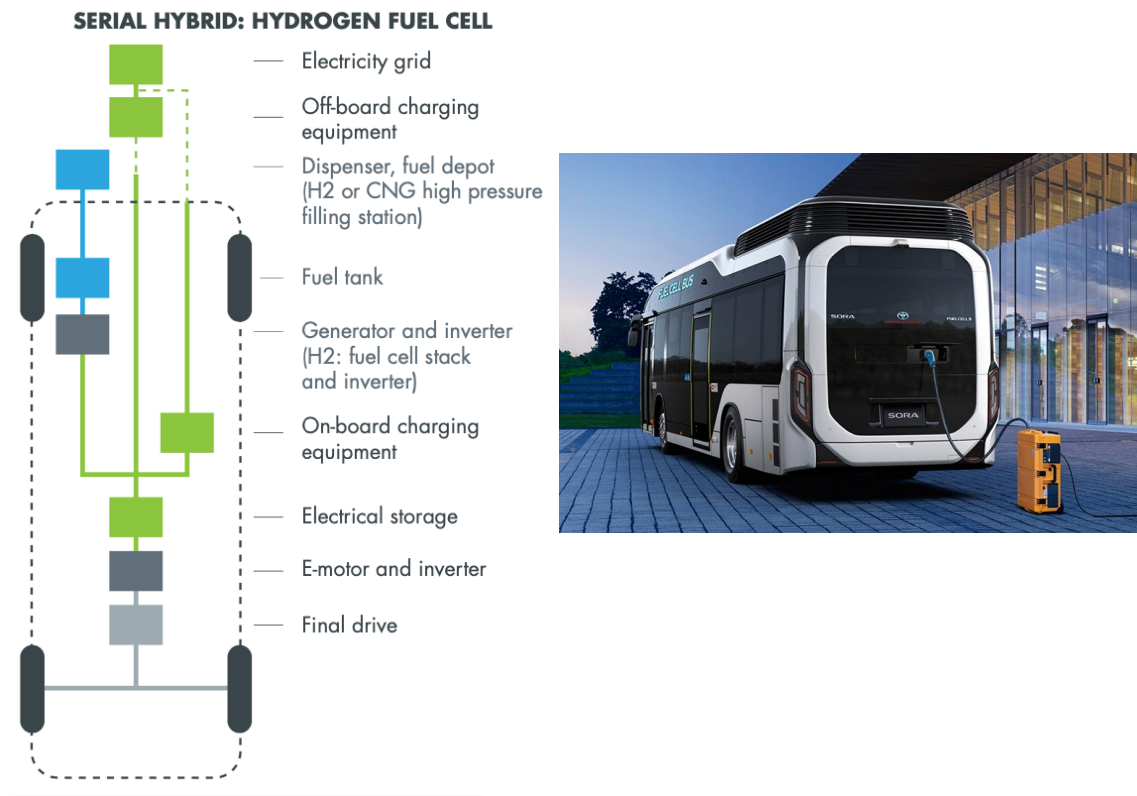


Figure 19 Showing: Hydrogen fuel cell powertrain layout (left) and Hydrogen Fuel Cell Bus (Right) (Toyota, 2020)

Hydrogen fuel cell buses require a specific filling infrastructure, that includes a specific dispenser and supply infrastructure to provide the hydrogen to the vehicle at a pressure of 350 bar. Local pollutant emissions and tank to wheels (TTW) GHG emissions are zero for hydrogen fuel cell buses. Well to wheels (WTT) GHG emissions depend largely on the hydrogen production method that is employed. A waste to energy scenario of hydrogen production from biogas using the Hazer Process, will be investigated as a possible alternative to electrolysis and steam reformation both of which are energy intensive processes.

The noise emissions from a hydrogen fuel cell bus is low and comparable to battery or trolley electric buses. However, the cooling fans that cool the fuel cell stack can produce additional noise compared to electric buses. The purchase price of a hydrogen fuel cell bus is approximately 800,000.00 Euros. This amounts to R14,666,783.91 per bus in South African Rands (CIVITAS, 2016).

The cost of a hydrogen fuel cell bus is currently extremely high compared to other energy alternatives. However, this price will become cheaper overtime, once economy of scale is reached with regards to the mass production of hydrogen fuel cell buses and the future growth of component supply chain. The CAPEX for hydrogen fuel cell buses are also high due to the fuelling and supply infrastructure which are very expensive (CIVITAS, 2016).

The main advantages of hydrogen fuel cell buses are that they are one of the cleanest available technologies given the local zero emission of pollutants and lower noise emissions. The main disadvantages of hydrogen fuel cell buses is that the technology is not mature yet. There are also safety concerns associated with the high pressure fuelling and storage of hydrogen gas. The hydrogen fuel cell bus powertrain is also less efficient than a fully electric one. Lastly, hydrogen fuel cell buses have high associated vehicle and infrastructure costs which may be prohibitive in the current South African economic climate.

2.5 Waste to Energy Scenarios at Dube Tradeport

The Dube Tradeport and surrounding Durban Aerotropolis has been designed using sustainable development principles which encourage the integration of sustainability initiatives within the precinct (Dube Tradeport, 2020).

The Dube Tradeport masterplan envisions the development of a new regional wastewater treatment works to be developed to meet the increase in demand for treating wastewater produced from the surrounding developments (Dube Tradeport Masterplan, 2016). It was hypothesised that the new regional wastewater treatment works that is planned for Dube Tradeport, could produce a substantial supply of biogas via anaerobic digestion of wastewater sludge and organic waste from the Dube AgriZone, to fuel a portion of the buses which operate on the C8 line of the proposed Go! Durban BRT system.

This would allow the eThekweni Municipality to meet their goals of reducing the well to wheels GHG emissions of the Go! Durban Bus Fleet, whilst assisting Dube Tradeport to deal with excess of wastewater sludge that will be produced at the proposed new wastewater treatment works that is being designed for the precinct (eThekweni Climate Action Plan, 2019).

The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. It is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO₂) (EPA, 2020). Methane (CH₄) is estimated to have a GWP of 28–36 over a period of 100 years (EPA, 2020). This means that methane gas has a global warming potential of 28 to 36 times the warming potential of CO₂.

Therefore, if Dube Tradeport chooses anaerobic digestion, as a solution towards dealing with excess wastewater sludge being produced at the proposed new regional wastewater treatment works, the subsequent biogas, of which a large portion is biomethane, that is produced must be used in a sustainable way to limit the negative impact on the environment (Dube Tradeport Masterplan, 2016).

A detailed case study of the wastewater treatment demand at Dube Tradeport in terms of quality and quantity has been documented in Chapter 4 to develop input criteria for a biogas projection model. The results of biogas modelling as presented in Chapter 5, compares four different wastewater treatment methods, to quantify which wastewater treatment method would produce the largest amount of excess biogas and therefore energy after meeting the operational energy needs to the wastewater treatment plant itself. The following section consists of a literature review of the four chosen wastewater treatment methods for which biogas projection models will be applied.

2.5.1 Wastewater Treatment Methods

Wastewater treatment processes are designed to improve the quality of wastewater for safe discharge or reuse. Treatment processes are designed to reduce the following suspended solids, biodegradable organics, pathogenic bacteria, nutrients such as nitrogen and phosphorus. (Nozaic and Freese, 2009). These pollutants contribute towards eutrophication and pollution of water bodies if not reduced during the treatment process before discharge.

Wastewater treatment consists of four main phases: Primary (mechanical) treatment is designed to remove large, suspended, and floating solids from the raw sewage (Nozaic and Freese, 2009). This process includes the screening (or sieving) of solid objects, degritting, fat removal, and sedimentation by gravity to remove suspended solids. Chemicals are sometimes used to accelerate the sedimentation process. Primary

treatment without chemicals can reduce the BOD of the incoming wastewater by 20-35% and the total suspended solids by 50-65% (Global Methane Initiative, 2016).

Secondary (biological) treatment removes the dissolved organic matter that escapes primary treatment (Nozaic and Freese, 2009). Aerobic systems are often used with a supply of artificial aeration (e.g. conventional activated sludge [CAS]) or with natural aeration (e.g. trickling filters). In aerobic systems, microbes in the water are boosted by the air supply and consume the organic matter as food, and converts it to carbon dioxide, water, and energy for their own growth and reproduction (Global Methane Initiative, 2016).

The biological process is then followed by additional settling tanks known as secondary sedimentation to settle and keep the microbes in the treatment system. About 85-95% of the suspended solids and BOD can be removed with secondary treatment (Global Methane Initiative, 2016). Alternatively, biological treatment in aerated systems can be replaced by an anaerobic system (without artificial aeration or ventilation) (Global Methane Initiative, 2016).

Tertiary treatment is any additional treatment beyond secondary treatment. This process can remove more than 99 percent of all the impurities from sewage (Nozaic and Freese, 2009). Tertiary treatment technologies can be expensive, requiring technically skilled treatment plant operators, a steady energy supply, chemicals and specific equipment. A tertiary treatment process is the modification of a conventional secondary treatment plant to remove additional phosphorus and nitrogen (Global Methane Initiative, 2016).

Anaerobic Digestion and Co-digestion is the final phase where biodegradable organics (BOD) and excess microbes ("sludge") is removed from the primary and (aerobic) secondary treatment to be processed in anaerobic sludge digesters (Nozaic and Freese, 2009). Anaerobic digesters are sealed vessels where microorganisms break down biodegradable material in the absence of oxygen (Global Methane Initiative, 2016).

In addition to eliminating pathogens and reducing odours, one of the end products of anaerobic digestion is biogas, which can be combusted to generate electricity and heat, or can be processed into renewable natural gas and transportation fuels (Global Methane Initiative, 2016).

In addition to the sludge digestion, anaerobic digesters can be designed to accept additional organic waste feedstocks (such as fats, oil, greases, restaurant and canteen waste, dairy waste, crop residues, animal manure, etc.) (Nozaic and Freese, 2009).

These additional waste streams boost biogas yields, and depending on the size of the wastewater facility, can improve the financial feasibility of a biogas project (Global Methane Initiative, 2016).

2.5.1.1 Conventional Activated Sludge Method with Anaerobic Co-Digestion

A typical Conventional Activated Sludge plant with anaerobic co-digestion consists of a process where wastewater influent first goes through a primary settling tank to remove suspended and floating solids (Nozaic and Freese, 2009). Sludge that is removed from the primary settling tank (known as primary sludge) is diverted to an anaerobic digester.

After leaving the primary settling tank, the wastewater enters the activated sludge process (secondary treatment). The wastewater passes through a series of aeration tanks to remove biodegradable organics. In these tanks, microorganisms cultivated in the treatment process are kept in suspension, aerated, and in contact with the waste they are treating (Global Methane Initiative, 2016).

After the aeration tanks, the wastewater is held in a secondary clarifier to settle out any remaining sludge (secondary sludge or waste activated sludge) (Nozaic and Freese, 2009). Some of the secondary sludge is sent to the beginning of the activated sludge process, providing the microorganisms that drive the treatment process, and the rest is diverted to the anaerobic digester (Nozaic and Freese, 2009)

The anaerobic digester produces biogas from the primary sludge, secondary sludge, and any other organic feedstocks sent to the facility for co-digestion (Global Methane Initiative, 2016). The Figure 20 below shows a schematic of the conventional activated sludge process:

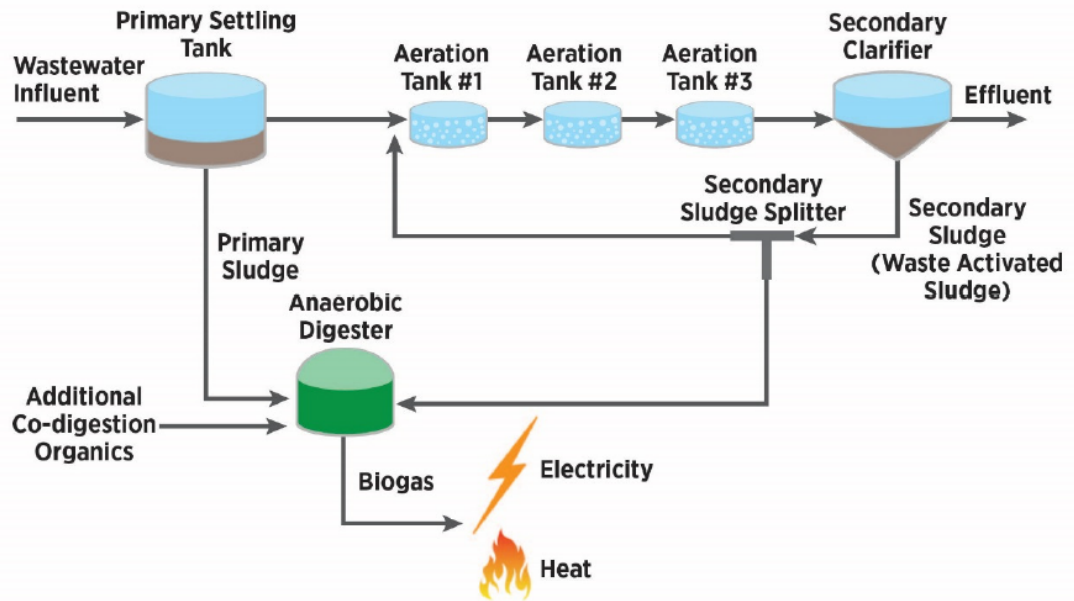


Figure 20 Showing a typical Conventional Activated Sludge Plant with Anaerobic Digestion (Global Methane Initiative, 2016).

The advantages of a Conventional Activated Sludge WWTW consists of the following: activated sludge is the best documented and most widely used form of secondary wastewater treatment, efficient removal of organic material and nutrients, when designed and professionally operated according to local requirements, flexibility and numerous modifications that can be tailored to meet specific requirements (e.g. for nitrogen removal) and lastly Low land requirements for the development of the plant (Global Methane Initiative, 2016).

The Conventional Activated Sludge WWTW is also expensive in terms of both capital and operation and maintenance costs, it requires a constant supply of energy, trained operators to monitor the system and react to changes immediately, and the availability of spare parts and chemicals may be a hindrance in some cases (Global Methane Initiative, 2016).

2.5.1.2 Trickling Filter with Anaerobic Co-digestion

In the typical wastewater treatment process involving Trickling Filters and anaerobic digestion, wastewater influent first goes through a primary settling tank to remove suspended and floating solids (Nozaic and Freese, 2009).

Sludge that is removed from the primary settling tank (primary sludge) is diverted to the anaerobic digester. After leaving the primary settling tank, the wastewater enters the trickling filter (secondary treatment) (Global Methane Initiative, 2016).

In a similar way to the activated sludge process, trickling filters are used to remove organic matter from wastewater, but rather than pumping air through the wastewater (as is done with conventional activated sludge), trickling filters consist of a bed of a highly permeable medium, usually made from specially designed plastics, to which microorganisms attach themselves (Nozaic and Freese, 2009).

Wastewater is trickled onto the medium from the top using a rotary distributor, while natural ventilation through air convection provides aeration and allows the organic material to degrade (Global Methane Initiative, 2016). After leaving the trickling filter, wastewater goes to a secondary clarifier to settle out microbes that have been detached from the media and flushed out (secondary sludge) (Nozaic and Freese, 2009). This secondary sludge is diverted to the anaerobic digester and is digested along with the primary sludge and any other organic feedstocks sent to the facility for co-digestion to produce biogas (Global Methane Initiative, 2016). The Figure 21 below shows a schematic of the Trickling Filter process:

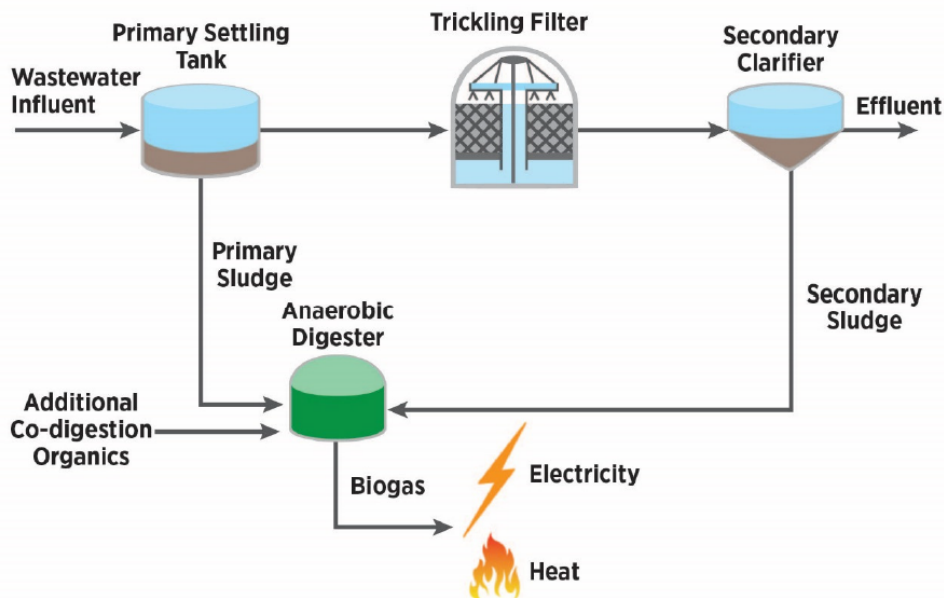


Figure 21 Showing Trickling Filter Plant with Anaerobic Digestion (Global Methane Initiative, 2016)

The advantages of the Trickling Filter wastewater treatment method consists of the following aspects: it is a simple, reliable, biological process, effective in treating organics and nitrogen, durable, low power requirements, low land requirements, moderate level of skill and technical expertise needed to manage and operate a Trickling Filter wastewater treatment plant (Global Methane Initiative, 2016).

This type of wastewater treatment plant also requires regular operator attention. Without due attention and regular filter flushing the incidence of clogging can be high due to an accumulation of excess biomass (Nozaic and Freese, 2009). Additional treatment may be needed to meet more stringent discharge standards. Flexibility and control are limited in comparison with activated-sludge processes. There is also a certain risk of filter flies, if the wastewater is not uniformly distributed over the complete filter surface (Global Methane Initiative, 2016).

2.5.1.3 Up-flow Anaerobic Sludge Blanket (UASB) Reactors

An Up flow Anaerobic Sludge Blanket (UASB) reactor is a type of anaerobic digester. In this treatment methodology, sludge settlement and digestion take place in one or more large tanks, which is a combination of primary and secondary treatment processes. The post UASB treatment liquids, which have a reduced organic content, require aeration and/or treatment to remove any remaining pathogens (Global Methane Initiative, 2016).

In UASBs wastewater is pumped upwards through a 'blanket' of granular sludge which treats the wastewater. Bacteria living in the sludge break down organic matter by anaerobic digestion, producing biogas which can be captured at the top of the reactor. The upward hydraulic flow works in conjunction with gravity settling to suspend the sludge granules until they reach a threshold density and fall to the bottom of the reactor as a 'sludge bed,' which is then treated (Global Methane Initiative, 2016).

The advantages of this treatment process is that the trickling filter can treat high organic loads using short hydraulic retention times. Typical efficiency of about 60-70% BOD removal. Does not require expensive aerating system. Low land requirements (can be constructed underground). Lower energy demands than conventional activated sludge. The excess sludge from subsequent post-treatment can also be digested in the UASB and lastly there is a low sludge production rate (Global Methane Initiative, 2016). The Figure 22 below shows a schematic of the Up Flow Anaerobic Sludge Blanket (UASB) reactor:

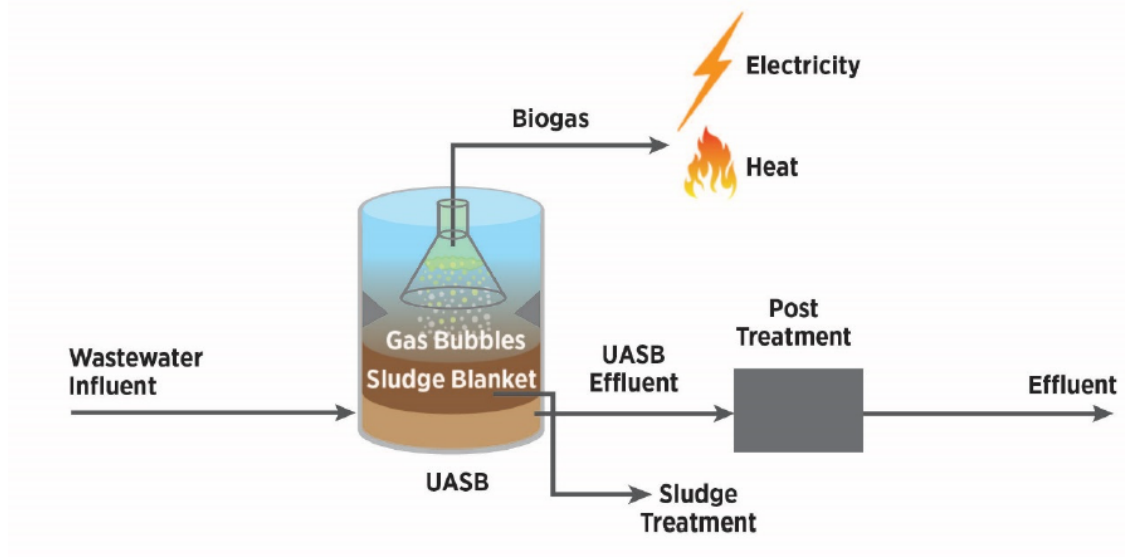


Figure 22 showing the Up Flow Anaerobic Sludge Blanket (UASB) Reactor (Global Methane Initiative, 2016).

An Up Flow Anaerobic Sludge Blanket plant has a slower start-up than conventional activated sludge, because the anaerobic sludge yield is lower than aerobic sludge yield; therefore, it takes more time until enough biomass for proper treatment has been built up. An efficient preliminary treatment is very important (efficient screening, or better sieving) to minimize scum accumulation under the biogas collector (Global Methane Initiative, 2016).

A skilled operator is required to monitor the reactor, repair parts, and ensure that excess sludge is removed, and that biogas is properly collected. It is a cheaper system with regards to construction and maintenance compared to the conventional aerobic processes. Lastly, this type of plant requires corrosion resistant materials (Global Methane Initiative, 2016).

2.5.1.4 Covered Anaerobic Pond

Anaerobic ponds are basins in which wastewater is treated under the absence of oxygen. Wastewater influent flows directly into the anaerobic pond after screening and degritting (Nozaic and Freese, 2009). Solids settle to the bottom of the pond, where they are digested. Usually anaerobic ponds are open (i.e. no aeration process occurs) but when the pond is covered, biogas can be captured and used for the generation of electricity and heat or upgraded for use as a transport fuel.

Anaerobic ponds are a primary treatment process, but secondary treatment can be added with facultative and maturation ponds, trickling filters, CAS, or other aerobic technologies (Global Methane Initiative, 2016). This Figure 23 below shows a schematic of a Covered Anaerobic Pond system:

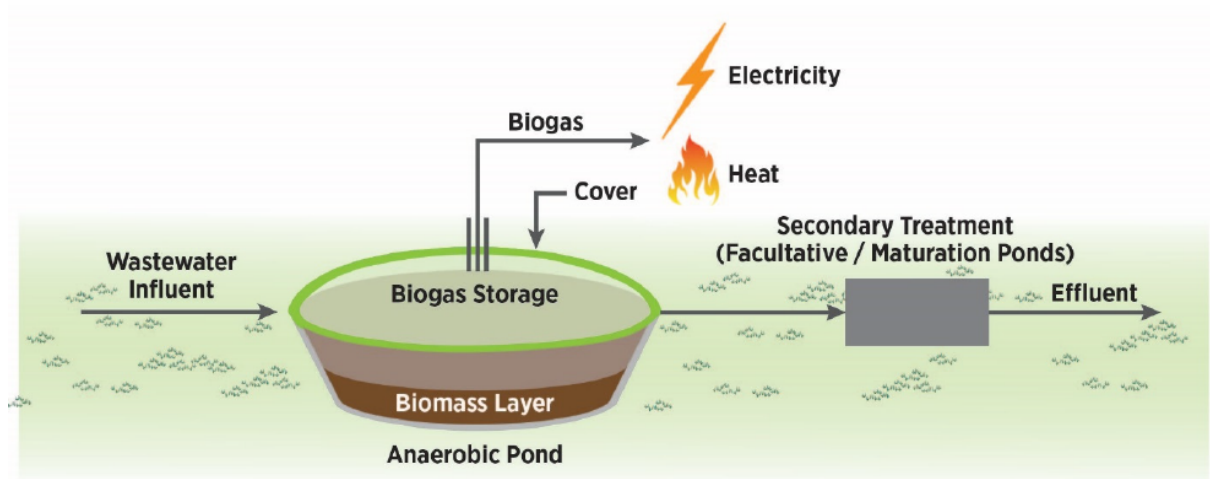


Figure 23 Showing Covered Anaerobic Pond treatment method (Global Methane Initiative, 2016).

The advantages of a Covered Anaerobic Pond system is that it is a simple and robust treatment method, it has a typical efficiency of about 50% BOD removal and 60-80 % suspended solids removal, the excess sludge from subsequent secondary treatment can also be digested in the anaerobic pond, it is economical to build and operate and can be managed relatively easily by small and medium-sized communities (Global Methane Initiative, 2016).

A Covered Anaerobic Pond takes time to reach full treatment efficiency, it requires large amounts of land compared to conventional activated sludge or other secondary treatment technologies and a strategy for sludge removal from the pond should always be part of the design and not left to the operator (Global Methane Initiative, 2016).

2.5.2 Developing Waste to Energy Scenarios for Dube Tradeport

Once the biogas model has been run and the outputs compared to determine which wastewater treatment technology will be chosen for Dube Tradeport, a strategy for dealing with the biogas that is produced from the anaerobic digestion of the wastewater sludge is required.

Considering that the eThekweni Municipality is looking for a solution to reduce the well to wheels (WTW) GHG emissions of the new bus fleet which will be purchased for Line 8 of the Go! Durban Bus Rapid Transit system. As well as the need to develop sustainable energy systems for the Durban Aerotropolis as per the Dube Tradeport Integrated Development Plan (Dube Tradeport Masterplan, 2016). There is an opportunity to develop and integrated Waste to Energy Solution which will assist both parties to achieve their sustainable development requirements.

Following this understanding, three waste to energy scenarios have been developed for a proposed new wastewater treatment works to be developed at Dube Tradeport: Biogas extraction for onsite electricity generation and or storage for battery electric Go! Durban BRT buses, Biogas extraction and upgrade to pure biomethane (compressed natural gas) fuel for Go! Durban BRT buses and Bio-Gas extraction and upgrading using the Hazer Process to pure Bio-hydrogen to power fuel cells for hydrogen fuel cell electric Go! Durban BRT buses. These scenarios were developed from the literature review of sustainable bus propulsion technologies (CIVITAS, 2016).

These three Waste to Energy scenarios form the basis of an analysis with regards to the calculation of a sustainability indicator which indicates how many buses can be fuelled per day at Dube Tradeport using the excess biogas that is produced from the anaerobic digestion of the wastewater sludge. The following section investigates the process of biogas upgrade to pure biomethane which can be used to power a Compressed Natural Gas (Bio-CNG) Euro VI ICE bus.

2.5.2.1 Automated Water Scrubbing Based Methane Enrichment and Compression System

The presence of a high concentration of CO₂ in biogas lowers the energy content per unit mass or volume and limits the resulting gas to only low-quality energy applications. Biogas containing a large amount of CO₂ is undesirable for use as a vehicular fuel because it lowers the power output from the engine and occupies additional space in the storage cylinders. Therefore, this will reduce the refilling range of the vehicle. The presence of excess carbon dioxide in biogas can result in the freezing at valves and metering points (Demirbas,2009). Therefore, it is important that biogas undergoes an upgrade process to remove the unwanted impurities, before it can be used as a sustainable vehicle fuel alternative. Biogas contains approximately 45 to 70 percent methane, 1 to 2 percent hydrogen sulphide, 35 to 55 percent carbon dioxide and trace elements of oxygen, siloxanes, carbon monoxide and water vapour (Angelidaki et al,

2019). The Table 8 below shows the a summary of the compounds which make up biogas:

Table 8 Showing Compounds that make up biogas (Angelidaki et al, 2019):

Typical Concentration of Biogas	
Compound	Concentration (%)
Methane (CH ₄)	45–70
Hydrogen sulphide (H ₂ S)	1–2
Oxygen (O ₂)	Trace
Siloxanes	Trace
Carbon dioxide (CO ₂)	35–55
Carbon monoxide (CO) Trace	Trace
Water vapor Trace	Trace

There are a number of factors which need to be considered when evaluating which biogas upgrading method to choose for a wastewater treatment plant. Some of the factors include the Capex and Opex costs of the biogas upgrade system, the amount of methane gas which is lost during each upgrade process, the amount of energy that is required for the upgrade process, disposal of the by-product of the chosen biogas upgrade system, the pressure requirement for the system to work and the purity of the biomethane gas that is produced at the end of the upgrade process.

Other factors that should be included involve the availability of skilled technicians to monitor and manage the upgrade process. In the context of the eThekweni Municipality, skills training of wastewater treatment plant operators may be required to ensure that the upgrade process is successfully carried out and remains economically viable over the long term. According to the Table 9 below (Chandra et al, 2012), water absorption or water scrubbing of biogas is the cheapest and most energy efficient method of enriching the bio-methane content of bio-gas for use as a vehicular fuel.

Table 9 Showing: A comparison of advantages and disadvantages of different biogas upgrade methodologies (Chandra et al, 2012)

Sl. No.	Method	Advantages	Disadvantages
	Absorption in water	One of the easiest and cheapest methods for CO ₂ removal. Recommended for rural application.	Water pumping load is high and some loss of methane with washing water.
	Absorption by chemicals	The chemical absorbents are more efficient in low pressure and can remove CO ₂ to low partial pressures in treated gas.	Regeneration of the solvent requires a relatively high energy input. Disposal of by-product formed due to chemical reactions is a problem.
	Pressure swing adsorption	By proper choice of the adsorbent, this process can remove CO ₂ , H ₂ S, moisture and other impurities.	Adsorption is accomplished at high temperature and pressure. Regeneration is carried out by vacuum. It is a costly process.
	Membrane separation	Modular in nature and separate CO ₂ and CH ₄ effectively.	High pressure requirement. The processing cost is also high.
	Cryogenic separation	Allows recovery of pure component in the form of liquid, which can be transported conveniently	High cost involved makes it impractical for biogas applications.
	Chemical conversion	Extremely high purity in the product gas.	Process is extremely expensive and is not warranted in most cases of biogas applications.

There are available technologies, which are economically feasible, to enrich the methane content of biogas up to natural gas level. The Table 10 below shows the efficiency of the main physicochemical biogas upgrading technologies (Andriani et al., 2014; Bauer et al., 2013a; Bekkering et al., 2010; Jürgensen et al., 2014; MeGa-stoRE, 2016; Muñoz et al., 2015; Ryckebosch et al., 2011; Serejo et al., 2015; Toledo-Cervantes et al., 2017).

Table 10 Showing: A comparison of different biogas upgrade techniques by literature review

	Cryogenic	Sabatier Process	PSA	Water Scrubbing	Physical Scrubbing	Chemical Absorption	Membrane Separation
Consumption for raw biogas (kWh/Nm ³)	0,76	n/a	0.2341.30	0.25-0.3	0.2--0.3	0.05--0.15	0.18--0.20
Consumption for clean biogas (kWh/Nm ³)	n/a	n/a	0.29-1.00	0.341.9	0,4	0.05--0.25	0.14--0.26
Heat consumption (kWh/Nm ³)	n/a	n/a	None	None	<0.2	0.5--0.75	None
Heat demand (°C)	-196	270	-	-	55-80	100-180	
Cost	High	Medium	Medium	Medium	Medium	High	High
CH ₄ losses (%)	2	n/a	<4	<2	2-4	<0.1	<0.6
CH ₄ recovery (%)	97-98	97-99	96-98	96-98	96-98	96-99	96-98
Preunification	Yes	Recommended	Yes	Recommended	Recommended	Yes	Recommended
H ₂ S co-removal	Yes	No	Possible	Yes	Possible	Contaminant	Possible
N ₂ and O ₂ co-removal	Yes	No	Possible	No	No	No	Partial
Operation pressure (bar)	80	8-10	3-10	4-10	4-8	Atmospheric	5-8
Pressure at outlet (bar)	8-10	-	4-5	7-10	1.3-7.5	4-5	4.-6

The methane enrichment of biogas to biomethane quality and feeding into the natural gas grid or compression into cylinders is an effective way of integrating biogas into the energy sector (Kapdi,2005). Carbon dioxide has a higher solubility in water than methane.

Therefore, more carbon dioxide is dissolved in water than methane, particularly at a lower temperature. The water scrubbing process, causes carbon dioxide to dissolve in the water, while the methane concentration in the gas phase increases. As shown in the table above a methane recovery rate of between 96% to 98% can be achieved using this process.

The gas leaving the scrubber has, therefore, an increased concentration of methane. Apart from carbon dioxide, water can remove other impurities such as hydrogen sulphide, ammonia, hydrogen phosphide, chlorinated hydrocarbons, and others. The water leaving the absorption column contains dissolved gases mainly carbon dioxide

with very little amount of methane and others. The operation of water scrubbing system is highly dependent on the solubility of carbon dioxide at a specific temperature and pressure in the water to form dilute carbonic acid (Chandra et al, 2012).

The compressed raw biogas is fed to a packed bed absorption column from the bottom of the scrubber, and pressurized water is sprayed from the top (counter-current flow of biogas and water) (Chandra et al, 2012). This process is one of the simplest and cheapest methods of methane enrichment of biogas.

Another advantage of the water scrubbing system over other processes is that the outcoming water containing dissolved carbon dioxide and other impurities from the scrubbing column is easy to dispose. However, in other processes the chemicals used require special handling and disposal due to environmental safety and health hazards (Bauerfield et al,2009). It is recommended that the wastewater, that is produced from the water scrubbing process, is treated via a passive, low energy polishing facility such as a reedbed or artificial wetland before being discharged into the natural environment.

The Figure 24 below shows a schematic of the water scrubbing enrichment process:

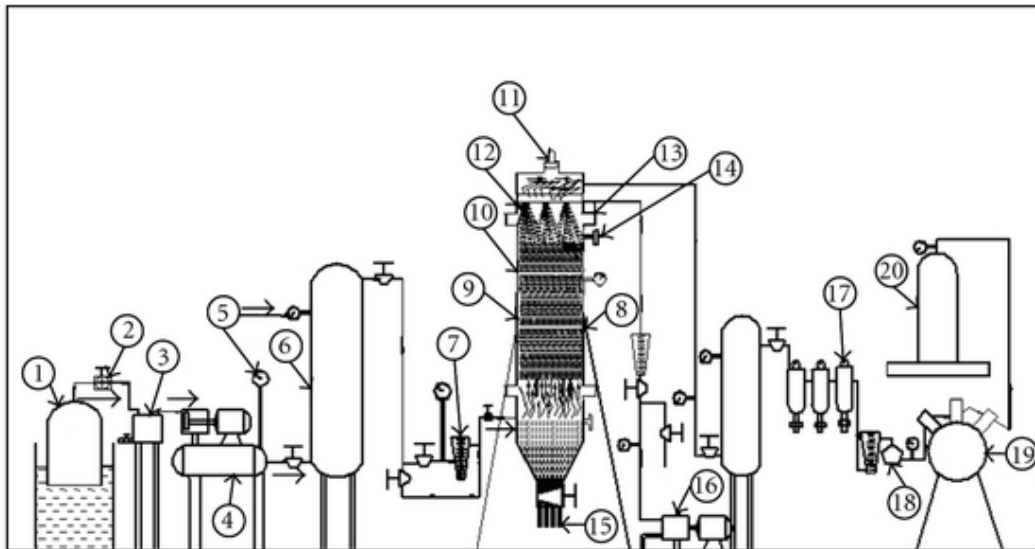


Figure 24 Showing a schematic diagram of water scrubbing based methane enrichment in biogas and compression system (Chandra et al, 2012)

The Table 11 below describes the different components of the water scrubbing system as shown in the diagram above:

Table 11 Showing the components of the water scrubbing based methane enrichment and compression system (Chandra et al. 2012)

<i>Table Showing the components of the water scrubbing based methane enrichment and compression system</i>
1. Biogas Plant
2. Ball Valve
3. Water Remover
4. Compressor mounted with biogas receiver
5. Pressure Gauge
6. Gas Storage Vessel
7. Rotameter
8. Supporting Stand
9. Reshching Rings
10. Scrubber
11. Pressure Safety Valve
12. Water Sprayer
13. Flange
14. Water Level View Glass
15. CO ₂ laden water outlet
16. High pressure water pump
17. Moisture removing filter
18. Pressure Reducer
19. Three Stage Gas Compressor
20. CNG Cylinder

Chandra et al (2012) recommends that the water scrubbing system for methane enrichment in biogas should be modified and automated using an electronic control system. The electronic control system operates the process under steady state and

maintains a consistent methane quality in the purified gas outlet stream, in order to produce vehicular quality biomethane from biogas.

According to Chandra et al (2012), the percentage absorption of carbon dioxide increases with an increase in the scrubbing column pressure. It was found that the highest carbon dioxide absorption rate of 90.6% was observed at a column operating pressure of 1.0 MPa. A methane purity of 97% has been observed at this pressure.

Further it has been shown that the performance of a 5.9 kW stationary diesel engine, that has been converted into a spark ignition model, and run on both compressed natural gas (CNG) and methane-enriched biogas (Bio-CNG) has shown a similar engine performance without any significant power loss (Chandra et al, 2011).

The use of an automatic control system in the water scrubbing process results in a steady state system operation which provides a consistent methane quality in the outlet stream of purified gas. Chandra et al (2012) showed that an improved automated water scrubbing unit enriched biogas up to 97% methane content, using a 1.0 MPa column-operating pressure with 2.5 m³/h biogas in-flow rate and 2.0 m³/h water in-flow rate.

The typical water flow that is needed to upgrade 1000 Nm³/h of raw biogas ranges between 180 and 200 m³/h depending on the pressure and water temperature (Bauer et al., 2013). The large volume of water that is required for this process can be easily sourced from the treated wastewater that will be produced at Dube WWTW.

2.5.2.2 Biogas upgrade to biohydrogen via the Hazer Process

The two most widely used methods of hydrogen production consists of electrolysis and the steam reformation of natural gas. The steam reformation of natural gas contributes to almost 95% of the total global hydrogen production. This method however contributes towards significant CO₂ emissions during the hydrogen production process.

Electrolysis is the process of passing an electric current through water, which results in the splitting of the H₂O molecule into hydrogen and oxygen respectively. This process is extremely energy intensive and is only sustainable if renewable energy sources are used. Both methods described above require a significant supply of fresh water which is not feasible over the long term, in a water scarce country such as South Africa. The Figure 25 below shows an overview of the Hazer Process which produces hydrogen gas by splitting the methane molecule:

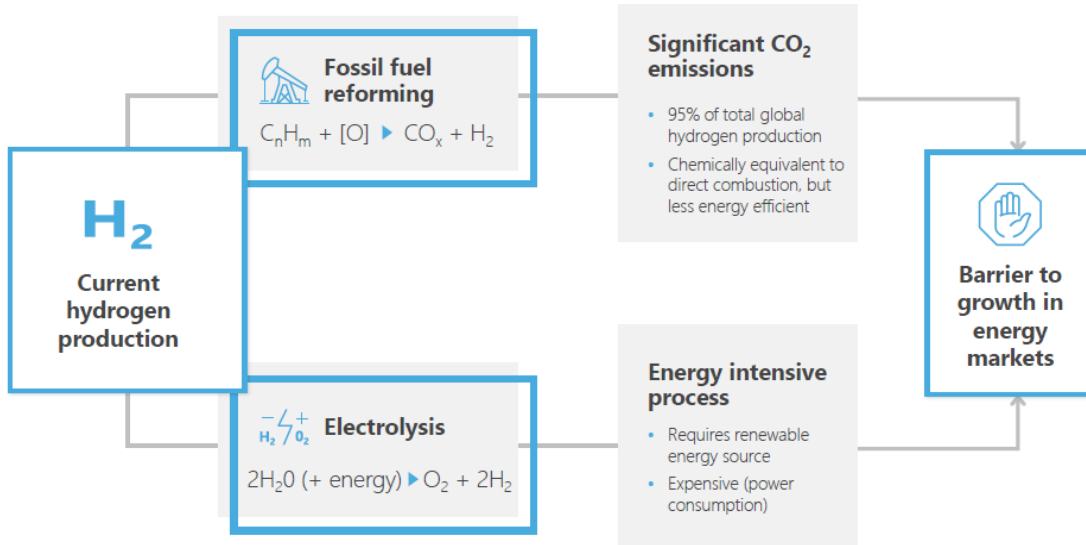


Figure 25 Showing the current methods of producing Hydrogen Gas

The sustainable alternative to electrolysis is the conversion of renewable bio-methane into bio-hydrogen. The traditional method of steam reformation produces CO₂ as a by-product as shown in the Figure 26 below. The Hazer Process is innovative in that it produces hydrogen gas and carbon graphite as a by-product, both of which are revenue generating products. The income generated from the sale of the carbon graphite by-product can be used to offset the cost of a clean, renewable hydrogen-based energy system (Hazer Group, 2018).

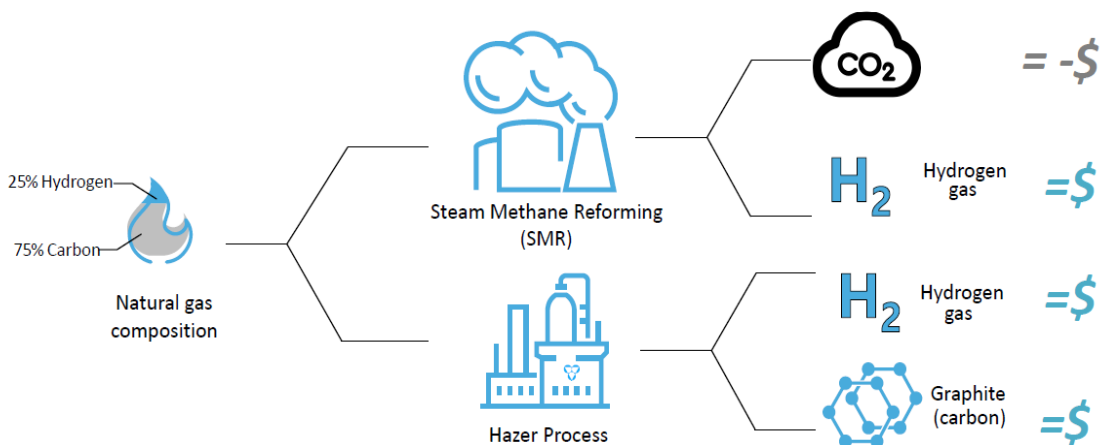


Figure 26 Showing a by-product comparison of Steam Methane Reformation vs. the Hazer Process (Hazer Group, 2018)

The Hazer Process unlocks the value chain of the Circular Economy by using an innovative method of capturing, storing and utilising the CO₂ that is produced during hydrogen production (Hazer Group, 2018). Carbon graphite can be used in various components of a hydrogen fuel cell powered vehicle or bus as shown in the Figure 27 below.

This presents an interesting opportunity to develop an entire new manufacturing industry in South Africa which revolves around the production of Hydrogen Fuel Cell powered vehicles and the developed of the extended value chain which includes hydrogen production, storage, pipelines and fuelling stations. According to Mintek, South Africa has 80% of the worlds known platinum reserves which results in an attractive proposition for the South African Government to investigate the development of the Hydrogen Fuel Cell Economy, both for local consumption and export purposes (Mintek, 2020). This is because platinum metal is an important catalyst which is used in hydrogen fuel cells.

Fuel Cell Vehicle

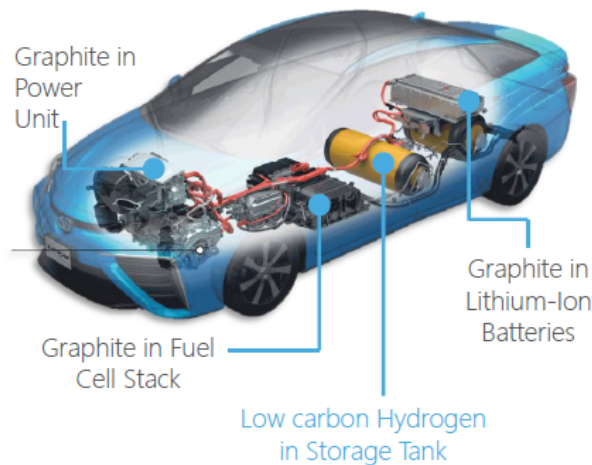


Figure 27 Showing the application of Hazer Process by-products in a hydrogen fuel cell powered vehicle (Hazer Group, 2018)

The Hazer process uses a methane cracking process to split bio-methane (CH₄) into hydrogen gas (H₂) and carbon graphite as shown in the figure below. Iron ore is used as a catalyst in this reaction.

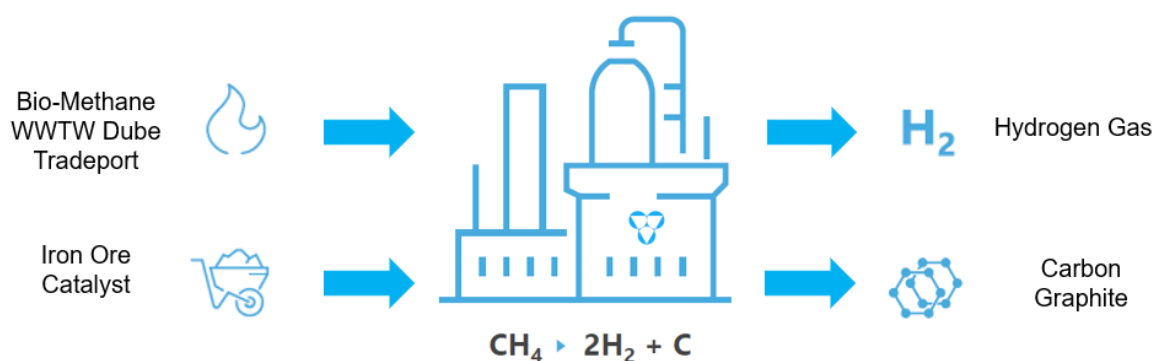


Figure 28 Showing: Methane cracking process that is used in the Hazer process (Hazer, 2018)

Data obtained from the Hazer Group (2018) regarding the mass and energy feed requirements, per tonne of hydrogen, that is produced via the Hazer Process is shown in the table below:

Table 12 Showing the mass and energy feed requirements per tonne of hydrogen that is produced via the Hazer Process: (Hazer Group, 2018)

Mass and Energy feeds and outputs (per tonne of Hydrogen Product)				
Hazer Process Overall Conversion	(%)	50%	70%	90%
Primary Product				
H ₂ Product (99.999%) ²	(t)	1.0	1.0	1.0
Graphite Product (85-90% w/w)	(t/t H ₂)	5.0	4.4	4.1
Gas Input and Output				
Natural Gas Feed	(t/t H ₂)	11.9	7.5	5.4
	(TJ/t H ₂)	0.60	0.38	0.27
Output - Fuel Gas By-Product	(TJ/t H ₂)	0.33	0.13	0.03
Net Gas (Energy) Consumption	(TJ / t H ₂)	0.27	0.25	0.24
Other Feed				
Iron Ore feed	(t/t H ₂)	1.02	0.90	0.83
Process Heating Duty	(MWhrs / t H ₂)	9.26	8.23	7.67
Electricity (For Gas Compression)	(MWhrs / t H ₂)	0.62	1.20	1.53

The data in this table will be used in Chapter 5 to evaluate how much hydrogen can be produced using the Hazer process at Dube Tradeport which in turn would indicate how many hydrogen fuel cell buses could be fuelled per day on Line 8 of the Go! Durban Bus Rapid Transit system.

2.5.3 Biogas Projection Models for Wastewater Treatment Plants

A critical review of the current literature regarding biogas projection tools for wastewater treatment plants, identified two biogas modelling tools which were most suitable for application to the Dube Tradeport precinct at the heart of the Durban Aerotropolis. This involved the selection of one International Biogas model and one South African biogas model which was developed for local conditions. The Biogas Wastewater Assessment Technology Tool (BioWATT) and the Municipal Wastewater Treatment Works Biogas to Combined Heat and Power Evaluation Tool were selected as the final two biogas projection models and compared for potential use. A comparative analysis of the two selected biogas models is shown in the table below:

The date at which each model was published, the organisations which authored the models, the target market for which the models were developed, the currency in which the Opex costs are modelled, the ability to run the model for different wastewater treatment types and the level of detail that is provided when running the analysis for each model were considered. This is summarised in the Table 13 below:

Table 13 Showing a comparison of the final two biogas projection models

Name of Model	Biogas Wastewater Assessment Technology Tool (BioWATT)	Municipal Wastewater Treatment Works Biogas to Combined Heat & Power (CHP) Evaluation Tool
Date Published	2016	2015
Authors	World Bank & Global Methane Initiative	GIZ, SALGA & WEC Projects (Pty) Ltd
Target Market	Developing Countries	South Africa
Currency Calibration	US Dollar	Rands
Opex Reductions	Yes	Yes
Capex Calculation	No	Yes
Analyses Multiple WWTW Methods	Yes	Yes
Analysis Detail	Advanced	Basic

The qualitative data in the table above regarding the two biogas evaluation models for wastewater treatment works led to the data driven decision to use the Biogas Wastewater Assessment Technology Tool (BioWATT) model. BioWATT was published more recently (2016) than the Municipal Wastewater Treatment Works Biogas to Combined Heat & Power (CHP) Evaluation Tool (2015).

Secondly the BioWATT model is able to provide a greater level of detail with regards to the biogas analysis output. The analysis output of the BioWATT model was very useful with regards to comparing the projected biogas generation capabilities of four different wastewater treatment technologies assuming that the wastewater inflow quality and quantity characteristics remained the same each time. The BioWATT analysis tool has been developed by the Global Methane Initiative in conjunction with the World Bank to create a decision-making tool which can be used by wastewater managers to design treatment processes based on projected bio-gas generation and its subsequent use as an energy source to offset the electricity and heat requirements of a treatment plant.

2.6 Multi-Criteria Analysis Decision Making Tools for Sustainable Urban Mobility

Two Alternative Bus Fuel Frameworks were identified from literature as strong inventories of Sustainability Indicators and Alternative Bus Fuel Scenarios. Both of the selected frameworks are standardised international tools which can be applied in the South African context.

The selected frameworks comprised of the Alternative Bus Technologies Framework, which was developed by the C40 Cities Finance Facility in collaboration with Grütter Consulting, in 2018 and the CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework which was published in 2016.

The Alternative Bus Technologies Framework, which was developed by the C40 Cities Finance Facility in collaboration with Grütter Consulting presented a strong and well researched inventory of Sustainability Indicators and Bus Fuel Alternative Scenarios. However, this framework had fewer Smart Fuel Scenarios overall and did not include Biofuel options such as Bio-diesel or Bio-Ethanol. Therefore it was not selected as a baseline framework of the T.R.O.I.S multi-criteria decision making model which is explored in greater detail in Chapter 5.

The purpose of this dissertation is to provide a Transport Engineer at the eThekweni Municipality with the best possible recommendation and so the CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework (2016) was ultimately chosen for modification and development into the Smart Fuel Scenario Assessment Matrix.

The following sustainability indicators are used within the CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework (2016): Range, Route Flexibility, Energy Consumption, Refuelling Frequency, Refuelling Time, GHG Emissions (WTW), PM10 (TTW), NOx (TTW), Noise Emissions, Cost Per Bus. This framework was modified with addition of a new sustainability indicator: Number of buses which can be fuelled per day at Dube Tradeport to link the biogas modelling and Waste to Energy Strategy modelling into a single integrated public transport fleet planning tool. This is highlighted in blue in the table 14 below.

Table 14 Showing 10 Sustainability Indicators obtained from the CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework (2016) modified by the addition of number of buses fuelled per day at Dube Tradeport

Sustainability Indicator	Unit
Range	km
Route Flexibility	n/a
Energy Consumption	kWh/km
Refuelling Frequency	Days
Refuelling Time	Minutes
GHG Emissions (WTW)	gCO ₂ e/km
PM10 (TTW)	g/km
NOx (TTW)	g/km
Noise Emissions	dB
Cost Per Bus	Rands
Number of buses which can be fuelled per day at Dube Tradeport	n/a

2.7 Chapter Summary

The Literature Review which was conducted in Chapter 2, consisted of a critical analysis of Sustainable Urban Mobility, the relationship between Transport, Climate Change and the Greenhouse Effect, an investigation into the Go! Durban Bus Rapid Transit System, a comparative review of sustainable Smart Fuel alternatives for bus systems and Waste to Energy Scenarios for Dube Tradeport with regards to wastewater management.

Chapter 3: Methodology

In this chapter, the methodological approach used in this dissertation will be displayed in the form of a flow-chart. The methodology explained in this section of the dissertation explores the use of the BioWATT Wastewater Treatment Scenario Evaluation Model, the development of the SMART Sustainability Indicator Assessment Matrix, the Smart Fuel Scenario Assessment Matrix and the final development of a multi-criteria decision making tool to assist Transport Engineers in the eThekweni Transport Authority.

3.1 Introduction

The Figure 28 below shows the methodological approach which was used to develop this dissertation. The stepwise process has been detailed in the form of a flowchart.

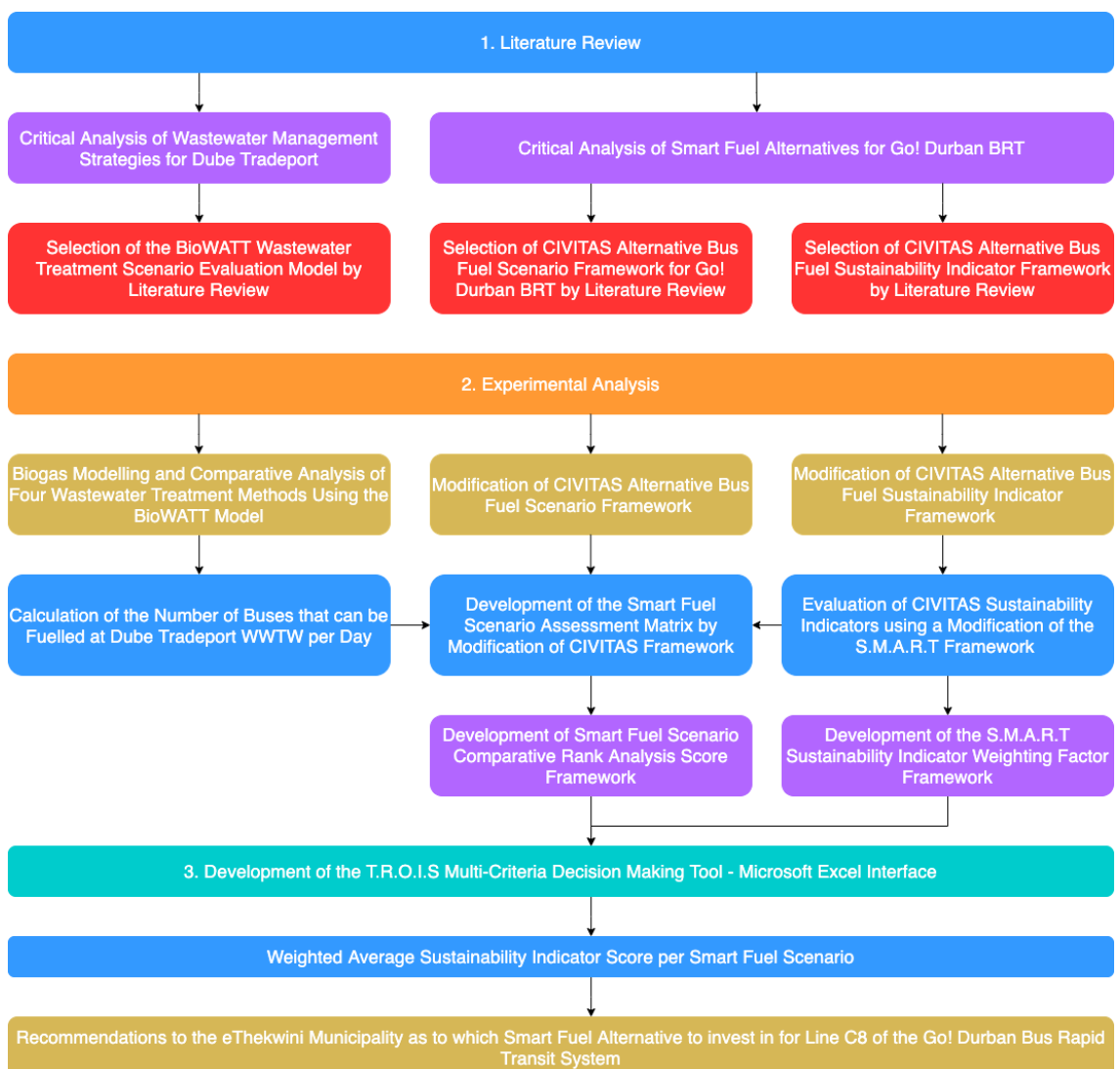


Figure 28 Showing: Methodological Approach taken to develop this dissertation

It has been hypothesised that the planned new wastewater treatment works that is planned for Dube Tradeport, can produce sufficient excess biogas and therefore energy, to power a portion of the Go! Durban Bus Rapid Transit (BRT) fleet which will operate on Line C8 which passes through Dube Tradeport and the King Shaka International Airport.

The use of Waste to Energy scenarios at Dube Tradeport to fuel a portion of the Go! Durban BRT buses would assist the eThekweni Municipality with regards to reducing the Well to Wheels (WTW) GHG emissions of the bus propulsion technology that they eventually decide to select for Line C8.

This is mandated by South Africa's global commitment to the Paris Climate Change Agreement, the South African Green Transport Strategy (2018 to 2050) and the eThekweni Climate Action Plan (CAP) (2018). This would also assist Dube Tradeport with regards to meeting its sustainability goals as outlined in the Dube Tradeport Integrated Development Plan, which seeks to safely treat and dispose of wastewater produced in the precinct with as little impact on the environment as possible.

The following three Waste to Energy Scenarios were investigated for Dube Tradeport using Biogas Modelling to determine which type of wastewater treatment process will produce the most amount of excess biogas and therefore energy. This would then be used to determine which Waste to Energy Scenario would be able to fuel the most number of Go! Durban Bus Rapid Transit Buses on Line C8 which passes through Dube Tradeport and the King Shaka International Airport.

1. Biogas extraction for onsite electricity generation and or storage for electric Go! Durban BRT buses
2. Biogas extraction and upgrade to pure biomethane (compressed natural gas) fuel for Bio-CNG Go! Durban BRT buses
3. Bio-Gas extraction and upgrading using the Hazer Process to pure Bio-hydrogen to power fuel cells for hydrogen fuel cell electric Go! Durban BRT buses

These Waste to Energy Scenarios were chosen based on the literature review of sustainable, low emission bus propulsion technologies which were investigated in Chapter 2: Literature Review of this dissertation. Bus propulsion technologies which were identified include, Battery Electric, Electric Trolley Bus, Hydrogen Fuel Cell Electric and Bio-CNG BRT buses. These Smart Fuel scenarios for Line C8 of the Go! Durban Bus Rapid Transit System will be elaborated on in greater detail in Section 3.4 of this Chapter.

3.2 BioWATT Wastewater Treatment Scenario Evaluation Model

The BioWATT Biogas Wastewater Assessment Technology Tool was chosen as the medium through which a biogas modelling exercise for the Dube Tradeport could be developed. This was to determine which wastewater treatment method would produce the most amount of excess biogas and therefore energy which could fuel a portion of the Go! Durban BRT buses which will operate on Line C8 of the system passing through Dube Tradeport. An explanation of how this model was chosen by literature review is explained in the following section 3.2.1.

3.2.1 Selection of Wastewater Biogas Model for Analysis

A literature review was used to investigate potential biogas projection models, which resulted in a final selection of two wastewater biogas projection models. The Biogas Wastewater Assessment Technology Tool (BioWATT) and the Municipal Wastewater Treatment Works Biogas to Combined Heat and Power Evaluation Tool were selected as the final two biogas projection models and compared for potential use.

The date at which each model was published, the organisations which authored the models, the target market for which the models were developed, the currency in which the Opex costs are modelled, the ability to run the model for different wastewater treatment types and the level of detail that is provided when running the analysis for each model were considered. This is summarised in the Table 16 below:

Table 15 Showing a comparison of the final two biogas projection models

Name of Model	Biogas Wastewater Assessment Technology Tool (BioWATT)	Municipal Wastewater Treatment Works Biogas to Combined Heat & Power (CHP) Evaluation Tool
Date Published	2016	2015
Authors	World Bank & Global Methane Initiative	GIZ, SALGA & WEC Projects (Pty) Ltd
Target Market	Developing Countries	South Africa
Currency Calibration	US Dollar	Rands
Opex Reductions	Yes	Yes
Capex Calculation	No	Yes
Analyses Multiple WWTW Methods	Yes	Yes
Analysis Detail	Advanced	Basic

The qualitative data in the table above regarding the two biogas evaluation models for wastewater treatment works led to the data driven decision to use the Biogas Wastewater Assessment Technology Tool (BioWATT) model. BioWATT was published more recently (2016) than the Municipal Wastewater Treatment Works Biogas to Combined Heat & Power (CHP) Evaluation Tool (2015).

Secondly the BioWATT model is able to provide a greater level of detail with regards to the biogas analysis output. The analysis output of the BioWATT model was very useful with regards to comparing the projected biogas generation capabilities of four different wastewater treatment technologies assuming that the wastewater inflow quality and quantity characteristics remained the same each time. The BioWATT analysis tool has been developed by the Global Methane Initiative in conjunction with the World Bank to create a decision-making tool which can be used by wastewater managers to design treatment processes based on projected bio-gas generation and its subsequent use as an energy source to offset the electricity and heat requirements of a treatment plant.

Four wastewater treatment options were considered for the proposed new WWTW at Dube Tradeport: Conventional Activated Sludge (CAS) with Anaerobic Digester (with co-digestion of organic waste from Agrizone), Trickling Filter (TF) with Anaerobic Digester (with co-digestion of organic waste from Agrizone), Up Flow Anaerobic Sludge Blanket (UASB) reactor and lastly a Covered Anaerobic Pond. The Figure 29 below shows the four wastewater treatment methods which were evaluated using the BioWATT biogas projection model which was later used to develop results for the three Waste to Energy strategies which are described in section 3.1 of this Chapter.

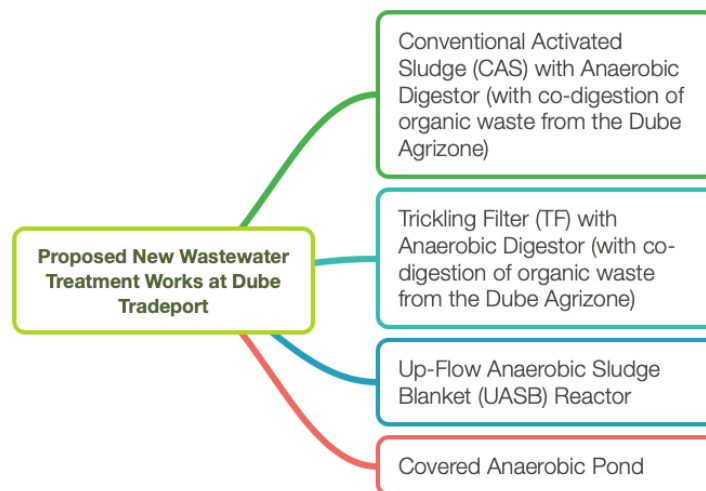


Figure 29 Showing Wastewater Treatment Options which will be evaluated for Dube Tradeport using the BioWATT biogas model

Co-digestion of organic waste from the Dube Agrizone is not taken into consideration for the Up Flow Anaerobic Sludge Blanket and Covered anaerobic pond methods due to a limitation of the Biogas Wastewater Assessment Technology Tool (BioWATT) which was chosen as the biogas projection model for this analysis.

3.2.2 Identification of Wastewater Quantity and Quality Parameters to be used in the biogas projection models

The rapid development of the King Shaka International Airport and the surrounding Dube Tradeport, has created the need for a new wastewater treatment works to be developed for Dube Tradeport. The precinct consists of numerous phases of industrial, commercial, office and mixed-use development which has led to the production of a large amount of wastewater, which is required to be collected, treated at an on-site facility and suitably disposed of.

The proposed new wastewater treatment plant will be required to meet stringent effluent quality parameters before disposal can take place. The sustainability ethos of the Dube Tradeport also requires the maximum reuse of treated wastewater for irrigation purposes within the precinct. The proposed design of the facility comprises of the complete on-site treatment of all wastewater produced at Dube Tradeport with maximum reuse of the treated effluent. This will reduce the costs of transporting the upgraded fuel to the point of use at the proposed Go! Durban Bus Rapid Transit Station at the King Shaka International Airport.

Population and wastewater projection modelling according to the 2060 development masterplan has shown that ultimately an 18MI/day wastewater treatment plant is required for the Dube Tradeport using the average dry weather flow model or ADWF. (Reddy, 2017). For bio-gas modelling purposes, a wastewater treatment works to be developed in three modular phases of 6MI/day each, was used as a basis for the model. The wastewater quality and quantity parameters which were used as an input into the chosen biogas projection model, is detailed in Chapter 4: Case Study of Dube Tradeport.

The full data tables explaining all assumptions, references and calculations used in the BioWATT model can be found in Appendix A. According to (Da Silva et al, 2018) the Agrizone at Dube Tradeport produces approximately 5m³ of organic waste per day.

Therefore, the first two treatment options investigated the co-digestion of organic waste from the Dube Agrizone with the wastewater sludge produced at the proposed new treatment plant at Dube Tradeport. The wastewater influent quantity and quality characteristics which are explained in detail in Chapter 4: Case Study of Dube Tradeport is also summarised in the table below: and were used as input values into the Biogas Wastewater Assessment Tool (2016). The summary in Table 16 below shows the influent quantity and quality characteristics for Phase 1 of the proposed new wastewater treatment plant at Dube Tradeport.

Table 16 Showing: Wastewater Quality and Quantity Input Values used for the BioWATT model used to project Biogas production per wastewater treatment method

WASTEWATER ENTERING WWTP	Value	Unit	Reference
Average hydraulic load	6 000	m ³ /d	Average Dry Weather Flow Rate Analysis – Dube Tradeport Population Growth Rate
Average inflow BOD ₅ concentration	548	mg/L	GCS Report 2016/2017

GREENHOUSE GAS EMISSIONS	Value	Unit	Reference
Local GHG emissions for electricity generation	1 000	g CO ₂ /kWh	International Energy Agency IEA (2012): "CO2 Emissions from Fuel Combustion", www.iea.org – High fossil fuel use

UNIT COST	Value	Unit	Reference
Electricity tariff	0,90	Rands/kWh	Eskom, 2019
Sludge disposal unit cost	300	Rands/m ³	Sludge Disposal at landfill: R275/m ³ (GreenCape,2019), Cost of fuel - Dube Tradeport to Buffelsdraai Landfill = R25 per m ³
Average labour cost	90 000	Rands/personnel/year	Estimated: R7500/month

3.3 SMART Sustainability Indicator Assessment Matrix

During the Literature Review process two Alternative Bus Fuel Frameworks were identified as strong inventories of Sustainability Indicators and Alternative Bus Fuel Scenarios. This comprised of the Alternative Bus Technologies Framework, which was developed by the C40 Cities Finance Facility in collaboration with Grütter Consulting, in 2018 and the CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework which was published in 2016.

The Alternative Bus Technologies Framework, which was developed by the C40 Cities Finance Facility in collaboration with Grütter Consulting presented a strong and well researched inventory of Sustainability Indicators and Bus Fuel Alternative Scenarios. However, this framework had fewer Smart Fuel Scenarios overall and did not include Biofuel options such as Bio-diesel or Bio-Ethanol.

The purpose of this dissertation is to provide a Transport Engineer at the eThekweni Municipality with the best possible recommendation and so the CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework (2016) was ultimately chosen for modification and development into the Smart Fuel Scenario Assessment Matrix.

The SMART acronym was first written down in November 1981 in Spokane, Washington, by George T. Doran, a consultant and former Director of Corporate Planning for Washington Water Power Company, when he published a paper entitled "There's a SMART Way to Write Management's Goals and Objectives". This framework has been developed overtime to enable a set of sustainability indicators to be evaluated based on the SMART Framework criteria as shown below (Duran, 1981).

- **Specific:** target a specific area for improvement.
- **Measurable:** quantify, or at least suggest, an indicator of progress.
- **Achievable:** can this result be achieved?
- **Relevant:** state what results can realistically be achieved given available resources.
- **Time-bound:** specify when the result can be achieved.

This SMART Framework has been modified by the author, so that it can be used to evaluate the sustainability indicators which were obtained from the CIVITAS Smart Choices for Cities: Alternative Fuel Buses (2016). The CIVITAS framework was chosen during the literature review process after comparison with other Alternative Bus Fuel Frameworks.

This framework has been applied to the set of Smart Fuel sustainability indicators which were obtained from Chapter 2: Literature Review: The Table 17 below shows a screenshot of the Smart Fuel Sustainability Indicator Assessment Process which was followed. A full scale table explaining the process is shown on page 65 as Table 18.

Table 17 Showing: SMART Sustainability Indicator Assessment Matrix Applied

Sustainability Indicator	Unit	SMART Analysis				
		Specific	Measurable	Achievable	Relevant	Time Bound
Range	km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Route Flexibility	n/a	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Energy Consumption	kWh/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Refueling Frequency	Days	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Refueling Time	Minutes	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
GHG Emissions (WTW)	gCO2e/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
PM10 (TTW)	g/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
NOx (TTW)	g/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Noise Emissions	dB	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Cost Per Bus	Rands	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Number of buses which can be fueled per day at Dube Tradeport	n/a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

The SMART Sustainability Indicator Assessment Matrix was used to evaluate and score each of the eleven Smart Fuel sustainability indicators which were obtained from literature review. The results of this analysis is presented and discussed in Chapter 5. This process involved the creation of a Sustainability Indicator Evaluation Matrix on a Microsoft Excel Spreadsheet.

Check boxes were created for each of the eleven Sustainability Indicators in the matrix such that could be evaluated against the SMART criteria of Specific, Measurable, Achievable, Relevant and Time Bound. Each Sustainability Indicator was thus awarded a score out of five to evaluate if the selected indicators from the CIVITAS Smart Choices for Cities: Alternative Fuel Buses (2016) met the criteria of being called SMART indicators. The SMART score which was obtained for each Sustainability Indicator was then converted into a factor between 0 and 1. This factor was then used later on in the experimental stage as a weighting factor to calibrate the first output of the T.R.O.I.S model which was used as one of the potential recommendations to the eThekweni Municipality

Table 18 Showing Sustainability Indicator Evaluation Matrix using the Modified SMART Framework

Sustainability Indicator	Unit	SMART Analysis					Score	Weighting Ratio
		Specific	Measurable	Achievable	Relevant	Time Bound		
Range	km							
Route Flexibility	n/a							
Energy Consumption	kWh/km							
Refuelling Frequency	Days							
Refuelling Time	Minutes							
GHG Emissions (WTW)	gCO2e/km							
PM10 (TTW)	g/km							
NOx (TTW)	g/km							
Noise Emissions	dB							
Cost Per Bus	Rands							
Number of buses which can be fuelled per day at Dube Tradeport	n/a							

3.4 Smart Fuel Scenario Assessment Matrix

The Smart Fuel Scenario Assessment Matrix has been developed from the sustainability indicators which were collected through a literature review which was conducted in Chapter 2 of this this dissertation. In addition, the number of buses which can be fuelled per day using Waste to Energy strategies at Dube Tradeport was also added an additional sustainability indicator which was developed through the BioWATT biogas modelling process.

This was in the context of a proposed new wastewater treatment works that is planned for Dube Tradeport. Once these sustainability indicators were collected they were evaluated using the SMART Indicator Framework as discussed in section 3.3 of this Chapter. The Table 19 below shows a screenshot of the matrix that was developed and will be discussed in detail in Chapter 5: Results and Discussion.

Table 19 Showing the Smart Fuel Scenario Assessment Matrix which has been developed from Chapter 2 Literature Review

Smart Fuel Alternatives for the Go! Durban Bus Rapid Transit System - C8 Line										
Operational Sustainability Indicators	Diesel ICE (Euro VI)	Compressed Natural Gas (CNG - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	References
Range	600-800km	300 - 400 km	670-800 km	400 - 600 km	<100 km	100 - 250 km	Unlimited within the network providing constant electricity supply	600-800 km	200 - 400 km, the range depends on tank size of hydrogen and the storage pressure. A higher pressure of 700 bar would increase the range at the same volume of the storage tanks.	Smart Choices for Cities, Alternative Fuel Buses, CNVTAS, 2016
Route Flexibility	High	High	High	High	Limited	Higher	Flexibility beyond the network is only possible using an auxiliary power unit or battery	High	High	
Energy Consumption	4.1 kWh/km	5.2 kWh/km	4.1 kWh/km	4.1 kWh/km	1.4 kWh/km	1.4 kWh/km	1.4 kWh/km	3.2 kWh/km	3.1 kWh/km	
Refueling Frequency	Every 2nd day	every 1st or 2nd day	every 2nd day	every for 2 days	Recharging needed multiple times a day	Recharging at the end of each day or during the day	Does not incorporate refuelling or recharging time in normal operation except where auxiliary power unit battery needs to be recharged	Refilling needed only after every 2nd day	Refilling every day at the end of operation	
Refueling Time	5-10 min	5-10 min	5-10 min	5-10 min	Short recharging time: 5-10 min	Very long recharging time: more than 3 h		5 min	10 min	
Environmental Sustainability Indicators										
Relevance Euro VI	Diesel ICE	Compressed Natural Gas (CNG - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
GHG WTT - gCO2e/km	1317	273	842	792	791	791	791	1054	1290	
GHG Well-to-Wheel (gCO2e/km)	0	0	0	0	0	0	0	0	0	
NOx TFW (mg/km - g/km)	0.5-1.1	<1	0.5-1.1	0.5-1.1	0	0	0	0.5-1.1	0	
PM10 TFW (microg/km)	0.015	<0.01	0.015	0.015	0	0	0	0.015	0	
Social Sustainability Indicators										
Noise Emission	Diesel ICE	Compressed Natural Gas (CNG - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Operating	80 dB	78 dB	80 dB	80 dB			Lowest Noise Emission	80 dB	73 to 78 dB	Smart Choices for Cities, Alternative Fuel Buses, CNVTAS, 2016
Passive	77 dB	75 dB	77 dB	77 dB				73 to 78 dB		
Financial Sustainability Indicators										
One Full Bus (Euro)	Diesel ICE	Compressed Natural Gas (CNG - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
One Full Bus (Euro)	EUR 220,000.00	EUR 250,000.00	EUR 220,000.00	EUR 250,000.00	EUR 320,000.00 to EUR 500,000.00 per bus	EUR 400,000.00 to EUR 600,000.00 per bus	EUR 400,000.00 to EUR 600,000.00 per bus	EUR 220,000.00 to EUR 300,000.00 per bus	EUR 800,000.00	Smart Choices for Cities, Alternative Fuel Buses, CNVTAS, 2016
Full Fuel Bus (Euro)	R4346,317.50	R4398,315.34	R4346,317.50	R4398,315.34	R6385,943.54 to R9194,630.00	R7307,304.55 to R9194,630.00	R7307,304.55 to R9194,630.00	R4346,317.50 to R4398,315.34	R14,714,000.00	
Dube Tradeport Waste to Energy Scenario										
Scope to Electricity Generation for Dube Tradeport	Diesel ICE	Compressed Natural Gas (CNG - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Scope to Electricity Generation for Dube Tradeport	0	0	0	0	0	0	0	0	0	
Scope to Hydrogen (Bio-ethanol)	0	0	0	0	0	0	0	0	0	
Scope to Hydrogen (Bio-ethanol)	0	0	0	0	0	0	0	0	0	
Technical Sustainability Indicators										
Energy Consumption (kWh/km)	Diesel ICE	Compressed Natural Gas (CNG - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Total Energy Consumption per bus per Day (kWh) - Assume City bus drives 300km per day	4.1	5.2	4.1	4.1	1.4	1.4	1.4	3.2	3.1	
Number of buses which can be fuelled per day at Dube Tradeport	1293	1960	1293	1293	420	420	420	660	830	
Dube WWTW Phase 1	0	1.04	0	0	1.35	1.18	1.35	0.87	0.71	
Dube WWTW Phase 2	0	2.09	0	0	2.70	2.36	2.70	1.15	1.41	
Dube WWTW Phase 3	0	3.13	0	0	4.05	3.54	4.05	1.72	2.12	

Once the Smart Fuel Scenario Assessment Matrix was developed from literature review, the matrix was populated for all nine bus propulsion technologies which were identified against the eleven sustainability indicators in the matrix. This result is presented and discussed in full in Chapter 5 of this dissertation. A full scale template of the Matrix is shown on page 70 as Table 20. The next step was to use the data in the populated Smart Fuel Scenario Assessment Matrix to develop a Comparative Rank Analysis Score, which can be used to differentiate between the various bus propulsion technologies evaluated in the Smart Fuel Assessment Matrix.

Table 21 Showing Smart Fuel Assessment Matrix Template

Operational Sustainability Indicators	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	References
Range										
Route Flexibility										
Energy Consumption										
Refuelling Frequency										
Refuelling Time										
Environmental Sustainability Indicators										
Emissions Euro VI	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
GHG WTT - (gCO2e/km)										
NOx TTW (direct) - (g/km)										
PM10 TTW (direct) - (g/km)										

Social Sustainability Indicators										
Noise Emissions	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Standing										
Pass by										
Financial Sustainability Indicators										
	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Cost Per Bus (Euros)										
Cost Per Bus (Rands)										
Dube Tradeport Waste to Energy Scenarios										
	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Biogas to Electricity Generation for Dube Tradeport										
Biogas Upgrade to compressed Bio-methane (Bio-CNG)										

Biogas Upgrade to Bio-hydrogen (Hazer Process)																			
Technical Sustainability Indicators	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell										
Energy Consumption (kWh/km)																			
Total Energy Consumption per bus per Day (kWh) - Assume City bus travels 300km per day																			
Number of buses which can be fuelled per day at Dube Tradeport																			
Dube WWTW Phase 1																			
Dube WWTW Phase 2																			
Dube WWTW Phase 3																			

The Table 22 below shows the Comparative Rank Analysis Scale which was then used to rank each bus propulsion technology from 1 to 9 as per each of the eleven sustainability indicators in the assessment matrix:

Table 22 Showing: the Comparative Rank Analysis Scale that was used to assess each of the bus propulsion technologies in the Smart Fuel Scenario Assessment Matrix

Scale	Value
1	Least Suitable
2	
3	
4	Suitable
5	
6	
7	Most Suitable
8	
9	

The Table 23 below shows the application of the of Comparative Rank Analysis Score and the SMART Sustainability Indicator Assessment Weighting factor to the matrix of nine bus propulsion technologies against the eleven Smart Fuel sustainability indicators. The Table 24 below shows a template of the Comparative Rank Analysis Matrix that was used.

Table 23 Showing the Smart Fuel Scenario Comparative Rank Analysis Score Applied

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	0.8	8	4	7	5	1	2	9	8	3
Route Flexibility	0.4	9	5	7	6	2	3	1	9	4
Energy Consumption	0.8	4	1	4	4	9	7	9	5	6
Refuelling Frequency	1	8	4	6	5	1	2	9	8	3
Refuelling Time	1	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	0.8	1	9	4	5	8	8	8	3	2
PM10 (TTW)	0.8	4	5	4	4	9	9	9	4	9
NOx (TTW)	0.8	4	5	4	4	9	9	9	4	9
Noise Emissions	0.8	3	4	3	3	9	9	9	5	9
Cost Per Bus	0.8	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	1	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	4.200	4.218	4.091	3.673	5.200	4.436	6.491	4.764	4.073
Unweighted Average Sustainability Indicator Score	-	5.273	5.091	5.091	4.545	6.182	5.455	7.545	5.909	5.000

The final average weighted scores that were achieved for each of the nine bus propulsion technologies were then used to evaluate and recommend which technology should be selected by the eThekweni Municipality for the bus fleet that will operate Line C8 of the Go! Durban Bus Rapid Transit System. This final recommendation is presented in Chapter 6: Conclusion and Recommendations.

Table 24 Showing a template of the Comparative Rank Analysis Matrix that was populated in Chapter 5

Smart Fuel Technology Type	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range									
Route Flexibility									
Energy Consumption									
Refuelling Frequency									
Refuelling Time									
GHG Emissions (WTW)									
PM10 (TTW)									
NOx (TTW)									
Noise Emissions									
Cost Per Bus									
Number of buses which can be fuelled per day at Dube Tradeport									

3.5 T.R.O.I.S Multi-Criteria Decision Making Tool

The next step of this methodology was to integrate the outcomes of the Smart Fuel Scenario Assessment Matrix, the SMART sustainability indicator weighting factors and the Comparative Rank Analysis Scores to develop a Microsoft Excel spreadsheet based decision making tool. The T.R.O.I.S model has been developed to enable a set of Smart Fuel sustainability indicators to be used as a multi-criteria decision making tool to assist Transport Engineers in the eThekweni Municipality to decide as to which bus propulsion technology to select for the bus fleet that will operate Line C8 of the Go! Durban Bus Rapid Transit system. The T.R.O.I.S evaluation model consists of the following sustainability evaluation criteria:

- **Transport:** Promotion of Shared Use, High Occupancy Public Transport
- **Reduction:** GHG emissions, Air pollution (PM₁₀ and NO_x) and Noise Pollution
- **Optimisation:** Range, Route Flexibility, Energy Consumption, Refuelling Frequency and Refuelling Time
- **Implementation:** Cost per Bus, Number of Buses which can be fuelled per day
- **Scenario:** Comparative Analysis of all possible propulsion technology scenarios

The motivation behind developing a Microsoft Excel spreadsheet based decision making tool was that a Transport Engineer, should be able to adjust the weighting factor on the model based on what the priorities of the eThekweni Municipality are with regards to Operational, Environmental, Social, Financial and Technical Sustainability. The Figure 30 below shows a screenshot of the Microsoft Excel Interface which was developed and named as the T.R.O.I.S Multicriteria Decision Making Tool.

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	1	8	4	7	5	1	2	9	8	3
Route Flexibility	0	9	5	7	6	2	3	1	9	4
Energy Consumption	0.1	4	1	4	4	9	7	9	5	6
Refuelling Frequency	0.1	8	4	6	5	1	2	9	8	3
Refuelling Time	0.2	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	0.3	1	9	4	5	8	8	8	3	2
PM10 (TTW)	0.4	4	5	4	4	9	9	9	4	9
NOx (TTW)	0.4	4	5	4	4	9	9	9	4	9
Noise Emissions	0.5	3	4	3	3	9	9	9	5	9
Cost Per Bus	0.6	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	0.7	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	0.8	5.273	5.091	5.091	4.545	6.182	5.455	7.545	5.909	5.000
	0.9									
	1									

Figure 30 Showing: a user interface of the T.R.O.I.S Multicriteria Decision Making Tool

The Figure 31 below shows the graphical model of the T.R.O.I.S Multi-Criteria Decision Making Tool which is populated once the user selects the appropriate weighting factor for each of the Smart Fuel sustainability indicators, as per the priorities of the eThekweni Municipality.

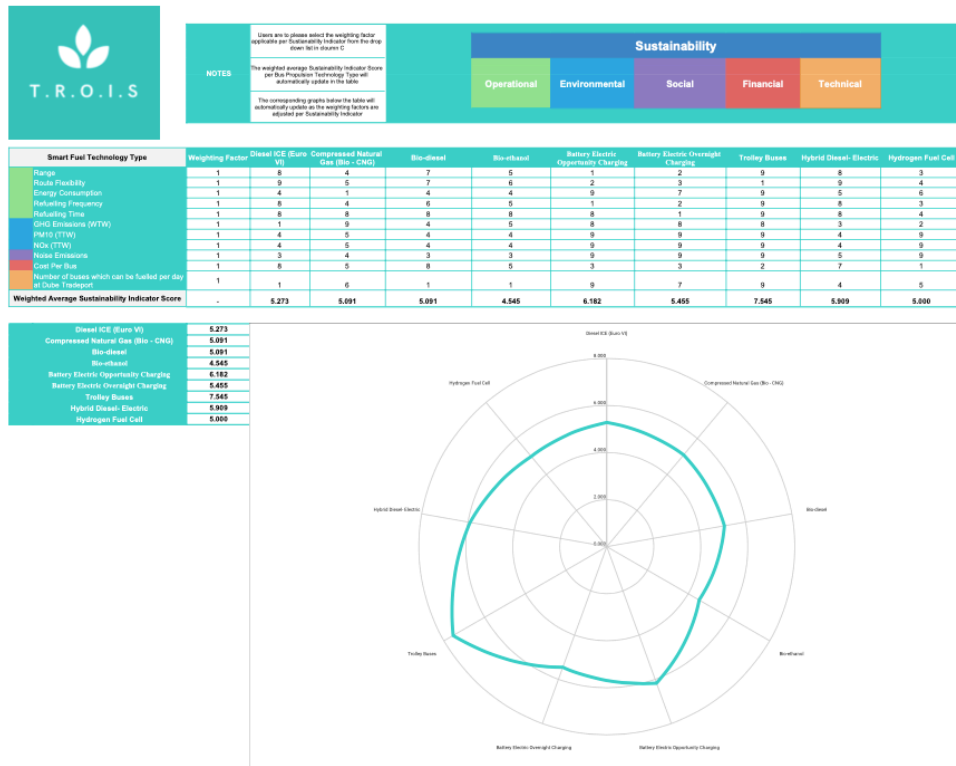


Figure 31 Showing: Graphical model on the T.R.O.I.S Multi-Criteria Decision Making Tool Interface

The T.R.O.I.S model output is a final average weighted score for each of the nine bus propulsion technologies. This graphical and tabulated weighted comparison can then be used to evaluate and recommend which technology should be selected by the eThekweni Municipality for the bus fleet that will operate Line C8 of the Go! Durban BRT.

3.6 Chapter Summary

The research methodology comprised of : a literature review of wastewater management strategies for Dube Tradeport and biogas projection modelling, for different treatment scenarios using the BioWATT Wastewater Treatment Scenario Evaluation Model; the development of the SMART Sustainability Indicator Assessment Matrix; the Smart Fuel Scenario Assessment Matrix and the final development of the T.R.O.I.S multi-criteria decision making tool to assist Transport Engineers in the eThekweni Transport Authority. This Chapter will now be followed by a detailed Case Study of Dube Tradeport.

Chapter 4: Case Study

In this chapter, a Case Study of the Durban Aerotropolis and in particular the core Airport City of Dube Tradeport will be developed. The Case Study will investigate the wastewater quality and quantity demand over the 50 year masterplan of Dube Tradeport. This will be used as input data in Chapter 5 to conduct a biogas projection analysis

4.1 Introduction

The Durban Aerotropolis is a Smart City development that is planned around the King Shaka International Airport, in the eThekweni Municipality. The precinct has been designed to become a major business and trade hub in Sub-Saharan Africa and is in close proximity to industrial manufacturing centres and Africa's biggest seaport, the Durban harbour, which provides strategic access to major shipping lanes.

An Aerotropolis is a city which is centred around an international airport and a supporting integrated rapid transport network which provides high speed connectivity between suppliers, consumers and industry stakeholders (Kasarda, 2017). A multimodal, airport based, commercial core is linked via an integrated rapid transportation network to clusters of aviation-linked businesses and mixed-use commercial and residential developments. These components work in a symbiotic relationship based on their proximity and accessibility to the airport (Kasarda, 2017).

The competitive edge of the Aerotropolis development model lies in the utilisation of the time-cost accessibility principle to enable rapid physical connectivity. The provision of long distance accessibility enables business to reduce costs, increase productivity and expand market reach to improve competitiveness and effectiveness in the international division of labour (Kasarda, 2017).

Harrison et al. (2010) defines a Smart City as an instrumented, interconnected and intelligent city. This is achieved via the capturing and integrating of live real-world data through the use of sensors, meters, appliances, personal devices (Harrison et al., 2010). This is followed by the integration of the collected data into a computing platform to allow for the intra-communication of different city services. Lastly, complex analytics, modelling, optimization and visualization services are employed to improve operational decisions (Harrison et al., 2010).

Thus, a Smart city can be described as a technologically advanced city that connects people, information and city elements using Information and Communication Technology (ICT) infrastructure to create a more sustainable, greener city which is competitive and commercially innovative to increase the quality of life of its citizens (Bakıcı et al. 2012).

4.2 Overview of the Durban Aerotropolis

Line C8 of the Go! Durban Bus Rapid Transit System passes through the Dube Tradeport and King Shaka International Airport, on its way to Tongaat from the Durban Central Business District via the commercial hub of Umhlanga. This research presents an interesting opportunity to meet the GHG reduction needs of eThekweni Municipality's Go! Durban Bus Rapid Transit bus fleet and the need to sustainably manage the excess sludge that is produced at the proposed new Dube Tradeport wastewater treatment works. This initiative will support the efforts of Dube Tradeport and the Durban Aerotropolis to develop sustainable public transport services for workers and airline passengers who require safe and reliable transport services from the suburbs of Durban to the King Shaka International Airport.

This integrated sustainable design thinking framework is an example of successful partnerships which can be achieved by various Government departments and entities to achieve sustainable smart mobility solutions in the eThekweni Municipality. The Durban Aerotropolis Masterplan is shown in the Figure 32 below and is comprised of residential, commercial, industrial and mixed-use zones. It is envisioned, that when complete the Durban Aerotropolis will comprise approximately 32 000 hectares of land area, 42 million m² of development space, 750 000 permanent jobs and 1 500 000 residents.

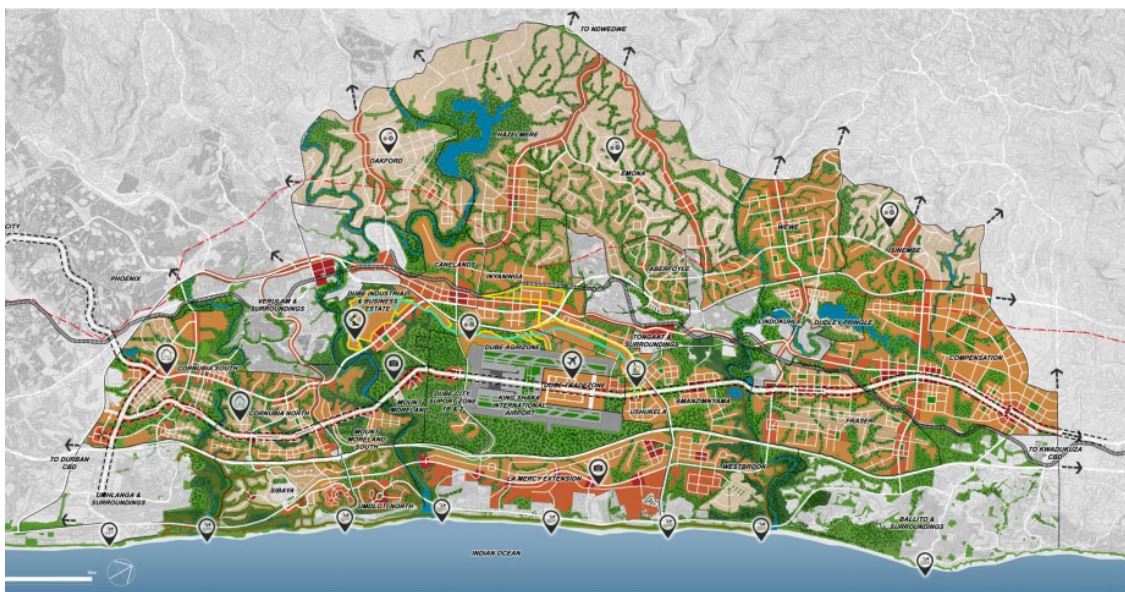


Figure 32 Showing the Durban Aerotropolis Masterplan (Dube Tradeport, 2020)

4.3 Overview of Dube Tradeport

The development of the King Shaka International Airport, which was opened in 2010, led to the formation of Dube Tradeport (DTP) comprising of a 2840-hectare greenfield development in La Mercy, North of Durban. The precinct masterplan was designed to become a multimodal hub and world class airport city around King Shaka International Airport.

The location of Dube Tradeport in close proximity to the two largest seaports in Southern Africa (Durban and Richards Bay), provides a commercial edge as a transport and logistics hub and greatly expands the capacity of KwaZulu-Natal to import and export goods. The Dube Tradeport 50-year Masterplan is shown in the Figure 33 below and is comprised of several Trade zones, Agri zones (Greenhouses) and Dube City. Dube Trade Zone is a 26-hectare site which consists of fully serviced airside real estate that is designed for new-generation warehousing, manufacturing, assembling, air-related cargo distribution, electronics, pharmaceuticals, high-tech aerospace services, automotive industries, clothing, textiles and cold storage activities.

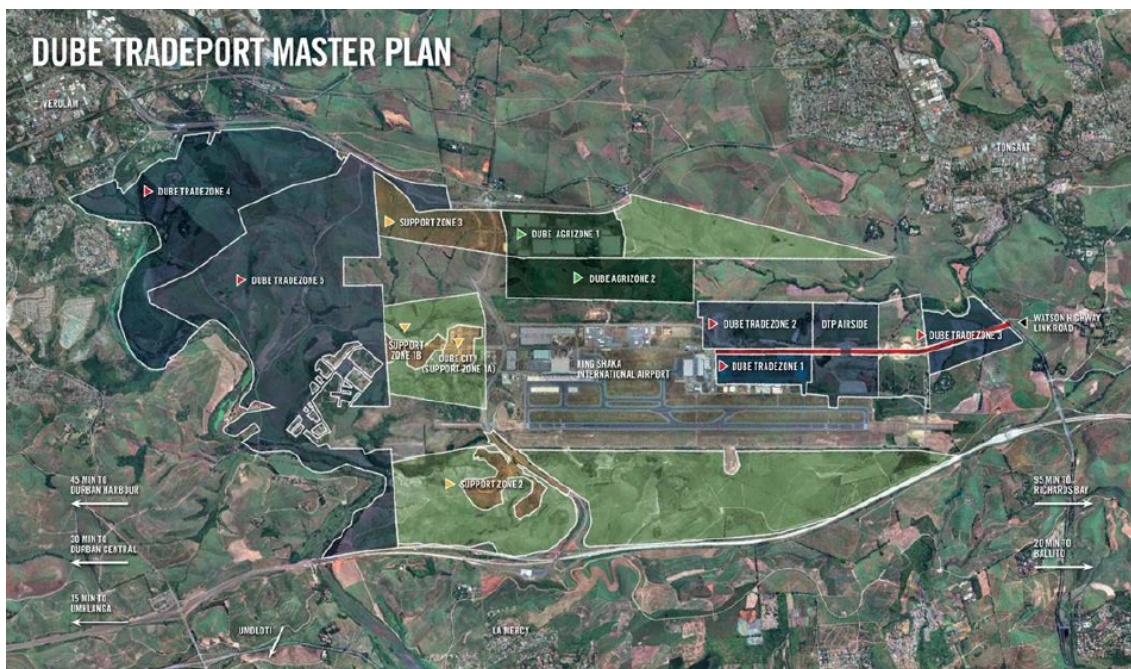


Figure 33 Showing: 50-year Dube Tradeport Masterplan (Dube Tradeport, 2019)

Dube City is Africa's first purpose-planned airport city and follows sustainable development principles, consisting of a modern urban "green" hub and a mix of hotel, conference, entertainment, retail and knowledge-intensive activities. Dube Agri Zone consists of 16 hectares of greenhouses and focuses on the production of short shelf-life

vegetables and cut flowers requiring immediate post-harvesting airlifting. In addition to the greenhouses, the Agri Zone consists of packhouses, a distribution centre, a nursery and Dube Agri Lab (a specialised tissue culture laboratory).

4.4 Wastewater Quantity Projections for Dube Tradeport

The quantity of wastewater that will be produced by Dube Tradeport was determined by modelling the projected population growth of the precinct according to the development plan as per the 2060 masterplan shown in the previous figure. The average dry weather flow rate will be used to design the new facility. The Figure 34 below shows the average dry weather flow rate at Dube Tradeport over the 50 year development masterplan. The maximum average dry weather flow can be seen to reach approximately 17,406 MI/day after 50 years of development (Dube Tradeport, 2020).

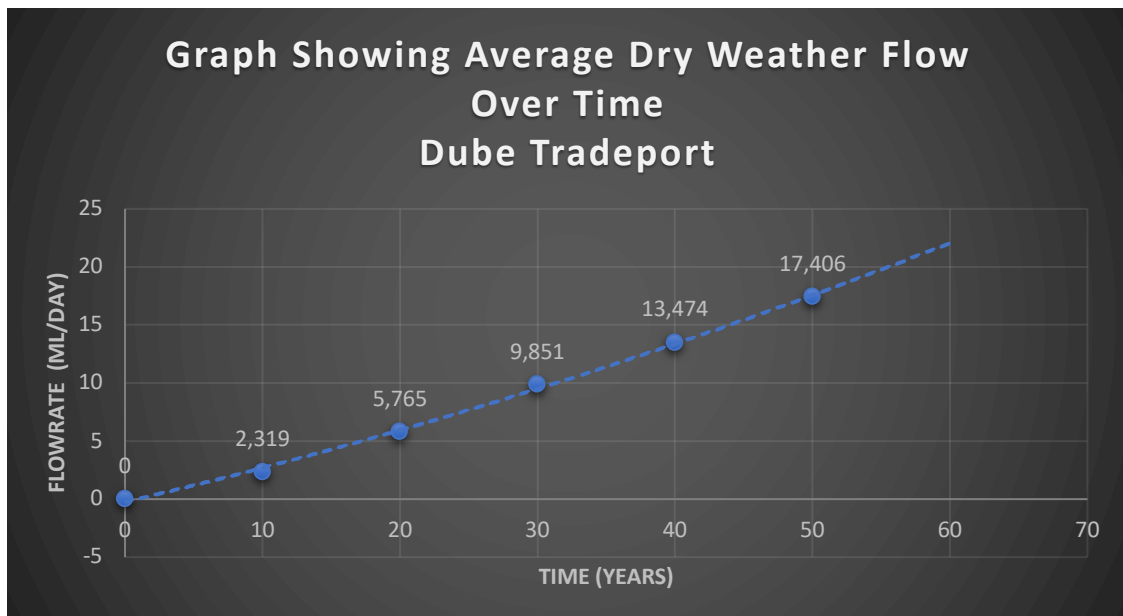


Figure 34 Showing Graph of Average Dry Weather Flow Over Time (Dube Tradeport, 2020)

The Figures 35 and 36 below show the growth in population size at Dube Tradeport over the course of the 50-year development masterplan. The peak population is estimated to be around 315,094 people after 50 years of development. This represents a considerable number of people who will contribute towards the growth of wastewater production within the Dube Tradeport precinct. This indicates that a significant amount of biogas could also be produced from the resulting sludge depending on which wastewater treatment process is chosen for Dube Tradeport.

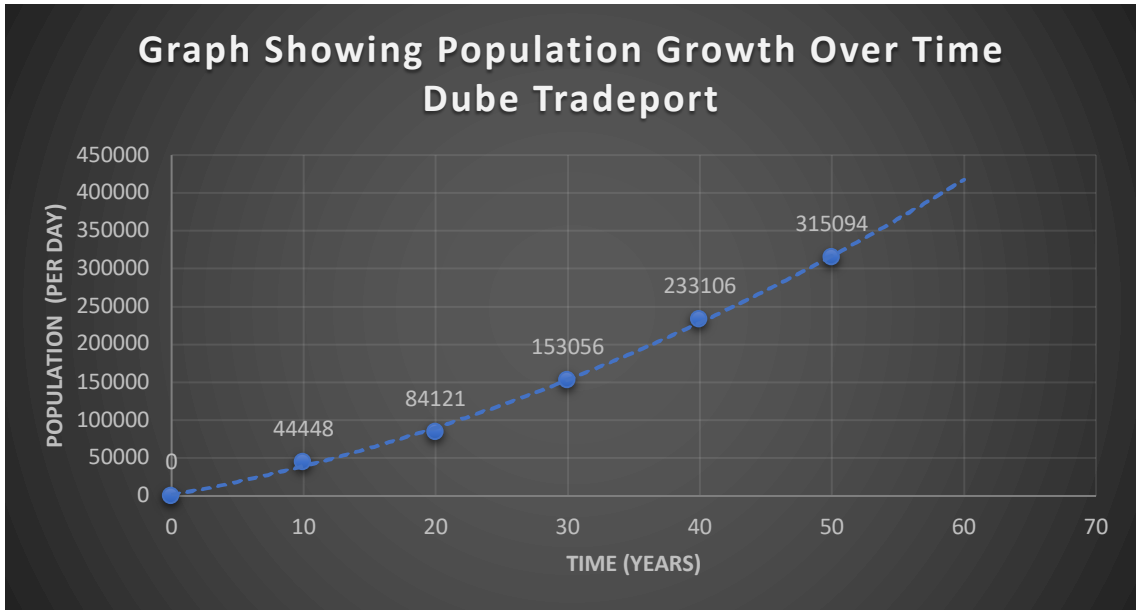


Figure 35 Showing Graph of Population Growth Over Time (Dube Tradeport, 2020)

The figure 36 below shows the Peak factor vs. Population growth rate over time at Dube Tradeport. This is a good indication of the growth in the amount of wastewater that will be produced over time within the Dube Tradeport precinct. This would also indicate the amount of biogas that could potentially be produced from the wastewater sludge .

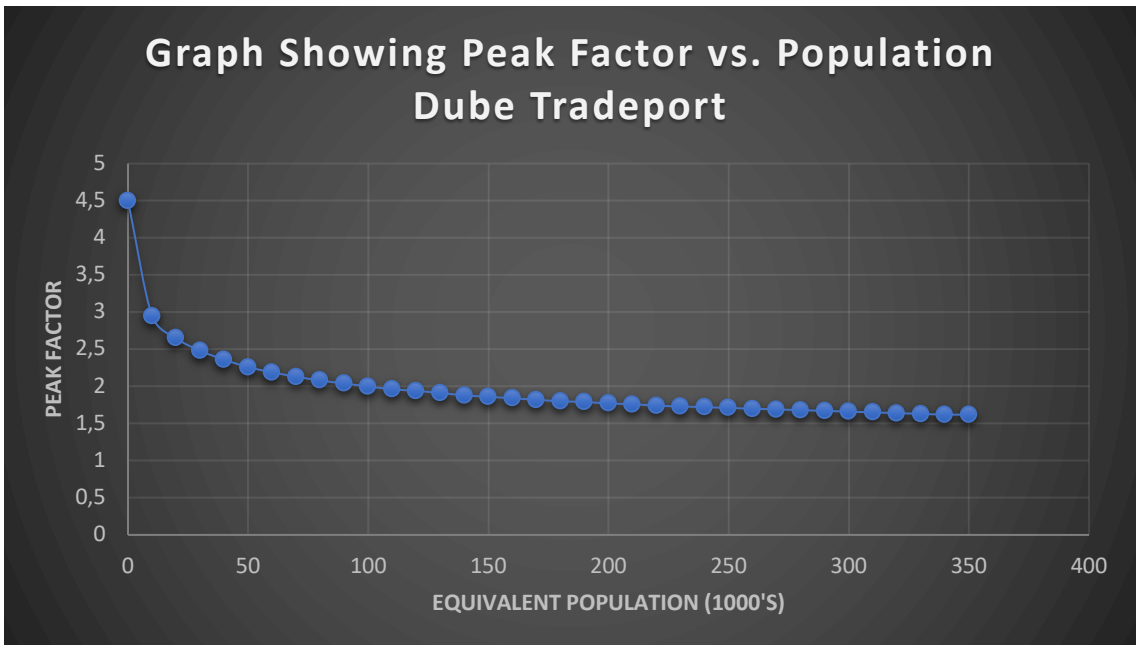


Figure 36 Showing Graph of Peak Factor vs. Population (Dube Tradeport, 2020)

The Figure 37 below shows the expected Peak Dry Weather Flow Over Time at Dube Tradeport which increases up to 28.55 MI per day in 2050.

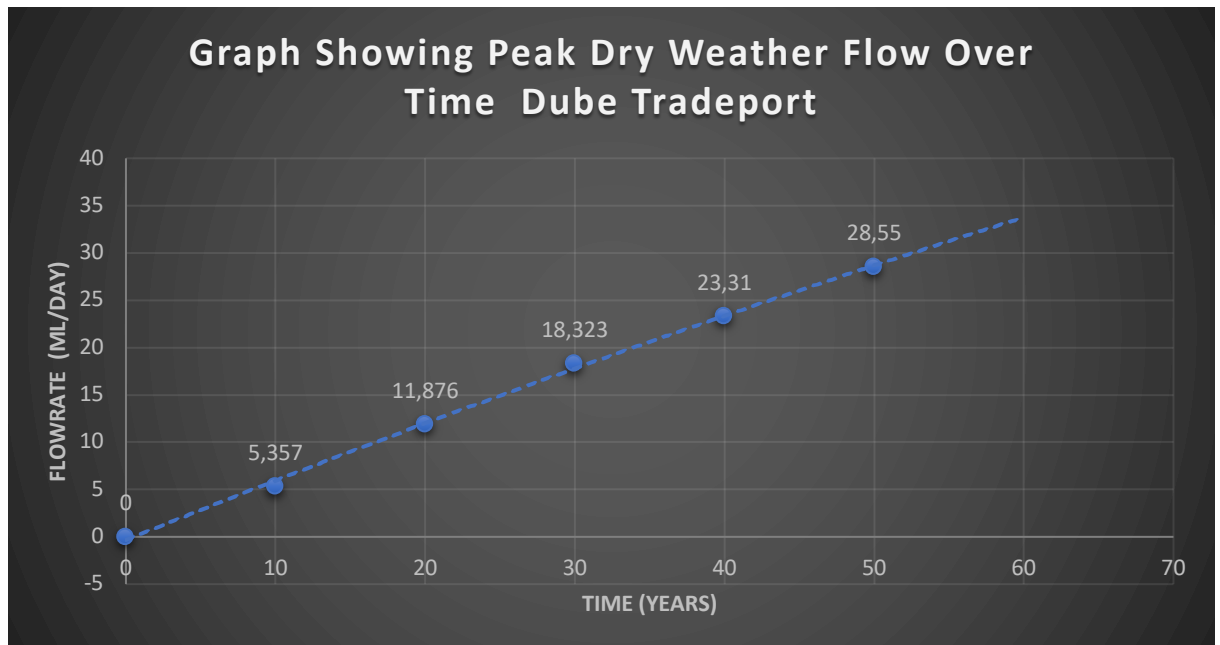


Figure 37 Showing Graph of Peak Dry Weather Flow Over Time

The Figure 38 below shows the Peak Wet Weather Flow which increases up to 32.83 MI per day in 2050.

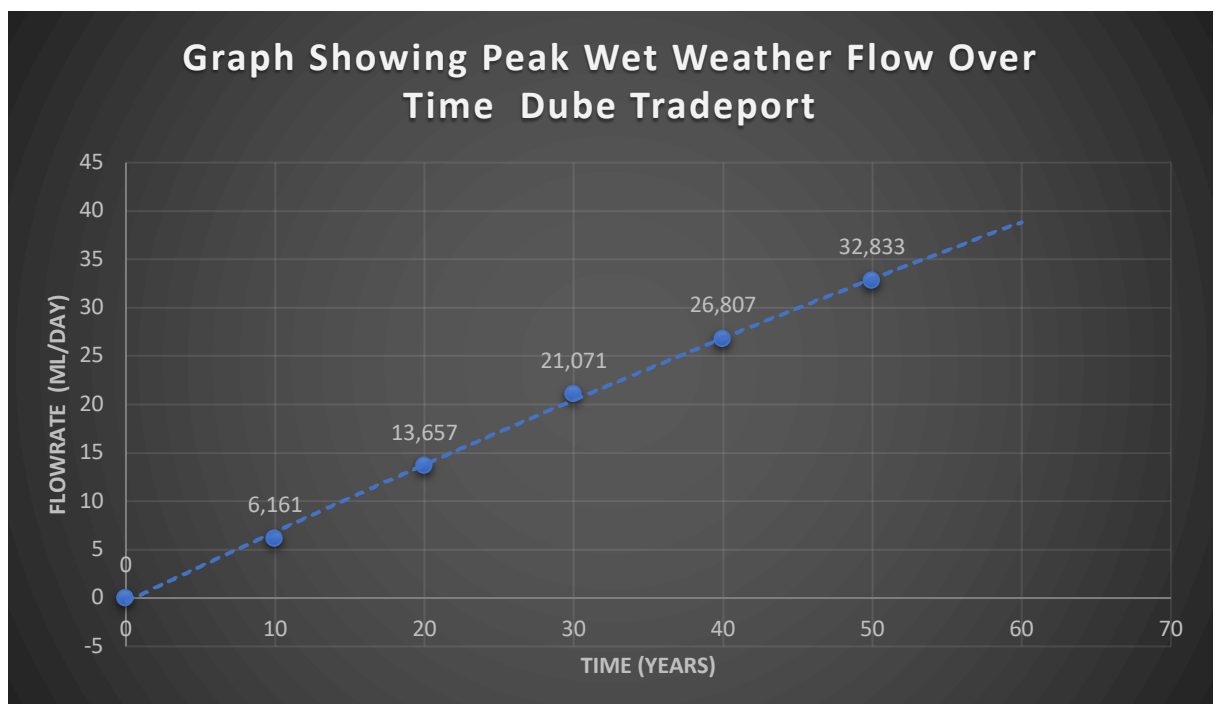


Figure 38 Showing Graph of Peak Wet Weather Flow Over Time (Dube Tradeport, 2020)

4.5 Wastewater Quality at Dube Tradeport

Quality statistics for the two, existing wastewater treatment works at Dube Tradeport were obtained from the Wastewater Treatment Works Monitoring reports compiled by GCS Environmental Engineering and Veolia Water. The reports consisted of various influent and effluent quality parameters as well as the Special Limit Values (SLV) needed to be achieved before effluent discharge or reuse. The estimated influent quality parameters expected at the new wastewater treatment works were obtained by analysing monthly results from October 2016 to February 2017 and choosing the maximum value for each parameter (Veolia, 2016/2017). In cases, such as for COD where extreme outlier values were obtained, an arithmetic average taken over 5 months was used to get a final quality value. This data is shown in Tables 25 and 26 below:

Table 25 Showing: Influent Quality Parameters

Influent Quality Parameter	Unit	Value
pH	-	7.9
Conductivity	mS/m	157
COD (Chemical Oxygen Demand)	mg/l COD	1095
FOG (Fats, Oils and Grease)	mg/l	208
SS (Suspended Solids)	mg/l	923
TDS (Total Dissolved Solids)	mg/l	773
BOD ₅ (Biological Oxygen Demand)	mg/l	548
Ammonia (TKN)	mg/l	85

Table 26 Showing Effluent Special Limit Values

Effluent Quality Parameter	Unit	Special Limit Value
pH	-	5.5 – 7.5
Conductivity	mS/m	100
COD	mg/l COD	30
Ammonia	mg/l NH ₃ -N	2
Nitrate	mg/l NO ₃ --N	1.5
Phosphate	mg/l PO ₄ ³⁻	2.5
SS	mg/l	10
E. coli	Counts/100ml	0
FOG	ml/g	3
Alkalinity	mg/l CaCO ₃	-

4.6 Chapter Summary

The case study of wastewater quantity that is projected to be produced at the Dube Tradeport over the period of 2050 masterplan, shows that a significant quantity of wastewater will need to be treated (6ML, 12ML and 18ML over 3 equal phases) and disposed of safely such that there is a limited impact on the environment.

The influent quality parameters of wastewater that is currently being treated at existing plants at Dube Tradeport, in conjunction with the wastewater quantity projections will be used as input criteria for the BioWATT model in Chapter 5, which will be used to project the amount of biogas that can be produced per day for four different types of wastewater treatment.

It is hypothesised that an excess amount of biogas and therefore energy, can be produced at the proposed new wastewater treatment works at Dube Tradeport which would then be able to fuel a portion of the Go! Durban BRT buses which will operate on Line C8 that passes through Dube Tradeport and the King Shaka International Airport.

This data will be used to recommend which wastewater treatment method should be used for the proposed new treatment plant that is planned for Dube Tradeport such that the most number of Go! Durban BRT buses can be fuelled per day. The number of buses which can be fuelled per day at Dube Tradeport is an important sustainability indicator which can be used to make a decision regarding the type of propulsion technology which should be selected for Line C8 of the Go! Durban BRT system.

This is an important consideration with regards to reducing the Well to Wheels (WTW) Greenhouse Gas (GHG) emissions of the propulsion technology that is chosen. The following Chapter will therefore evaluate three Waste to Energy Scenarios for a proposed new Wastewater Treatment plant at Dube Tradeport which will then inform how many vehicles that can be fuelled per day based on energy consumption in kWh/km per propulsion technology as identified from the Literature Review in Chapter 2 of this dissertation.

The following chapter will also see the development of Smart Fuel Scenario Assessment Matrix which has been developed using sustainability indicators found through the Literature Review in Chapter 2 of this dissertation.

Chapter 5: Results and Discussion

In this chapter, the results of the research aim and objectives as outlined in Chapter 1 of this thesis will be presented and discussed critically.

5.1 Introduction

This Chapter of the dissertation consists of four main results as per the four objectives of the study that was explained in Chapter 1. The first result output that is presented is the BioWATT Wastewater Treatment Scenario Evaluation Model which is comprised of the Biogas projection modelling output, a comparative analysis of Waste to Energy scenarios and the number of buses that can be fuelled per day at Dube Tradeport for each of the Waste to Energy scenarios.

The second result that is presented is the SMART Sustainability Indicator Assessment Matrix which was used to assess a set of eleven indicators which were obtained from the CIVITAS, Smart Choices for Cities: Alternative Fuel Buses Framework. This was achieved using a scoring system that is a modification of the existing SMART Framework as detailed in Chapter 3. This assessment aimed to determine if the Sustainability Indicators obtained from Literature Review, qualified as SMART (Specific, Measurable, Achievable, Relevant and Time Bound) Indicators which could be used to develop the Smart Fuels Assessment Matrix.

This Framework and inventory of Sustainability Indicators and Smart Fuel Scenarios was chosen from literature review based on the maximum number of bus propulsion technologies which were represented in the framework. This led to the rejection of other similar alternative bus fuel frameworks which did not include Biofuels such as Biodiesel and Bioethanol. The next result that is presented is the Smart Fuel Assessment Matrix which integrated the assessed set of eleven Sustainability Indicators and the Smart Fuel scenarios which were modified from the existing CIVITAS Smart Choices for Cities: Alternative Fuel Buses Framework. This quantitative data was then used to conduct a Comparative Rank Analysis involving all nine bus propulsion technologies modified from the CIVITAS Framework. The Comparative Rank Analysis Scores were then multiplied by a set of weighting factors (From the SMART Indicator Analysis) to produce an Average Weighted Indicator Score per bus propulsion technology which informed a recommendation. This process then fed into the development of the T.R.O.I.S model as shown in the Figure 39 below:

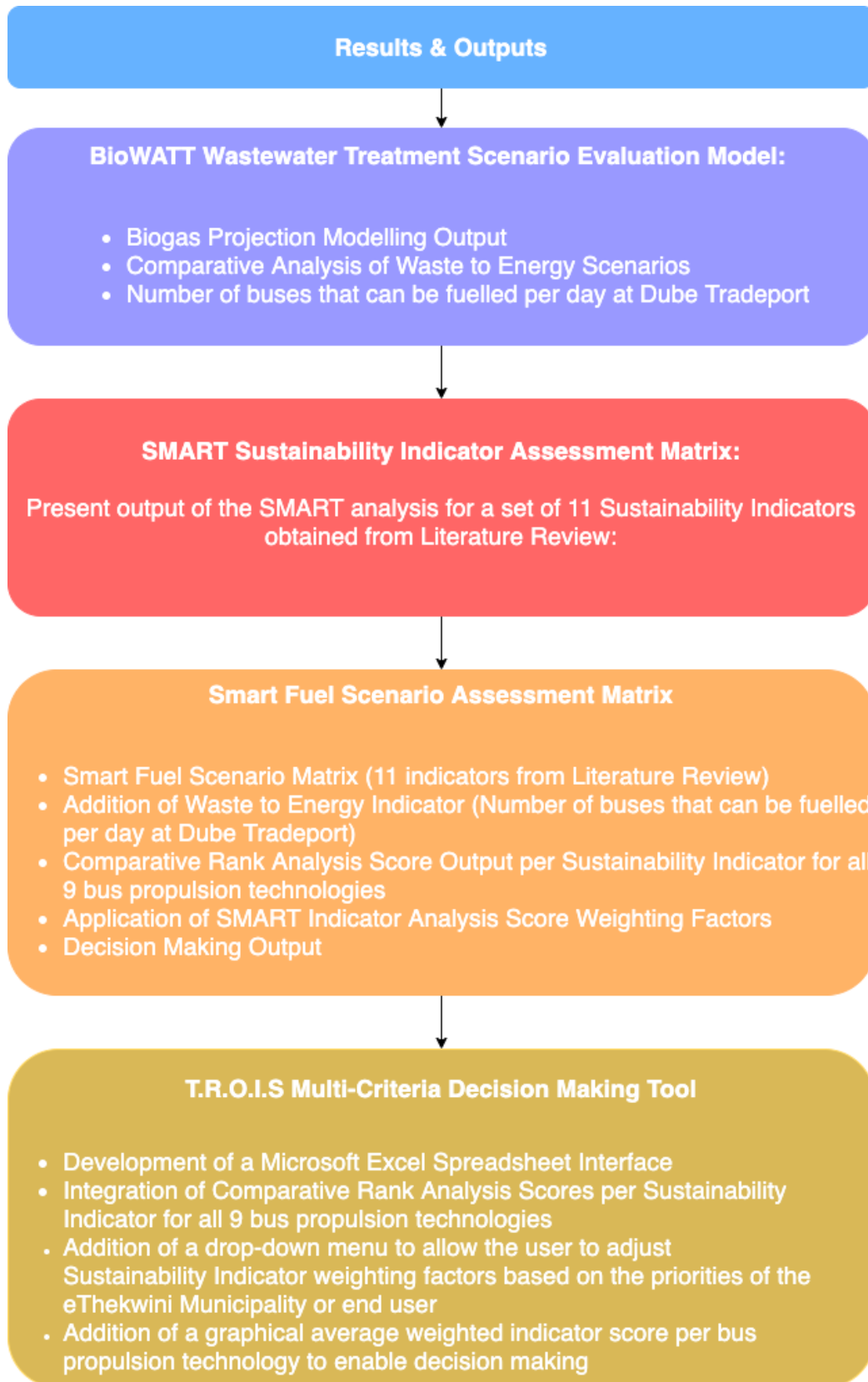


Figure 39 Showing: Set of results and outputs that will be presented in Chapter 5

5.2 BioWATT Wastewater Treatment Scenario Evaluation

5.2.1 Biogas Wastewater Assessment Technology Tool (BioWATT) Model Output per Wastewater Treatment Type

The following summary of outputs were obtained for the four chosen wastewater treatment technology types. Four wastewater treatment options were considered for the proposed new WWTW at Dube Tradeport: Conventional Activated Sludge (CAS) with Anaerobic Digester (with co-digestion of organic waste from Dube Agrizone), Trickling Filter (TF) with Anaerobic Digester (with co-digestion of organic waste from Dube Agrizone), Up Flow Anaerobic Sludge Blanket (UASB) reactor and a Covered Anaerobic Pond.

Co-digestion of organic waste from the Dube Agrizone was not taken into consideration for the Up Flow Anaerobic Sludge Blanket and Covered anaerobic pond methods due to limitations of how the BioWATT model is calibrated.

Wastewater treatment plants are usually designed using a modular approach, therefore the analysis can be conducted once for Phase 1 for the 6MI/day Wastewater Treatment Plant. Subsequent expansion of the plant would involve replicating Phase 1 in further 6MI/day capacity modules.

The expansion of Phase 2 is the addition of another 6MI module creating a total capacity of 12MI/day. Finally, the third and final expansion Phase 3 would involve the addition of another 6MI/day module creating a total capacity of 18MI/day.

5.2.1.1 Conventional Activated Sludge with Anaerobic Co-digestion of Organic Waste from Dube Tradeport Agrizone

The Table 27 below summarises the BioWATT model outputs for wastewater treatment Option 1 where a Conventional Activated Sludge treatment with Anaerobic Co-digestion of organic waste from Dube Tradeport Agrizone is proposed as a possible solution for the new WWTW that is planned for the Dube Tradeport precinct. The list of assumptions which were used as an input into the BioWATT biogas projection model for Option 1 is detailed in Chapter 3: Methodology:

Table 27 Showing biogas projection analysis results for a Conventional Activated Sludge with Anaerobic Co-Digestion of Organic Waste from Dube Tradeport Agrizone

CAS + DIGESTER (Including Co-digestion of Organic Waste from Dube Agri-zone)	Result	Unit
Biogas production	520 239	m ³ /year
Electricity generation from biogas	994 756	kWh/year
	2725	kWh/day
GHG emission reduction through electricity from biogas	-995	tons CO _{2e} /year
Total GHG emission reduction	-995	tons CO_{2e}/year
Reduction of electricity cost	-898 934,15	Rands/year
Reduction of aeration cost in aeration tank	-311 990,00	Rands/year
Reduction of sludge disposal cost	-757 783,12	Rands/year
Additional O&M cost	584 114,61	Rands/year
Total OPEX saving	-1 384 592,66	Rands/year
Digester	1 211	m ³
Biogas holder	285	m ³
CHP - total electric power	136	kW

Biogas production		
Biogas production from Primary Sedimentation	703	m ³ /d
Biogas production from Waste Activated Sludge	363	m ³ /d
Biogas production from organic feedstock	360	m ³ /d
Total biogas production	1 425	m ³ /d
	520 239	m ³ /year

Once the output had been achieved, the analysis was repeated for wastewater treatment Option 2 which is explained below:

5.2.1.2 Trickling Filter with Anaerobic Co-digestion of Organic Waste from Dube Tradeport Agrizone

The Table 28 below summarises the BioWATT model output for wastewater treatment Option 2 where a trickling filter with anaerobic co-digestion of organic waste from Dube Tradeport Agrizone is proposed as a possible solution for the new WWTW that is planned for the Dube Tradeport precinct.

Table 28 Showing biogas projection analysis results for a trickling filter with Anaerobic Co-digestion of Organic Waste from Dube Tradeport Agrizone

TRICKLING FILTER + DIGESTER (Including Co-digestion of Organic Waste from Dube Agri-zone)	Result	Unit
Biogas production	502 597	m ³ /year
Electricity generation from biogas	960 354	kWh/year
	2631	kWh/day
GHG emission reduction through electricity from biogas	-960	tons CO _{2e} /year
Total GHG emission reduction	-960	tons CO_{2e}/year
Reduction of electricity cost	-867 853,67	Rands/year
Reduction of sludge disposal cost	-726 939,66	Rands/year
Additional O&M cost	584 114,61	Rands/year
Total OPEX saving	-1 010 663,90	Rands/year
Digester	1 154	m ³
Biogas holder	275	m ³
CHP - total electric power	132	kW
Biogas production		
Biogas production from PS	703	m ³ /d
Biogas production from TFS	314	m ³ /d
Biogas production from organic feedstock	360	m ³ /d
Total biogas production	1 377	m ³ /d
	502 597	m ³ /year

Once the output had been achieved, the analysis was repeated for wastewater treatment Option 3 which is explained below:

5.2.1.3 Up Flow Anaerobic Sludge Blanket

The Table 26 below summarises the BioWATT model output for wastewater treatment Option 3 where an Up Flow Anaerobic Sludge Blanket is proposed as a possible solution for the new WWTW that is planned for the Dube Tradeport precinct.

Table 14 Showing biogas projection analysis results for a Up Flow Anaerobic Sludge Blanket

UASB	Result	Unit
Biogas production	260 426	m ³ /year
	713	m ³ /d
Electricity generation from biogas	507 831	kWh/year
	1391	kWh/day
GHG emission reduction through electricity from biogas	-508	tons CO _{2e} /year
Total GHG emission reduction	-508	tons CO_{2e}/year

Reduction of electricity cost	-458 918,62	Rands/year
Additional O&M cost	207 297,06	Rands/year
Total OPEX saving	-251 621,56	Rands/year
Biogas holder	143	m ³
CHP - total electric power	70	kW

Once the output had been achieved, the analysis was repeated for wastewater treatment Option 4 which is explained below:

5.2.1.4 Covered Anaerobic Pond

The Table 27 below summarises the BioWATT model outputs for wastewater treatment Option 4 where a covered anaerobic pond is proposed as the new WWTW that is planned for the Dube Tradeport precinct.

Table 15 Showing biogas projection analysis results for a Covered Anaerobic Pond

COVERED ANAEROBIC POND	Result	Unit
Biogas production	308 602	m ³ /year
	845	m ³ /d
Electricity generation from biogas	648 065	kWh/year
	1776	kWh/day
GHG emission reduction through electricity from biogas	-648	tons CO _{2e} /year
Total GHG emission reduction	-648	tons CO_{2e}/year
Reduction of electricity cost	-585 640,49	Rands/year
Additional O&M cost	249 340,16	Rands/year
Total OPEX saving	-336 300,33	Rands/year
CHP - total electric power	89	kW

Once a BioWATT biogas projection model output had been achieved for all four wastewater treatment options, the result outputs were compared graphically to determine which wastewater treatment method would produce the largest amount of biogas.

5.2.2 Comparative Analysis BioWATT Biogas Projection Model Outputs for each selected wastewater treatment method

The BioWATT biogas projection model outputs for each of the wastewater treatment options presented in Section 5.2.1 were then used to create a graphical comparison to enable the evaluation of which wastewater treatment method would produce the most biogas for Dube Tradeport. The wastewater treatment method which produced the most

amount of biogas, would subsequently be able to fuel the most number of Go! Durban Bus Rapid Transit Buses, which services Line C8 running through Dube Tradeport and the Durban Aerotropolis. The results of this comparative analysis by wastewater treatment type is shown in the Figure 40 below:

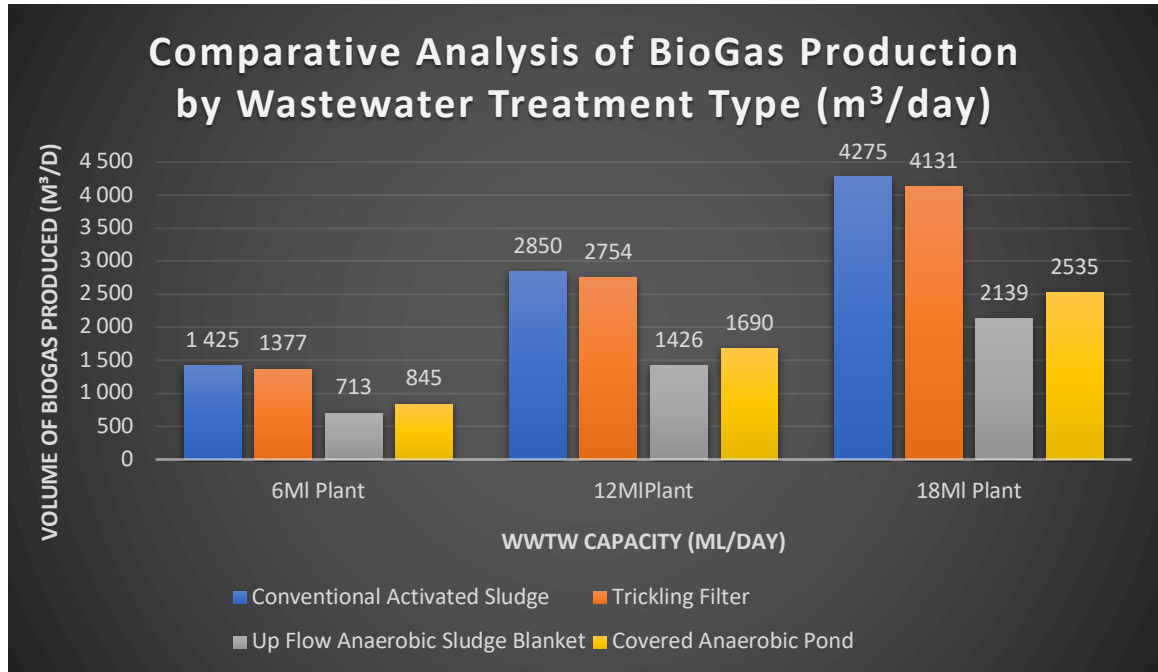


Figure 40 Showing Comparative Analysis of Biogas production by wastewater treatment type (m³/day)

A comparative analysis found that the conventional activated sludge method (with co-digestion of organic waste from Dube Agrizone) produced the most bio-gas (1425 m³/day) for a 6MI/day plant. Subsequently, the conventional activated sludge method also produced the most electricity (2725 kWh/day) for a 6MI/day plant. Operational GHG emissions reduction, due to the use of onsite biogas generated electricity instead of the electricity grid, showed the most reduction of 995 tons of CO_{2eq}/year for the conventional activated sludge method (for a 6MI/day plant). The reduction in OPEX costs (electricity, sludge disposal, operations and maintenance) was found to be the greatest for the conventional activated sludge method with co-digestion, with a savings of approximately R1 384 592,66 per year for a 6MI/day plant.

The Figure 41 below shows a comparative analysis of electricity generation by wastewater treatment type in kWh per day:

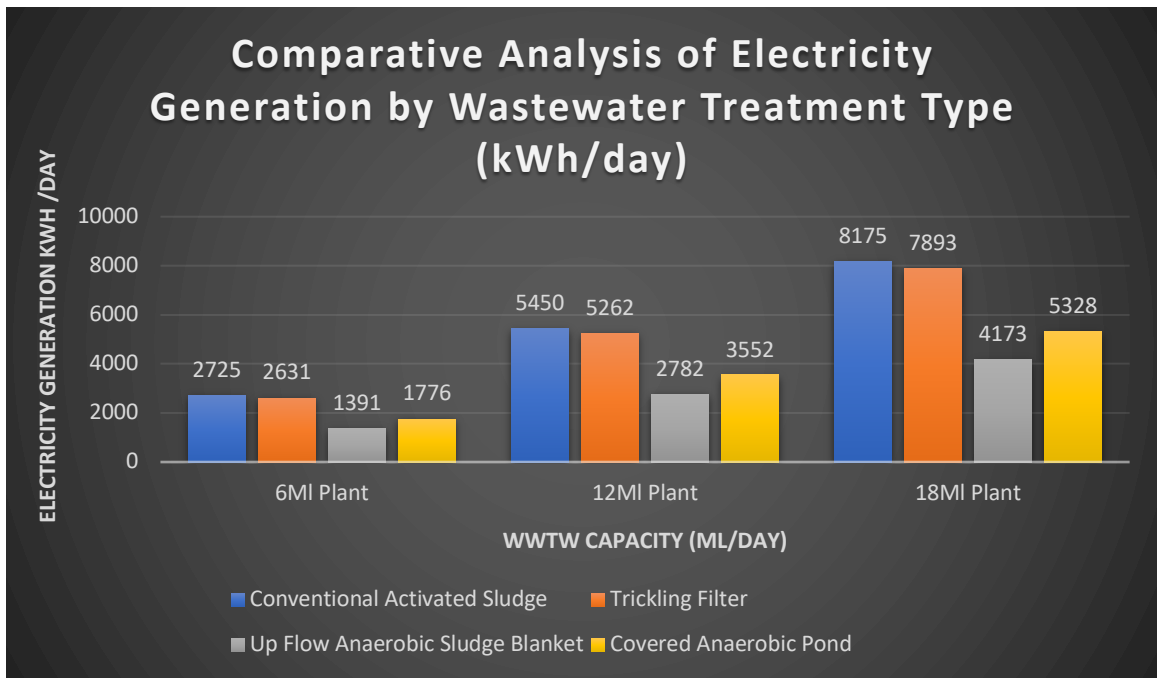


Figure 41 Showing Comparative Analysis of Electricity Generation by Wastewater Treatment Type (kWh/day)

The Figure 42 below shows a comparative analysis of GHG Emissions Reduction by Wastewater Treatment Type (Tonnes CO_{2eq} / Year):

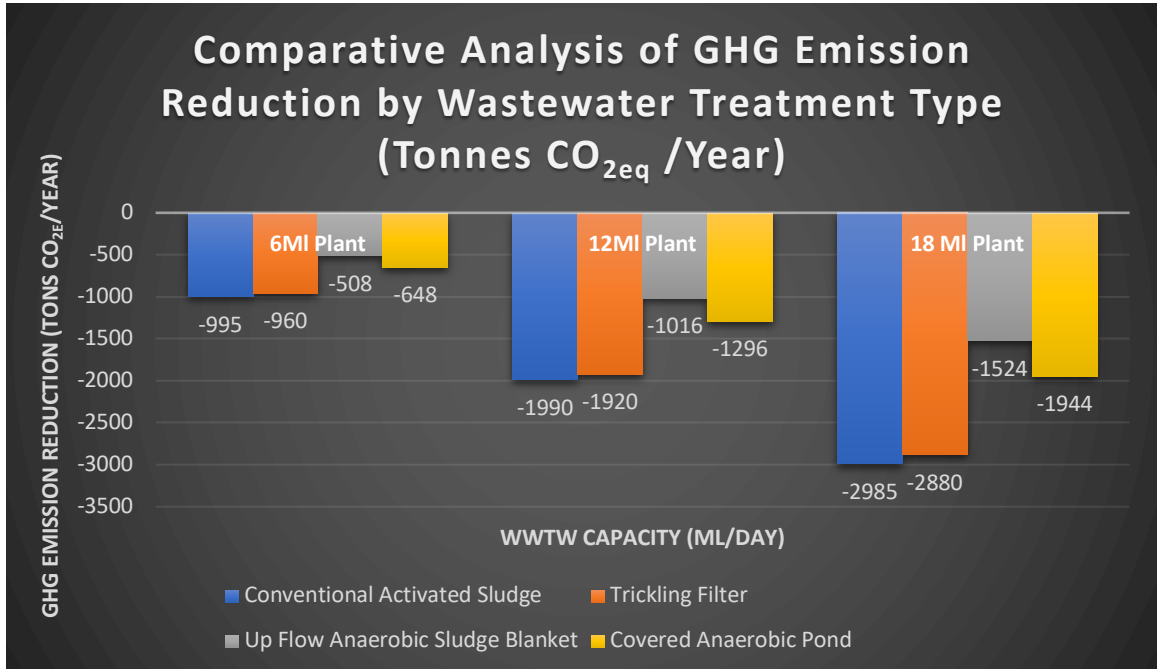


Figure 42 Showing Comparative Analysis of GHG Emission Reduction by Wastewater Treatment Type (Tonnes CO_{2eq}/Year)

The Figure 43 below shows a comparative analysis of OPEX Cost Reduction by Wastewater Treatment Type (Rands/Year):

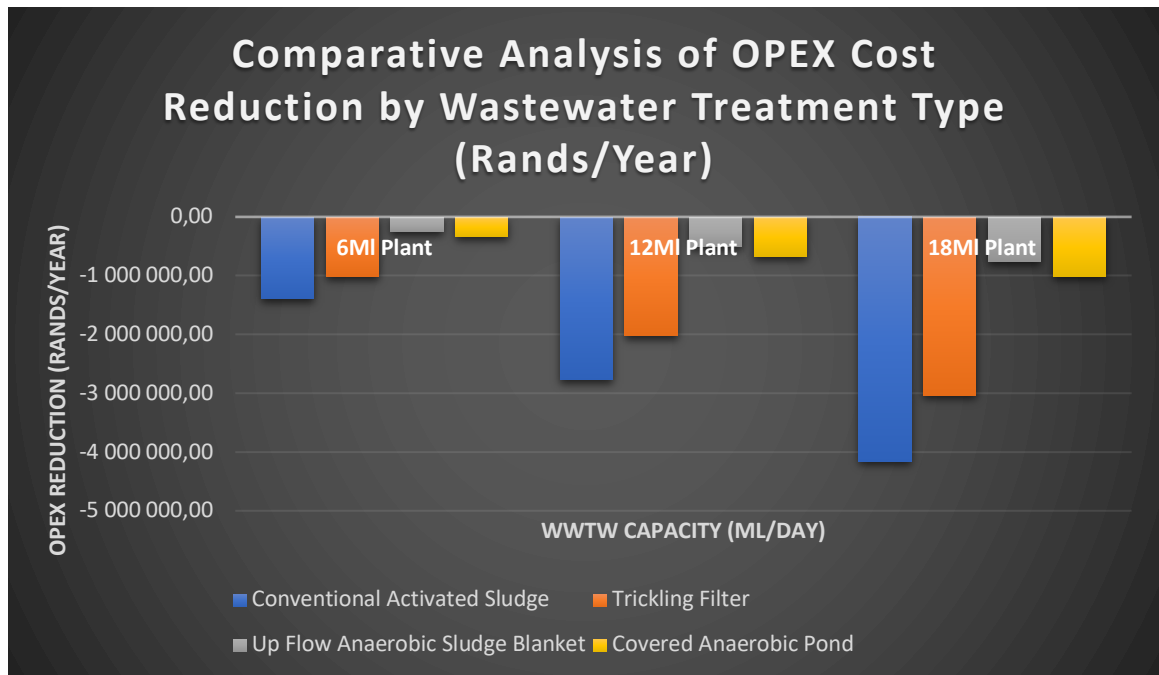


Figure 43 Showing Comparative Analysis of GHG OPEX Cost Reduction by Wastewater Treatment Type (Rands/Year)

An analysis of biogas production vs. WWTW energy consumption of the four selected wastewater treatment methodologies found that Conventional Activated Sludge, Trickling Filter and Up Flow Anaerobic Sludge Blanket methodologies, produced an insufficient biogas surplus per day after meeting the energy requirements of the plants themselves as shown in the Figure 44 below:

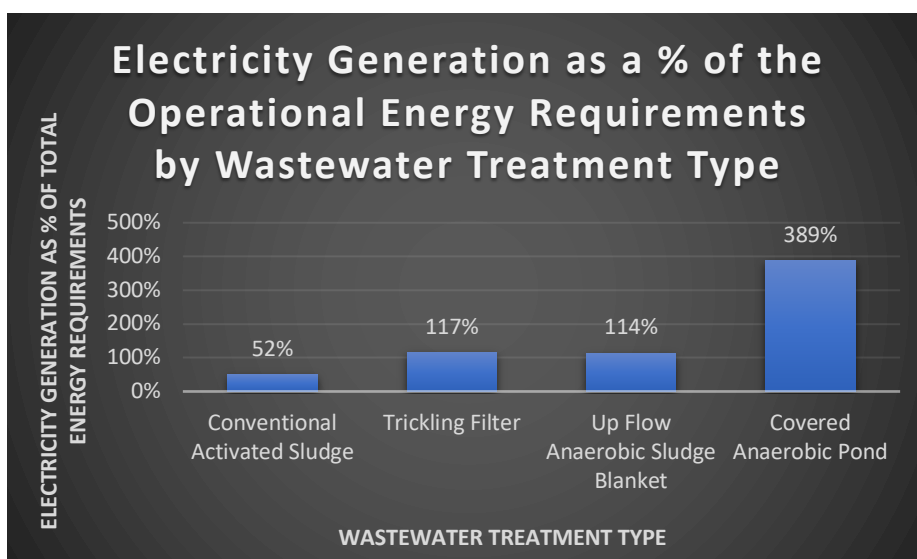


Figure 44 Showing electricity generation as a % of the operational energy requirements by wastewater treatment type

The Covered Anaerobic Pond treatment method was found to produce enough biogas to meet operational energy requirements, with a daily surplus that is large enough to meet the needs of the Go! Durban BRT Buses that pass through the Durban Aerotropolis. The Covered Anaerobic Pond biogas projection, obtained using the BioWATT model, will be used to calibrate the T.R.O.I.S Multi-criteria Decision Making Tool. The low operational energy requirements of this plant allow for the maximum generation of surplus bio-gas for upgrade as a transport fuel (either through CNG, direct conversion to electricity and storage for battery electric buses or conversion of the biogas to hydrogen via the Hazer Process for fuel cell powered buses).

The Covered Anaerobic Pond may not produce the required wastewater outflow characteristics as required by Dube Tradeport. Therefore, the selection of the Covered Anaerobic Pond biogas projection is strictly to calibrate the T.R.O.I.S model to determine the maximum number of buses that could theoretically be fuelled per day at Dube Tradeport. With regards to meeting wastewater effluent standards at Dube Tradeport, it is recommended that a Conventional Activated Sludge Plant be built even if the energy usage of the plant is higher because of the higher quality of the treatment effluent that is produced post treatment.

Additionally, some energy can also be recovered via the heat produced from the CHP system, which can go some way towards of setting the energy requirements of the plant. The Figure 45 below shows the expected Chemical Oxygen Demand (COD) removal for the various stages of a typical Conventional Activated Sludge plant.

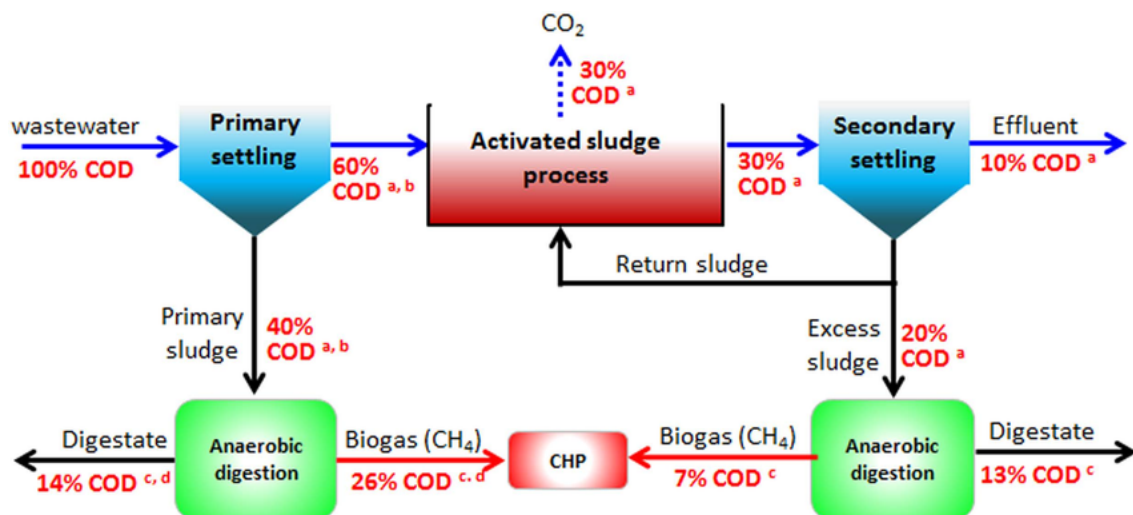


Figure 45 Showing the expected Chemical Oxygen Demand (COD) removal for the various stages of a typical Conventional Activated Sludge wastewater treatment plant (Metcalf & Eddy, 2012)

Operational data from the existing Sequencing Batch Reactor wastewater treatment plants as well as the effluent Special Limit Values and General Limit Values are shown in the figure below for comparison purposes: Dube Tradeport currently has two Sequencing Batch Reactor wastewater treatment plants, the North WWTW (Figure 46) and the South WWTW (Figure 47) respectively.

North Plant - Effluent						
Determinand	Unit	SLV	GLV	31/10/2016	SLV Comp.	GLV Comp
pH	-	5.5 - 7.5	5.5 - 9.5	6.6	Compliant	Compliant
Conductivity	mS/m	100	150	57	Compliant	Compliant
COD	mg/ℓ COD	30	75	24	Compliant	Compliant
Ammonia	mg/ℓ NH ₃ -N	2	6	0.77	Compliant	Compliant
Nitrate	mg/ℓ NO ₃ ⁻ -N	1.5	15	57	Non-Compliant	Non-Compliant
Phosphate	mg/ℓ PO ₄ ³⁻	2.5	10	0.125	Compliant	Compliant
SS	mg/ℓ	10	25	4	Compliant	Compliant
E.Coli	counts/100mℓ	0	1000	0	Compliant	Compliant
OG	mg/ℓ	3	3	<3	Compliant	Compliant
Alkalinty	mg/ℓ CaCO ₃	-	-	37		

Figure 46 Showing the effluent quality indicators post treatment at the North Plant compared against the Special Limit and General Limit Parameters (Veolia Water, 2017)

South Plant - Effluent						
Determinand	Unit	SLV	GLV	31/10/2016	SLV Comp.	GLV Comp
pH	-	5.5 - 7.5	5.5 - 9.5	6.1	Compliant	Compliant
Conductivity	mS/m	100	150	89	Compliant	Compliant
COD	mg/ℓ COD	30	75	24	Compliant	Compliant
Ammonia	mg/ℓ NH ₃ -N	2	6	2.82	Non-Compliant	Compliant
Nitrate	mg/ℓ NO ₃ ⁻ -N	1.5	15	19.8	Non-Compliant	Non-Compliant
Phosphate	mg/ℓ PO ₄ ³⁻	2.5	10	1.59	Compliant	Compliant
SS	mg/ℓ	10	25	9	Compliant	Compliant
E.Coli	counts/100mℓ	0	1000	0	Compliant	Compliant
FOG (DWS)	mℓ/g	3	3	<3	Compliant	Compliant
Alkalinty	mg/ℓ CaCO ₃	-	-	18		

Figure 47 Showing the effluent quality indicators post treatment at the North Plant compared against the Special Limit and General Limit Parameters (Veolia Water, 2017)

Figures 46 and 47 above show that the Sequencing Batch Reactor Plants are non-compliant for ammonia and nitrate effluent Special Limit and General Limit standards as per the report from Veolia Water in 2017. Therefore, the data indicates that additional treatment or a different treatment process entirely is required to meet the Special limit and General Limit requirements for wastewater treatment at Dube Tradeport (Veolia Water, 2017).

5.2.3 Waste to Energy Scenarios for Dube Tradeport

The Figure 48 below shows three Waste to Energy Scenarios which were investigated once the Covered Anaerobic Pond wastewater treatment method was chosen as the recommendation for Dube Tradeport. This is because, this treatment method produces the most surplus biogas energy after taking into consideration the energy requirements of the plant itself. Therefore this treatment option would be able to fuel the most number of Go! Durban Bus Rapid Transit buses per day at Dube Tradeport.

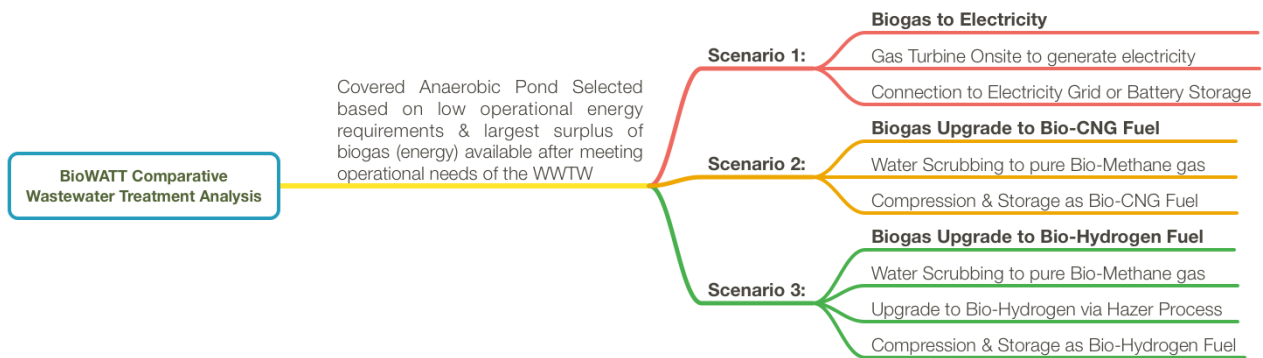


Figure 48 Showing: Three Waste to Energy Scenarios which were evaluated for Dube Tradeport

5.2.3.1 Scenario 1: Bio-gas extraction for onsite Electricity Generation to fuel Electric Go! Durban buses on the C8 Line

Scenario 1 evaluates the potential of biogas extraction and onsite electricity generation for the Covered Anaerobic Pond wastewater treatment method. As explained previously this wastewater treatment method was chosen because the biogas surplus that is produced after meeting the energy requirements of running the plant itself, is the greatest of the four treatment methods that were evaluated. The electricity will be generated by means of a micro gas turbine onsite at the proposed new wastewater treatment plant at Dube Tradeport. The Figure 49 below shows the projected electricity generation potential of the Covered Anaerobic Pond, per phase of the WWTW development:

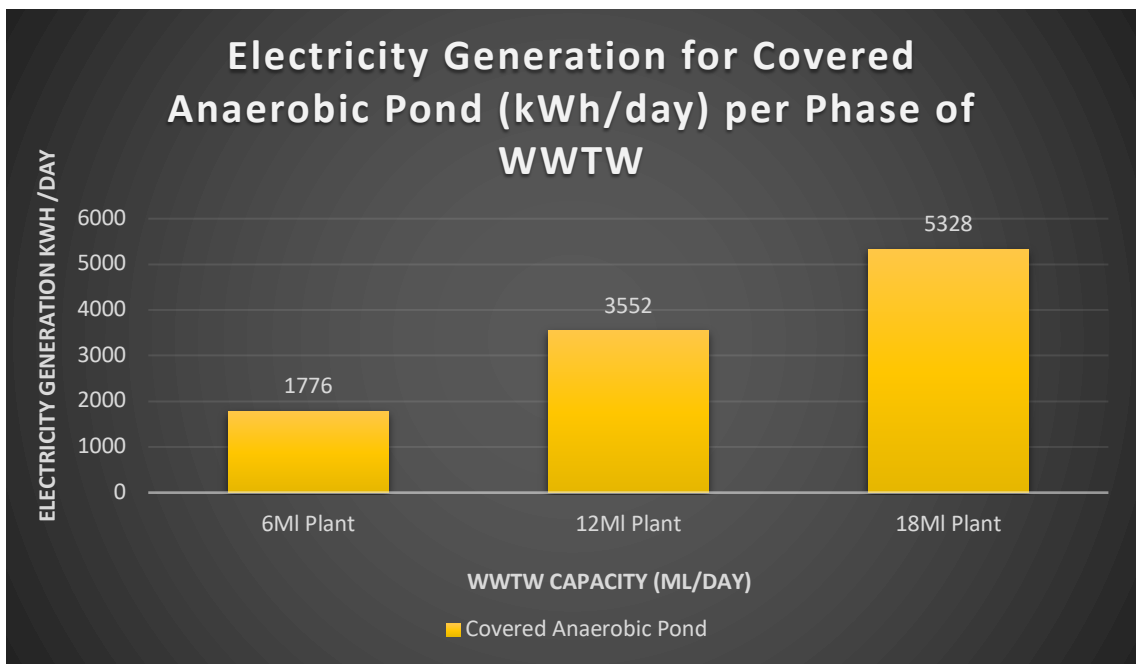


Figure 49 Showing the projected electricity generation for a Covered Anaerobic Pond WWTW

Approximately 74.27% of the potential electricity which can be produced per day, using biogas produced from a Covered Anaerobic Pond wastewater treatment method, can be used to charge electric Go! Durban BRT buses. The tables below summarise the amount of electricity available per day per phase of the proposed WWTW. According to Clarke Energy (2020) the efficiency conversion rate for a typical CHP biogas powered turbine is approximately 43%.

The Table 28 below shows the results of the investigation into the number of Go! Durban BRT buses which could be fuelled per day at Dube Tradeport. For Scenario 1: Biogas to electricity to charge electric buses operating Line C8 of the Go! Durban BRT system, it was found that the most number of buses would be fuelled if Battery Electric Opportunity Charging or Electric trolley bus was chosen as the preferred bus propulsion technology. The number of buses that could be fuelled per day was calculated by dividing the electricity surplus at Dube Tradeport WWTW (kWh per day) by the total energy consumption per electric bus propulsion technology (kWh/km) using an average daily mileage of 300km for a city bus (eThekwini, 2019). The figures obtained were rounded down to the nearest whole number so that a conservative figure of the number of buses which could be fuelled per day could be calculated.

Table 16 Showing a summary of electricity production per day available to charge electric buses for the Go! Durban BRT Line 8

		6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Electricity Surplus per day (KWhrs)		1319.04	2638.07	3957.11
Propulsion Technology	Energy Consumption (kWh/km)	Number of Buses Fuelled per Day		
Battery Electric Opportunity Charging	1.4	1	2	4
Battery Electric Overnight Charging	1.6	1	2	3
Trolley Buses	1.4	1	2	4
Hybrid Diesel- Electric	3.3	0	1	1

5.2.3.2 Scenario 2: Biogas extraction and upgrade to pure biomethane fuel (Bio-CNG) to fuel Go! Durban BRT buses on the C8 Line

Scenario 2 evaluates the upgrade of biogas to bio-methane for use as a vehicular fuel for the Go! Durban BRT buses that pass through the Durban Aerotropolis. The bio-methane fuel will be used as Compressed Natural Gas (CNG) or Bio-CNG as the fuel is biogenic in nature.

The projected supply of surplus bio-gas using Covered Anaerobic Ponds is shown in the Table 29 below: As stated earlier, for the Covered Anaerobic Pond method, the electricity generated as a percentage of the operational energy requirements of the plant itself is 389%.

This means that approximately, 25.73% of the biogas that is generated at the plant must be used to sustain the operational energy requirements of the plant itself. This leaves approximately 74.27% of the biogas which is available as a surplus for upgrade to pure bio-CNG fuel for buses.

The total bio-methane surplus that is available per day (m³/day) for each phase of development of the proposed new wastewater treatment plant at Dube Tradeport, is shown in the table below. A methane content of 70% has been assumed for this calculation.

Table 17 Showing biogas generation, surplus available and upgraded bio-methane surplus available per day at the Dube WWTW

	6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Biogas Generation (m³ / day)	845	1690	2535
Biogas Surplus Available for Upgrade (m³ / day)	627.56	1255.13	1882.68
Bio-methane Surplus Available per day (m³ / day) Assume @70% Methane Content	439.29	878.59	1317.88

A methane density value of 0.667 kg/m³ (Dutt, MGM International, 2003) was used to calculate the amount of bio-methane surplus (kg/day) that is available for use as a transport fuel. This density factor assumes a bio-methane gas pressure of 1atm and a temperature of 20°C. Table 30 shows the bio-methane surplus available per day.

Table 18 Showing bio-methane surplus available per day in m³/day and kg/day respectively

	6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Bio-methane Surplus Available (m³ / day)	439.29	878.59	1317.88
Bio-methane Surplus Available (kg / day)	293	586	879

Before the surplus bio-gas can be used as a transport fuel, the CO₂ and other residual chemicals must be removed so that an above 90% methane content is obtained. This will allow for enhanced engine operational efficiencies in Compressed Natural Gas (CNG) powered vehicles.

Once the biogas upgrade has been complete, the high-quality bio-methane must be safely compressed and stored in cylinders for use as a transport fuel. The water scrubbing method is the most commonly used method of upgrading biogas to pure biomethane fuel. The process that is followed has been described in detail in Chapter 2: Literature Review.

The Table 31 below shows the results of an investigation into how many Bio-CNG Go! Durban BRT buses could be fuelled per day at Dube Tradeport operating on Line C8 of the Go! Durban Bus Rapid Transit System. A lower heating value of 13.9kWh/kg of methane gas was used to calculate how many BRT buses could be fuelled per day at Dube Tradeport. (Engineering Toolbox, 2020). An energy conversion efficiency rate of 40% is assumed for a compressed bio-methane bus engine (Jääskeläinen, 2019).

Table 19 Showing a summary of electricity production per day available to charge electric buses for the Go! Durban BRT Line 8

		6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Energy Surplus per day (kWh)		1629.08	3258.16	4887.24
Propulsion Technology	Energy Consumption (kWh/km)	Number of Buses Fuelled per Day		
Bio-CNG Buses (Compressed Bio-Methane)	5.2	1	2	3

The number of buses that could be fuelled per day was calculated by dividing the energy surplus at Dube Tradeport WWTW (kWh per day) by the total energy consumption (kWh/km) using an average daily mileage of 300km for a city bus (eThekwini, 2019). The figures obtained were rounded down to the nearest whole number so that a conservative figure of the number of buses which could be fuelled per day could be calculated.

5.2.3.3 Scenario 3: Bio-Gas extraction and upgrading to Bio-hydrogen to power fuel cells for an electric Go! Durban BRT alternative

An alternative option involving the upgrading of biomethane into bio-hydrogen via the Hazer Process will be evaluated as a third and final scenario. Hydrogen fuel cell technology was chosen as the third scenario for this study as a zero carbon alternative to electric (Scenario 1) and Bio-CNG (Scenario 2). Taiwanese electric solutions manufacturer CHEM Corporation has built the first hydrogen fuel cell factory in South Africa at Dube Tradeport (CHEM, 2019).

Therefore, a third scenario has been developed to determine the feasibility of using hydrogen fuel cells to power an electric Bus Rapid Transit fleet. The Go! Durban C8 BRT line passes through the King Shaka International Airport at Dube Tradeport and would be a suitable opportunity to trial the use of hydrogen fuel cell powered buses. The Hazer Process will be investigated to determine how many Go! Durban BRT fuel cell buses could

be fuelled per day at Dube Tradeport. This technology was chosen through the literature review in Chapter 2.

According to the Fuel Cell and Hydrogen Energy Association (FCHEA, 2016) a hydrogen fuel cell can be described as a device that generates electricity through an electrochemical reaction instead of combustion. This process involves the combination of hydrogen and oxygen within a fuel cell to generate electricity, heat and water.

The hydrogen atoms enter the fuel cell at the anode. The positively charged protons pass through the membrane to the cathode and the negatively charged electrons are forced through a circuit, generating electricity. The atoms are stripped of their electrons in the cathode. After passing through the circuit, the electrons combine with the protons and oxygen from the air to generate the fuel cell's by-products: water and heat (FCHEA, 2016). Figure 50 below shows the components of a Hydrogen fuel Cell:

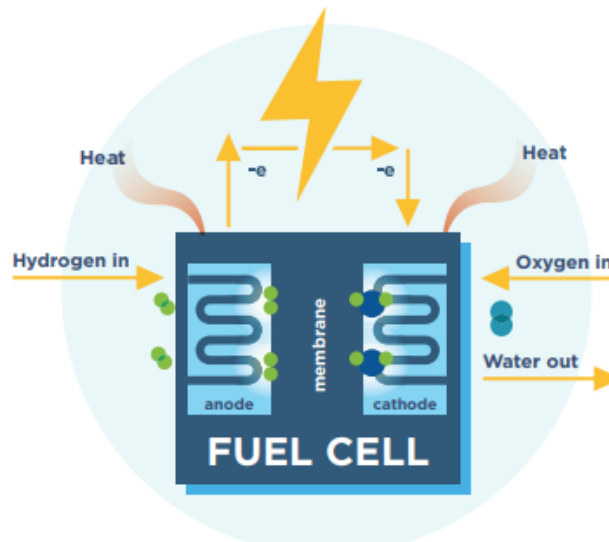


Figure 50 Showing the Components of a Hydrogen Fuel Cell

This technology therefore has the environmental benefit of zero carbon emissions due to the only by-product being heat and water. The use of hydrogen fuel cells to power the Go! Durban BRT bus fleet would significantly reduce the transport carbon footprint in the eThekweni Municipality. The use of green hydrogen, produced from bio-gas and the Hazer Process, results in a sustainable transport energy source with the added benefit of reduced air pollution. An electric bus powered by hydrogen fuel cells is an efficient, reliable and quiet alternative to the conventional internal combustion engine (FCHEA, 2016). According to the US Department of Energy, conventional combustion power plants generate electricity at efficiencies of 33% to 35%, compared to hydrogen fuel cells which can generate electricity at efficiencies of approximately 60%. In addition, the gasoline engine in a conventional car is less than 20% efficient in converting the chemical energy in gasoline

into vehicle propulsion. When hydrogen fuels are used in vehicles to run an electric motor, efficiencies of around 40% to 60% can be achieved. This results in a more than 50% fuel consumption reduction when compared to conventional gasoline powered internal combustion engines (US Department of Energy, 2006). When compared to battery electric vehicles, hydrogen fuel cell vehicles have a greater range of between 300km to 400km on a single tank of hydrogen fuel. Hydrogen fuel cell powered vehicles also have a short refuelling time of between three to five minutes, compared to battery electric vehicles which may take hours to charge (FCHEA, 2016).

In the context of South Africa's unstable electricity grid, which is prone to load shedding, it does not make sense to further burden the national grid by adopting the use of battery electric vehicles which could strain the grid during peak energy demand. The development of a hydrogen fuel cell manufacturing supply chain could be developed in the Special Economic Zone that has been developed at Dube Tradeport to facilitate the roll out of fuel cell powered vehicles and the corresponding refuelling stations that will be required. Data obtained from the Hazer Group (2018) regarding the mass and energy feed requirements, per tonne of hydrogen, that is produced via the Hazer Process is shown in the Table 32 below:

Table 20 Showing mass and energy feed requirements per tonne of hydrogen that is produced using the Hazer Process

Mass and Energy feeds and outputs (per tonne of Hydrogen Product)				
Hazer Process Overall Conversion	(%)	50%	70%	90%
Primary Product				
H ₂ Product (99.999%) ²	(t)	1.0	1.0	1.0
Graphite Product (85-90% w/w)	(t/t H ₂)	5.0	4.4	4.1
Gas Input and Output				
Natural Gas Feed	(t/t H ₂)	11.9	7.5	5.4
	(TJ/t H ₂)	0.60	0.38	0.27
Output - Fuel Gas By-Product	(TJ/t H ₂)	0.33	0.13	0.03
Net Gas (Energy) Consumption	(TJ / t H ₂)	0.27	0.25	0.24
Other Feed				
Iron Ore feed	(t/t H ₂)	1.02	0.90	0.83
Process Heating Duty	(MWhrs / t H ₂)	9.26	8.23	7.67
Electricity (For Gas Compression)	(MWhrs / t H ₂)	0.62	1.20	1.53

As discussed in Scenario 2 the Covered Anaerobic Pond treatment method produced the largest surplus of bio-gas for use as a transport fuel. The hydrogen production factors for 50%, 70% and 90% conversion rates, as shown in the table above have been applied to the projected supply of surplus bio-gas using Covered Anaerobic Ponds as discussed in Scenario 2. This is displayed in Table 33 below:

Table 21 Showing biogas generation per day compared to biogas surplus available for upgrade per day and bio-methane surplus available per day at Dube WWTW

	6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Biogas Generation (m³ / day)	845	1690	2535
Biogas Surplus Available for Upgrade (m³ / day)	627.56	1255.13	1882.68
Bio-methane Surplus Available per day (m³ / day) Assume @70% Methane Content	439.29	878.59	1317.88

A methane density value of 0.667 kg/m³ (Dutt, MGM International, 2003) was used to calculate the amount of bio-methane surplus (tonne/day) that is available for conversion to bio-hydrogen via the Hazer Process. This density factor assumes a bio-methane gas pressure of 1atm and a temperature of 20°C. Table 34 below shows hydrogen produced per day projections at different levels of efficiency. This is also shown in Figure 50 below:

Table 22 Showing Bio-methane surplus per day compared to hydrogen production using the Hazer Process at Dube WWTW

	6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Bio-methane Surplus Available per day (m³ / day)	439.29	878.59	1317.88
Bio-methane Surplus Available per day (kg / day)	293	586	879
Hydrogen Production @ 50% conversion (kg/day)	24,6	49,2	73,8
Hydrogen Production @ 70% conversion (kg/day)	39,1	78,2	117,3
Hydrogen Production @ 90% conversion (kg/day)	54,3	108,6	162,9

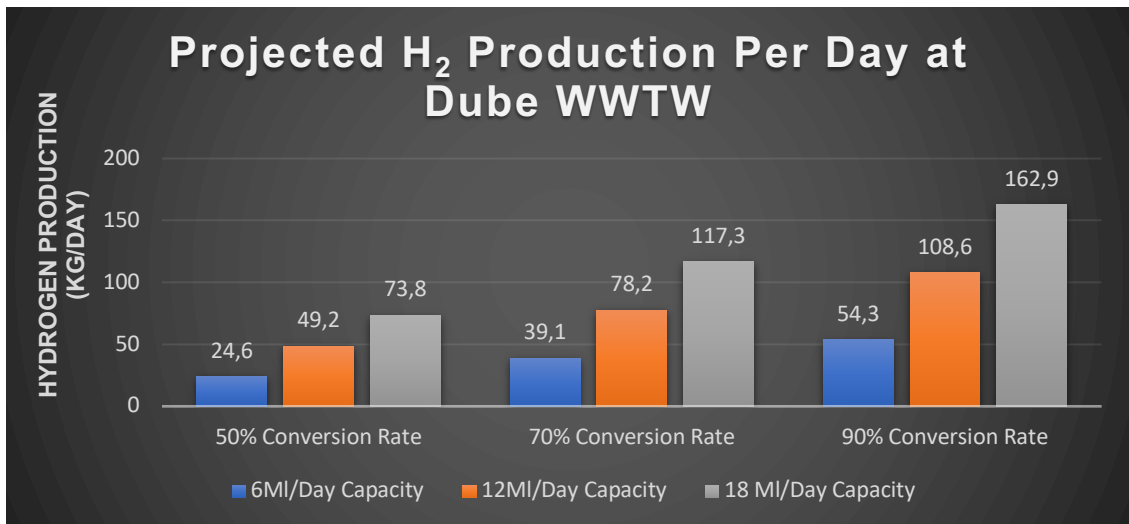


Figure 51 Showing projected hydrogen production using the Hazer Process at Dube WWTW

According to the Fuel Cell and Hydrogen Energy Association (FCHEA, 2016), a hydrogen fuel cell powered vehicle can travel approximately 300km to 400km on a single tank of hydrogen fuel. The Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM) is the type of hydrogen fuel cell that is typically used for transportation purposes. This type of fuel cell has a conversion efficiency rate of between 50% to 60% from chemical potential energy to electricity generation. The Table 35 below summarises the daily hydrogen production projections using the Hazer Process. The optimum level of 70% conversion rate will be assumed for calculating how many hydrogen fuel cell buses could be fuelled per day at Dube Tradeport servicing the C8 Go! Durban BRT Line.

Table 23 Showing projected hydrogen production using the Hazer Process at Dube WWTW

	6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Hydrogen Production @ 50% conversion (kg/day)	24,6	49,2	73,8
Hydrogen Production @ 70% conversion (kg/day)	39,1	78,2	117,3
Hydrogen Production @ 90% conversion (kg/day)	54,3	108,6	162,9

According to International Gas Union, Natural Gas Conversion Guide (2019), the calorific value of hydrogen gas is approximately 120 MJ per Kg or 0.12 GJ per Kg. The hydrogen conversion rate to energy at 70% efficiency (Hazer Process, 2018) is shown in Table 36 below:

Table 24 Showing a summary of hydrogen production per day using the Hazer Process at a 70% conversion rate as well as the calorific equivalent

	6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Hydrogen Production @ 70% conversion (kg/day)	39,1	78,2	117,3
Calorific Value of hydrogen produced per day (GJ/day)	4.692	9.384	14.076

An efficiency factor of 50% was used to calculate the number of hydrogen fuel cell buses which can be fuelled per day at Dube Tradeport. The energy value of the surplus hydrogen generated by the Hazer process was converted to kWh by using a lower heating value of 33.3 kWh /kg for hydrogen gas (Engineering Toolbox, 2020).

Table 25 Showing a summary of hydrogen production per day available to charge fuel cell electric buses for the Go! Durban BRT Line 8

		6MI / Day Capacity	12MI / Day Capacity	18MI / Day Capacity
Energy Surplus per day (kWh)		651.02	1302.03	1953.05
Propulsion Technology	Energy Consumption (kWh/km)	Number of Buses Fuelled per Day		
Bio-hydrogen Fuel Cell Buses	3.1	0	1	2

The number of buses that could be fuelled per day was calculated by dividing the energy surplus at Dube Tradeport WWTW (kWh per day) by the total energy consumption (kWh/km) using an average daily mileage of 300km for a city bus (eThekwini, 2019). The figures obtained were rounded down to the nearest whole number so that a conservative figure of the number of buses which could be fuelled per day could be calculated. The results obtained for Waste to Energy Scenario 3 shows that the least number of Go! Durban BRT buses would be able to be fuelled per day at Dube Tradeport. Waste to Energy Scenario 2: Biogas upgrade to Bio-CNG Fuel would be able to fuel the second highest number of Go! Durban BRT buses per day. Waste to Energy Scenario 1: Biogas to generate electricity through a gas turbine, would be able to fuel the highest number of Go! Durban Buses per day with Electric Trolley and Battery Electric Opportunity Charging proving to be the most energy efficient this analysis.

5.3 SMART Sustainability Indicator Assessment Matrix

The table below shows the SMART Sustainability Indicator Assessment Matrix which was applied to the eleven Smart Fuel Sustainability Indicators which were obtained from literature review in Chapter 2.

Table 26 Showing: Results obtained from applying the SMART Sustainability Assessment Matrix to eleven Smart Fuel Indicators

Sustainability Indicator	Unit	SMART Analysis				
		Specific	Measurable	Achievable	Relevant	Time Bound
Range	km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Route Flexibility	n/a	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Energy Consumption	kWh/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Refuelling Frequency	Days	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Refuelling Time	Minutes	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
GHG Emissions (WTW)	gCO2e/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
PM10 (TTW)	g/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
NOx (TTW)	g/km	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Noise Emissions	dB	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Cost Per Bus	Rands	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Number of buses which can be fuelled per day at Dube Tradeport	n/a	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

It was found that almost all of the eleven Smart Fuel Sustainability Indicators performed well with regards to the Specific, Measurable, Achievable, Relevant and Time Bound criteria of the SMART indicator framework (Duran, 1981). Almost all indicators achieved a high score ranging from 4 to 5 (out of a maximum score of 5).

The only indicator which performed poorly was Route Flexibility achieving a score of 2 out of a maximum of 5. This is because Route Flexibility was found to be not Specific, Measurable or Time Bound and thus received a zero score for those particular criteria.

5.4 Smart Fuel Scenario Assessment Matrix

The Smart Fuel Scenario Assessment Matrix was developed using data obtained from literature review as detailed in Chapter 2 of this dissertation. The eleven sustainability indicators which were identified and assessed in Section 5.3 were populated in a matrix against nine Smart Fuel bus population alternatives (Smart Choices for Cities, Alternative Fuel Buses, CIVITAS, 2016). This matrix was then used as a baseline to conduct a Comparative Rank Analysis for each of the eleven sustainability indicators covering the nine bus propulsion technologies to determine how they performed in relation to each other. This was possible due to the standardised nature of the

sustainability indicator matrix which was applied evenly across all nine bus propulsion technologies.

Thereafter, an Average Weighted Score was calculated for each bus propulsion technology using the weighting factors obtained from the SMART Indicator Assessment Matrix in Section 5.3. This then produced an output which enabled a semi-quantitative recommendation to be made regarding which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System. This recommendation is presented and discussed in Chapter 6 of this dissertation.

Following this, it was discovered that the eThekweni Municipality might want to manipulate the weighting factors for the different sustainability indicators, based on the funding available and policy priorities of the eThekweni Transport Authority. It was at this stage that a Microsoft Excel spreadsheet interface for a Multi-Criteria Decision Making Tool was developed.

This Multi-Criteria Tool was named the Transport, Reduction Optimisation, Implementation, Scenario (T.R.O.I.S) model, which has been designed to assist Transport Engineers at the eThekweni Transport Authority to decide which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System which passes through the Dube Tradeport and King Shaka International Airport.

The T.R.O.I.S model was designed with a drop down menu which allows the user to select a different weighting factor between 0 and 1, at intervals of 0.1, so that the algorithm can calculate an Average Weighted Score for each of the nine bus propulsion technologies taking into consideration constraints to provide a recommendation.

The full scale Smart Fuel Assessment Matrix that has been developed, by modifying the existing Smart Choices for Cities: Alternative Fuel Buses Framework which was developed by CIVITAS in 2016, is shown in Table 39 below: This matrix was populated with data obtained by Literature Review and structured in an Assessment matrix such that a Comparative Analysis between the nine different bus propulsion technologies could be conducted. This then feeds into the Comparative Rank Analysis Scoring shown in Table 40.

Table 27 Showing: Smart Fuel Alternatives for the Go! Durban Bus Rapid Transit System - C8 Line

Smart Fuel Alternatives for the Go! Durban Bus Rapid Transit System - C8 Line										
Operational Sustainability Indicators	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	References
Range	600-900km	350 – 400 km	570-850 km	400 – 600 km	<100 km	100 - 250 km	Unlimited within the network providing constant electricity supply.	600-900 km	200 – 400 km, the range depends on tank size of hydrogen and the storage pressure. A higher pressure of 700 bar would increase the range at the same volume of the storage tanks.	Smart Choices for Cities, Alternative Fuel Buses, CIVITAS, 2016
Route Flexibility	High	High	High	High	Limited	Higher	Flexibility beyond the network is only possible using an auxiliary power unit or battery.	High	High	
Energy Consumption	4.1 kWh/km	5.2 kWh/km	4.1 kWh/ km	4.1 kWh/km	1.4 kWh/km	1.6 kWh/km	1.4 kWh/km	3.3 kWh/km	3.1 kWh/km	
Refuelling Frequency	Every 2nd day	every 1st or 2nd day	every 2nd day	every 1or 2 days	Recharging needed multiple times a day	Recharging at the end of each day or during the day	Does not incorporate refuelling or recharging time in normal operation (except when auxiliary power unit battery needs to be recharged).	Refilling needed only after every 2nd day	Refilling every day at the end of operation	
Refuelling Time	5-10 min	5-10 min	5-10 min	5-10 min	Short recharging time: 5-10 min	Very long recharging times: more than 3 h		5min	10 min	
Environmental Sustainability Indicators							Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Emissions Euro VI	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging				

GHG WTT - (gCO2e/km)	1317	273	842	792	731	731	731	1054	1290	Smart Choices for Cities, Alternative Fuel Buses, CIVITAS, 2016
GHG Emissions Direct (gCO2e/km)	-	0	0	0	0	0	0	-	0	
NOx TTW (direct) - (g/km)	0.5-1.1	<1	0.5-1.1	0.5-1.1	0	0	0	0.5 - 1.1	0	
PM10 TTW (direct) - (g/km)	0.015	<0.01	0.015	0.015	0	0	0	0.015	0	
Social Sustainability Indicators										
Noise Emissions	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	
Standing	80 dB	78 dB	80 dB	80 dB	Lowest Noise Emission			69 dB	The noise emissions are low and comparable to electric buses.	Smart Choices for Cities, Alternative Fuel Buses, CIVITAS, 2016
Pass by	77 dB	78 dB	77 dB	77 dB				73 to 78 dB		
Financial Sustainability Indicators										
Cost Per Bus (Euros)	EURO 220,000.00	EURO 250,000.00	EURO 220,000.00	EURO 250,000.00	EURO 320,000.00 to EURO 500,000.00 per bus.		EURO 400,000 - EURO 450,000 per trolleybus	EURO 220,000.00 - EURO 300,000.00 per bus	EUR 800,000.00	Smart Choices for Cities, Alternative Fuel Buses, CIVITAS, 2016
Cost Per Bus (Rands)	R4,046,517.50	R4,598,315.34	R4,046,517.50	R4,598,315.34	R5,885,843.64 to R9,196,630.69		R7,357,304.55 to R8,276,967.62	R4,046,517.50. to R5,517,978.41	R14,714,609.10	
Dube Tradeport Waste to Energy Scenarios										
	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell	

Biogas to Electricity Generation for Dube Tradeport	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE						
Biogas Upgrade to compressed Bio-methane (Bio-CNG)	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE						
Biogas Upgrade to Bio-hydrogen (Hazer Process)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE						
Technical Sustainability Indicators	Diesel ICE	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell						
Energy Consumption (kWh/km)	4.1	5.2	4.1	4.1	1.4	1.6	1.4	3.3	3.1						
Total Energy Consumption per bus per Day (kWh) - Assume City bus travels 300km per day	1230	1560	1230	1230	420	480	420	990	930						
Number of buses which can be fuelled per day at Dube Tradeport															
Dube WWTW Phase 1	0	1.04	0	0	1.35	1.18	1.35	0.57	0.71						
Dube WWTW Phase 2	0	2.09	0	0	2.70	2.36	2.70	1.15	1.41						
Dube WWTW Phase 3	0	3.13	0	0	4.05	3.54	4.05	1.72	2.12						

The Table 40 below shows the application of a Comparative Rank Analysis of each of the nine bus propulsion technologies for each of the eleven Smart Fuel Sustainability Indicators in the Assessment Matrix:

Table 28 Showing Comparative Rank Analysis Scores per Sustainability Indicator

Smart Fuel Technology Type	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	8	4	7	5	1	2	9	8	3
Route Flexibility	9	5	7	6	2	3	1	9	4
Energy Consumption	4	1	4	4	9	7	9	5	6
Refuelling Frequency	8	4	6	5	1	2	9	8	3
Refuelling Time	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	1	9	4	5	8	8	8	3	2
PM10 (TTW)	4	5	4	4	9	9	9	4	9
NOx (TTW)	4	5	4	4	9	9	9	4	9
Noise Emissions	3	4	3	3	9	9	9	5	9
Cost Per Bus	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	1	6	1	1	9	7	9	4	5

The scale that was used to complete the Comparative Rank Analysis is shown in the Table 41 below:

Table 29 Showing: Comparative Rank Analysis Scale

Scale	Value
1	Least Suitable
2	
3	
4	Suitable
5	
6	
7	Most Suitable
8	
9	

The Figures 52 and 53 below show a graphical representation of the Comparative Rank Analysis Scores which were summarised in the tables above: Diesel Euro VI buses performed well with regards to route flexibility, range, cost per bus and refuelling time and frequency.

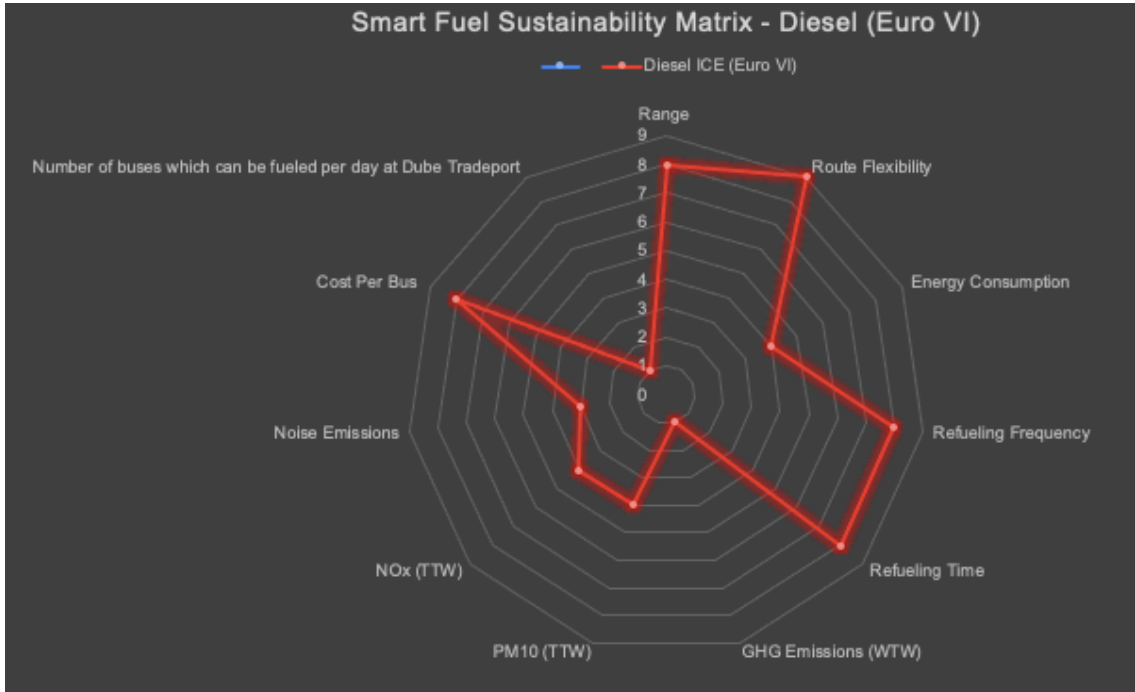


Figure 52 Showing the Comparative Rank Analysis Matrix applied to Diesel (Euro VI)

Bio-CNG performed well with regards to GHG emissions due to its carbon neutral nature.

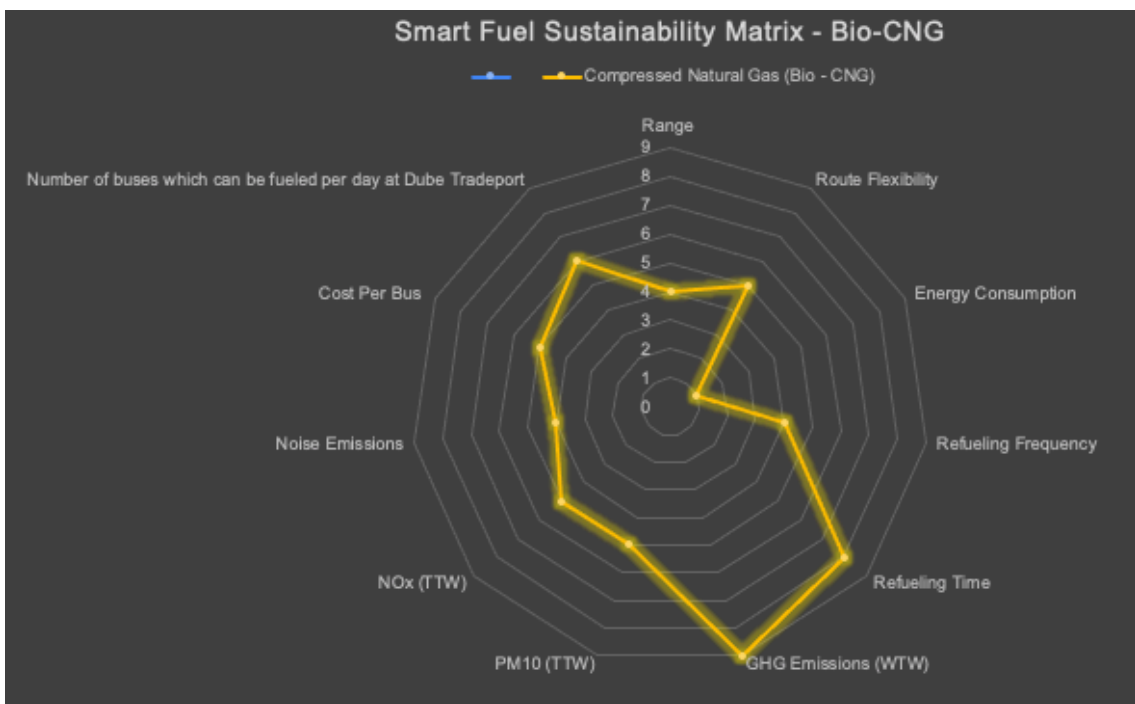


Figure 53 Showing the Comparative Rank Analysis Matrix applied to Bio-CNG

The Bio-diesel and Bio-ethanol bus propulsion options performed well with regards to refuelling time, route flexibility, range and cost compared to the other available options.

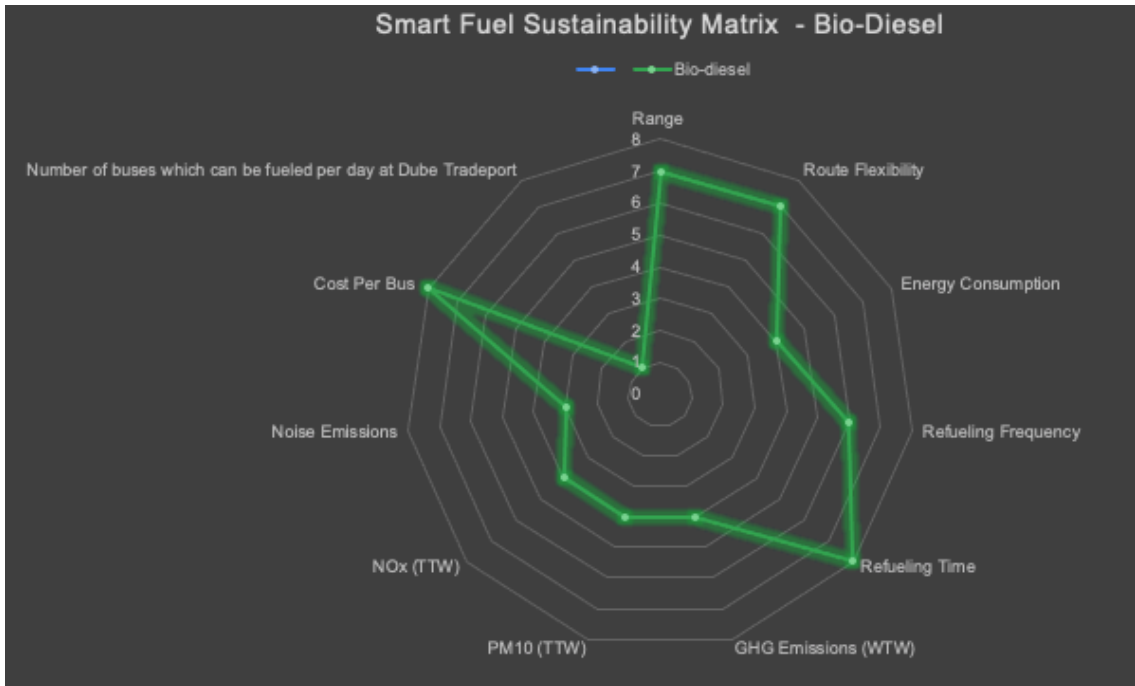


Figure 54 Showing the Comparative Rank Analysis Matrix applied to Bio-Diesel

Bio-diesel and Bio-ethanol are not feasible as a fuel source in South Africa, with regards to local laws which protect against energy crops affecting food security. Energy crops are however allowed to be planted on contaminated land such as landfills.

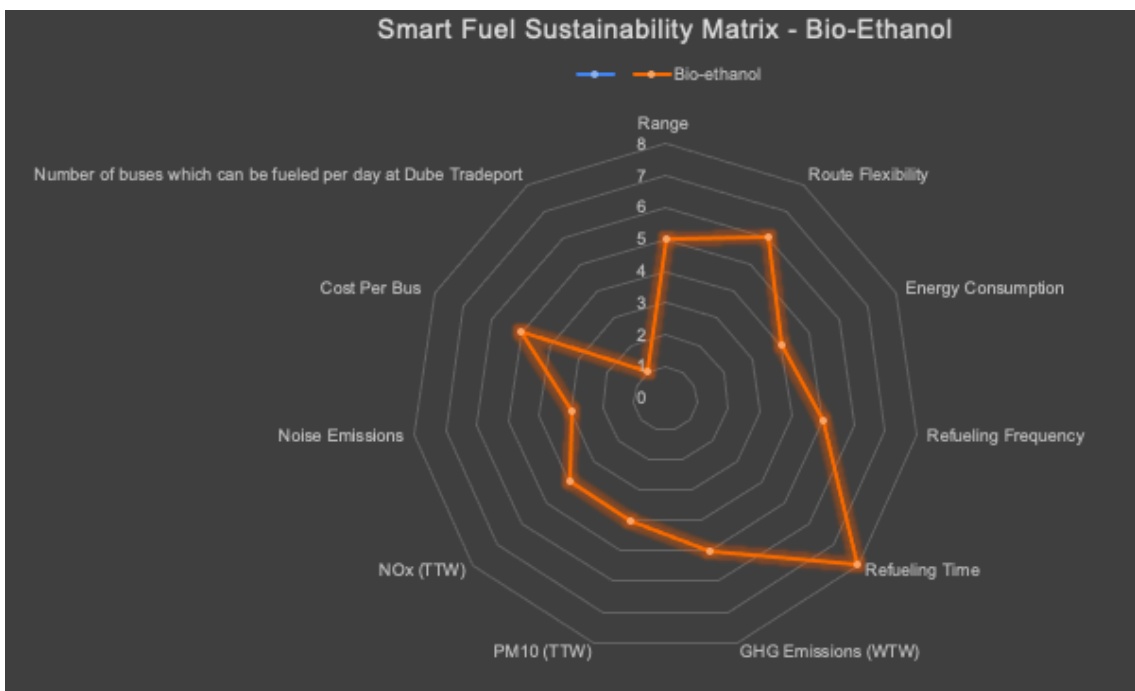


Figure 55 Showing the Comparative Rank Analysis Matrix applied to Bio-Ethanol

The Battery electric opportunity charging option performed well with regards to energy consumption, GHG, noise and air pollution emissions. This option also had a good energy consumption rate with a fast refuelling time. The overnight charging option performed poorly with regards to refuelling time and a higher energy consumption.

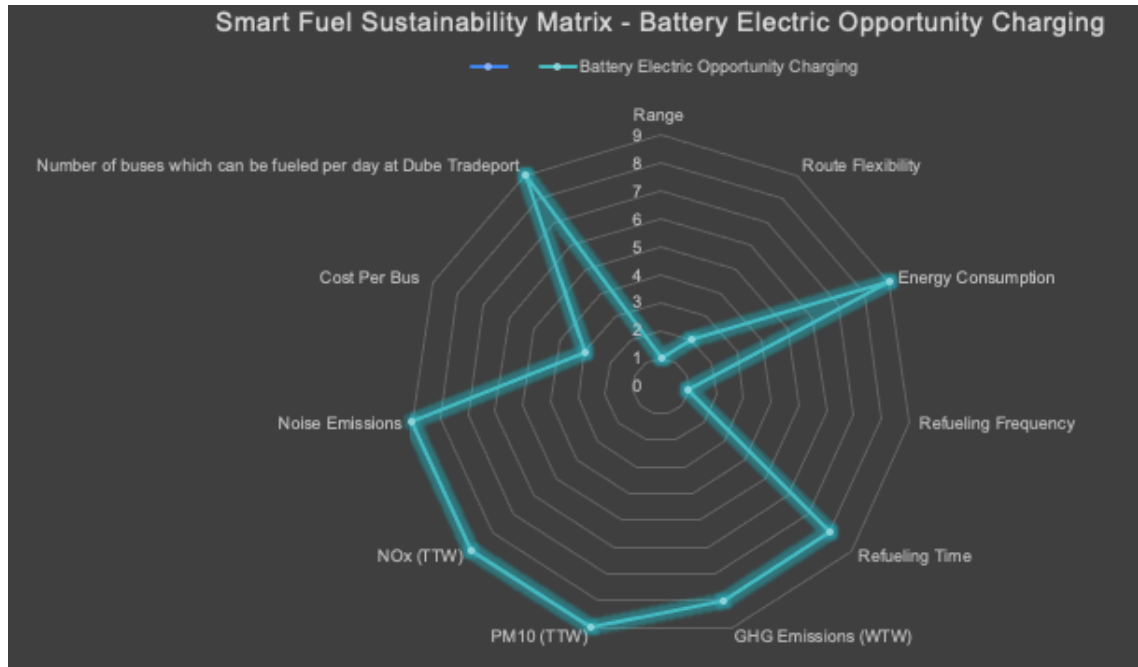


Figure 56 Showing the Comparative Rank Analysis Matrix applied to Battery Electric Opportunity Charging

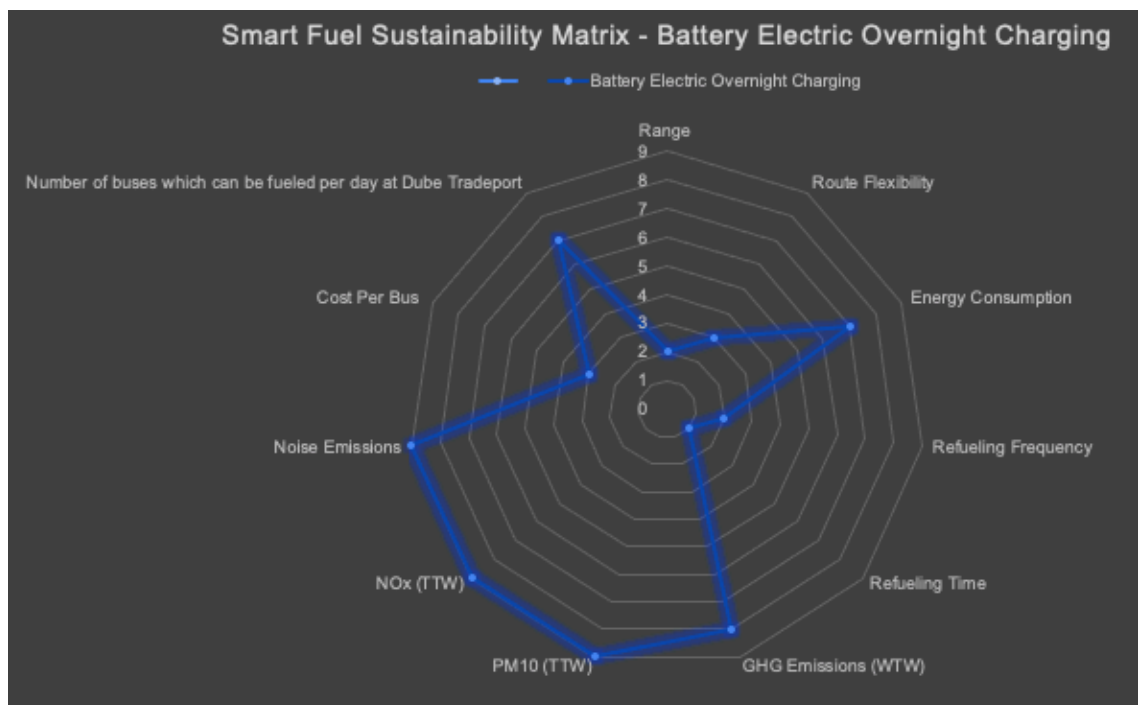


Figure 57 Showing the Comparative Rank Analysis Matrix applied to Battery Electric Overnight Charging

The Electric Trolley bus performed well with the reduction of GHG, noise and air pollution emissions. The refuelling time and frequency is low due to the trolley bus being constantly connected to the overhead power supply. The energy consumption is low and has a large range due to the overhead charging lines along the entire bus route. The diesel-electric hybrid performed well with route flexibility, refuelling time and frequency.

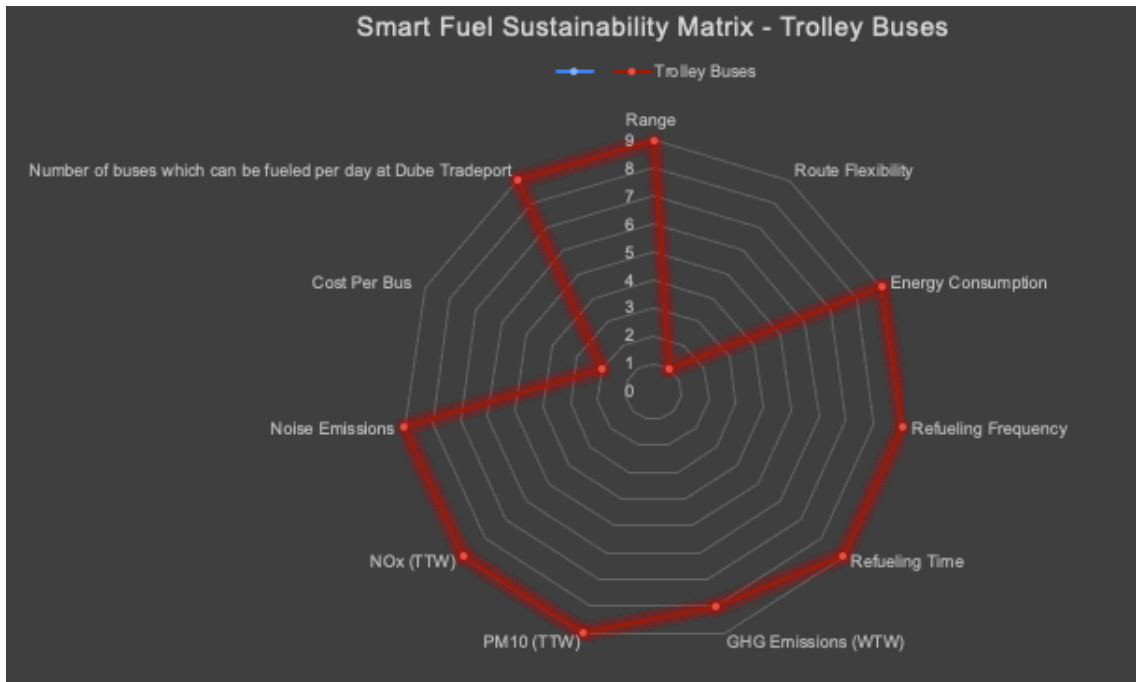


Figure 58 Showing the Comparative Rank Analysis Matrix applied to Electric Trolley Bus

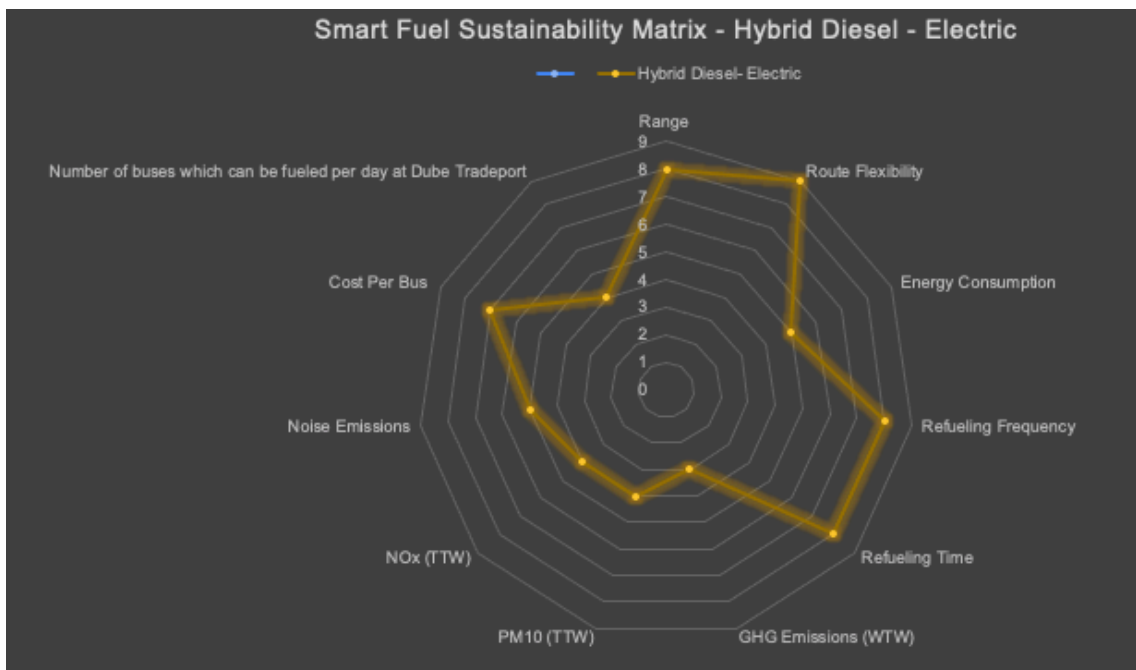


Figure 59 Showing the Comparative Rank Analysis Matrix applied to Hybrid Diesel Electric Bus

The hydrogen fuel cell option performed the highest with regards to the positive impact on the reduction of GHG emissions, air pollution and noise emissions. However, the cost per hydrogen fuel cell bus was extremely high and scored zero compared to the other eight propulsion technologies.

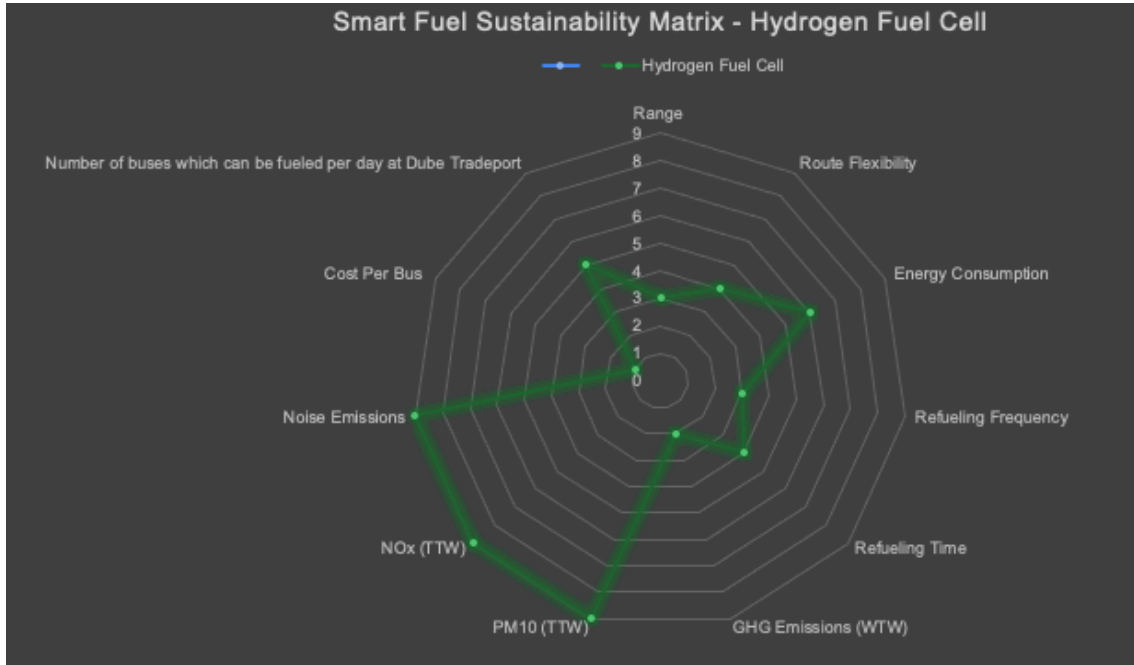


Figure 60 Showing the Comparative Rank Analysis Matrix applied to Hydrogen Fuel Cell Bus

The figure below shows a summary of the Comparative Rank Analyses for all nine bus propulsion technologies that were analysed in the Smart Fuel Sustainability Matrix. This data will play an important role towards building a multi-criteria decision making tool in Section 5.5 of this Chapter.

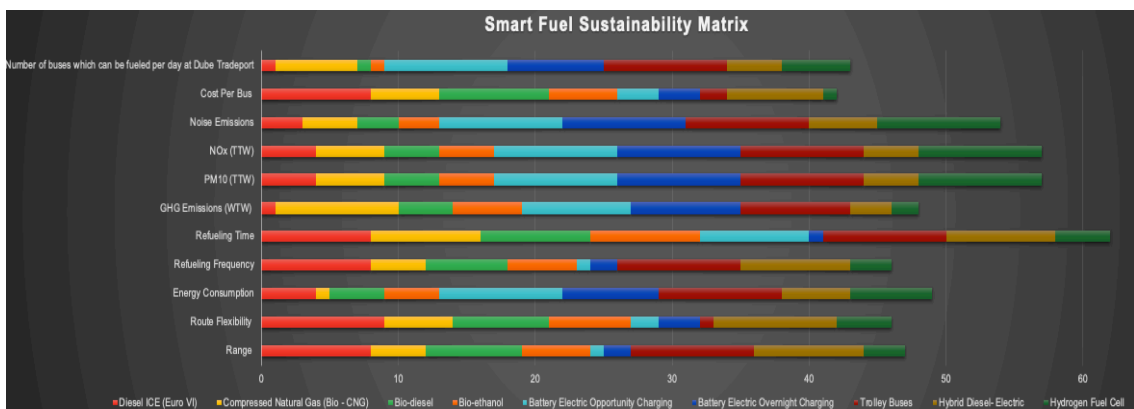


Figure 61 Showing the Comparative Rank Analysis Matrix applied to all nine bus propulsion technologies

A weighting factor as calculated in Section 5.3 was then applied to the matrix to determine an average weighted score for each of the nine bus propulsion technologies which were selected for the Assessment Matrix. This is shown in Table 42 below:

Table 30 Showing Average Weighted Score per bus propulsion technology

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	0.8	8	4	7	5	1	2	9	8	3
Route Flexibility	0.4	9	5	7	6	2	3	1	9	4
Energy Consumption	0.8	4	1	4	4	9	7	9	5	6
Refuelling Frequency	1	8	4	6	5	1	2	9	8	3
Refuelling Time	1	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	0.8	1	9	4	5	8	8	8	3	2
PM10 (TTW)	0.8	4	5	4	4	9	9	9	4	9
NOx (TTW)	0.8	4	5	4	4	9	9	9	4	9
Noise Emissions	0.8	3	4	3	3	9	9	9	5	9
Cost Per Bus	0.8	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	1	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	4.200	4.218	4.091	3.673	5.200	4.436	6.491	4.764	4.073
Unweighted Average Sustainability Indicator Score	-	5.273	5.091	5.091	4.545	6.182	5.455	7.545	5.909	5.000

The formula that was used to calculate the Average Weighted Score per bus propulsion technology is shown in the figure below:

Equation 1: Showing Average Weighted Score per Bus Propulsion Technology

$$AWS = \frac{\sum_i^n (SI_{Rank\ Score} * K_{weight})}{n}$$

Where:

AWS = Average Weighted Score

n = 11

SI_{Rank Score} = Sustainability Indicator Comparative Rank Score

K_{weight} = Selected Weighting Factor per Sustainability Indicator

5.5 T.R.O.I.S Multi-Criteria Decision Making Tool

The Table 43 below shows an output of the T.R.O.I.S Multi-Criteria Decision Making Tool, where the weighting factors have been chosen to be 1 for each of the sustainability indicators in the matrix. This particular iteration of the model would suggest that all indicators are to be treated with the same level of importance when the Average Weighted Score for each bus propulsion technology is calculated.

Table 31 Showing: T.R.O.I.S model output where a weighting factor of 1 is used throughout

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	1	8	4	7	5	1	2	9	8	3
Route Flexibility	1	9	5	7	6	2	3	1	9	4
Energy Consumption	1	4	1	4	4	9	7	9	5	6
Refuelling Frequency	1	8	4	6	5	1	2	9	8	3
Refuelling Time	1	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	1	1	9	4	5	8	8	8	3	2
PM10 (TTW)	1	4	5	4	4	9	9	9	4	9
NOx (TTW)	1	4	5	4	4	9	9	9	4	9
Noise Emissions	1	3	4	3	3	9	9	9	5	9
Cost Per Bus	1	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	1	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	5.273	5.091	5.091	4.545	6.182	5.455	7.545	5.909	5.000

This T.R.O.I.S model output is a standard evaluation, when the tool is used by a Transport Engineer at the eThekweni Transport authority, the user would take into consideration the policy (Environmental and Social Sustainability) or budget constraints (Financial Sustainability) of the time and select appropriate weighting factors from the drop down list such that a more accurate Average Weighted Score (AWS) is calculated. The weighting factor could also consider infrastructure constraints which would be considered by weighting Operational Sustainability higher than the other factors comprising of Range, Route Flexibility and Refuelling Time and Frequency respectively.

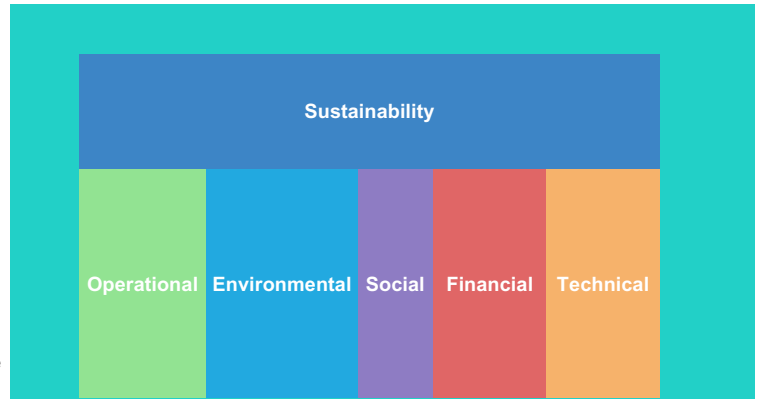
Table 32 Showing T.R.O.I.S model output where a weighting factor of 1 is used throughout



Users are to please select the weighting factor applicable per Sustainability Indicator from the drop down list in column C

The weighted average Sustainability Indicator Score per Bus Propulsion Technology Type will automatically update in the table

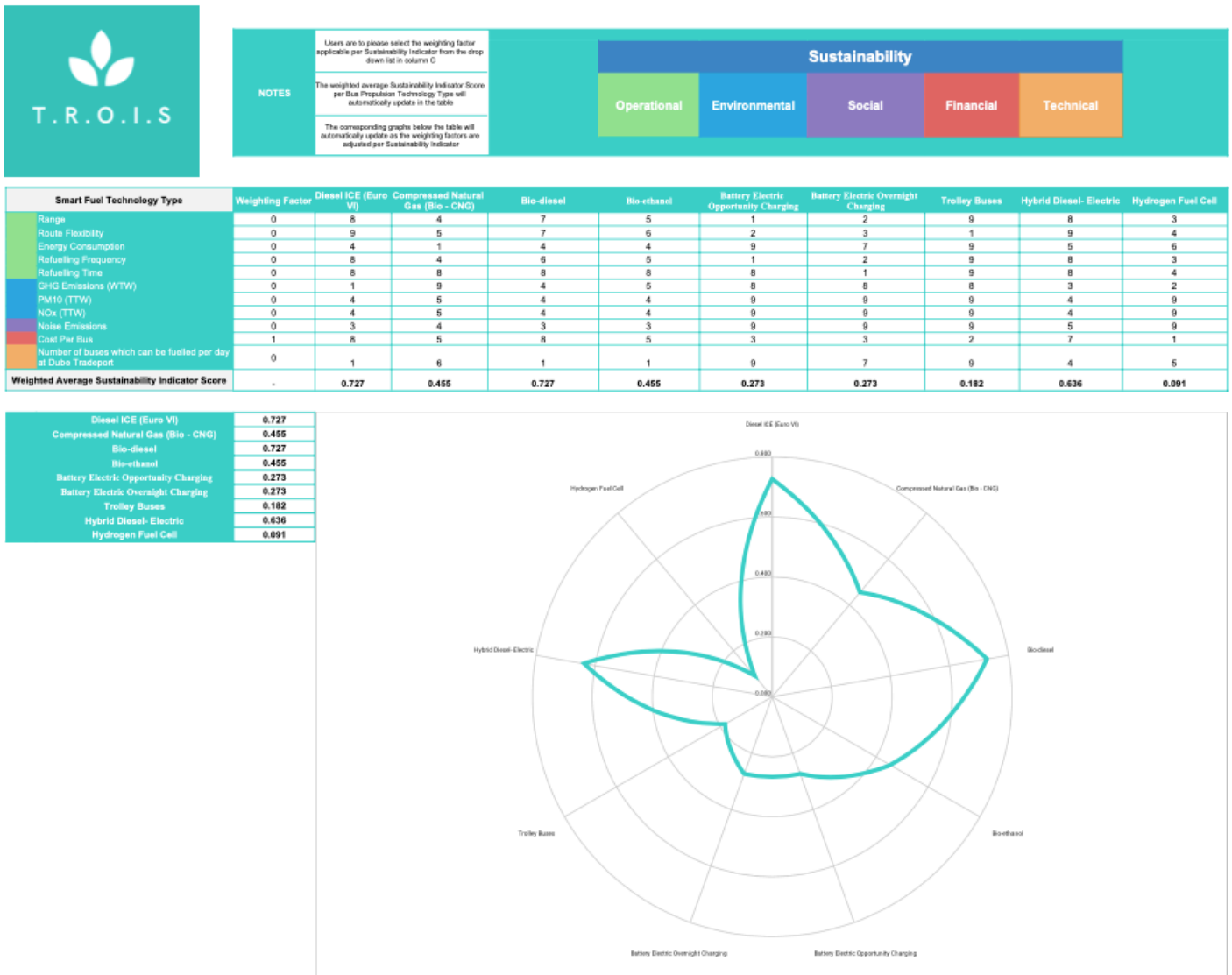
The corresponding graphs below the table will automatically update as the weighting factors are adjusted per Sustainability Indicator



Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	1	8	4	7	5	1	2	9	8	3
Route Flexibility	1	9	5	7	6	2	3	1	9	4
Energy Consumption	1	4	1	4	4	9	7	9	5	6
Refuelling Frequency	1	8	4	6	5	1	2	9	8	3
Refuelling Time	1	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	1	1	9	4	5	8	8	8	3	2
PM10 (TTW)	1	4	5	4	4	9	9	9	4	9
NOx (TTW)	1	4	5	4	4	9	9	9	4	9
Noise Emissions	1	3	4	3	3	9	9	9	5	9
Cost Per Bus	1	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube	1	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	5.273	5.091	5.091	4.545	6.182	5.455	7.545	5.909	5.000

The current prototype of the T.R.O.I.S Multi-Criteria Decision Making Tool can be used to run different permutations based on the selection of different weighting factors from the drop down menu for each of the Sustainability Indicators in the matrix. This provides the user with the opportunity to customise the recommendation output based on a particular set of restraints. For example if there is a limited budget, then the Financial Sustainability Indicator of Cost per Bus can be weighted as one and the other indicators weighted as zero from the drop down menu. This would result in the strength or weakness of the Cost per Bus Indicator to contribute most towards the Average Weighted Score (AWS) which will result in a new recommendation from the T.R.O.I.S Model. This permutation has been run using the T.R.O.I.S model and the Diesel and Biodiesel options were recommended based only on Financial Sustainability.

Table 33 Showing: T.R.O.I.S Model Output prioritising Cost per Bus



If Technical Sustainability is prioritised then a weighting factor of one should be applied to the Sustainability Indicator: Number of buses that can be fuelled per day at Dube Tradeport. Weighting the other indicators as zero from the drop down menu will result in a recommendation that prioritises Technical Sustainability as shown in the Table 46 below: This permutation of the T.R.O.I.S model recommended Electric Trolley Bus and Battery Electric Opportunity Charging Bus based only on Technical Sustainability.

Table 34 T.R.O.I.S Model Output prioritising Number of Buses that can be Fuelled per day at Dube Tradeport



Users are to please select the weighting factor applicable per Sustainability Indicator from the drop down list in column C.

The weighted average Sustainability Indicator Score per Bus Propulsion Technology Type will automatically update in the table.

The corresponding graphs below the table will automatically update as the weighting factors are adjusted per Sustainability Indicator.

Operational

Environmental

Social

Financial

Technical

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel- Electric	Hydrogen Fuel Cell
Range	0	8	4	7	5	1	2	9	8	3
Route Flexibility	0	9	5	7	6	2	3	1	9	4
Energy Consumption	0	4	1	4	4	9	7	9	5	6
Refueling Frequency	0	8	4	6	5	1	2	9	8	3
Refueling Time	0	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	0	1	9	4	5	8	8	8	3	2
PM10 (TTW)	0	4	5	4	4	9	9	9	4	9
NOx (TTW)	0	4	5	4	4	9	9	9	4	9
Noise Emissions	0	3	4	3	3	9	9	9	5	9
Cost Per Bus	0	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	1	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	0.091	0.545	0.091	0.091	0.818	0.636	0.818	0.364	0.455

Diesel ICE (Euro VI)	0.091
Compressed Natural Gas (Bio - CNG)	0.545
Bio-diesel	0.091
Bio-ethanol	0.091
Battery Electric Opportunity Charging	0.818
Battery Electric Overnight Charging	0.636
Trolley Buses	0.818
Hybrid Diesel- Electric	0.364
Hydrogen Fuel Cell	0.455



If Environmental Sustainability is prioritised then a weighting factor of one should be applied to the Sustainability Indicator: GHG Emissions and Air Pollution respectively. Weighting the other indicators as zero from the drop down menu will result in a recommendation that prioritises Environmental Sustainability as shown in the table below: This permutation of the T.R.O.I.S model recommended Electric Trolley Bus, Battery Electric Opportunity Charging Bus and Battery Electric Overnight Charging Bus based only on Environmental Sustainability. Hydrogen Fuel Cell Buses have zero Tank to Wheels (TTW) GHG emissions however, the T.R.O.I.S model considers Well to Wheels Emissions (WTW) assuming that hydrogen production releases GHG emissions

Table 35 Showing: T.R.O.I.S Model Output prioritising Environmental Sustainability



NOTES

- Users are to please select the weighting factor applicable per Sustainability Indicator from the drop down list in column C.
- The weighted average Sustainability Indicator Score per Bus Propulsion Technology Type will automatically update in the table.
- The corresponding graphs below the table will automatically update as the weighting factors are adjusted per Sustainability Indicator.

Sustainability

- Operational
- Environmental
- Social
- Financial
- Technical

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel- Electric	Hydrogen Fuel Cell
Range	0	8	4	7	5	1	2	9	8	3
Route Flexibility	0	9	5	7	6	2	3	1	9	4
Energy Consumption	0	4	1	4	4	9	7	9	5	6
Refueling Frequency	0	8	4	6	5	1	2	9	8	3
Refueling Time	0	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	1	1	9	4	5	8	8	8	3	2
PM10 (TTW)	1	4	5	4	4	9	9	9	4	9
NOx (TTW)	1	4	5	4	4	9	9	9	4	9
Noise Emissions	0	3	4	3	3	9	9	9	5	9
Cost Per Bus	0	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dubai Tradeport	0	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	0.818	1.727	1.091	1.182	2.364	2.364	2.364	1.000	1.818

Diesel ICE (Euro VI)	0.818
Compressed Natural Gas (Bio - CNG)	1.727
Bio-diesel	1.091
Bio-ethanol	1.182
Battery Electric Opportunity Charging	2.364
Battery Electric Overnight Charging	2.364
Trolley Buses	2.364
Hybrid Diesel- Electric	1.000
Hydrogen Fuel Cell	1.818



If Social Sustainability is prioritised then a weighting factor of one should be applied to the Sustainability Indicator: Noise Emissions. Weighting the other indicators as zero from the drop down menu will result in a recommendation that prioritises Social Sustainability as shown in the Table 48 below: This permutation of the T.R.O.I.S model recommended Electric Trolley Bus, Battery Electric Opportunity Charging Bus, Battery Electric Overnight Charging Bus and Hydrogen Fuel Cell Bus based only on Environmental Sustainability.

Table 36 Showing: T.R.O.I.S Model Output prioritising Social Sustainability



NOTES

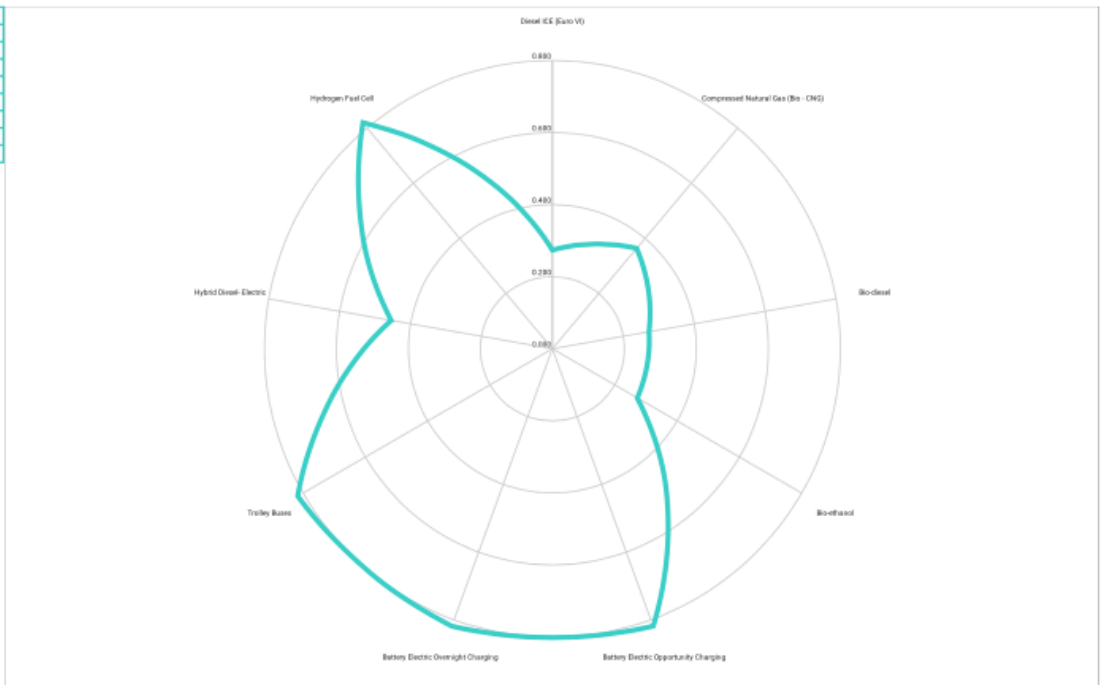
- Users are to please select the weighting factor applicable per Sustainability Indicator from the drop down list in column C
- The weighted average Sustainability Indicator Score per Blue Production Technology Type will automatically update in the table
- The corresponding graphs below the table will automatically update as the weighting factors are adjusted per Sustainability Indicator

Sustainability

- Operational
- Environmental
- Social
- Financial
- Technical

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel-Electric	Hydrogen Fuel Cell
Range	0	8	4	7	5	1	2	9	8	3
Route Flexibility	0	9	5	7	6	2	3	1	9	4
Energy Consumption	0	4	1	4	4	9	7	9	5	6
Refueling Frequency	0	8	4	6	5	1	2	9	8	3
Refueling Time	0	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	0	1	9	4	5	8	8	8	3	2
PM10 (TTW)	0	4	5	4	4	9	9	9	4	9
NOx (TTW)	0	4	5	4	4	9	9	9	4	9
Noise Emissions	1	3	4	3	3	9	9	9	5	9
Cost Per Bus	0	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dubai Transport	0	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	0.273	0.364	0.273	0.273	0.818	0.818	0.818	0.455	0.818

Diesel ICE (Euro VI)	0.273
Compressed Natural Gas (Bio - CNG)	0.364
Bio-diesel	0.273
Bio-ethanol	0.273
Battery Electric Opportunity Charging	0.818
Battery Electric Overnight Charging	0.818
Trolley Buses	0.818
Hybrid Diesel-Electric	0.455
Hydrogen Fuel Cell	0.818



If Operational Sustainability is prioritised then a weighting factor of one should be applied to the Sustainability Indicators: Range, Route Flexibility, Energy Consumption, Refuelling Frequency and Refuelling Time. Weighting the other indicators as zero from the drop down menu will result in a recommendation that prioritises Operational Sustainability as shown in the Table 49 below: This permutation of the T.R.O.I.S model recommended Electric Trolley Bus, Diesel-Electric Hybrid and Diesel Euro VI based only on Operational Sustainability.

Table 37 Showing: T.R.O.I.S Model Output prioritising Operational Sustainability



NOTES

- Users are to please select the weighting factor applicable per Sustainability Indicator from the drop down list in column C
- The weighted average Sustainability Indicator Score per Bus Propulsion Technology Type will automatically update in the table
- The corresponding graphs below the table will automatically update as the weighting factors are adjusted per Sustainability Indicator

Sustainability

- Operational
- Environmental
- Social
- Financial
- Technical

Smart Fuel Technology Type	Weighting Factor	Diesel ICE (Euro VI)	Compressed Natural Gas (Bio - CNG)	Bio-diesel	Bio-ethanol	Battery Electric Opportunity Charging	Battery Electric Overnight Charging	Trolley Buses	Hybrid Diesel- Electric	Hydrogen Fuel Cell
Range	1	8	4	7	5	1	2	9	8	3
Route Flexibility	1	9	5	7	6	2	3	1	9	4
Energy Consumption	1	4	1	4	4	9	7	9	5	6
Refuelling Frequency	1	8	4	6	5	1	2	9	8	3
Refuelling Time	1	8	8	8	8	8	1	9	8	4
GHG Emissions (WTW)	0	1	9	4	5	8	8	8	3	2
PM10 (TTW)	0	4	5	4	4	9	9	9	4	9
NOx (TTW)	0	4	5	4	4	9	9	9	4	9
Noise Emissions	0	3	4	3	3	9	9	9	5	9
Cost Per Bus	0	8	5	8	5	3	3	2	7	1
Number of buses which can be fuelled per day at Dube Tradeport	0	1	6	1	1	9	7	9	4	5
Weighted Average Sustainability Indicator Score	-	3.364	2.000	2.909	2.545	1.909	1.364	3.364	3.455	1.818

Diesel ICE (Euro VI)	3.364
Compressed Natural Gas (Bio - CNG)	2.000
Bio-diesel	2.909
Bio-ethanol	2.545
Battery Electric Opportunity Charging	1.909
Battery Electric Overnight Charging	1.364
Trolley Buses	3.364
Hybrid Diesel- Electric	3.455
Hydrogen Fuel Cell	1.818



5.6 Chapter Summary

The research question which was posed in Chapter: 1 asked the following: “How can Operational, Environmental, Social, Financial and Technical Sustainability indicators be used to develop a multi-criteria decision making tool to assist Transport Engineers at the eThekweni Municipality, to decide which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System?”.

The Smart Fuel Scenario Assessment Matrix integrated eleven Smart Fuel Sustainability Indicators and nine bus propulsion technology alternatives using a Comparative Rank Analysis Scoring system and applying a weighting factor to develop an Average Weighted Score (AWS). This Average Weighted Score was calculated for all nine bus propulsion technology alternatives and compared graphically to enable a Transport Engineer at the eThekweni Transport Authority, to identify which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System.

This model was transferred into a Microsoft Excel Interface to provide a Decision Making Tool to the eThekweni Municipality in a user friendly format with the addition of a graphical visualisation tool that automatically populates the Average Weighted Score (AWS) for each bus propulsion technology as the user selects a weighting factor from a drop down list for each of the Smart Fuel Sustainability Indicators.

The graphical decision making output which was obtained after running the T.R.O.I.S Multi-Criteria Decision Making Tool, using the weighting factors obtained from the SMART Indicator Assessment Matrix is presented in Chapter 6, where a final recommendation is provided to the eThekweni Municipality regarding which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System which runs through Dube Tradeport and the King Shaka International Airport.

The presentation of this recommendation in Chapter 6: Conclusion and Recommendations, will include a Strengths, Weaknesses, Opportunities and Threats (S.W.O.T) analysis to take into consideration other permutations of the T.R.O.I.S model which may be used by the eThekweni Municipality, using different weighting factors from the drop down menu on the tool. This would take into consideration other factors such as policy and or budget which allows for the different sustainability indicators to be weighted accordingly before calculating the Average Weighted Score per bus propulsion technology type.

Chapter 6: Conclusion & Recommendations

In this chapter, a summary of the T.R.O.I.S multi-criteria decision making model, which has been developed to assist the eThekweni Municipality in deciding which Smart Fuel alternative to choose for Line C8 of the Go! Durban Bus Rapid Transit System, will be presented as per the aim of this research as presented in Chapter 1 of this thesis.

6.1 Introduction

The aim of this dissertation was to develop a multi-criteria decision making tool which can assist Transport Engineers at the eThekweni Municipality to decide which bus propulsion technology to select for Line C8 of the Go! Durban BRT system, by taking into consideration Operational, Environmental, Social, Financial and Technical Sustainability indicators.

The objectives of this dissertation consisted of the following:

- Biogas modelling for a proposed new wastewater treatment works at Dube Tradeport to determine to determine how many BRT buses could be fuelled per day.
- Development of a Smart Fuel Scenario Assessment Matrix to calculate a Comparative Rank Analysis Score per scenario.
- Development of a SMART Sustainability Indicator Assessment Matrix and to determine a weighting factor for each Sustainability Indicator in the Matrix.
- Development of a Multi-criteria decision making tool to enable Transport Engineers at the eThekweni Municipality to decide as to which bus propulsion technology to select for the Line C8 of the Go! Durban BRT system.

Biogas projection modelling using the BioWATT Assessment Tool was conducted for four different wastewater treatment methods. The results were then used to create a graphical comparative analysis which was presented in Chapter 5. It was found that the Covered Anaerobic Pond would produce the most surplus biogas and therefore energy after meeting the energy requirements of the plant itself. This data was then used to model three Waste to Energy scenarios for Dube Tradeport, where the number of buses that could be fuelled per day per scenario was calculated. This was also extrapolated across the nine bus propulsion technologies which was presented and discussed in detail in Chapter 5.

Following this the critical analysis of bus propulsion technologies which was compiled in the Literature Review in Chapter 2, was used to build a Smart Fuel Scenario Assessment Matrix which consisted of eleven sustainability indicators and nine bus propulsion technologies. This matrix was used to develop a Comparative Rank Analysis Score for each sustainability indicator across the nine bus propulsion technology scenarios.

The SMART Sustainability Indicator Assessment Matrix produced a score (between 0 and 5) for each of the eleven sustainability indicators obtained from literature review. This score was then converted into a weighting factor between 0 and 1 (in intervals of 0.1) for each of the eleven indicators. This was then applied to the Comparative Rank Analysis Score to calculate an Average Weighted Score for each of the nine bus propulsion technologies. The formula used to develop this score is explained in detail in Chapter 5, Section 5.4. The Average Weighted Score calculated for each of the nine bus propulsion technologies is displayed in a table and graphical form in Section 6.2.

6.2 Summary of Results

Table 50 below shows the output of the Average Weighted Score Calculation for each of the nine bus propulsion technologies in the Smart Fuel Assessment Matrix. The weighted factors from the SMART Indicator Analysis was used to obtain a result. The result output shows that when the SMART Framework Weighting Factors are used the Electric Trolley Bus is the recommended and is highlighted in dark green in Table 47.

Table 38 Showing Application of the T.R.O.I.S decision making tool for Line C8 of the Go! Durban BRT system

Smart Fuel Technology Type	Weighted Average Sustainability Indicator Score
Diesel ICE (Euro VI)	4.200
Compressed Natural Gas (Bio - CNG)	4.218
Bio-diesel	4.091
Bio-ethanol	3.673
Battery Electric Opportunity Charging	5.200
Battery Electric Overnight Charging	4.436
Electric Trolley Buses	6.491
Hybrid Diesel- Electric	4.764
Hydrogen Fuel Cell	4.073

Figure 62 below shows a graphical comparison of the Average Weighted Score Output from the T.R.O.I.S Multi-Criteria Decision Making Tool, as shown in Table 47 above. This output of the T.R.O.I.S model and subsequent recommendation of the Electric Trolley Bus option is due to the selection of the SMART Framework Weighting Factors. This was used as an example to test the T.R.O.I.S model by the author.

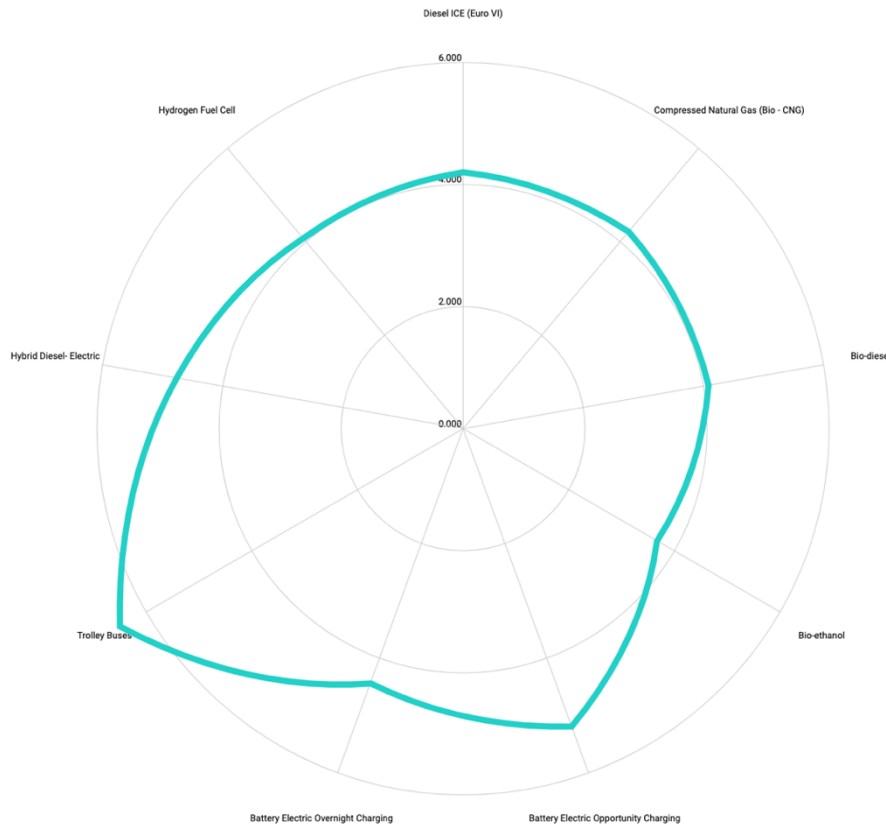


Figure 62 Showing a graphical comparative analysis from the T.R.O.I.S Model

The eThekweni Municipality or any other end user of the model may choose to calibrate the T.R.O.I.S model based on institutional policy or budget constraints and are able to adjust the weighting factors in the model accordingly. The weighting factors for each of the eleven sustainability indicators in the T.R.O.I.S model can be adjusted from the drop down menu. The user is able to select a weighting factor between 0 and 1 in intervals of 0.1. If the user selects zero as a weighting factor for any of the factors, the factor in question, will contribute zero to the Weighted Average Sustainability Indicator Score per Smart Fuel Scenario. By doing this the user is able to account for Institutional Factors which will increase the accuracy of the final recommendation that is provided as an output of the T.R.O.I.S Multi-Criteria Decision Making model.

Table 51 below summarises Recommendation Outputs of the T.R.O.I.S model for various types of priorities which may be encountered by the eThekwini Transport Authority when using the tool to decide which bus propulsion technology to select for Line C8 of the GO! Durban Bus Rapid Transit System.

Table 39 Showing Recommendation Outputs of the T.R.O.I.S Model for various priorities

Level of Prioritisation	Recommended Bus Propulsion Technology
SMART Framework	Trolley Bus
Environmental Sustainability	Trolley, Battery Electric Opportunity & Overnight Charging
Social Sustainability	Trolley, Hydrogen Fuel Cell, Battery Electric Opportunity & Overnight Charging
Financial Sustainability	Diesel Euro VI & Bio-Diesel
Operational Sustainability	Trolley, Diesel-Hybrid & Diesel Euro VI
Technical Sustainability	Trolley, Battery Electric Opportunity Charging

6.3 Recommendations

6.3.1 SMART Framework Prioritisation

The results output of the T.R.O.I.S Smart Fuel Decision Making Tool for this scenario shows that the most sustainable option for the eThekwini Municipality is to choose the Electric Trolley Bus technology solution for Line C8 of the Go! Durban Bus Rapid Transit System.

The choice of an electric grid connected Trolley Bus system indicates that Waste to Energy Scenario 1 would be recommended to Dube Tradeport. In this scenario, the excess biogas that is produced at the proposed new WWTW would be converted to electricity using a gas turbine generator which would then feed into the electricity grid. The Trolley Bus would then source power from the overhead electricity charging infrastructure.

The use of Smart Electricity meters would be encouraged so that it can be recorded how much electricity is produced by Dube Tradeport and fed into the eThekwini grid per day. This would allow the eThekwini Municipality to purchase electricity directly from Dube Tradeport. The two parties would have to negotiate an energy rebate tariff system or energy credits for renewable energy supplied by Dube Tradeport to the eThekwini grid.

According to the sustainability matrix, this option would only be able to sustain one electric trolley bus per day with the excess energy generated from Phase 1 of the proposed new wastewater treatment works at Dube Tradeport. This would rise to two buses per day during Phase 2 of the plant and four buses per day during phase 3 of the plant. The calculation of the number of buses which could be powered per day at Dube Tradeport is a conservative estimate in which the values were rounded down to the nearest whole number.

This indicates that for the electric trolley bus system to be financially feasible additional renewable energy supply will have to be generated from additional sources such as solar and wind energy so that the C8 electric trolley bus line would not put a strain on the electricity grid and to meet the sustainability ambitions of the eThekweni Municipality for the C8 BRT route.

6.4 Limitations of the T.R.O.I.S Model

The current prototype of the T.R.O.I.S Multi-Criteria Decision Making Tool has been creating using a Microsoft Excel user interface and is shown in the Figure 63 below. The system is limited to the eleven Sustainability Indicators which were identified during the Literature Review in Chapter 2. There is however scope to add to the Financial, Social and Technical Sustainability Indicators which make up the Smart Fuel Scenario Assessment Matrix.

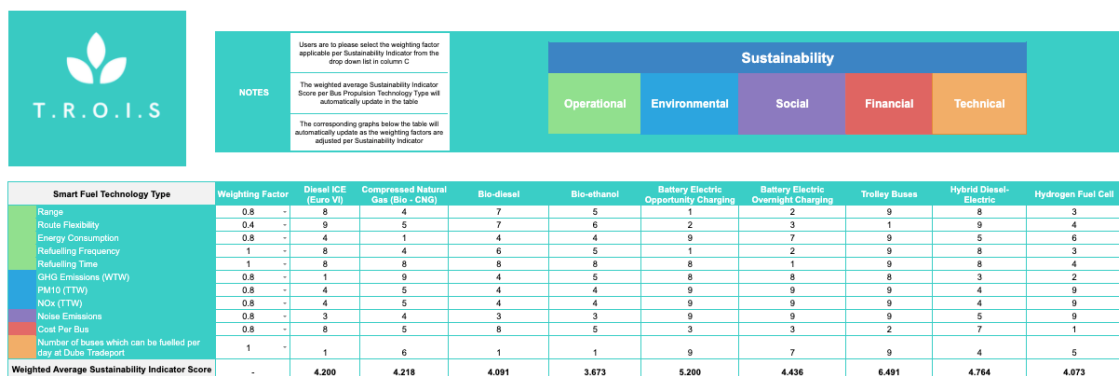


Figure 63 Showing: User Interface of the T.R.O.I.S Model

Further Financial Sustainability Indicators which can be added in future iterations of the model include, Total Cost of Ownership with regards to Capex (Vehicle fleet and fuelling infrastructure) and Opex (Fuel and Maintenance) costs. Further Social Sustainability Indicators which can be added include Job Creation and Quality of Passenger Experience.

Technical Sustainability Indicators which could possibly be added include the addition of additional Waste to Energy Scenarios for Dube Tradeport such as incorporating Organic Waste Separation in the precinct. There are various means of achieving this such as Source Separation either through separate waste collection bins or the mandatory installation and use of Garbage Disposal Units in all sinks in the Dube Tradeport precinct.

This would increase the amount of organic content in the wastewater treatment system which will ultimately produce more biogas and energy for the Go! Durban BRT system. Including this added waste stream to the Covered Anaerobic Pond treatment facility proposed for Dube Tradeport. This would involve the co-digestion of the new organic waste stream with the wastewater produced at Dube Tradeport.

Other Waste to Energy Scenarios include the addition of bio-diesel or bioethanol produced from crops grown on contaminated land such as nearby landfills or wastewater tertiary polishing wetlands. This would add an additional two Smart Fuel streams to the T.R.O.I.S model which have currently been given Comparative Rank Analysis Scores of 1 respectively on the Assessment Matrix. This is because the three chosen Waste to Energy Scenarios do not produce any Bio-Diesel or Bio-Ethanol in the current model and therefore fuel zero buses per day at Dube Tradeport for those two bus propulsion technologies.

6.5 Chapter Summary

The aim of this dissertation was to develop a multi-criteria decision making tool which could assist Transport Engineers at the eThekweni Municipality to decide which bus propulsion technology to select for Line C8 of the Go! Durban BRT system, by taking into consideration Operational, Environmental, Social, Financial and Technical Sustainability indicators.

The Transport, Reduction, Optimisation, Implementation, Scenario (T.R.O.I.S) model has been successfully developed using a Smart Fuel Scenario Assessment Matrix, Comparative Rank Analysis Scoring and Weighting factors to calculate an Average Weighted Score for each of the nine bus propulsion technologies which were identified during the Literature Review process in Chapter 2 of this dissertation.

A Microsoft Excel Interface has been developed to provide a pleasant user interface to be used by Transport Engineers at the eThekweni Transport Authority to decide as to

which bus propulsion technology to select for Line C8 of the Go! Durban Bus Rapid Transit System which passes through Dube Tradeport and the King Shaka International Airport.

The recommendations in this Chapter, have used the weighting factors developed from the SMART Sustainability Indicator Assessment Matrix to produce an example of what an output of the T.R.O.I.S model would look like. The tool has been designed to be flexible, in that the user can adjust the weighting factor for each of the eleven Sustainability Indicators in the matrix based on the needs and resources available at the eThekweni Transport Authority. The T.R.O.I.S model can be continuously updated using the latest data for the various Sustainability Indicators as well as the addition of new indicators in the future iterations of the model.

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Table 40 Showing BioWATT Model Interface, Input and Output Data during the Biogas Modelling Process

BioWATT (Biogas Wastewater Assessment Technology Tool)				v1.0 (11 May 2016)
Project:		(Name of WWTP)		
Date:		(Date)		
INPUT DATA				
WASTEWATER ENTERING WWTP	Value	Unit	Comment	
Average hydraulic load	6.000	m ³ /d	Provide estimate of the expected average daily wastewater flow reaching the WWTP. A rough estimate can be made by utilizing about 80% of the water supply to the same catchment, and by adding an assumption for stormwater flow and ground water intrusion. For separate sewer systems this may add up to another 30% flow, for combined sewer systems this may add up to another 100-200%.	
Average inflow BOD5 concentration	548	mg/L	Provide estimate of the expected average BOD5 concentration entering the WWTP.	
GREENHOUSE GAS EMISSIONS	Value	Unit	Comment	
Local GHG emissions for electricity generation	1.000	g CO2/kWh	Select appropriate value from drop-down menu, or utilize data from other sources (e.g. [1]).	
Do you have a UASB that is not collecting biogas?	NO		Select "YES" or "NO" from drop-down menu.	
Do you have an Anaerobic Pond that is not collecting biogas?	NO		Select "YES" or "NO" from drop-down menu.	
UNIT COST	Value	Unit	Comment	
Electricity tariff	0.16	USD/kWh	Insert locally prevailing unit cost for power purchase from public grid.	
Sludge disposal unit cost	20.16	USD/m ³	Insert locally prevailing unit cost for sludge disposal / reuse.	
Average labor cost	6.116	USD/personnel/year	Insert locally prevailing average unit cost for operators at WWTP.	
SUMMARY OUTPUT RESULTS				
CAS + DIGESTER	Result	Unit	Comment	
Biogas production	503 239	m ³ /year		
Electricity generation from biogas including co-digestion	694 796	kWh/year		
Do you have a UASB that is not collecting biogas?	YES			
Do you have an Anaerobic Pond that is not collecting biogas?	NO			
GHG emission reduction through electricity from biogas	-695	tons CO2e/year		
Elimination of existing GHG emissions from digester	0	tons CO2e/year		
Total GHG emission reduction	-695	tons CO2e/year		
Reduction of electricity cost	-69 680	USD/year		
Reduction of operation cost in aeration tank	-11 060	USD/year		
Reduction of sludge disposal cost	-51 152	USD/year		
Additional O&M cost	39 429	USD/year		
Total OPEX saving	-101 461	USD/year		
Digester	1 211	m ³		
Biogas holder	285	m ³		
CHP - total electric power	236	kW		
HYDROLYSIS + DIGESTER	Result	Unit	Comment	
Biogas production	502 507	m ³ /year		
Electricity generation from biogas including co-digestion	960 154	kWh/year		
Do you have a UASB that is not collecting biogas?	YES			
Do you have an Anaerobic Pond that is not collecting biogas?	NO			
GHG emission reduction through electricity from biogas	-960	tons CO2e/year		
Elimination of existing GHG emissions from digester	0	tons CO2e/year		
Total GHG emission reduction	-960	tons CO2e/year		
Reduction of electricity cost	-96 016	USD/year		
Reduction of sludge disposal cost	-49 070	USD/year		
Additional O&M cost	39 429	USD/year		
Total OPEX saving	-105 657	USD/year		
Digester	1 154	m ³		
Biogas holder	275	m ³		
CHP - total electric power	232	kW		
UASB	Result	Unit	Comment	
Biogas production	202 426	m ³ /year		
Electricity generation from biogas	507 831	kWh/year		
GHG emission reduction through electricity from biogas	-508	tons CO2e/year		
Elimination of existing GHG emissions from UASB	0	tons CO2e/year		
Total GHG emission reduction	-508	tons CO2e/year		
Reduction of electricity cost	-30 978	USD/year		
Additional O&M cost	14 963	USD/year		
Total OPEX saving	-16 015	USD/year		
Biogas holder	141	m ³		
CHP - total electric power	70	kW		
COVERED ANAEROBIC POND	Result	Unit	Comment	
Biogas production	388 682	m ³ /year		
Electricity generation from biogas	648 095	kWh/year		
GHG emission reduction through electricity from biogas	-648	tons CO2e/year		
Elimination of existing GHG emissions from Ana. Ponds	0	tons CO2e/year		
Total GHG emission reduction	-648	tons CO2e/year		
Reduction of electricity cost	-39 532	USD/year		
Additional O&M cost	16 811	USD/year		
Total OPEX saving	-22 721	USD/year		
CHP - total electric power	81	kW		
References:				
[1] ... International Energy Agency IEA (2012): "CO2 Emissions From Fuel Combustion", www.iea.org				

Project:		(Name of WWTP)	
Date:		(Date)	
GENERAL DATA			
WASTEWATER CHARACTERISTICS			
Average hydraulic load	6 000	m ³ /d	
Average influent BOD5 concentration	548	mg/L	
Average TSS/SCDS concentration	100	mg/L	Typical: 1.00 (0.8-1.2) (2.3-3.1)
Average influent TSS concentration	648	mg/L	Typical: same value as for BOD5 concentration
Average influent VS concentration	525	mg/L	Typical: VS/(TSS + 0.75 (0.6-0.8)) (2.1-3.4) In case of dominant number of septic tanks in the catchment it may go down to 0.2-0.3 (2)
Average influent VS concentration	411	mg/L	
Load of solids-specific BOD5 production	28	gBOD5/kgVS	Select appropriate value from drop-down menu, or other data from other sources (2,4,5)
Average pollution load (BOD5)	3 288	kg/d	
Average pollution load in population equivalents (PE)	54 800	PE/00	(Note: 1 PE/00 = 60 g BOD5/d)
Average pollution load in population equivalents (Dca)	65 700	cap	(Note: 1 cap = ca. g BOD5/d, according to project specific input data)
CS + SLUDGE DIGESTER			
WASTEWATER TREATMENT			
Primary Sedimentation Tank (PST)			
PST forebay?			Select "YES" or "NO" from drop-down menu
Volume PST	188	m ³	"YES" (recommended when influent TSS > 80 mg/L) "NO" (recommended when influent TSS < 80 mg/L)
Average retention time in PST	0.75	h	Typical: 0.75 (0.50-1.5) at average hydraulic load (3,5)
BOD5 removal efficiency of PST	30.0	%	Typical: 30 (20-35) (3,5)
TSS removal efficiency of PST	50.0	%	Typical: 50 (50-60) (3,5)
Reaction Tank (RT)			
Average influent BOD5 load	2 302	kg/d	
Average influent TSS load	1 664	kg/d	
SLUDGE PRODUCTION			
Primary sludge			
Daily PS production (DS)	1 664	kgDS/d	
DS of primary sludge after thickening	5.0	%DS	Gravity thickener: 2-4% (3,4) Mechanical thickener: 5-7% (3,4)
VS/DS of primary sludge after thickening	79	%VS	Typical: VS/(TSS + 0.75 (0.6-0.8)) (2.1-3.7) In case of many septic tanks it may go down to 0.2-0.3 (2)
Daily PS production, thickened sludge (m3)	47.0	m ³ /d	
Secondary sludge			
Daily raw WAS production (DS)	0.75	gDS/kgBOD5	Typical: 0.75 (0.5-2), dependent on influent TSS, sludge age, temperature (3,4,5)
	1.75	kgDS/d	
DS of WAS after thickening	6.0	%DS	Gravity thickener: 2-4% (3,4) Mechanical thickener: 5-7% (3,4)
VS/DS of WAS after thickening	70	%VS	(i) Sludge age < 10 days: avg. 60% (60-70%) (2.3-2.6) (ii) Sludge age > 10-15 days: avg. 60% (60-70%) (2.3-2.6) (iii) Sludge age > 20 days: avg. 50% (50-70%) (2.3-2.6)
Daily WAS production, thickened sludge (m3)	28.8	m ³ /d	
CO-DIGESTION OF ORGANIC WASTE			
Sludge treatment shall include co-digestion?	YES		Select "YES" or "NO" from drop-down menu
Type of organic feedback	Organic		Describe type of organic feedback
Average daily quantity of feedback	5.0	m ³ /d	
DS of organic feedback	10.0	% of weight	Select appropriate value from drop-down menu, or other data from other sources (2,3,6)
VS/DS of organic feedback	90.0	%VS	Select appropriate value from drop-down menu, or other data from other sources (2,3,6)
SLUDGE DIGESTION WITH ULTRAFILTRATION			
Sludge treatment shall include sludge ultrafiltration treatment prior to digester?	NO		Select "YES" or "NO" from drop-down menu
Expected increase of biogas yield from sludge	0	%	Typical: +20% (10-30%) (2)
DIGESTER			
Digester retention time	30	days	(i) mesophilic digester (30-38°C) < 15 d (large WWTPs) > 20 d (medium, small WWTPs) (2,3,4) (ii) ambient temperature: see figure (2,7,8)
Required digester volume	1 211	m ³	
CS feeding			
Average feeding of PS	47	m ³ /d	
Average feeding of WAS	29	m ³ /d	
Average feeding of organic feedback	5	m ³ /d	
Total average feeding	81	m ³ /d	
DS feeding			
Average feeding of PS	1 664	kgDS/d	
Average feeding of WAS	1 778	kgDS/d	
Average feeding of organic feedback	60	kgDS/d	
Total average feeding	3 502	kgDS/d	
VS feeding			
Average feeding of PS	1 233	kgVS/d	
Average feeding of WAS	1 058	kgVS/d	
Average feeding of organic feedback	60	kgVS/d	
Total average feeding	2 351	kgVS/d	
VS destruction (%)			
Average VS destruction of PS	60	% of VS	Typical: 55-60% (2,3,4)
Average VS destruction of WAS	60	% of VS	Typical: 50-60% (2,3,4)
Average VS destruction of organic feedback	60	% of VS	Select appropriate value from drop-down menu, or other data from other sources (2,3,6)
VS destruction (kg/d)			
Average VS destruction of PS	740	kgVSdestrym ³ /d	
Average VS destruction of WAS	483	kgVSdestrym ³ /d	
Average VS destruction of organic feedback	360	kgVSdestrym ³ /d	
Total average VS destruction	1 583	kgVSdestrym ³ /d	
SLUDGE DSH PRODUCTION / FEEDBACK			
DS after sludge dewatering	23	%DS	Typical: 23 (18-30) (3,4)
Total average DS production	2 287	kgDS/d	
Total specific DS production	0.37	gDS/m ³ DS/d	
Total average dewatered sludge production	0.3	m ³ /d	
	3 429	m ³ /year	

