QUALITATIVE EVALUATION OF KEY SECTORS OF A FUTURE CITY

by
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Abstract

Cities are experiencing exponential growth and, at the same time, increasingly more problems are arising. Cities have dated infrastructure and depend on dated solutions that may have been appropriate in the past but do not align with future trends. The rate of innovation and degradation in today's cities seem to run parallel. If cities are not urgently redesigned to reverse the trend of dated infrastructure, then innovation and economic growth could be hampered. Furthermore, cities are the most influential areas where economic growth and development occur, but more importantly, cities determine by orders of magnitude, whether the tipping point of climate change will be reached or not. Ensuring that cities of the future are prosperous bio-regions while safeguarding economic growth, is the primary goal. The global strive for sustainability and proliferating growth is compelling cities to adapt. However, cities of today are not designed to be flexible and some are not embracing the change fast enough.

This study identifies and discusses three main sectors of a future city namely, energy, transport and layout. Critical problems within each sector were exposed and the aim of the study was to present a baseline framework containing proposed solutions to the identified problems. The collated holistic framework from which urban developers, governments and project sponsors can start the city design from, was also qualitatively modelled in a financial model to estimate possible viability of adoption. The framework is sufficiently flexible to adapt to market changes, new innovations and global affairs. The framework design is called the Ripple City framework and the model was benchmarked against the City of Cape Town in South Africa.

Some key solutions addressed in this study include but are not limited to, electric vehicles, the Hyperloop system, green space, urban tunnels, renewable energy, microgrids and energy storage. The study proposes a new future orientated framework containing these key solutions with the reasoning that a new agile approach is required when envisioning how cities should be built.

The study concludes that instead of overhauling current dating cities, this framework should first be used as the starting baseline for a new city built from the ground up. The results of the evaluated scenarios suggest that by building this Ripple City framework from the ground up could potentially reduce Green House Gas emission by 124 222 000 tons per annum. The results indicate possible Benefit Cost Ratio (BCR) of 6.3 for the Hyperloop system, a BCR of 13.9 for adopting non-motorised transport, a BCR of 9.5 for adopting green space and a 2.8 BCR for adopting autonomous electric vehicles. Furthermore, just over 1.9 million jobs could be generated, more than R32 trillion NPV (Nett Present Value) benefit could be realised from the layout proposals over 60 years and over R 1.4 trillion NPV in transport benefits over 20 years.

Opsomming

Stede groei tans eksponensiëel en terselfdertyd ontstaan al hoe meer verwante probleme. Stede het verouderde infrastruktuur en is afhanklik van uitgedateerde oplossings wat geskik is vir vorige markte en nie in lyn is met toekomstige tendense nie. Die tempo van innovering en veroudering in stede blyk om parallel te loop en as stede nie dringend aangepas word om die tendense van verouderde infrastruktuur om te keer nie, kan innovasie en ekonomiese groei belemmer word. Verder is stede die mees invloedryke gebiede waar ekonomiese groei en ontwikkeling plaasvind, maar meer belangrik, stede bepaal telkens of die keerpunt van klimaatsverandering oorskreeu sal word of nie. Die oorheersende doelwit is om te verseker dat stede van die toekoms welvarende bio-streke is, terwyl ekonomiese groei plaasvind. Die wêreldwye druk vir volhoubaarheid en konstante groei, dwing stede om aan te pas. Tans is stede egter nie ontwerp om buigsaam te wees nie en sommiges neem die verandering nie vinnig genoeg aan nie.

Hierdie studie identifiseer drie invloedryke hoof sektore van 'n toekomstige stad en bespreek, naamlik energie, vervoer en uitleg. Kritiese probleme binne elke sektor is geïdentifiseer en die doel van die studie was om 'n raamwerk aan te bied wat voorgestelde oplossings vir hierdie probleme bevat. Die saamgestelde holistiese raamwerk waaruit stedelike ontwikkelaars, regerings en projek borge die stadsontwerpsproses kan begin, is ook kwalitatief gemodelleer in 'n finansiële model om moontlike lewensvatbaarheid daarvan te ondersoek. Die raamwerk is buigsaam om aan te pas by marks-veranderinge, nuwe innovasies en globale tendense. Die raamwerk word die “Ripple City” of Rimpel stad raamwerk genoem en is vergelyk met Kaapstad in Suid-Afrika.

Sommige sleuteloplossings wat in hierdie studie behandel word, sluit in, maar is nie beperk tot, elektriese voertuie, die Hyperloop-stelsel, groen ruimte, stedelike tonnels, hernubare energie, mikronetwerke en energieberging. Die studie stel 'n nuwe toekomsgerigte raamwerk voor wat hierdie sleuteloplossings bevat met die redenasie dat 'n nuwe ratse benadering nodig is rakend hoe stede gebou word.

Die studie kom tot die gevolgtrekking dat in plaas daarvan om huidige verouderende stede op te knap, hierdie raamwerk gebruik moet word as die beginpunt vir 'n stad wat van vooraf ontwikkel word. Die resultate van die geëvalueerde scenario's dui daarop dat deur hierdie Ripple City-raamwerk van die begin af te volg, moontlik kweekhuisgas vrystelling met 124 222 000 ton per jaar kan verminder. Die resultate dui op `n moontlike voordeelkosteverhouding (VKV) van 6,3 vir die Hyperloop-stelsel, 'n VKV van 13,9 vir die aanvaarding van nie-gemotoriseerde vervoer, 'n VKV van 9,5 vir die aanvaarding van groen ruimte en 'n 2,8 VKV vir die aanvaarding van die outomatiese elektriese voertuie. Verder kan meer as 1.9 miljoen werksgeleenthede geskep word, meer as R32 triljoen huidige waarde-voordeel kan uit die uitlegvoorstelle oor 60 jaar gerealiseer word en meer as R 1.4 triljoen huidige waarde in vervoer voordele oor 20 jaar.

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List of Abbreviations:

15-MC	15 Minute City
AC	Air Conditioning
AI	Artificial Intelligence
ASME	American Society of Mechanical Engineers
BEV	Battery Electric Vehicles
BIPV	Building Integrated Photovoltaics
BTM	Behind the meter
CAES	Compressed Air Energy Storage
CAGR	Compounded Annual Growth Rate
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CPT	Cape Town
CSP	Concentrated Solar Power
dBA	Decibels
DC	Direct Current
ESS	Energy Storage System
EV	Electric Vehicles
FCAS	Frequency Control Ancillary Services
FCEV	Fuel Cell Electric Vehicles
FFR	Fast Frequency Response
FOM	Front of Meter
GDP	Growth Domestic Product
GHG	Greenhouse Gasses
GHI	Global Horizontal Irradiation
H2EV	Hydrogen Electric Vehicle
HEV	Hybrid Electric Vehicles
HSR	High Speed Rail
HVAC	Heating Ventilation and Air Conditioning
ICE	Internal Combustion Engines
ICT	Information and Communications Technology
IoT	Internet of Things
IPF	International Patent Family
kWh	Kilowatt hour
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
LFP	Lithium Iron Phosphate Batteries
LNG	Liquid Natural Gas
MaaS	Mobility as a Services
mb/d	Million Barrels per day
MCOE	Marginal Cost of Energy
MTOE	Million Tons of Oil Equivalent
MUT	Multi-Utility Tunnel
MW	Megawatt
NMT	Non-Motorised Transport

NO	Nitrous Oxide
NPV	Nett Present Value
OPEX	Operating Expenditure
PPP	Private Public Partnership
PSH	Pumped Storage Hydro
PT	Public Transport
PV	Photovoltaics
PVOUT	Photovoltaics Output
RE	Renewable Energy
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RFB	Redox Flow Battery
RMIPPPP	Risk mitigation independent power producer procurement programme
ROI	Return on Investment
SA	South Africa
SDG	Sustainable Development Goals
SP	Solar Power
TaaS	Transport As a Service
TTC	Transport Time Cost
TTV	Traffic Time Value
TVS	Time Value Savings
TWh	Terawatt hour
UD	Urban Density
USD	United States Dollar
YoY	Year over Year
ZAR	South African Rand

1 INTRODUCTION

Every week, 3 million people move to cities (Collyer, 2015). That is the equivalent of a new Chicago city being formed every week. By 2050, 6.5 billion more city dwellers are expected (Oslo Governance Centre, 2020).

This rapid increase of the world population will mean that by 2050, 66% of the world's population will reside in cities (United Nations, 2015). This expansion of urban areas is defined as urbanisation. Current cities can not accommodate this influx as they have an ageing infrastructure with growing problems, restrictive policies and mismanagement (KPMG International, 2012). A vast majority of cities are constantly attending to faults and damages and do not have a plan or strategy (Muggah, 2017).

The rapid growth effect of urban sprawl is depicted visually in Figure 1.1 (Magidi and Ahmed, 2019). The COVID-19 2020 pandemic has shown that cities need to be more robust, resilient, and flexible (World Economic Forum, 2020b).

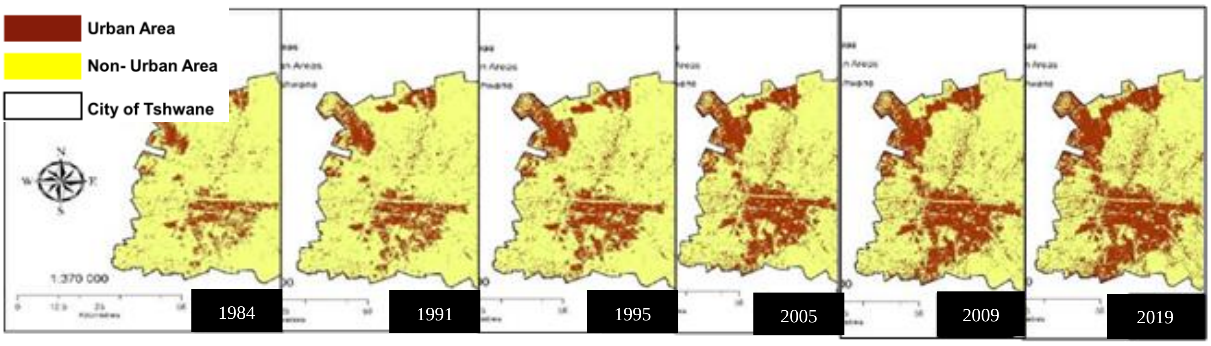


*Figure 1.1 - **City of Tshwane Urban Sprawl Visual Depiction** (Adapted from Magidi and Ahmed, 2019)*

In the past, cities expanded as the need arose. However, this urban sprawl led to disjointed, congested cities that are inefficient, unpractical and a victim to urban sprawl (Rafferty, 2020). "*Urbanisation is a global socio-economic phenomenon that has led to significant land use change in both developing and already well developed countries*" (Magidi and Ahmed, 2019).

South Africa is at high risk of the effects of urbanisation, with 55.5% of the population living in poverty (World Bank Group, 2020). Poverty exacerbates the effects of urban sprawl, which is evident as 90% of new urban areas are slums (FIG, 2010). Historical injustices in South Africa also led to cities not housing the workforce, which means commuting times for residents are excessively high leading to congestion, increased pollution, economic loss, social separation, and wealth gaps. This is especially prevalent in the city of Cape Town and cities in Gauteng, where the city outskirts are densifying instead of the areas with abundant resources and easy access to resources. (Ewing, 2007)

South African cities show how green spaces, linked to better and more healthy living (Urban Espora, 2019), are unequally distributed. Citizens earning 1000 ZAR per month are situated 2.6 kilometres away from the nearest park on average. Whereas citizens earning 30 000 ZAR per month are living on average, 770 meters from the nearest park (Caboz, 2020). It shows that these cities are inadequately laid out, and a redesign would supply the opportunity of accounting for these shortcomings. By planning for this inequality in future cities, urban areas can improve not only the environment but also better lives, livelihood and quality of life (Urban Espora, 2019).

Urbanisation does not only affect land issues but also other environmental and economic pitfalls which apply to any city anywhere. "*At the heart of creativity and growth, cities play a predominant role as motors of the global economy*" (Ellen MacArthur Foundation, 2017). When cities are strained due to their own infrastructure, they negatively affect their inhabitants' economy and livelihoods (Tanga *et al.*, 2014). The effect of failing cities extends to but are not limited to extensive environmental and social problems. It also includes unreliable and unsustainable energy use whose damaging effects are compounded by the Greenhouse Gas (GHG) emissions of energy use.

In addition, underutilised, inefficient and dated mobility infrastructure is causing a circular effect of economic degradation through its direct increase in congestion, health problems and private vehicle use (Bibri and Krogstie, 2017). These examples are but a few of the main shortcomings found in a poorly built environment.

The aforementioned built environment challenges are essentially a result of a linear design to cities and not a holistic 'circular economy' design. A linear design approach is a wasteful approach, both in terms of economic value and physical waste. This method of design leads to underutilisation and wasteful living (Ellen MacArthur Foundation, 2017). A typical example of such a design is in Europe, where a car on average is parked for 92% of its life, and food waste is 31% along the value chain (Ellen MacArthur Foundation, 2017). Commuting time lost due to congestion is also an example of a linear design problem. This haphazard design of current cities is found globally and is not only restricted to South Africa.

Lombraña and Dodge (2021) shows how if this haphazard urban development is not urgently addressed, climate change, which is most impacted by cities, will not improve. Increasing temperatures, extreme weather conditions and increased risk of flooding is increasingly felt in urban developments (Lombraña and Dodge, 2021). Flooding from sea-level rise due to climate change is especially concerning, as two-thirds of the worlds` cities are coastal (Muggah, 2017). A tool by EarthTime indicates the effects of a 4 degree Celsius global temperature increase (CMU Create Lab, 2019). The land area that will be lost to the increased ocean level, which is a result of ice caps melting, is indicated in Figure 1.2, together with a visual depiction of the Ice glaciers in 1984 vs 2019.

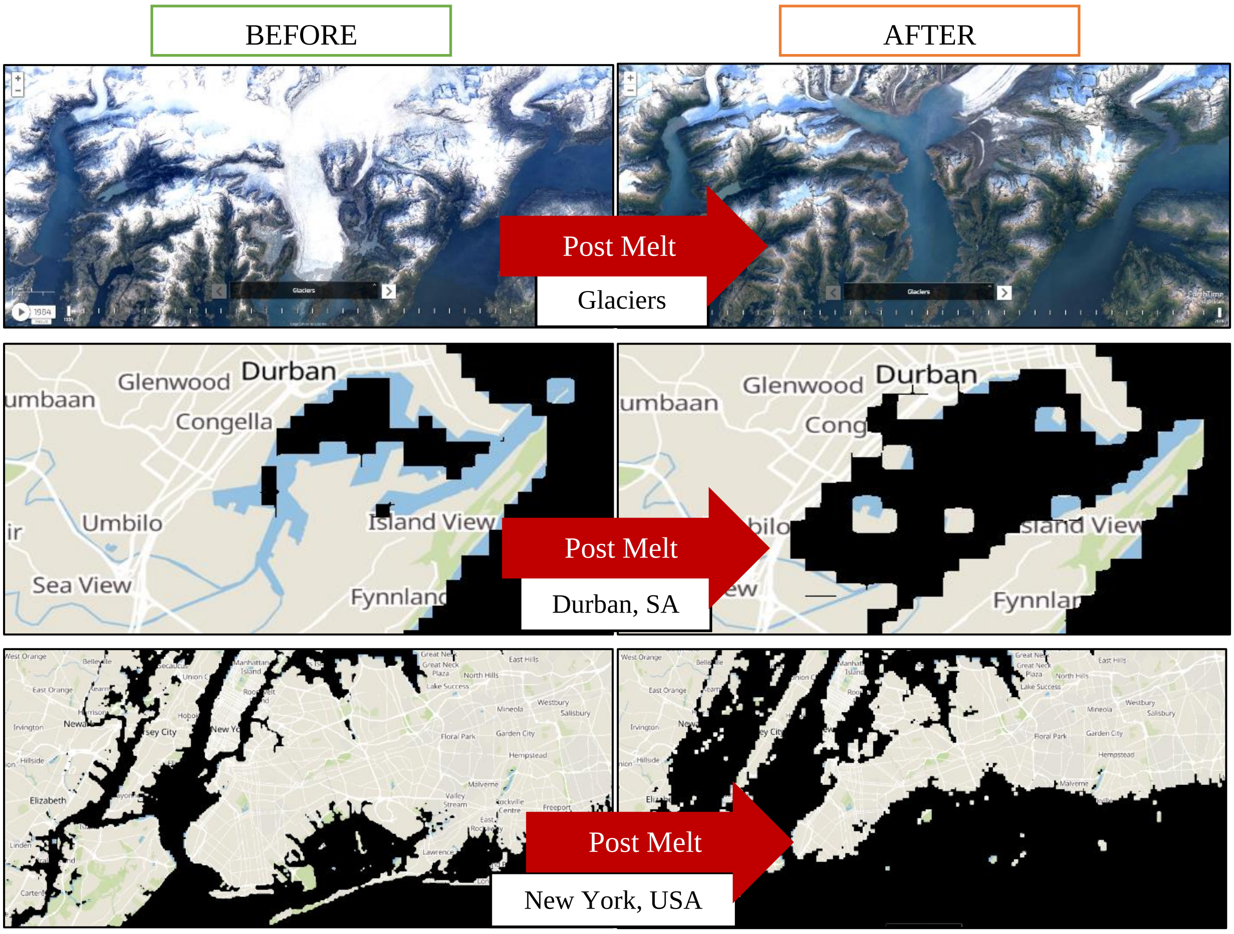


*Figure 1.2 - **Before and After Ice Caps Melt Resultant Land Area Loss** (Author) (Adapted from EarthTime)*

Globally, cities consume on average 78% of the energy available and generate 60% to 80% of the global GHG emissions, while only taking up 2% of the global land area. It relates to 80% of urban areas exceeding the safe air pollution levels set out by the WHO. (Ellen MacArthur Foundation, 2017)

The enormous energy consumption by cities, paired with the influx of growth in the urban population, creates a need for a robust and reliable energy sector within urban areas. An efficient energy infrastructure system has been lacking in recent years and has sparked the re-evaluation of energy infrastructure globally.

In an article by Bloomberg, it is stated that "*Cities are our best hope for surviving climate change*" (Poon *et al.*, 2021). The article identifies step one as reconfigure, which is typified in this study. If cities do not reconfigure, one could see more severe climate conditions in the future. Experts predict that if humanity continues at the current rate of GHG emission, the earth will increase in temperature by 4 degrees Celsius by the end of the decade. This will result in unliveable climate conditions. (Lombraña and Dodge, 2021)

The re-evaluation need of cities is burgeoning ever since the Coronavirus pandemic. The need for an urban development revisit was addressed during the 2020 World Economic Forum, which was labelled as "The Great Reset" for the urban environment. During a live-streamed event of the forum, H.M King Abdullah II ibn Al Hussien of Jordan said: "*The pandemic and its long term effects have exacerbated the long-standing crisis in our world. The climate crisis, poverty, hunger and socio-economic inequalities*" (World Economic Forum, 2020b). It highlights the need for a response that strengthens the urban economy but also addresses inequalities. A response is required that leads to technological and industrial progress but also ensures the sustainability of the shared environment is achieved.

Asian countries have been leading the development towards finding an approach, and focus on a smart cities approach (Graham *et al.*, 2015). An approach usually focussing on adapting already existing cities with technology to help solve the problems found in cities today (Rosati and Conti, 2016).

The global trend, which temporarily slowed down during the novel 2020 pandemic, of people shifting from rural to urban areas, supports the ever-growing need for transforming the way cities are developed. City designs have become resistive to change and templated in old designs (Sen, 2019). Methods that are inefficient and outdated, posing physical and technical issues, are still used as before (Bibri and Krogstie, 2017). However, the convention needs to be changed for efficiency and prosperity to improve. These problems have been growing because the world has changed and evolved, but the way cities are built has not.

Summarised Problem Statement

Infrastructure expansion and innovation is falling behind with the global growth rates and can not keep up with the population growth in urban areas. Compounded with a lack of holistic urban design, the way cities have been designed in the past will lead to significant economic losses and greater destructive environmental impacts.

There is an increasing demand for a new approach for designing cities of the future. A "*common Framework with more of an engineering approach*", as described by the World Economic Forum, 2020. There is a significant focus on smart city, liveable and circular economy designs but a lack of focus on these future cities' basic physical infrastructure. These aforementioned city designs focus on the singular quantitative solutions and fail to account for qualitative holistic approaches (Lachaize, 2017).

1.1 Research Question

Many of the most significant urban problems can be alleviated through a robust urban development framework. What does this framework look like, and can it be implemented in most areas, especially in South Africa, as a solution for future cities built from the ground up? What are the benefits compared to how cities are built/operated today?

1.2 Aim and Objectives.

The study aims to develop a framework for a new future city concept built from the ground up, called a Ripple City, which focuses on the shortcomings of current cities. It is important to note that the aim is not to nullify current cities but rather to create an opportunity for stress alleviation of current cities. The Ripple City should draw the majority of new urban inflow and create an environment for current cities to catch up and/or fix dated infrastructure without the burden of further urbanisation.

The city framework focuses on the major sectors of a city from which further development can grow. The framework strives for carbon and energy neutrality and provide for the most liveable city of the future while still allowing for economic growth and expansion. The city is for all social and economic levels of society.

The proposed city framework is based on striving for prosperity in the future. It incorporates old and new technologies and approaches that have either proven success or shown prospects of success.

For success, the framework must show promising monetary benefit, to the funding parties and the residents, in the long term compared to current methods. The framework must strive towards energy and carbon neutrality. Moreover, success criteria are defined for un-measurable items such as socio-economic benefits.

In order to evaluate the framework, the study considers a holistic approach for the development of the framework. Various studies have been undertaken to date with a focus on singular solutions by evaluating the quantitative output. However, this study combines findings from various studies and presents a more qualitative interpretation as traditional studies have failed to some extent to evaluate the qualitative impacts of new technologies and implementations (Lachaize, 2017).

1.2.1 Objectives:

To achieve the aim of this study, the following objectives are defined.

- Perform a literature study to obtain a fundamental understanding of the urban environment. Furthermore, identify various solutions to urban problems.
- Determine the main sectoral problem areas of an urban environment and focus on them.
- Evaluate the solutions available to the main problems within main sectors. From where, the study is to conceive and construct the best route forward for a baseline framework that attempts to solve or alleviate these sectoral problems.
- Develop a framework for South Africa which will also be relevant internationally.
- Use the data collected from literature and data banks, and evaluate indicative the financial feasibility of the proposed framework per sector. Implement cost-benefit analysis, life cycle evaluations, and forecasting models to achieve the outcomes.

- Measure the outcomes against existing solutions and urban settings.

1.2.2 Motivation for the study:

In recent years, there has been a great thrust for more exploration into the redesign of the urban environment. However, this study finds that there has been an overemphasis on the Internet of Things (IoT) or "smart cities" approach and not enough on the physical infrastructure. Numerous studies are focussing on singular solutions. For instance, the World Bank presents a study that a baseline scenario (do nothing scenario) would cost China 8.6% of their GDP, whereas a new "green and smart" approach would only cost 6.8% of their GDP. The research shows how this new approach provides a more innovative and dynamic economy that provides a better quality of living (Huang *et al.*, 2015).

These are, however, not recent studies. With ever-increasing innovation, declining cost curves and increasing adoption curves, this study aims to fill the need for a more recent evaluation with a holistic approach bringing together various solutions for urban problems, instead of just focussing on a singular solution such as a smart city, which often only focusses on IoT solutions.

However, this study aims to present a framework for the city from the ground up and not a redevelopment of a current city area. The study does not suggest a framework that is an addition to an existing city. The study investigates if a city built from the ground up is more efficient and economically viable in the long term. This is owing to the fact that in the past, cities were built/expanded as the need arose, with minimal consideration of the future. This led to the urban sprawl, disjointed communities, and unclear property zones where one could find residential properties right in the midst of an industrial zone.

More so than in the past, there is a better understanding of what cities require to be efficient and sustainable. By implementing best practice and innovative solutions, urban areas can be designed as an optimal urban structure with high efficiency.

The study shows that attempting to overhaul existing urban infrastructure in a fully operational city is not the most efficient course of action. The rationale for this is that the costs, time and disruption associated with breaking down and rebuilding dated infrastructure is higher than just planning for success and building it from the ground up.

The proposed framework approaches an optimistic outlook by using the increasing urbanisation as an opportunity to solve a problem facing modern society.

The very nature of urban areas needs to be reimagined from the ground up.

1.3 Uncertainty and Challenges

The study considers new ground-breaking technology and solutions, which is early in its adoption phase. Although there is a factor of uncertainty to the success of solutions that are not yet widely adopted. The proposed solutions are supported by data that provide an acceptable level of validity.

Costs often influence the adoption rate of new solutions; decreasing cost to customer often increases an adoption rate. There is a level of uncertainty to the prices of new innovations as they are in the infancy stages of their cost curves. This study therefore attempts to reduce cost uncertainty by adopting Wrights law, which is described further in this document (Ark-invest, 2021).

1.3.1 Scope:

The following section sets out the scope of this study:

- The study framework is validated in a South African environment, but is also internationally applicable and implementable.
- The study has a long-term outlook and implements methods that are trialled and tested for economic evaluation.
- To limit the scope, this study does not do a complete analysis of a city in its entirety:
  - The study focusses only on the most impactful sectors of an urban environment.
  - This research focusses on land-based modes as the design of this future city would not necessarily be based close to a seaport.
- The focus of this study is on a green fields city as it is theorised to be the best approach, however several of the concept discussed can be implemented in an existing city for a beneficial outcome.

1.4 Methodology

This section presents methodology utilised to achieve the aims of this study.

Identify main urban sectors:

A word mining approach was used to first identify the main urban sectors with the most significant impact on a city's sustainability and economic viability. The in-depth process is explained in Chapter 2. The critical urban sectors identified through from various studies are focussed on and explored.

Literature study:

Once the main sectors had been identified, a literature study was performed on available options available to each sector. From these identified solutions, a city design is constructed. Majority of research studies focus on a singular implementation, whereas this study evaluates multiple implementations together.

Research available from literature evaluates current practices and its challenges, while also exploring alternatives for future implementations.

Design specifications:

The information from literature is used as a guide to develop a preliminary framework of a city design. Data from peer reviewed studies are used in a cost analysis. The proposed framework implementations in each sector are presented with a rationale to motivate the choice of the specific solution.

Interview industry experts:

Once the preliminary designs had been set out, industry experts in each sector were interviewed to obtain input and/or commentary on the framework and approach. Due to restriction of the ethics approval acquired for this study, the thesis is not at liberty to disclose any background, personal and/or professional information. The thesis may only disclose what impact the interviewees had on the direction of this study. Furthermore, the thesis may disclose what the advice or key points were given by the interviewee, however, these discussions were not allowed to be transcribed and publicised.

The purpose of the interviews was to obtain verification from professional and industry experts on the proposed solutions to the problem. Additionally, these industry experts could suggest alternative solutions and/or approaches to the problem and/or suggested design. The experts were identified following the literature review.

The study identified the following expert areas:

- Project Finance specialist.
- Public Transport Engineer.
- Electrical Products chief
- Renewable energy expert

Data gathering and manipulation:

As mentioned, data was gathered from various literature sources and collated together. Large open-source data platforms were also explored to gather data. Any data gaps that could not be filled from online sources was filled from quotes or direct inquiries made to companies.

The data is first analysed per sector solution, after which it is used and compiled together in a singular qualitative model. All socio-economic benefits that are seen as unmeasurable is correlated to the data via a newly developed benefit matrix. The manipulation of these data sets focusses on the cost-benefit analysis approach and that of a pre-feasibility study.

Cost-Benefit Analysis

A Cost-Benefit Analysis (CBA) is one of the evaluation tools implemented in the data manipulation step. Transportation projects often implement this method. It is important first to define the most important aspects of a CBA. The United States (US) Department of Transport defines a CBA as "*a systematic process for identifying, quantifying, and comparing expected benefits and costs of a potential infrastructure project*." (USDOT, 2020)

The CBA is a tool often implemented by new or existing projects undertaken by public entities. The expected outcome of a CBA provides an indication of the feasibility of a project. At the core, the CBA attempts to determine the beneficial outcome, if any, with or without the project. A CBA, however, is not only an indicator to the producer's benefit but also to the consumer, which is always considered by the benefactor (Sartori *et al.*, 2014).

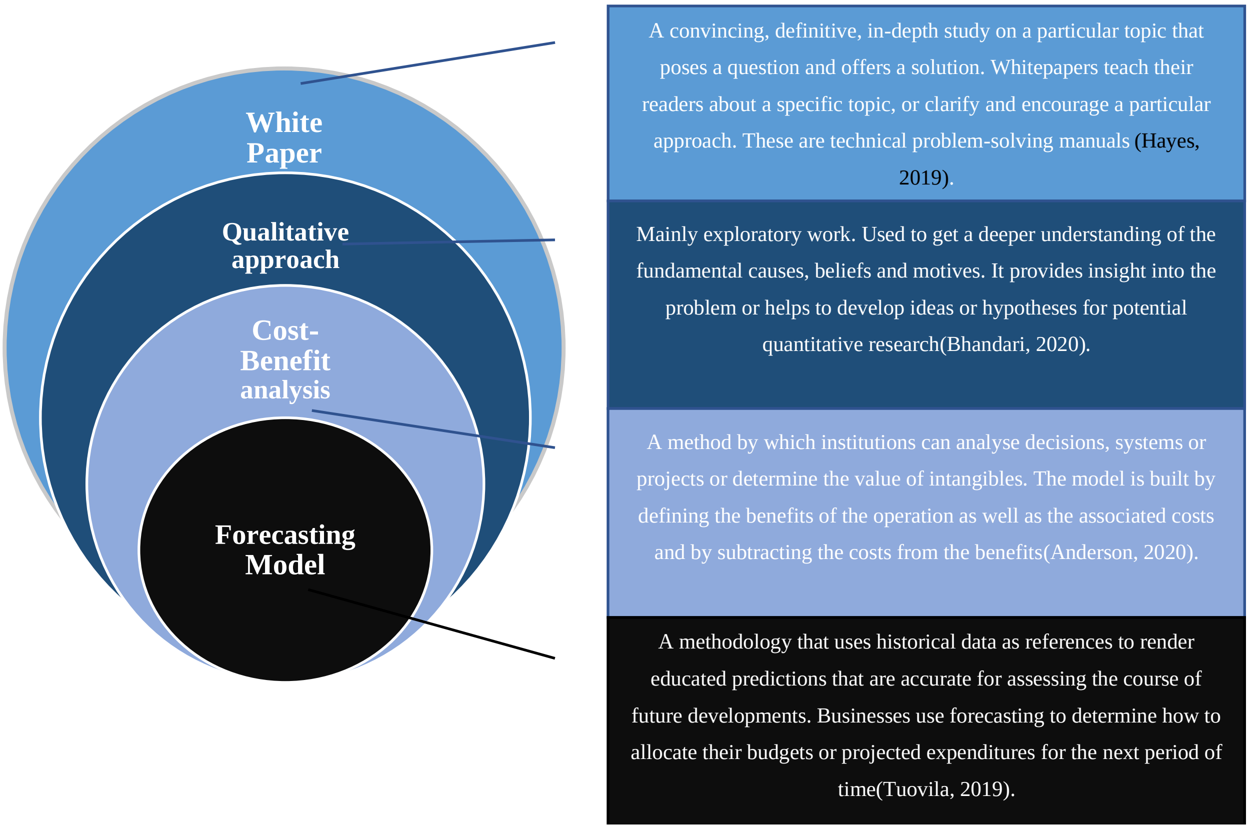
Analysis output evaluation and critical evaluation to follow:

The output of the analysis is critically evaluated and compared to market data. The outputs are condensed into simplistic figures while still showing the magnitude of the change in approach.

1.5 Report Structure

The presentation of the study does not follow traditional convention. The study proposes some design ideas and critically evaluate them by considering their cost/benefit, socio-economic benefit and their non-measurable aspects. The study, similar to a white paper, has a qualitative outlook with a specific focus on a cost-benefit analysis which contains aspects of a forecasting model.

The study does not attempt to offer a fully developed financial model but rather provides an indicative model of what current figures suggest and future prospects show. Figure 1.3 shows the approach taken.



A convincing, definitive, in-depth study on a particular topic that poses a question and offers a solution. Whitepapers teach their readers about a specific topic, or clarify and encourage a particular approach. These are technical problem-solving manuals (Hayes, 2019).

Mainly exploratory work. Used to get a deeper understanding of the fundamental causes, beliefs and motives. It provides insight into the problem or helps to develop ideas or hypotheses for potential quantitative research(Bhandari, 2020).

A method by which institutions can analyse decisions, systems or projects or determine the value of intangibles. The model is built by defining the benefits of the operation as well as the associated costs and by subtracting the costs from the benefits(Anderson, 2020).

A methodology that uses historical data as references to render educated predictions that are accurate for assessing the course of future developments. Businesses use forecasting to determine how to allocate their budgets or projected expenditures for the next period of time(Tuovila, 2019).

*Figure 1.3 - **Thesis Approach** (Author)*

1.5.1 Chapter Layout

The section hereunder briefly summarises the contents of each chapter found in this thesis document.

Chapter 1: This chapter provided the introduction to the thesis topic. The research question was identified with stated aims and objectives. The methodology of the research was also presented and so was any uncertainty or limitations.

Chapter 2: This Chapter is a brief investigation into what future entail and what are the approaches currently being taken to wards developing future cities. The chapter continues to evaluate various literature to determine what main impacting sectors should be focussed on for evaluation in this document.

Chapter 3: The third chapter investigates and evaluates key problems, solutions and approaches with specific focus to the main sectors identified in Chapter 2 – Energy, Transport and Layout. The chapter discusses research done by others to present key technologies currently being utilised in the market. The chapter deals with each main sector separately and after each sectoral literature, a problem identification section is presented. After the problem identification section, a solution identification section follows, together with a rationale for the chosen proposed solutions.

Chapter 4: The fourth chapter presents the outputs generated from a qualitative model generated to evaluate the proposed framework. The outputs are used to draw comparisons and conclusions from.

Chapter 5: This chapter presents the concluding remarks of the thesis findings and also continues to present some future work recommendations. Furthermore, the chapter presents monetisation recommendations which could help aid decision makers in funding a project of this scale.

Chapter 6: The sixth chapter contains the bibliography of all the sources used in the thesis.

Chapter 7: The second last chapter is a collection of general appendices. These appendices contain valuable information used in the body of the thesis but did not have a rightful place in the body of the thesis.

Chapter 8: The final chapter is an appendix that contains an extensive breakdown of the model created in this study for the proposed framework. The calculations and figures used to generate outcomes are discussed and referenced.

Layout Flow Diagram

Figure 1.4 shows the layout of the chapters and subsections.

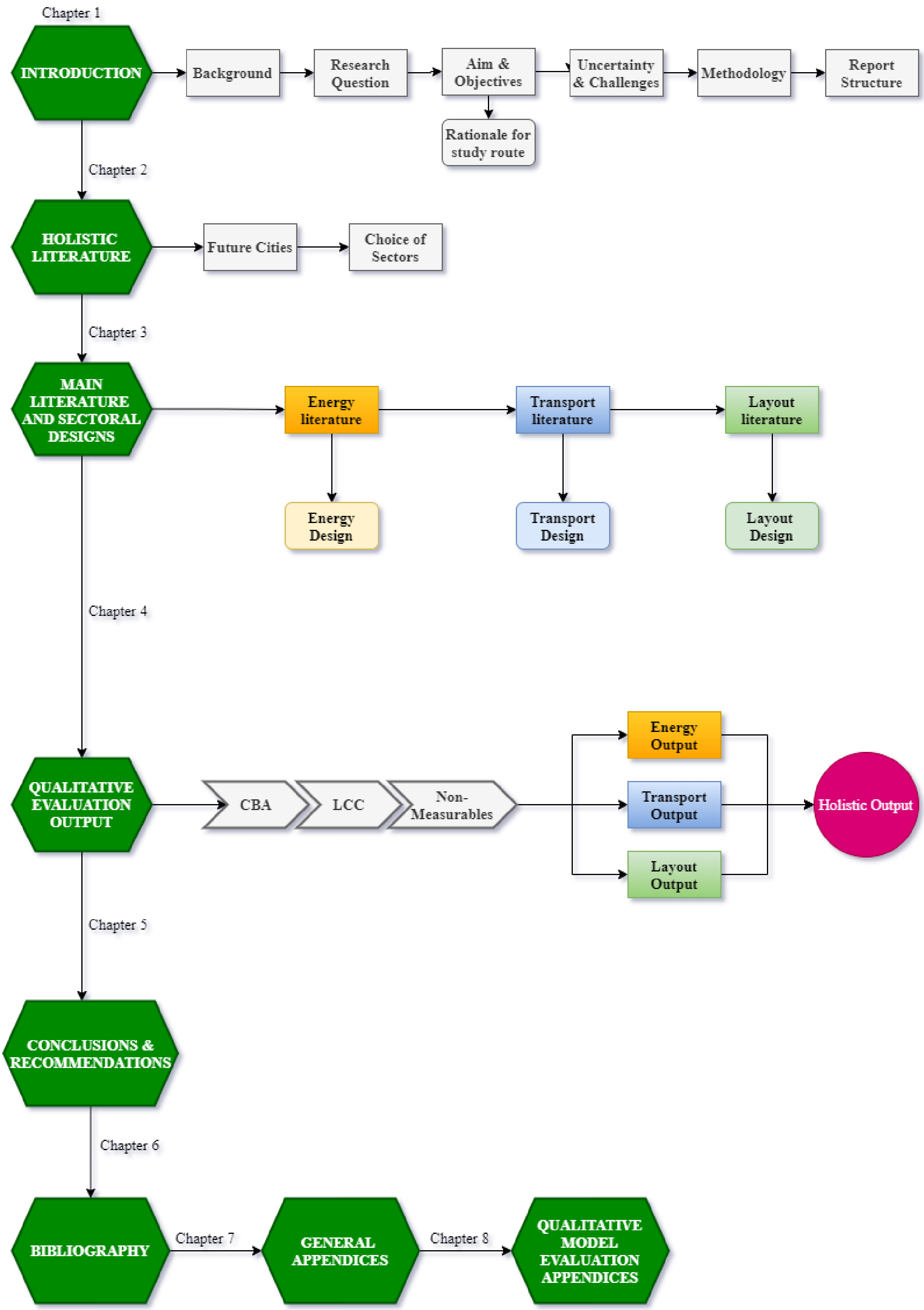


*Figure 1.4 - **Paper Roadmap** (Author)*

2 HOLISTIC LITERATURE

This chapter introduces the concept of future cities and introduces the reader to approaches used for design of future cities. First, literature on the urban environment is evaluated in a global context, and then in a local South African context. Secondly, the chapter gives an overview of the urban environment and identifies the focus areas of the urban environment. Finally, the process of identifying the three key sectors of an urban environment is presented as well as a summary of solutions explored in this study. These identified sectors were used throughout the study as focus areas.

2.1 Future Cities

The trend of innovation is causing renewal in the built environment. In September of 2015 193 countries agreed to the agenda of the Sustainable Development Goals(SDGs) where they subscribed to the requirement that urban environments need to be sustainable, flexible and prosperous (THALES, 2021).

Post the SDG goals, there has been a primary focus on what cities of the future exactly entails. This is addressed in the following subsections.

2.1.1 Smart Cities:

In the sub-section below, it is shown how there is an overemphasis on the smart city approach and not a large enough focus on the infrastructure of a city.

One of the approaches of envisioning a future city is a smart city. The definition of a smart city is still ill defined (Kamal-Chaoui, 2020). Fundamentally, it focuses on a software approach which refers to the operational side of a city, rather than the physical city. A smart city utilises Information and Communication Technologies (ICT) to solve urban issues (Kamal-Chaoui, 2020). These smart cities are also commonly referred to as digital cities (THALES, 2021).

Smart cities implement innovative technologies based on the Internet of Things and technology as a Service (TaaS). With the recent advancements and adoption of cloud-based technologies, smart cities have been able to implement more solutions (Harvard Business Analytics, 2020). It is not confounding to discover the urban problem being solved with an Information Technology approach when 27.6% of the S&P500 consists of Information technology companies (Lemke, 2020). This share of ICT in solutions will increase more so with the recent advancements made in Artificial Intelligence (AI) (Abdallat, 2021).

The American Society of Mechanical Engineers (ASME) shows that there are generally eight recognized aspects of a city that is overhauled using smart technologies. These include mobility, water, security, healthcare, energy, engagement and community, economic development, waste, and housing. These aspects are used as a benchmark to determine the success of smart cities, and the leader in all aspects is Singapore. Some other smart cities include Seoul, London, Dubai, Copenhagen, and Shanghai. Europe and Asia are considered to be the front runners in digitising city management. (Kosowatz, 2020)

The inaccessible nature of technology to low-income users can exclude these residents from a smart city design and this should be mitigated.(Kamal-Chaoui, 2020).

2.1.2 Circular Economy Cities

Where the smart city approach is an actual implementation of innovative technology, the circular economy city focuses on cities' management, policies, and operations. It has a significant focus point around materials used and wasted (Wenzel, 2019). The circular economy is designed around three principles: To remove waste and pollution in the design, keeping the highest possible value of materials, components and products and to have a natural system that is regenerative (Ellen MacArthur Foundation, 2017).

2.1.3 Megacities

The two aforementioned city approaches are commonly found in megacities. However, megacities are a product of urban sprawl (Dastrup, 2020). A megacity can either be efficiently operated by implementing approaches such as smart cities or be inefficient as they are still operated as traditional cities, while they are nothing compared to traditional cities (Webster and Burke, 2012).

The largest megacity to date is Tokyo in Japan which registers 37.4 million residents (Michael, 2019). It is estimated that in 2100, the largest megacity will be Lagos in Nigeria with 88 million residents. By definition a city of this scale is to be classified as a Gigacity if its population exceeds 50 million (Ellen MacArthur Foundation, 2017), and a city is defined as a Megacity if its residents exceed a population of 10 million (IBERDROLA, 2021).

An urban built environment with a highly concentrated population, such as mega- and giga-cities, is creating enormous challenges for urban planners and engineers, especially in sustainable development. (Ellen MacArthur Foundation, 2017).

2.1.4 Future cities in South Africa

South Africa (SA) is not excluded from the urbanisation trend. As of 2015, 29 megacities house more than 12% of the global urban population, which amounts to above 470 million residents. It is estimated that by 2030, twelve new megacities would have been formed, and 10 of these will be situated in African and Asian regions. (Ellen MacArthur Foundation, 2017)

The South African population growth rate is decreasing with a growth rate of 2.48% in 1992 to a rate of 1.4% in 2019 (The World Bank, 2019). However, this is an inaccurate metric to use as a singular indicator for the future of urbanisation. This metric needs to be juxtaposed with the urban population as a percentage of the total population to show the effect of urbanisation in South Africa.

The need for future cities in South Africa is shown in Figure 2.1 where one can see that SA's urban population percentage is more than that of the Global percentage average and catching up with that of Japan.

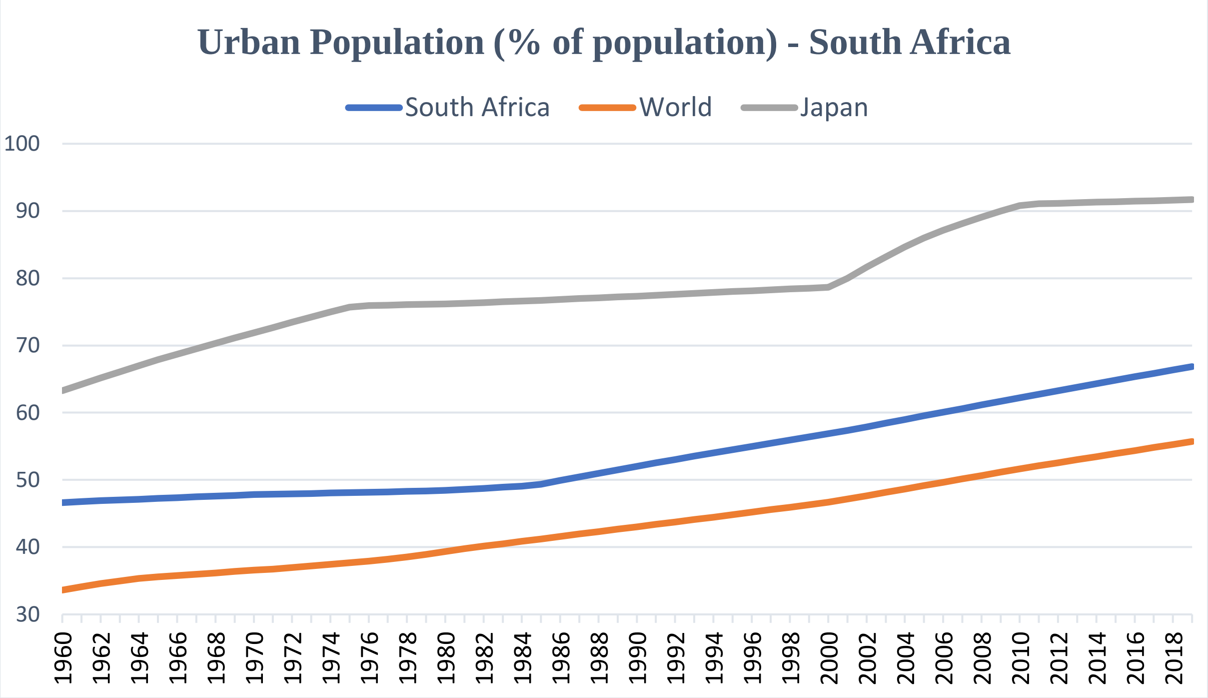
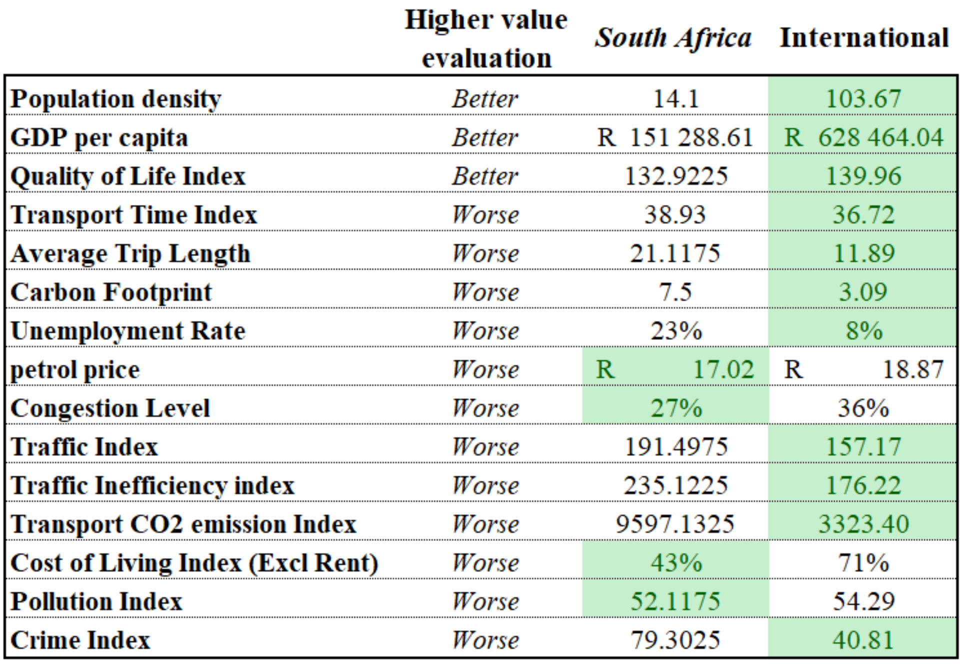


*Figure 2.1 - **Urban Population as a % of the Total Population**. (Author) (Adapted from The World Bank, 2019)*

The readiness of South African cities for this burgeoning effect of urbanisation is evaluated in many studies as well as in this study, one such study by the Financial and Fiscal Commission in partnership with the African centre for cities, indicate how SA cities are in danger. The study found that SA cities are typified by inequality, low densities and increasingly high GHG emissions. Moreover the study states that by international standards, SA cities are inefficient. (Palmer, Ian; Brown- Luthango, Mercy; Berrisford, 2011)

Looking at the comparison of South African cities with international cities in Figure 2.2, it is evident that SA cities underperform compared to international standards. Refer to Appendix A for a detailed expansion of individual cities.



	Higher value evaluation	*South Africa*	International
Population density	*Better*	14.1	103.67
GDP per capita	*Better*	R 151 288.61	R 628 464.04
Quality of Life Index	*Better*	132.9225	139.96
Transport Time Index	*Worse*	38.93	36.72
Average Trip Length	*Worse*	21.1175	11.89
Carbon Footprint	*Worse*	7.5	3.09
Unemployment Rate	*Worse*	23%	8%
petrol price	*Worse*	R 17.02	R 18.87
Congestion Level	*Worse*	27%	36%
Traffic Index	*Worse*	191.4975	157.17
Traffic Inefficiency index	*Worse*	235.1225	176.22
Transport CO2 emission Index	*Worse*	9597.1325	3323.40
Cost of Living Index (Excl Rent)	*Worse*	43%	71%
Pollution Index	*Worse*	52.1175	54.29
Crime Index	*Worse*	79.3025	40.81

*Figure 2.2 - **City comparison with various metrics** (Author) (Refer to for Appendix A for sources)*

South Africa lacks infrastructure, and the main contributing factor is that SA in the past has attenuated infrastructure investment (Palmer, Ian; Brown- Luthango, Mercy; Berrisford, 2011). SA invested 231 billion ZAR in 2019, amounting to 4.6% of SA GDP, which is a 7.6% decrease from the previous year (StatsSA, 2019).

The Gauteng province, Cape Town, Durban and Port Elizabeth is where 80% of SA economic growth is found (StatsSA, 2019). By comparing the efficiency rates of these cities to those of some of the best international cities, one can see the effect. Figure 2.3 shows the comparison by placing the data on radar charts in order to see the difference visually. The less expanded the radar chart area is, the more efficient and functioning a city is.

*Figure 2.3 - **City Comparison Visualisation on Radar Charts** (Author)*

Notably, however, the SA government has recently been looking more into smart city implementation (Moyo, 2020). From the literature that follows in this study, it is found that there is an overemphasis on the smart city approach. However, SA is a primarily divided country, and the country's economic situation exacerbates this. This is reinforced with the S&P Global rating's agency rating SA as the 8th most miserable country (Writer, 2021). Technology is often not accessible to low-income class groups (Wiggins, 2020), and hence an excessive tech solution will not be suitable in all areas. Various projects have been suggested by the SA government and implemented as of February 2021. Four of the main projects implemented is the Lanseria smart city, the Durban Aerotropolis, the Mooikloof "mega-city", and the Stellenbosch bridge project.

The aforementioned projects are briefly discussed below.

2.1.4.1 Lanseria smart city

Lanseria smart city is a project which is, as of February 2021, open for public comment. The city design aims to accommodate 500 000 residents by 2030, and it is situated in Gauteng's West Rand region. The city focuses on renewable energy and transport that is non-motorised. It focuses mainly on IT systems implementation, hence its` label as a smart city, such as a citywide CCTV system with facial recognition and 5G implementation. (Daniel, 2021)

This city is shaped around the Lanseria airport and form part of the greater Johannesburg (JHB) metro. It has different sector nodes, which, as development continues, expand and join into one city area. The first two planned for development is the Lanseria Business gateway and the three towers precinct. These will be the two central starting nodes that will form part of the attempt to "stitch" marginalised and gated communities together. (Gauteng Office of the Premier, 2021)

The Greater Lanseria Master Plan (GLMP) expands on the idea of what a smart city is, focussing not only on ICT implementation but also on sustainable and inclusive practices. (Gauteng Office of the Premier, 2021)

2.1.4.2 Durban Aerotropolis

Similar to the Lanseria smart city, the Durban Aerotropolis will be shaped around the Durban airport, King Shaka International, and trade port. The city aims to house 1.5 million residents and focuses on the trade industry in the area. Defined as a smart city in its master plan, the design focuses on freight transport and modern public transit taking a 70% share. (GlobalAfrica Network, 2021)

The Aerotropolis has a 50-year growth plan and is one of the first large scale city developments that is partially built on Greenfields and accounts for future urban expansion. The design focuses on three major transformation sectors, which include economic, social and spatial objectives. The plan is engrossed around six key investment sectors: Advanced Manufacturing, Health and Pharmaceuticals, Aviation and Aerospace, Tourism, Agriculture and Agro-processing and Electronics and Electrical components. (Dube Tradeport, 2021)

2.1.4.3 Mooikloof "mega-city"

The Mooikloof "mega-city" project is also defined incorrectly. As per the definition of what constitutes a megacity, this project cannot be labelled as a mega-city. The project design sets out 50 000 apartments (BusinessTech, 2021a) which, on an overestimated assumption of 4 residents per apartment, does not reach the 10 million resident requirement for the megacity label.

This development, which is spearheaded by Balwin properties, was announced in October of 2020 by President Cyril Ramaphosa and has a project cost of 84 billion ZAR. The project is part of the Strategic Integrated Projects (SIPs) gazetted in July of 2020 (BusinessTech, 2021a). Evidently, although labelled as a megacity, this development lacks the basic amenities that define a city. Therefore, this study does not consider the Mooikloof project as a viable alternative to future city design.

2.1.4.4 Stellenbosch Bridge Project

The Stellenbosch Bridge project sets out from the start that it is "*the first truly Smart City in Africa*" (StellenboschBridge, 2020). The project is still early in its development phase, which meant a lack of public information was available. Nevertheless, the project adopts the superblock structure layout and promises to be a sustainable, connected living and innovative city (StellenboschBridge, 2020).

Hence, South Africa has some developments of future cities, however, the projects announced thus far do not align with industry standards by definition and focus heavily on the smart city approach.

2.2 The identification of main urban sectors.

To determine the main sectors for this study, two methods were followed. Method 1, the more robust method, involves the process of text mining. Method 2, which is a reliability check of method 1, involves a large scope of studies, press and websites which were evaluated to determine what researchers consider to be the most impacting sectors of the urban environment. A hundred and forty-six studies were evaluated for areas of interest to determine a frequency indicator of which sectors are mentioned and explored.

2.2.1 Method 1: Text Mining

A survey study is typically used for focus area determination (Lau and Kuziemsky, 2016); however, as an alternative this study applied an automated text analysis. A research process often referred to as data mining entails transforming unstructured text into meaningful and structural insights. The process implements an approach similar to that used in Artificial Intelligence (AI), which evidently is machine learning. The process involves feeding large amounts of data into an algorithm that can then pick up similarities, patterns, and repetitions. The program then transforms the data to a simpler format which usually takes a tabular form or other visual forms. (IBM, 2021)

This study implemented tokenization of the data, which breaks lengthy text into singular words referred to as tokens (IBM, 2021). These tokenised words are evaluated to see which tokens are most recurring in the text. This study did not implement sentiment analysis as the study discusses relatively new innovative solutions, which inherently is prone to scepticism which would`ve skewed the results.

2.2.1.1 Text mining methodology.

For text mining, the first goal was to acquire a vast data set from which tokenisation can occur. This study formed a data set consisting of pdf documents acquired from Google Scholar, Stellenbosch University Compendix database and Google search. The documents were sourced using keywords that relate to future cities. These keywords were: "city", "urban", "infrastructure", "future", "development" and "urbanisation". The acquired studies from this keyword search were screened to ensure that it relates to urban development.

The result from the keyword search resulted in 56 viable documents. These documents collectively are referred to as the corpus, which is fed into a text mining algorithm on Voyant Tools (Sinclair and Rockwell, 2021). The tool proceeded to tokenise the corpus to 833 623 tokens and 51 240 unique word forms. The tokens were then transformed into the visual word cloud shown in Figure 2.4, which was evaluated to determine the main topics discussed in these research papers.

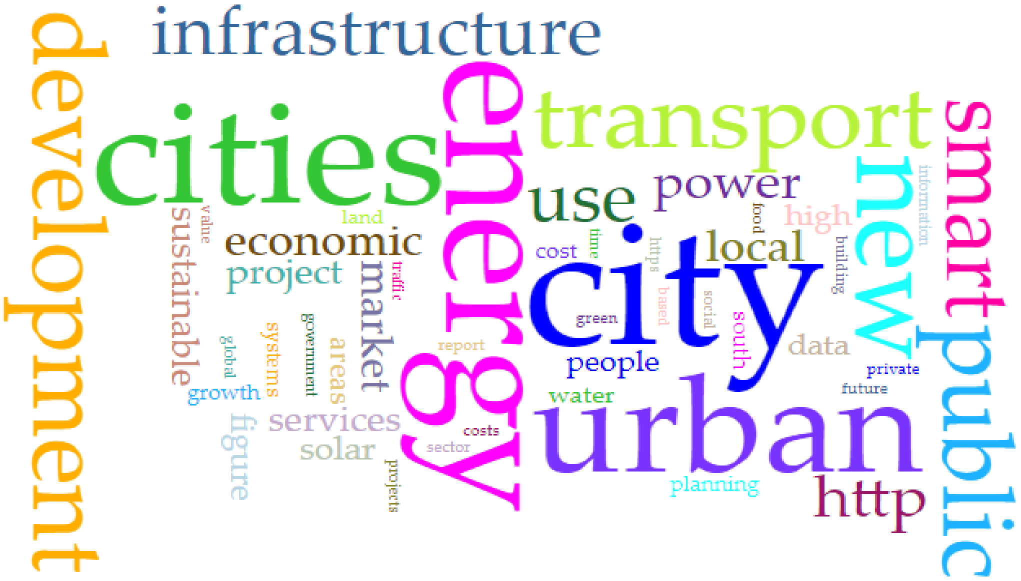


*Figure 2.4 - **Text Mining Word Cloud on Major Topics Discussed in Urban Development Research Papers** (Author)*

From the text mining exercise, the most prominent topics identified from these studies were: Energy, Urban, Cities, Transport, Infrastructure, Development, Smart, Economic, Sustainable, Public and Power.

2.2.2 Method 2:

Method 1 is a methodological approach to the research; however, papers omitted from the text mining could change the outcome to a different result. This is due to unconscious bias when determining the focus keywords. Hence this study implements a second method to verify the outcome of method 1.

For Method 2, 146 alternative studies were evaluated, 76 studies of the 146 were summarised by a study by the Cities Development Initiative for Asia study (CDIA, 2019) which evaluated which areas current projects invest in when developing future cities. Figure 2.5 shows the overall representation of the CDIA and the additional research conducted for projects in other countries for a more global data set. The additional research conducted over and above the CDIA study involved reading the documents and doing a frequency count of the heading topics in each document.

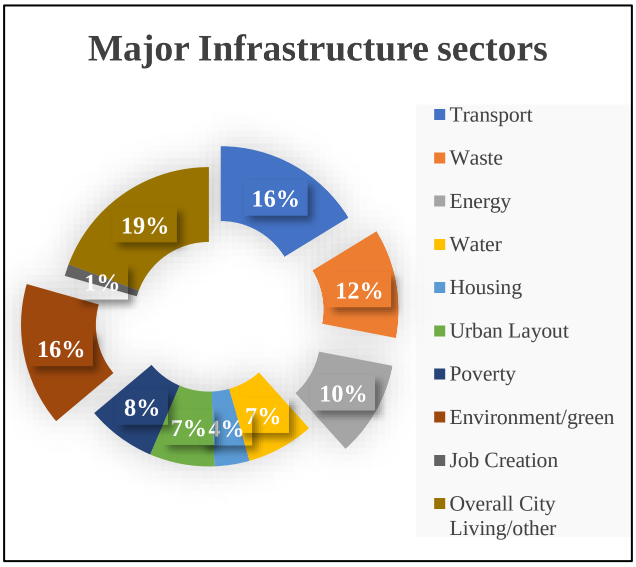


*Figure 2.5- **Total Representation of Infrastructure Sectors**. (Author)*

2.2.3 Final Identified Sectors

After implementing the above two methods to identify main sectors that impact the urban environment, the main sectors for this study were identified. Table 2.1 shows the top sectors from each method, ranked in frequency of occurrence, and the final selection for this study.

*Table 2.1 - **Major Urban Sector Evaluation Results***

Method 1	Method 2	Final Sectors
Energy	Overall City Living/ Urban Form	Energy
Transport	Environment/green	Urban Layout
Infrastructure	Transport	Transport
Development	Waste	Living • *Jobs* • *Poverty* • *Waste* • *Water*
Smart	Energy	
City	Poverty	
Economic	Water	

The final sector choice is further reduced to the 4 main sectors which most appeared in these studies as described below:

1. **Energy Sector:** This sector involves anything related to energy solutions, more specifically electricity and heat. The sector focuses on the goal of sustainable, carbon-neutral and efficient energy infrastructure.
2. **Transport Sector:** This sector focuses on what an urban transport infrastructure resembles, mainly focussing on public transport. The sector focuses on new innovative solutions to public transport and reduced congestion and GHG emissions.
3. **Layout Sector:** This sector involves the physical urban layout of the city. The sector looks at how an urban area is laid out, constructed and operated.
4. **Living Sector:** This sector encompasses the areas in an urban structure that involves how citizens live and survive. The sector focuses on waste management, food resources, housing and job creation.

2.2.3.1 Identified Sector aims.

Various options were identified from the literature study as solutions to the sectors. Figure 2.6 presents identified solutions and infrastructure developments for investigation in this study, to achieve the Ripple City design. The expanded list of innovations explored is found in Appendix B.

Figure 2.7 shows the allocation of each of the solutions related to each of the four main city sectors.

Figure 2.6 - ***Novel Developments*** *(Author)*

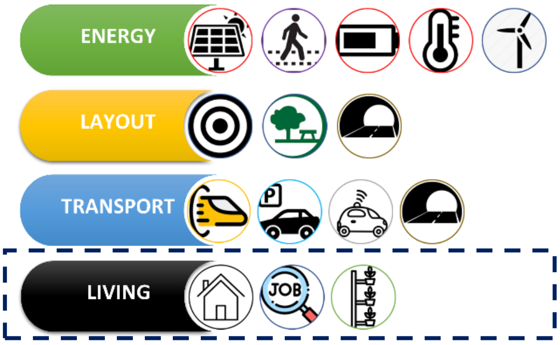


*Figure 2.7 - **Sectoral Allocation of Developments** (Author)*

The study investigates how each of these sectors can contribute to a city framework that is achievable and sustainable. The purpose of the **energy sector** is to investigate if a city entirely run by renewable sources of energy is both viable and profitable. The section investigates if the shortcomings of renewable sources of energy can be overcome with innovative technologies and well sought-after infrastructure. Additionally, the approach investigates if the environmental and efficiency benefits outweigh the perceived large initial capital expenditure of this project.

The **layout sector**'s purpose is to find a concept design that is more efficient and flexible than the current city designs. The sector investigates if the need to change how cities are physically laid out has an impact on the prosperity of a city. The study aims to investigate the surface layout and to financially compare the actual costs to income and savings.

The purpose of the **transport sector** is to investigate if, together with the new layout design, a new transport framework is of benefit. The section investigates if new technologies suggested are viable, achievable, and cost-effective in the long term. The framework of this sector presents an efficient public transport solution that accounts for an entire transport cycle from home to work and back. Moreover, the shift to a subsurface transport system is investigated.

The purpose of the **living sector** is to incorporate the basic needs of living in an urban setting. At the same time, it is imperative to ensure that the city approach is not exclusive to a specific class of income. The city needs to present adaptability to closing the gap between supplying affordable housing, reducing poverty and providing jobs at the expense of governmental funds. The living sector is also a representation of all the miscellaneous factors that play a part in the city. The framework city has an integrated ecosystem of supplies, services, and systems to ensure the city operates at full functionality. This sector is not as extensively evaluated as the other three sectors. The main goal is to show that the city in its entirety can be supplied with sustainable food, waste management and job creation. This sector branches throughout the first three sectors and hence do not have its own separate chapter of evaluation as the others.

Figure 2.8 shows the sectors in a summarised form in the circular concept proposed in this paper.

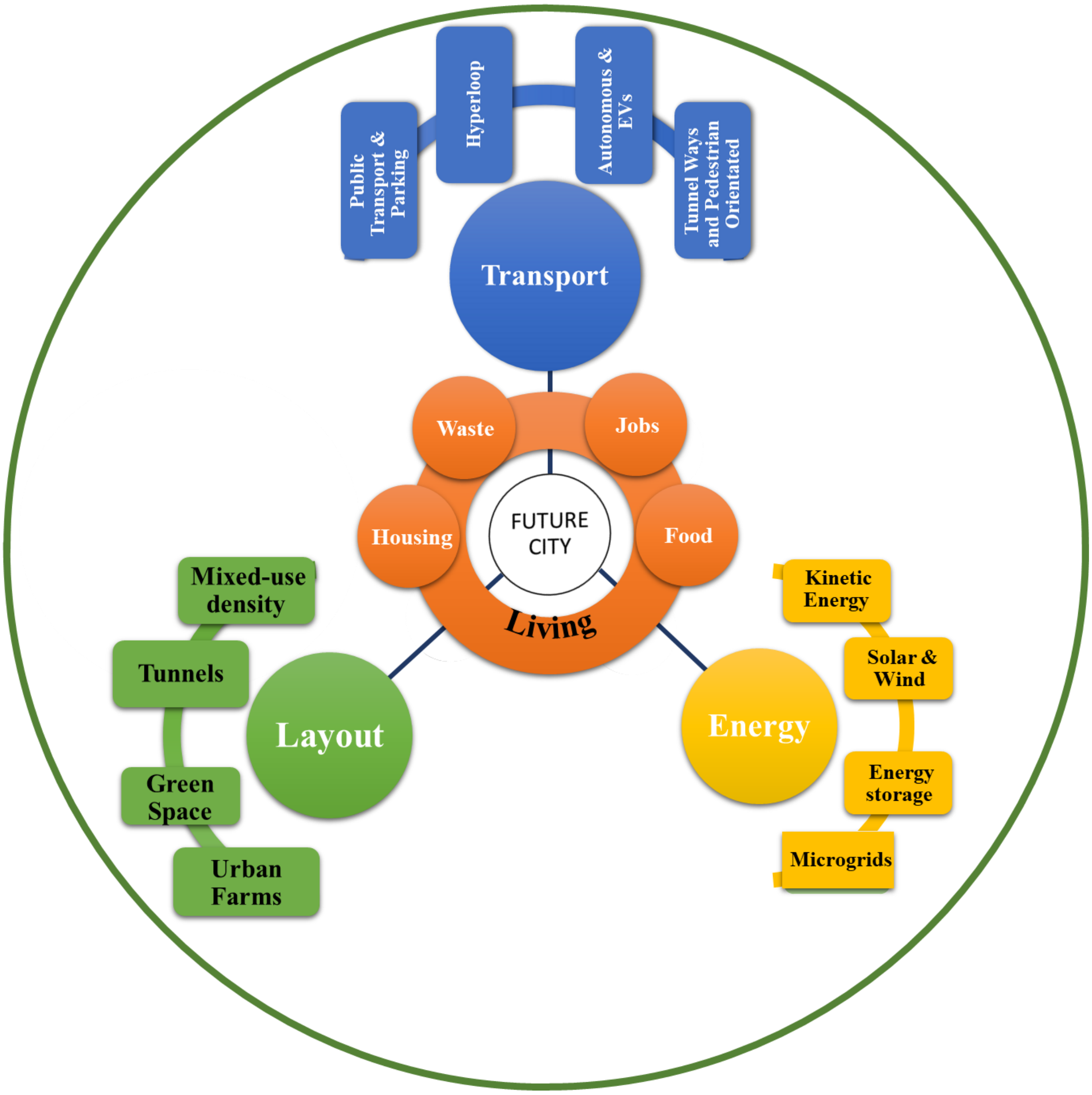


Figure 2.8 - ***Sectoral Summary*** *(Author)*

3 LITERATURE REVIEW & SECTOR FRAMEWORKS

The sectors identified in Chapter 2 are extensively explored in this chapter in order to identify problems and the best solutions to these. The chapter evaluates the literature in three themes. Firstly, to identify problems within each sector, both globally and locally. Secondly to identify current solutions to these problems. Finally, to explore alternative and innovative solutions. The overarching aim is to achieve an understanding of the fundamental makeup of the problems and solutions.

After each sectoral literature section follows, a proposed design section follows which identifies the key problems and proposed solutions for the framework.

Refer to the diagram in Figure 3.1 for a visual depiction of the key sections and the discussed topics. Furthermore, each sector leads with a key technologies roadmap to navigate the chapter.

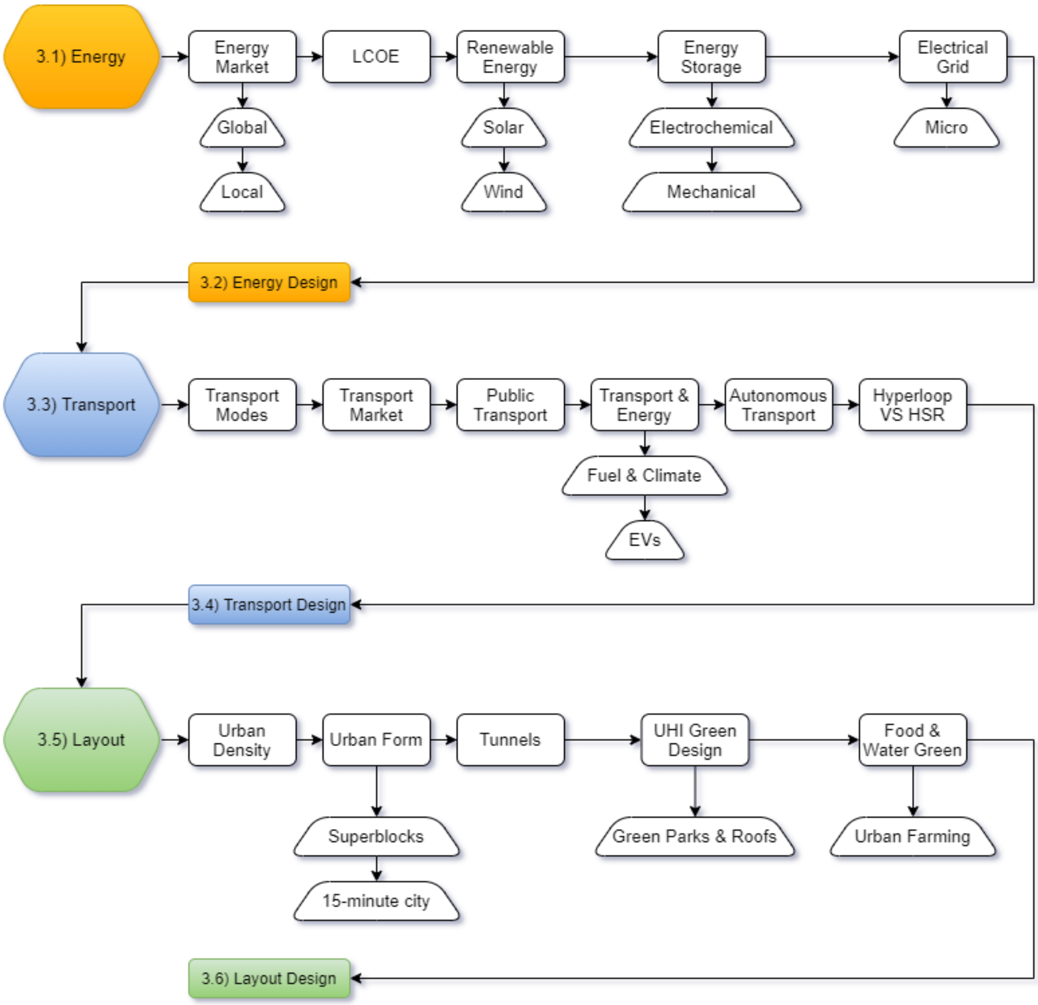


Figure 3.1 - ***Sectoral Layout and Topics Discussed.*** *(Author)*

3.1 Energy Sector

This section addresses the following key points of the energy sector:

- The energy market, its trends, and future prospects;
- The cost of energy with a focus on coal generated power;
- Renewable energy with a focus on solar and wind energy;
- The benefits and key innovations of the energy storage systems available;
- The synergistic setup of the energy network within an urban environment;

It is now accepted that the global population is on a steady increase. Even though the rate of increase has slowed down, the rate of energy consumption has not. Figure 3.2 shows how the global population is increasing at a steady rate and the GHG emission increases in a fluctuating manner.

However, energy consumption is ever increasing its differential gap. The increase in energy consumption is the result of an economic expansion linked to the 4th industrial revolution and the ever-increasing dependency on technology (PWC, 2017).

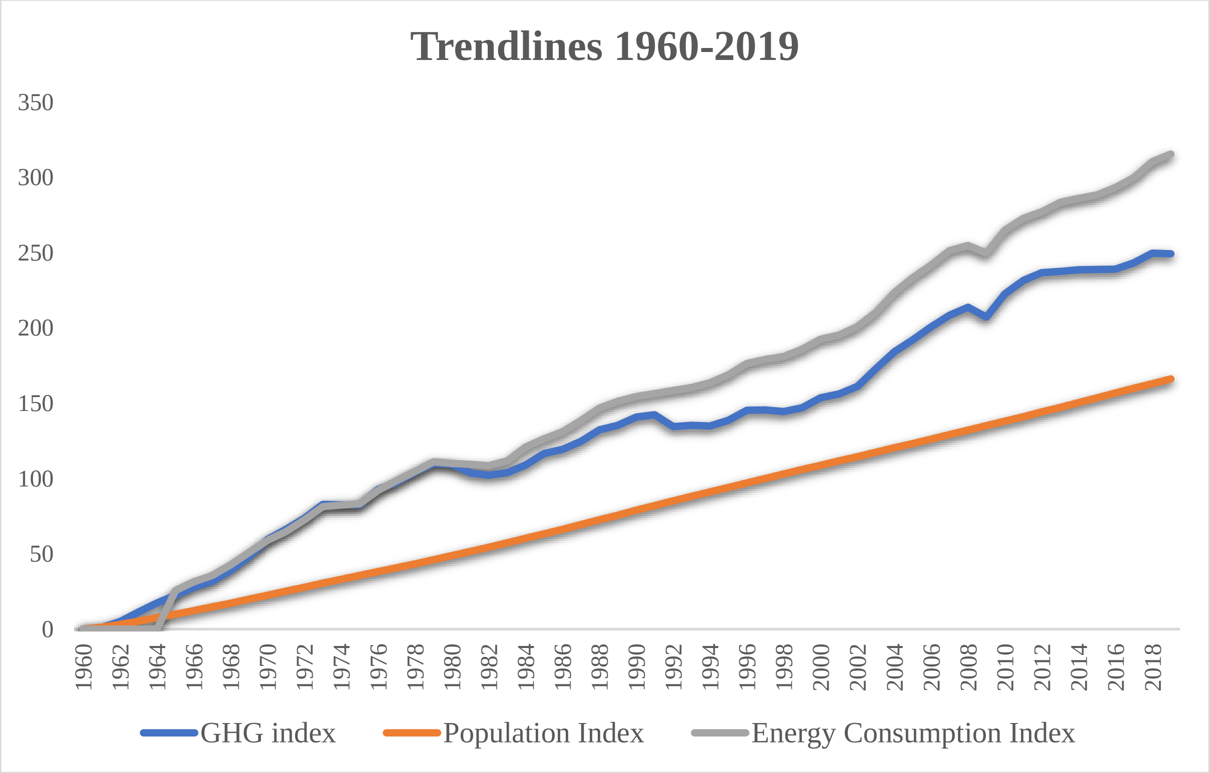


*Figure 3.2 - **Trendline comparison of the energy sector influencers.** (Author) (Adapted from various sources)*

To understand fully what energy is and who the role players are, one needs to understand that the energy sector of the urban environment cannot be mentioned without mentioning the impact it has on the climate. Energy's cradle to grave route amounted to 76% of global GHG emissions in 2018, where electricity and heat generation was the most significant contributor, followed by transport

(ClimateWatch, 2018). This is by virtue of the energy market being historically dominated by fossil fuel use, as shown in Figure 3.3.

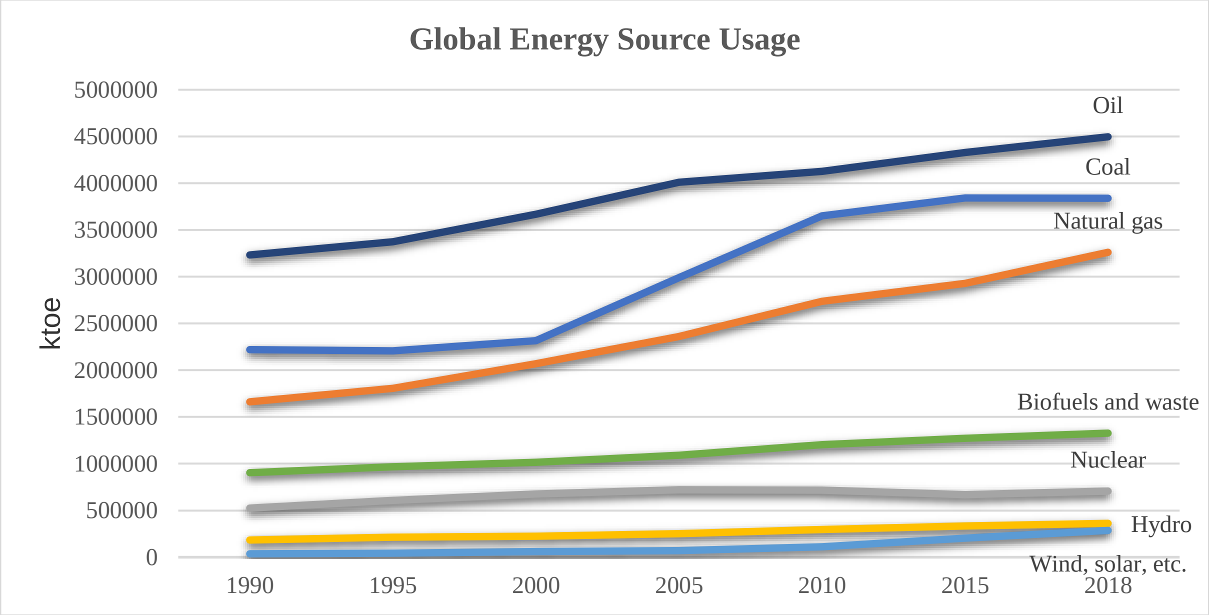


Figure 3.3 - ***Global Energy Source Use*** *–(Author) (Adapted from IEA World Energy Balances 2020)*

Looking at the difference between fossil fuels and renewable sources, the reasoning for pursuing fossil fuels initially, becomes evident. It has a considerable amount of energy density, its logistics are relatively easy and it can be stored in most phase forms. Traditionally, fossil fuels have also been cheap. Today, however, the world is faced with a severe climate change problem, ever decreasing fossil fuel reserves and increasing cost curves and waste (Union of Concerned Scientists, 2016).

Moreover, the 4th industrial revolution has increased the need for efficiency, and fossil fuels are not efficient when considering heat loss from combustion. An example of its inefficiency is found in internal combustion engines (ICE), which has an energy loss of 64-75% (Rodrigue, 2020b).

The energy sector overflows into other sections of this research as it is the key sector to a sustainable city. Hence, not all energy literature is found in the section addressing the energy sector. The following sub-section looks at the global and local situation of the electrical energy sector of the urban environment. The urban heat energy discussion is found in the layout section and the transportation energy impact can be found in the transport literature section.

3.1.1 ‘Electrical’ Energy Market

In this section the market situations and trends are explored to present the reader with an understanding of where the market is moving and, moreover, what economical potential industries can be formed from the market trends.

Global 'Electrical' Market

The world is experiencing an ever-increasing energy demand, commonly referred to as "energy sprawl" (Kiesecker and Naugle, 2020). With a focus on using fossil fuels, the need for a different approach to match the demand becomes evident, else, humanity faces exacerbated effects of climate change (Jenkins *et al.*, 2018).

A number studies have been done on climate change and its effects on urban living. One of these studies is that of the Urban Climate Change Research Network, where in-depth research is done on climate change. Amongst many findings, the study finds that climate change, resulting from the electricity production of cities, increases anthropogenic temperatures and GHG. This creates problems such as inequality, low health conditions which evidently lead to increased deaths and disease forming. The research also shows how there is an increased risk of flooding in urban areas and infrastructure degradation. (Rosenzweig *et al.*, 2015)

These risks have been the catalyst to the international market re-evaluating its designs. Figure 3.4 shows how there has been a joint effort to reduce the amount of fossil fuel use in the international economy, especially coal, and a shift towards renewable energy sources (EMBER, 2020).

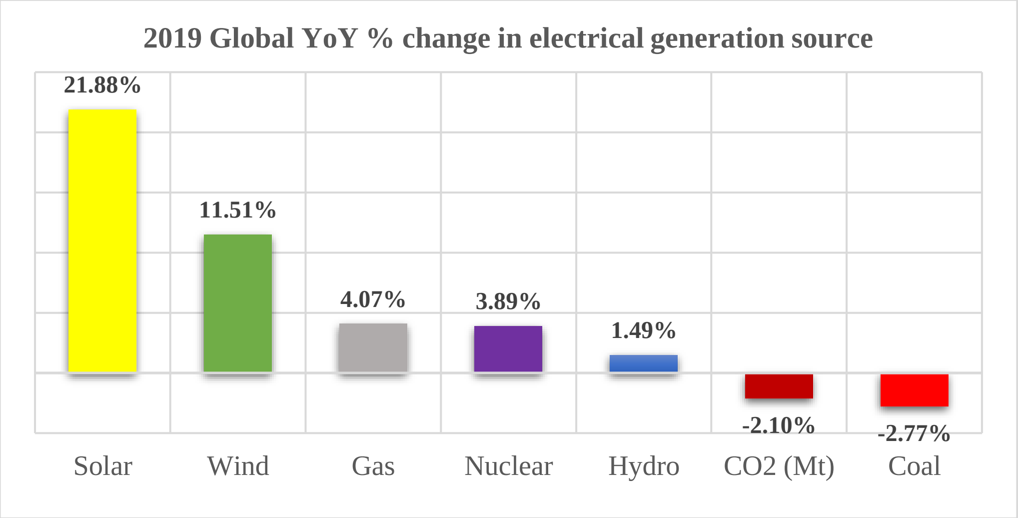


*Figure 3.4 - **2019 Global YoY % Change in Electrical Generation Source** - Adapted from (EMBER,2020)*

Figure 3.5 shows how much of the G20 countries' energy production share is dependent on fossil fuels. Some of these countries have made public commitments to reduce their climate impact, which is summarised in Appendix C.

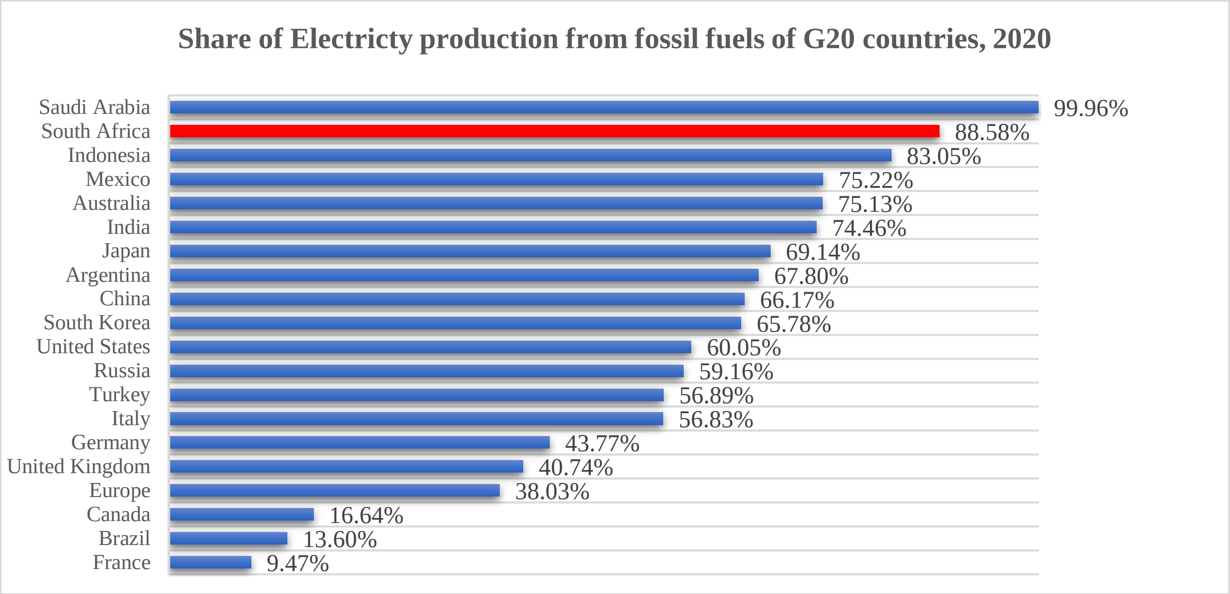


*Figure 3.5 - **G20 countries share of fossil fuel used in electricity production.** (Adapted from Our World Data, 2021)*

The majority of G20 countries have more than 50% of their power supply dependant on coal, even though the globally accepted indicator for the future of coal, the Dow Jones US Coal Index, shows a decaying future. The index collapsed in 2020 when it was decommissioned due to underperformance, as depicted in Figure 3.6.

*Figure 3.6 - **Dow Jones U.S. Coal Index** (MarketWatch, 2020)*

Sub-Section Summary

It can thus be seen that the global market has identified the need for a shift away from fossil fuels. It is seen that cities have a significant impact on the GHG emissions. And although key market indicators show the need for a new approach, the shift is not being adopted fast enough as is clear from the G20 countries' share of fossil fuels.

Local `Electrical` Market

South Africa has been slow to adopt the change of energy. Figure 3.7 shows how SA's generation mix has barely changed Year over Year (YoY) in comparison to other countries. This is evident when 88.6% of SA electricity is still being generated by polluting fossil fuels (Our World Data, 2021).

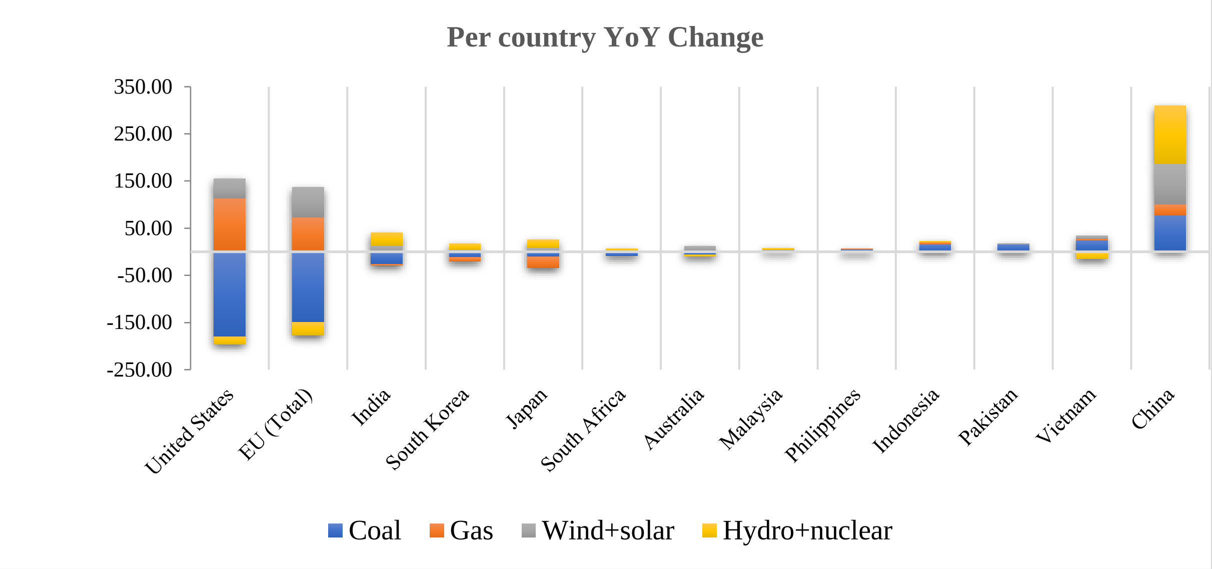


Figure 3.7 - ***YoY Energy mix change per country*** *– (Adapted from EMBER,2020)*

With excessive electricity tariff increases from the national power utility, Eskom, SA is under increasing scrutiny. The tariff increases, shown in Figure 3.8, result from cost overruns, project delays, lacking maintenance, and a supply chain largely dependent on coal (Pienaar et al., 2020). Recent supply shortages and corruption exacerbate the situation (Steyn *et al.*, 2017b). The supply shortage has resulted in a crippling economy by-product, load-shedding, a process internationally known as rolling blackouts, with about 860 hours of load-shedding occurring in 2020 (Business Insider SA, 2021).

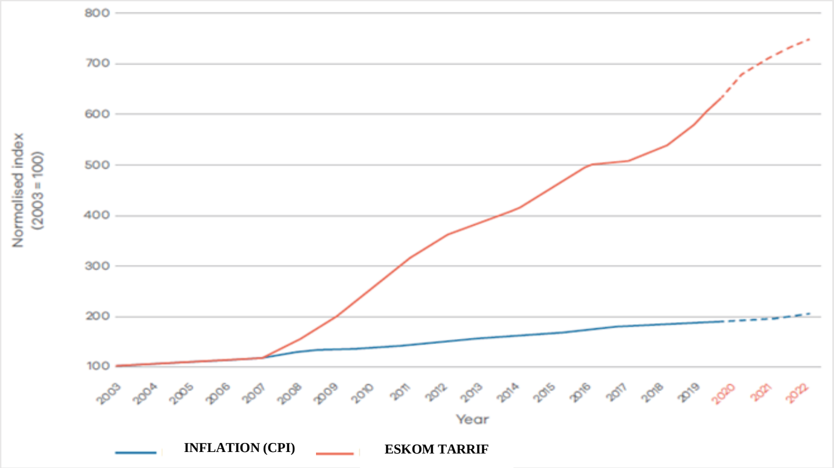


Figure 3.8 - ***Eskom tariff increase index line****. (Pienaar et al., 2020)*

An analysis group called Intellidex, stated that the cost data point used to account for economic loss due to load-shedding, amounts to 500 million ZAR per stage per day (BusinessTech, 2019). This study recalculates the economic impact of unserved energy in section 8.1.3 for a more updated view of the impact.

The extent of the capacity shortage extends to non-direct monetary problems, with credit ratings agency Fitch sending out a warning about the situation (BusinessTech, 2021b). Moreover, Moody's credit rating agency has downgraded SA to ‘junk’ status, highlighting the power problem as one of the major deciding factors (Moody`s, 2020).

Fitch raised the concern of Eskom planning to decommission 3 340 MW and only bringing online 3 200 MW of power capacity by March 2025. However, the new capacity is mainly from Kusile and Medupi, two coal power stations that are behind schedule and over budget (Steyn *et al.*, 2017b).

As of April of 2021, Eskom has a peak demand level of 34 000 MW, however, it falls short of this by 4 000MW. The Department of Mineral Resources and Energy released a statement of the intent to reduce this shortage, the announcement sets out only 2 000 MW to be connected only in August of 2022. Moreover, this does not meet the utility's acceptable capacity standard of 45 000 MW (BusinessTech, 2021b).

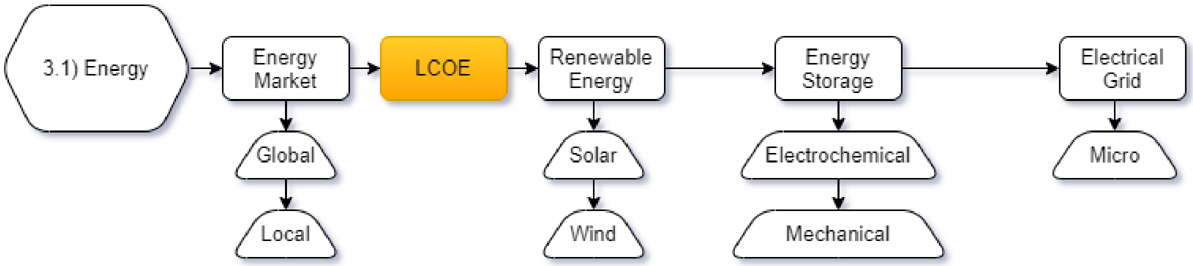
The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) is a solution to acquire 2 600MW of additional power for Eskom as the sole buyer (Department of Mineral Resources & Energy, 2021). The recent Risk Mitigation Power Producers Procurement Programme (RMIPPPP) announced by the Department of Energy (Nathan, 2021), opposes the approach to RE. The RMIPPPP considers the solution for an additional 1 220 MW from Powerships, a method of implementing utility ships that anchor off-coast and generates power from GHG emitting fuels and then transmits it on-land.

The contract is for a fixed 20-year period for which the CSIR estimated it would cost SA 218 billion ZAR, 10.9 billion ZAR per year (Burkhardt, 2021). Based on the CSIR study, the Democratic Alliance estimates the Levelised Cost of Energy (LCOE) to be 2.30 ZAR per kilowatt-hour (Mileham, 2021) and not the regulators LCOE claim of 0.61 ZAR per kilowatt-hour (Nathan, 2021).

Sub-Section Summary

As can be seen, SA is not following international trends of adopting RE. The country has a high dependency on coal generated power, which is partially the reason to the increasing energy prices. Furthermore, the problem is worsened by the supply shortages and increasing demand. The difference in LCOE shows the level of inefficiency and uncertainty within the local conventional energy market. For a more secure future energy system, this inaccuracy and lack of power security needs to be removed.

3.1.2 *Levelised Cost of Energy for Coal*



The LCOE is a metric used to compare different projects relating to energy production. The method of LCOE is a commonly accepted method to project energy costs. It gives an indication of the cost required to cover the production of a unit of electricity from a facility, over a set lifespan (CFI, 2021).

The metric takes into account fixed and variable costs. In accounting terms, it is referred to as the cost of goods sold. The orthodoxy of a Net Present Value (NPV) analysis is in many ways similar to that of the LCOE, where the outcome can be used to evaluate the viability of a project as a worthwhile investment (CFI, 2021). Equation (8) is the formula represented by the Corporate Finance Institute for LCOE (CFI, 2021).

$$LCOE = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime} \qquad (1)$$

The LCOE provides utilities and customers an indication of what their energy would cost and if a new approach is needed. During this research, the researcher found various studies (IRENA, 2019a; IEA, 2020b; NRDC, 2020a) overestimating or ignoring a vital metric of these energy plants - the capacity factor. The capacity factor is a representation of the actual units of power produced and - sold to customers, - not just produced. The capacity factor should only include units sold to customers.

After the interview with an Energy Expert (Renewable Energy Expert, 2021), the researcher was referred to a recent study that addresses the capacity factor problem. The study shows how the dogma created by widely cited sources, such as the International Renewable Energy Agency (IRENA), National Renewable Energy Laboratory (NREL), the Natural Resource Defence Council (NRDC) and the International Energy Agency (IEA), has created a death spiral of inaccurate predictions and a financial bubble (Dorr and Seba, 2021).

Table 3.1 shows how each literature source estimates the capacity factor and the respective LCOE calculated.

Table 3.1 ***-2020 Projected Capacity Factors and LCOE of Coal Power from Various Sources***

	Coal Capacity Factor	**LCOE /kwh** ***USD/ZAR = 14.48***	**Source:**
NRDC	75.0%	R 1.39	(NRDC, 2020b, 2020a)
Lazard_vers12.0	93.0%	R 1.47	(Lazard, 2018)
Lazard_vers14.0	90.5%	R 1.62	(Lazard, 2020)
EIA	70.0%	R 1.09	(EIA, 2021)
IEA	85.0%	R 1.27	(IEA, 2020b)
IRENA	*Not stated*	R 0.73	(IRENA, 2019a)
NREL	70.0%	R 1.09	(NREL, 2019)
OpenEI	93.0%	R 1.01	(OpenEI, 2015)
US_actual_average	40.0%	R 4.64	(EIA, 2020)(Dorr and Seba, 2021)

The EIA predicted an increase in coal plants' capacity factor, as shown in Figure 3.9. The EIA states that dated turbines will be replaced by more efficient turbines (EIA, 2019). However, they also note an increase in renewable energy uptake, but from their assumptions, it is not enough to reduce capacity factors of coal power. The inaccuracy is evident when their own actual data shows a 40.2% capacity factor for coal in 2020 (EIA, 2020). This is not an issue exclusive to the USA only. The IEA, IRENA, NRDC, and Lazard account for global data as well.

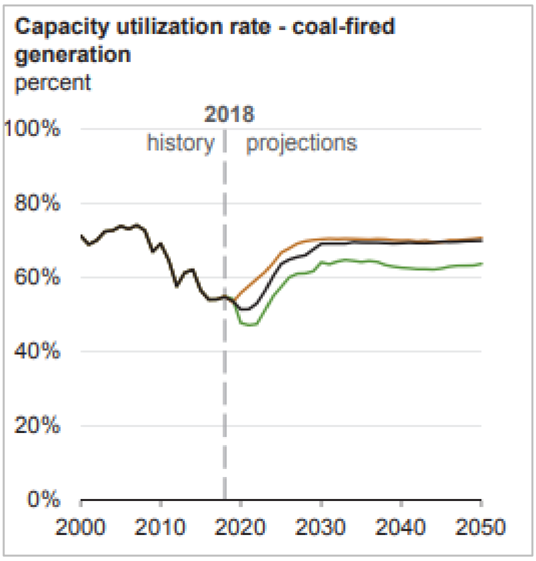


Figure 3.9 - ***EIA Projected International Coal Capacity Factor*** *- (EIA, 2020)*

This research re-evaluates LCOE of South Africa in Chapter 4, as the study by the team of RethinkX did for the USA (Dorr and Seba, 2021). This study of RethinkX shows how a financial bubble has been created in the energy sector from using an incorrect capacity factor.

Dorr and Seba (2021) shows how almost all mainstream analytical teams overestimate the capacity factor and assume efficient sales throughout the entirety of the plants' life. This results in figures assuming existing and newly built power plants will produce and sell power units at a nearly constant rate all through the 20-year lifespan.

RethinkX shows how the average capacity factor in the USA was 67% in 2010 and has fallen to an actual figure of 40% in 2020. Similarly, in the UK, it was calculated to be 58% in 2013 and 8% in 2019 (Dorr and Seba, 2021). Figure 3.10 and Figure 3.11 indicate the assumed versus actual capacity factors of USA and UK coal plants. Which shows the inaccurate capacity factors utilised in the calculation of the LCOE of these coal plants.

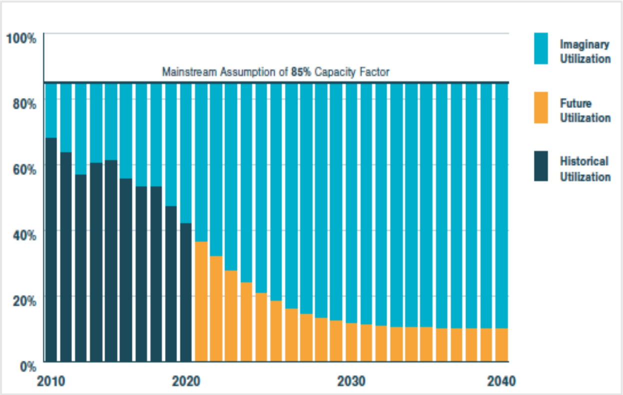


*Figure 3.10 - **US Coal Capacity Factor Estimates VS Actual** - (Dorr and Seba, 2021)*

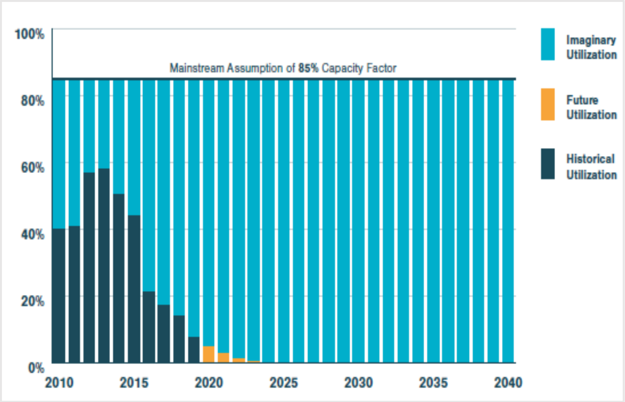


*Figure 3.11 - **UK Coal Capacity Factor Estimates VS Actual** - (Dorr and Seba, 2021)*

Gimon *et al.* (2019) found that in recent years, with the advent of electric vehicles, fracking, solar and wind energy, the USA coal plants have become increasingly insolvent and struggling to sell their power units. The analysis done by Vibrant Clean Energy, LLC, looks at the risk posed to existing assets by renewable energy sources such as Wind and Solar (Gimon *et al.*, 2019). The study evaluates the Marginal Cost of Coal plants (MCOE) to that of the LCOE of Wind and Solar plants of similar capacity. The study finds coal cost crossover MCOE margins for the energy sources as depicted in Table 3.2.

*Table 3.2 - **MCOE Findings of Coal Cost Crossover Study** (Adapted from Gimon et al., 2019)*

Electric Energy Source	MCOE
Coal	$ 33-111 per MWh
Solar	$ 28-52 per MWh
Wind	$ 13-88 per MWh

Figure 3.12 shows a visual adaptation of the results from the Vibrant Clean Energy study. The x-axis is the various coal plants evaluated. When the graph falls below the zero axes, it shows that a solar or wind plant would be more economically viable than the coal plant to which it is compared.

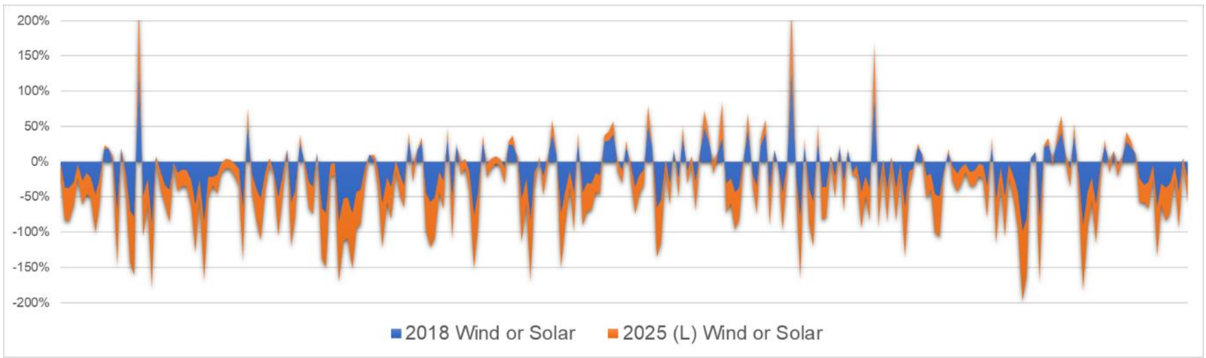
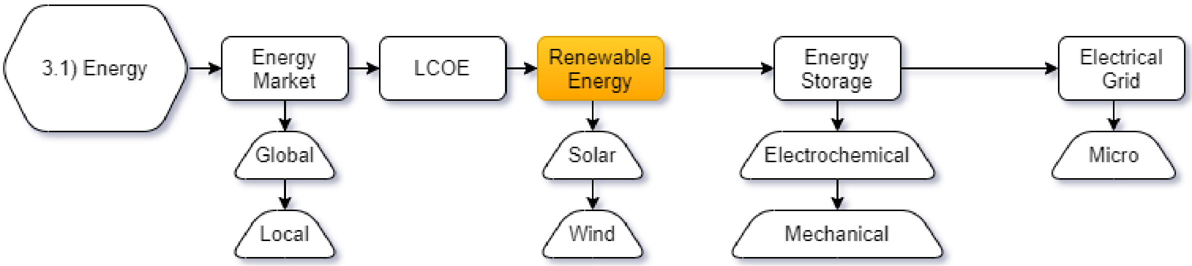


*Figure 3.12 - **Adaption of Results on Study Comparing Coal To Wind or Solar Plants** (Author)*

Sub-Section Summary

From the above it is found that the LCOE plays a significant role in the future trends of adoption of technologies. However, these LCOE costs have been miscalculated by many sources and results in an energy generation mix that is unsustainable and requires rethinking. Finally, the section also shows that energy sources such as wind and solar can be more financially viable than coal.

3.1.3 Renewable Electrical Solutions



Thus far, the literature has shown the need for Renewable Energy (RE) solutions and the suggested benefits. In this section, the research considers RE and the solutions available. The literature of existing projects, market conditions and studies were explored.

Some of the primary RE sources include solar, wind, hydroelectric, biomass, geothermal and tidal/wave energy (Shinn, 2018).

Roser (2020) finds the adoption of RE technologies in recent years have proliferated. The reason for this adoption is a due to different factors, but the most engrossed factor is possibly the learning curve experienced with these technologies (Roser, 2020). The curve follows the law of Wright, which states that: "*With each percent increase in cumulative production in a given industry, results in a fixed percentage improvement in production efficiency*" (Wright, 1961).

This improving efficiency and production capacity lead to a cost reduction from improved mass production. The resulting cost curves outperform that of the fossil fuel sources, which used to be cheaper than RE sources. However, the need for climate change mitigation has forced countries to invest more into research and development of RE technologies, as shown in Figure 3.13. The advancements which resulted from the R&D then resulted in cost declines, as indicated in Figure 3.14 (NRDC, 2020c).

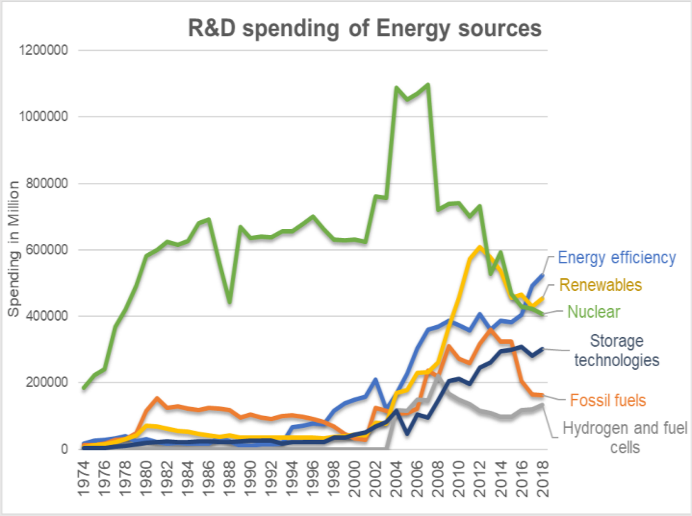


*Figure 3.13 - **R&D Spending Budget of Energy Sources** (Author) Adapted from EIA Energy Technology RD&D Budgets (2020 edition)*

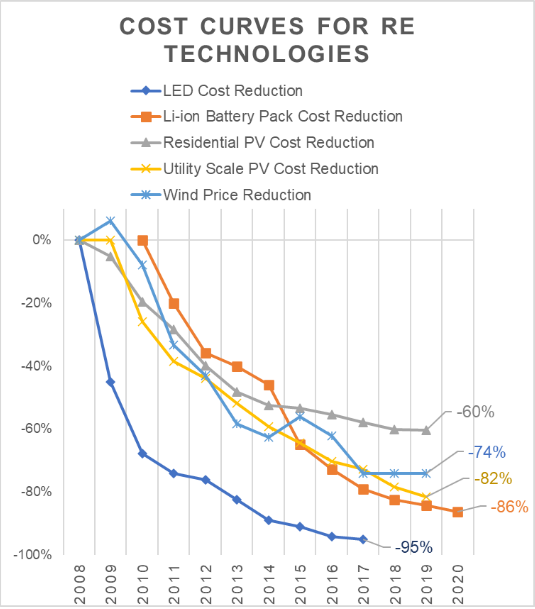


*Figure 3.14 - **Cost curves for RE Technologies** (Author) Adapted from (NRDC,2020c)*

Notably, with the increasing capacity of RE sources, excluding nuclear, the LCOE drops, but coal does not. Declining from 111 to 109 USD, the global LCOE for coal fell by 2%. Nuclear went from 96 to 155 USD, a 61% increase. Whereas solar and wind, decreased its LCOE by 89% and 70%, respectively (Roser, 2020).

The ability of RE sources to reduce its comparative cost structure in this way, is attributed to its lack of fuel costs. Nuclear and fossil fuels limiting factor to its cost competitiveness are founded in 2 factors, fuel cost and plant operating cost. RE sources have relatively low operating costs and do not have fuel costs (Roser, 2020).

This cost structure of RE sources has introduced a systematic diminishing structure into the traditional power utility environment. Utilities that are resistive to change, as in the case of Eskom in South Africa, find themselves in a financial Death Spiral (Dorr and Seba, 2021). Figure 3.15 depicts this financial term visually.

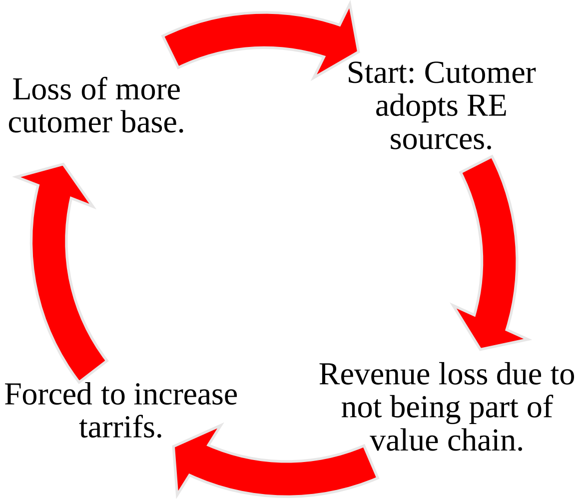


Figure 3.15 - ***Utility customer death spiral*** *(Author)*

Power utilities can also find themselves in this spiral by incorrectly determining the cost parity of their generative sources. To mention one example, RethinkX (Dorr and Seba, 2021) found that solar PV has reached cost parity with coal in 2013 and not 2016, as analysts initially calculated (Dorr and Seba, 2021). This means that power utilities could be under the impression that fossil fuels are still a viable route, which the literature of this study shows is not the case.

RE sources have not only become cheaper than fossil fuels, it is also safer by order of magnitude than that of fossil fuels, as shown in Figure 3.16 (Desjardins, 2018). Some of these deaths are installation related deaths.

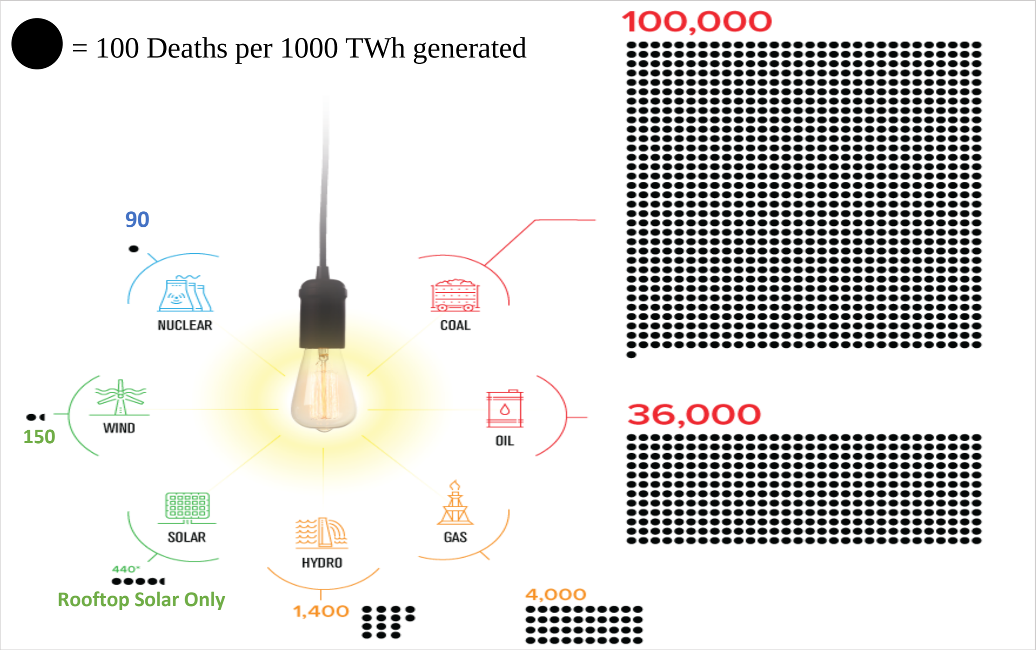


Figure 3.16 - ***Death per Energy Source*** *(Desjardins, 2018)*

Sub-Section Summary

The above sections show the improving market conditions, adoption and development rates for renewable energy. This leads to costs reducing and the added socio-economic benefits of safety. RE also helps alleviate the possibility of a financial spiral.

The following sections introduce and investigate solar and wind energy. Nuclear energy is acknowledged as a RE source, however, for this study, it is excluded, as a nuclear power plant cannot, with current technology, be integrated into a city in close proximity.

3.1.3.1 Solar Energy

The fossil energy industry post the industrial revolution is possibly most influenced by the RE technology of solar energy.

Solar energy, also referred to as Solar Power (SP), can be harnessed in various ways. The most prominent methods of SP capturing is via Photovoltaic (PV) solar panels or via thermal heat capture (EnergySage, 2016). SP is considered a limitless power source as the sun has millions of years of lifespan left. Compared to fossil fuels where the fuel reserves are rapidly depleting (Ritchie, 2017), the limiting factor in SP is the resources used to make the harnessing technology and not the ‘fuel’.

This study evaluates various solutions and integration methods of utilising solar energy. This research focuses only on the Solar PV approach and not the Concentrated Solar Power (CSP) systems, as the CSP system is on a larger macro scale that can supply more than one city. The CSP market is also not as exploited and growing in adoption as the PV market (Hariharan and Prasas, 2019).

3.1.3.1.1 Solar PV

Solar PV, the most used and promising form of SP on a residential, commercial and industrial level (Wamsted, 2019), became a viable source of energy in 1954 when it was developed by Bell Labs (EnergySage, 2016). Solar PV is made possible primarily by Silicon, an abundant material found in beach sand. The Silicon is formed in three forms, thin-film, mono-crystalline and polycrystalline, which often determine the type of solar panel and efficiency (The Renewable Energy Hub UK, 2020).The first-ever created solar cells were only 4% efficient at converting sunlight to electricity (EnergySage, 2016).

Solar PV is the third most utilised RE today after hydro and wind (Chowdhury *et al.*, 2020). This utilisation led to an increase in research and development, which allowed for an increase in the efficiency of Solar PV technologies. A wide variety of solar panels are available, but generally, most utilised solar panels have efficiency ratings ranging from 15-23%, with the company SunPower making the most efficient at 22.6% (Svarc, 2021). Solar panels are favoured due to their lifespan, which ranges around 25 years and upwards (Sunrun, 2020).

It is also noted that solar panels made from Perovskite and Cadmium telluride (Hariharan and Prasas, 2019) and not Silicon, have been growing in research in recent years. The perovskite panels are of great interest as the panel efficiency went from 3% to 25.2% in little over a year. Whereas Silicone-based panels took over 70 years to achieve a 23% efficiency range (NREL, 2020). More notably, however, is a recent (2020) lab-produced solar cell by NREL, which achieved a solar efficiency of 47.1% (Laboratory., 2020).

Hence, with the rate of development and improvement, solar PV shows great prospect of reaching economies of scale easier and allows room for constant improvement.

Typical solar setup

Solar panels generate a Direct Current (DC), which can feed directly into most batteries. However, for SP to be used in the larger grid and building network, it needs to be converted to Alternating Current (AC) (EnergySage, 2016). This conversion is the role of an inverter. This converted current can then flow through the electrical panel and into the grid at large. When a non-utility entity implements the setup it can typically be done via two setups, a hybrid or off-grid setup.

A hybrid setup involves still being connected to the national distribution grid from which electric utility units can be pulled. The hybrid solution is typical in situations where net metering is allowed. Net metering is when a building/entity can feed electricity units back into the national distribution grid and then be remunerated for those units. (CCT, 2018)

An off-grid solution is when the building/entity is entirely independent of the national distribution grid and would hence not have a connection point with the grid. This setup would require a form of energy storage integrated into the setup to allow for energy availability in periods when RE sources are temporarily unavailable. (CCT, 2018)

3.1.3.1.2 Solar market and solar costs:

The solar market for many years was thought to be an unrewarding venture, as conventional analysis often suggested that the grid stability would decay if more than 20% of the grid power came from solar and wind (Roberts, 2017). Roberts (2017) claims this led to the energy industry being convinced that RE sources could have no future role due to their variability. This limit percentage has been re-evaluated many times and pushed up and today, it sits at 60% (Roberts, 2017). This shows how the energy market has time and again underestimated the RE innovation trends.

In 2018, the Solar energy market was valued at 52.5 billion USD and extrapolated to reach 223.3 billion USD by 2026 (Hariharan and Prasas, 2019). This equates to a 20.5% Compounded Annual Growth (CAGR). South Africa is expected to only have a 10% CAGR from 2021-2026, even though the figures show a 37% capacity increase in 2020 (Mordor Intelligence, 2020a).

The advancements in solar efficiency led to solar system LCOE costs being in the range of 2.8 and 1.8 USD per watt for residential and commercial, respectively. Unsubsidised, these cost points allow for a

0.17 and 0.12 USD per kwh for residential and commercial, respectively (Fu *et al.*, 2017). Figure 3.17 shows the cost curves of the average costs of solar modules (Our World in Data, 2019b) and solar systems (Our World in Data, 2015; SEIA, 2020) with the US solar PV deployment rate (Our World in Data, 2019a).

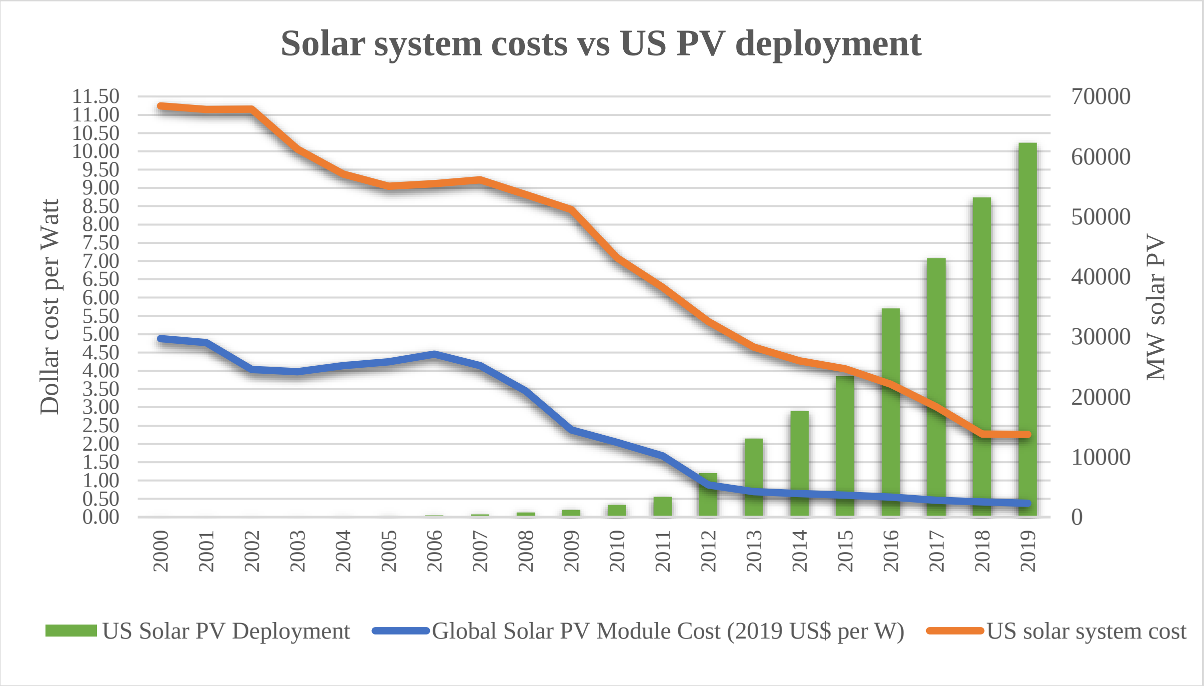


Figure 3.17 - ***Solar System Cost Curves and US Deployment*** *(Adapted from various sources)*

In the past two years, the local market has been growing, especially in the rooftop solar PV sector. The annual available market is expected to grow to 500 MWp installed annually (Pienaar *et al.*, 2020). Extrapolated to 2035 the total installed capacity could reach 7.5 GW, which is a 75 billion ZAR market.

Thus, the economic potential that could be generated from this industry is significant if the value chain can be integrated into future cities.

Solar Potential

The previous section shows the economic market potential of the solar PV industry. The next section shows the power potential.

Solar Potential can be divided into two parts. Lopez *et al.* (2012) first defined Resource Potential, which looks at the total solar resource available on a specified area, namely the amount of solar radiation falling on the area.

The second is technical potential, an area`s achievable power capacity considering only suitable land area for infrastructure. Areas such as protected areas, obstructing terrain features and difficult to reach areas are excluded from the area potential (Lopez *et al.*, 2012). Resource potential is measured using the Global Horizontal Irradiation (GHI), while technical potential is measured using the practical PV potential metric, defined as PVOUT (Lopez *et al.*, 2012). Figure 3.18 shows a collated depiction of the global GHI and PVOUT data.

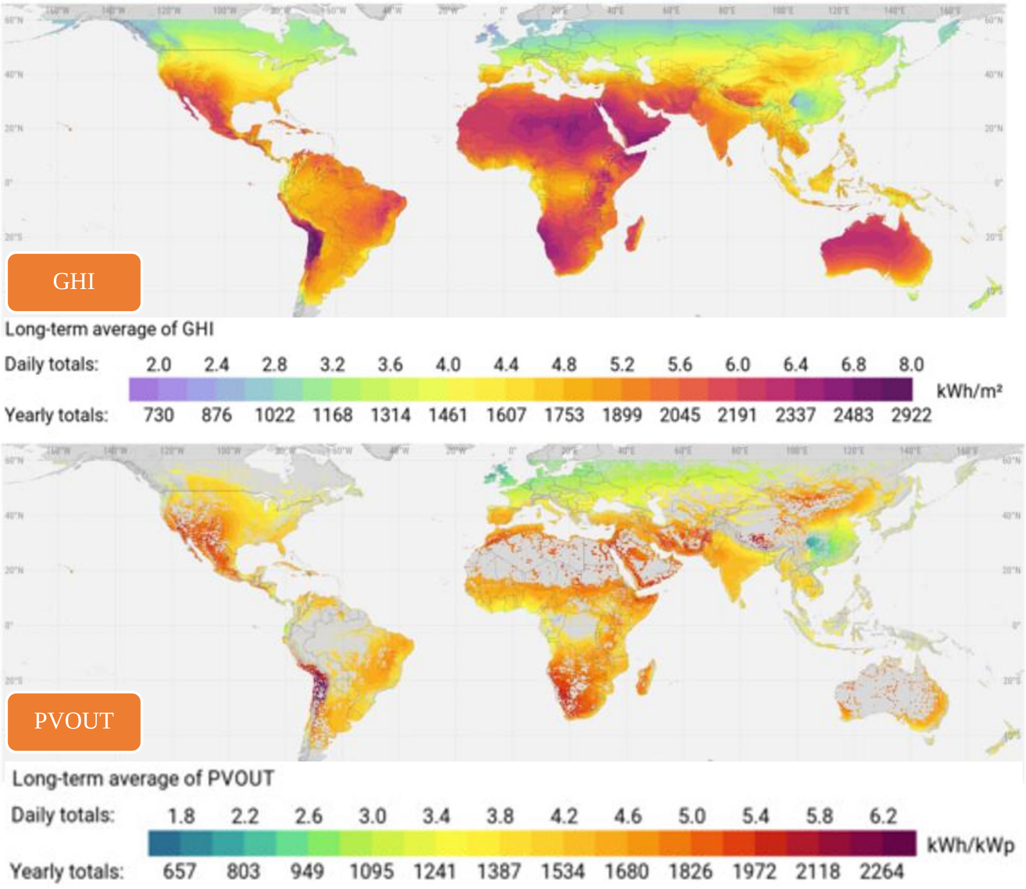


Figure 3.18 - ***GHI vs PVOUT*** *(World Bank, 2020)*

The Global Solar Atlas uses the GHI and PVOUT data to determine a ranking order of which countries could benefit most from solar PV. Namibia is a potential superpower being the country that has the most solar PV potential. South Africa is ranked 15th with a GHI in the range of 4.5 to 6.5 kWh per square metre in one day (World Bank, 2020).

To put it into perspective, assuming a solar panel is one square metre, three panels could supply enough energy for SA average per capita power use. The Department of Energy also highlights this, citing an annual 24-hour global solar radiation average of 220 Watts per square metre for SA. USA and Europe only records 150 and 100 Watts per square metre, respectively (SA Department of Energy, 2020). Figure 3.19, of the Visualcapitalist, shows the global solar potential combined, and it shows the magnitude of underutilisation of this RE source (Viens, 2019).

*Figure 3.19 - **Energy Generation Potential** (Viens, 2019)*

This study labels the top 18 countries on the power potential list as potential superpowers in the solar PV industry. Figure 3.20, on the left, shows from highest to lowest, the top 18 potential superpowers` share of electricity from solar and on the right, the 16 biggest solar share percentage countries other than those in the Top18.

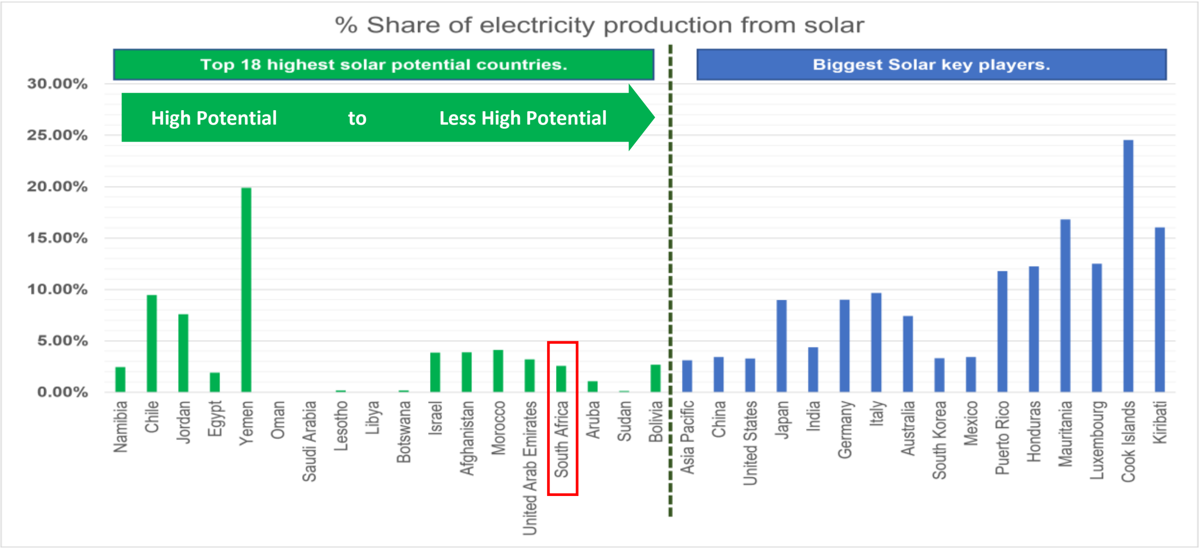


*Figure 3.20 - % **Share of Electricity Production from Solar for various Countries** (Author) (Adapted from EMBER, 2020; BP p.l.c., 2021; World Bank, 2020).*

Considering that electricity can be exported, one should consider the actual watts generated from solar as this would be the best utilisation of RE. Figure 3.21 shows the Terawatt hours of SP generated by each respective country.

Note how the so called solar "superpowers" barely reflect on the scale.

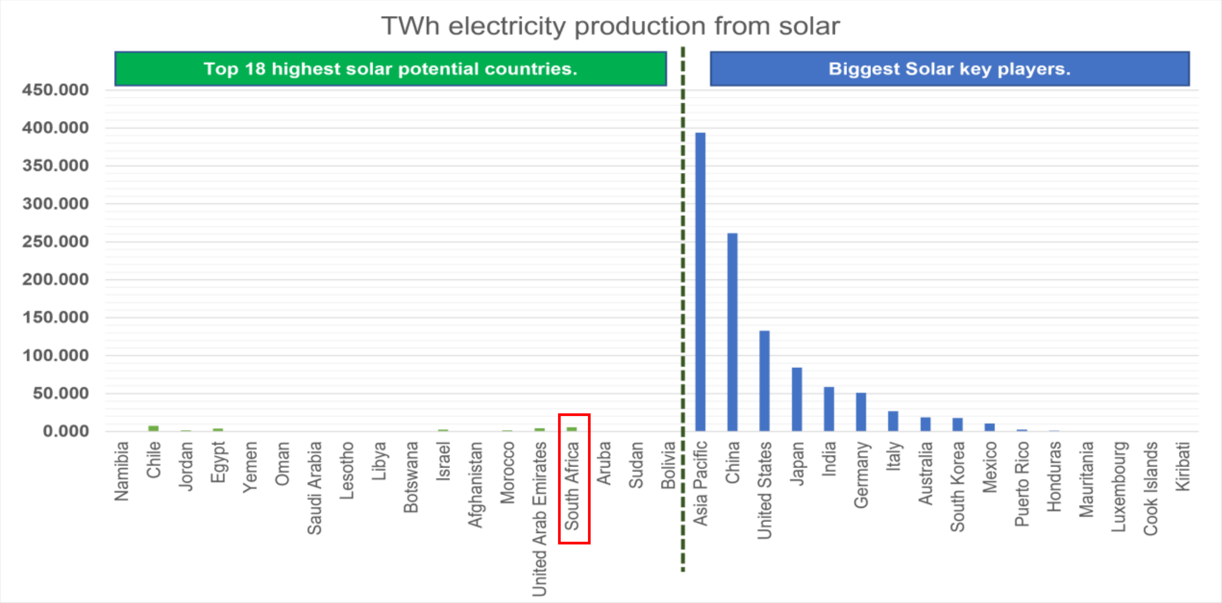


Figure 3.21 - ***TWh Electricity Production from Solar for various Countries*** *(Author) (Adapted from EMBER, 2020; BP p.l.c., 2021; World Bank, 2020)*

This study now evaluates the solar implementations utilised by these countries.

3.1.3.1.3 Solar Solutions

To show the rapid adoption that this industry can experience, the three largest solar farms are presented. The Noor Abu Dhabi in the UAE consists of 3.2 million solar panels and has a capacity of 1.17 GWp, which is enough to supply power to 90 000 people. The GHG emission reduction from this project is equivalent to taking 200 000 ICE vehicles out of the equation. (Pagliaro, 2019)

The Bhadla Solar Park in India came online in March of 2020 and has a capacity of 2.25 GWp (Murray, 2021). Finally, the Huanghe Hydropower Hainan Solar Park in China has a 2.2 GWp capacity. The plant also includes a 202.8 MW/MWh storage capacity (Murray, 2021) and will sell power to the grid at 0.75 ZAR per kWh (Bellini, 2020).

The SP industry, however, is not secluded to only large farms of solar panels. The industry has been developing various technologies and solutions to harness the power of solar PV while consuming less land.

Building Integrated PV (BIPV):

BIPV is one of the innovative solutions used to harness solar PV power, with a CAGR of 18.7% (PVsites, 2019). A BIPV system entails integrating solar PV panels into the envelope of the building (Natural Resources Canada, 2020). The panels are not exclusive to the roof, as one can also ingrate the panels into the building facade. This allows for more efficient surface area use, material cost, GHG emission and electricity costs reduction while being architecturally pleasing (Strong, 2016).

BIPV does not have to implement conventional solar panels as a solution. ClearVuePV is an innovative solution where the glass panes of a building can be dual purpose. The panes can have the purpose of conventional windows and at the same time can generate electricity. These PV glass panes operate in two major methods: having solar cells embedded throughout the pane (Vasiliev, Nur-E-Alam and Alameh, 2019) or having microparticles redirecting the UV rays to the edges of the panels where monocrystalline PV modules collect the photonic energy. (ClearVuePV, 2020)

A study from the University of Stavanger evaluated the economic feasibility of having a building facade envelope constructed from BIPV. The findings show that the project investment is wholly reimbursed and can even become a nett income generator (Gholami and Røstvik, 2020).

The BIPV system can become a nett generator since its discounted payback period (DPP) is less than that of traditional methods. BIPV can also be extended to smaller use-cases such as street lights.

Solar LED street lights:

Street lighting in cities is a vast network that is essential for both efficiency and security. City street lights consume on average 25-30% of the total energy spent in cities (Subramani *et al.*, 2019).

An innovative solution to the dated lighting network in cities is LED solar lights. These street lights can optionally run independent from the national power grid, meaning no trenching and cabling is required. The system incorporates onboard battery storage, which on average can run at nominal power for up to wto days. (Rubicon, 2021)

A study from Universitas Gadjah Mada, shows how replacing street lights with LEDs can save 78.4% of conventional street lights power consumption (Sudarmono *et al.*, 2018). Similarly, it is reported in the journal of Asian Architecture and Building Engineering how implementing a smart dimming feature onto the street lights could save a further 77% of lighting energy (Kim and Hwang, 2017).

Solar Roads:

Solar PV is often synonymous with taking up large swaths of space, especially when a single site solar farm is built. An innovation to mitigate this limitation of solar PV is solar roads. Solar roadways are constructed from decentralised, modular solar PV units (Northmore and Tighe, 2012).

Roadways in summertime absorb on average roughly 40 MJ per square metre of solar radiation (Zhou *et al.*, 2013). The Korea Institute of Construction Technology (KITC) evaluated the possibility of embedding solar cells into the roadway and harvesting solar energy. However, it was found that the thin film PV cells were prone to corrosion and wore due to the applied mechanical stresses and the environmental impact (A. Coutu *et al.*, 2020). After these findings, Waterloo University used a hardened, tempered glass solar panel to test its viability (Northmore and Tighe, 2012).

The first implementation of this solution was in the US by Solar Roadways Incorporated. Each of their hexagonal panels has an area of 0.37 square meters and generates 36 W at an 11.2% efficiency (Brusaw, 2012). Various implementations for test sites have started. A cycle lane spanning 70 meters generating 3 000 kWh over six months (A. Coutu *et al.*, 2020), a 1 km solar road in France and China, generating roughly 1 million kWh annually and a solar bikeway in the Netherlands which generates 70 kWh per square metre (McFadden, 2019).

The solar roadway solution, however, is in its early phase of development. Further R&D is required to overcome the problems obstructing its wide adoption. The test sites running as of 2012 and 2014 have shown that problems are found in panels being covered by waste, shade, and dust. The panels' output do not justify its cost, as the cost of WattWay`s panels proves at a 20 US dollar per kWh (Marquart, 2021). This innovative solution needs more development before it can be considered as a viable solution to urban development. The study, therefore, does not further consider this innovation as a solution as the current facts and data do not support it.

Sub-Section Summary

The limitless solar energy potential over fossil fuels is seen in the prior sections. The solutions are widely available made from abundant materials and have been increasing in adoption, efficiency and economic potential. While the costs are reducing due to increased development and the durable life span, variations of the technology are becoming more. Additionally, it is seen that sub-Saharan Africa has significant potential gain from this energy source but is not utilising it. The variations of this technology such as solar LED lights furthermore show the saving potential of this resource.

From the above literature, it is seen how solar PV presents great prospects in many forms. Wind energy discussed below, also presents a few different approaches.

3.1.3.2 Wind energy

Solar energy is being adopted faster than wind energy by the market, but wind power is nevertheless increasing in adoption. On- and offshore capacity increased by a factor of 75 from 1997 to 2018 (IRENA, 2019b).

Initially, wind turbines could generate 0.05 MW, but today capacities are registered of 2MW for onshore. Offshore wind power generation has a higher capacity ranging from 3 to 5 MW.(IRENA, 2019b)

3.1.3.2.1 Wind market and wind costs:

As of 2020, the wind energy market is valued at 6 948.6 Million US dollars. The market is expected to grow to 184.65 Billion US dollars by 2026, which amounts to a 10.37% CAGR (Market Research Future, 2021).

As with solar, the market drivers for wind power are linked to climate change and the depletion of fossil fuels. Figure 3.22 shows on the primary axis the LCOE costs of wind power for both on and off shore. The secondary axis shows the adoption of wind capacity globally.

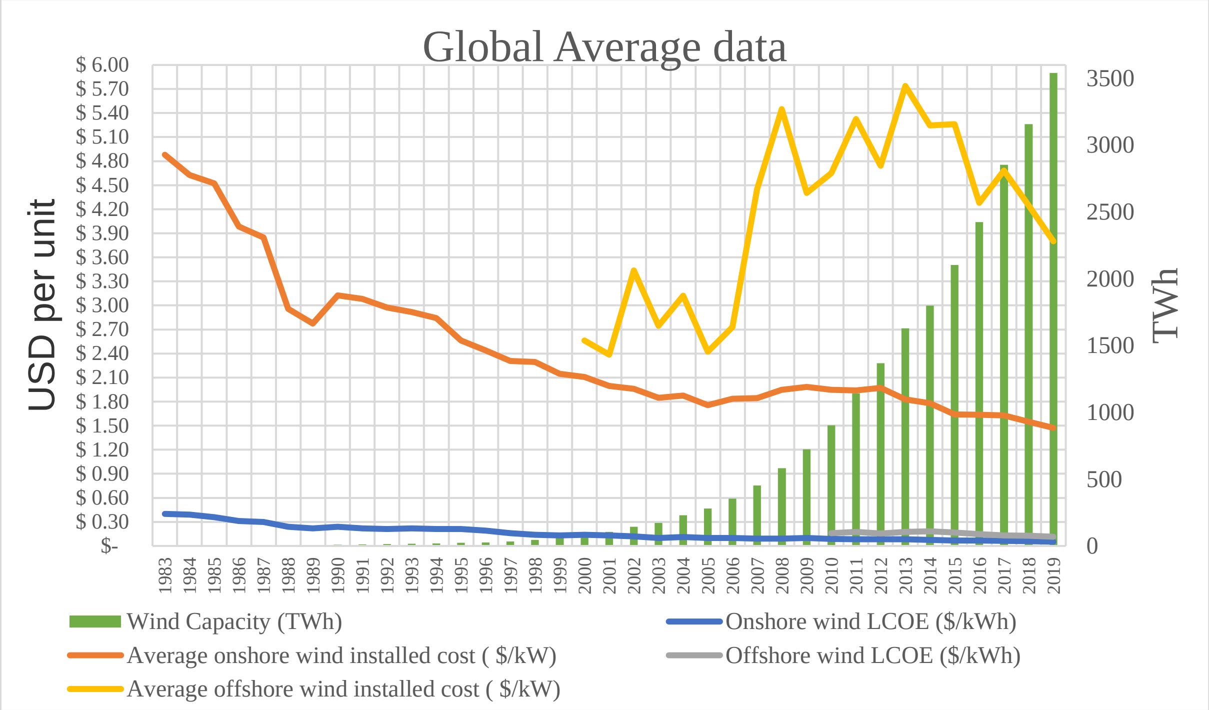


Figure 3.22 - ***Global Wind Power Cost and Capacity*** *(IRENA, 2019b; OWID, 2016)*

SA has the largest wind energy generation capacity in Africa, with 2.1GW operational as of 2019 (ESI Africa, 2019). SA`s wind energy market is expected to grow by a CAGR of 3% by 2025. The IEA expects SA to have a wind energy capacity of 81 TWh by 2040, however, the SA Integrated Resource Plan of 2019 only sets out a goal to install 1600 MW annually (Mordor Intelligence, 2020b). The REIPPP program of SA outlines a LCOE of 1.42 ZAR /kWh for the first bidding window of the program and a LCOE of 0.62 ZAR /kWh for the fourth (Sustainable Energy Africa, 2017). These values are estimated to be 40% of the cost of electricity at the newest Eskom coal plants, Medupi and Kusile (Sustainable Energy Africa, 2017). Chapter 4.3 shows how this value is much less.

3.1.3.2.2 Wind Potential

The Global Wind Atlas has a database that shows the data visually for the wind potential of the world and its various regions. Figure 3.23 shows the northern and southern hemisphere wind power potential at 150 metres altitude. The figure also shows the global potential of wind power compared to what is currently being used (Viens, 2019). The global potential for the 10% windiest areas amounts to an average of 1 582 Watts per square metre and an 11.36 m/s wind speed (World Bank Group, 2021).

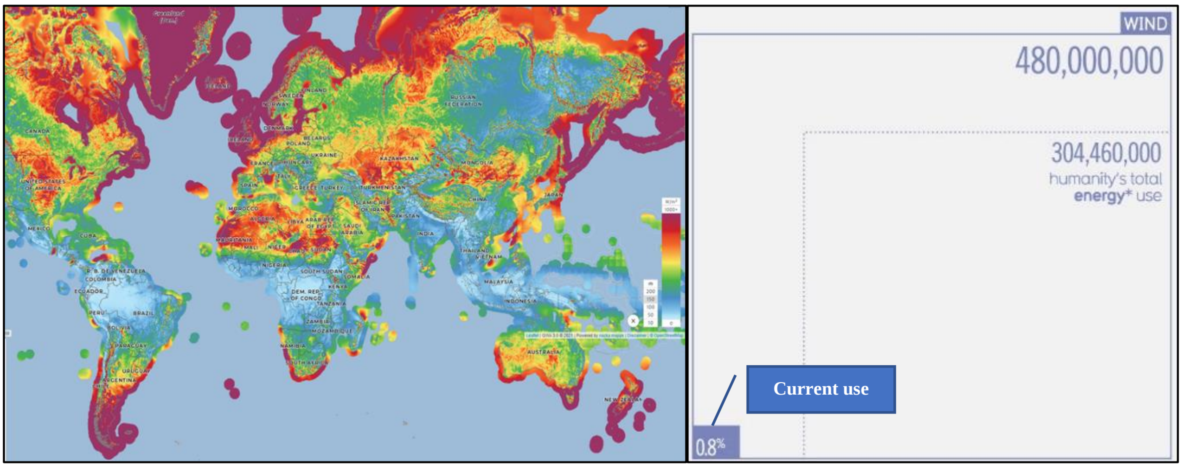


Figure 3.23 - ***Wind Power Potential vs Current Utilisation*** *- (World Bank Group, 2021)*

Onshore wind power has a higher potential to reach price parity with grid prices from a price perspective even though it might have a lower wind potential than offshore. This is because onshore infrastructure is cheaper than offshore due to the complexity of the design. Deloitte found that because of this, onshore wind has an unsubsidised LCOE of 30 to 60 USD per MW. With a global wind deployment of about 495 GW onshore, the leading countries are Canada, the UK and US, Germany, India, Brazil, Spain and France. (Motyka *et al.*, 2018)

Using the same "superpower" countries and top performers from the solar section, the wind data is added to the graphs as shown in Figure 3.24 and Figure 3.25. This illustrates again how the countries, which can most benefit from these technologies, are not utilising them.

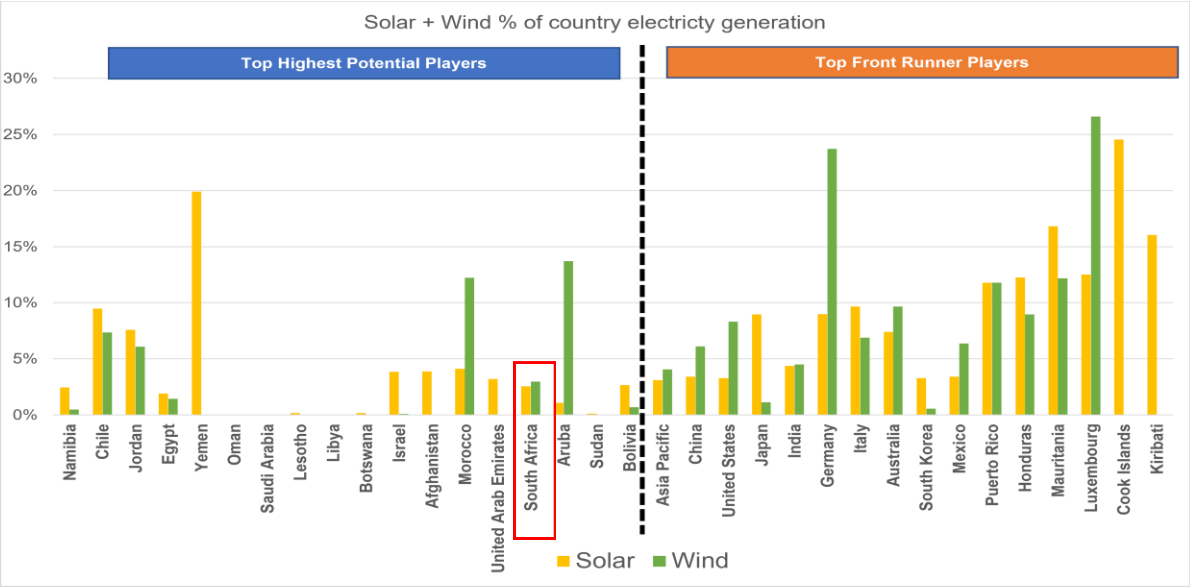


*Figure 3.24 -****Wind and Solar Generation share of Selected Countries.*** *(Author) (Adapted from EMBER, 2020; BP p.l.c., 2021; World Bank, 2020)*

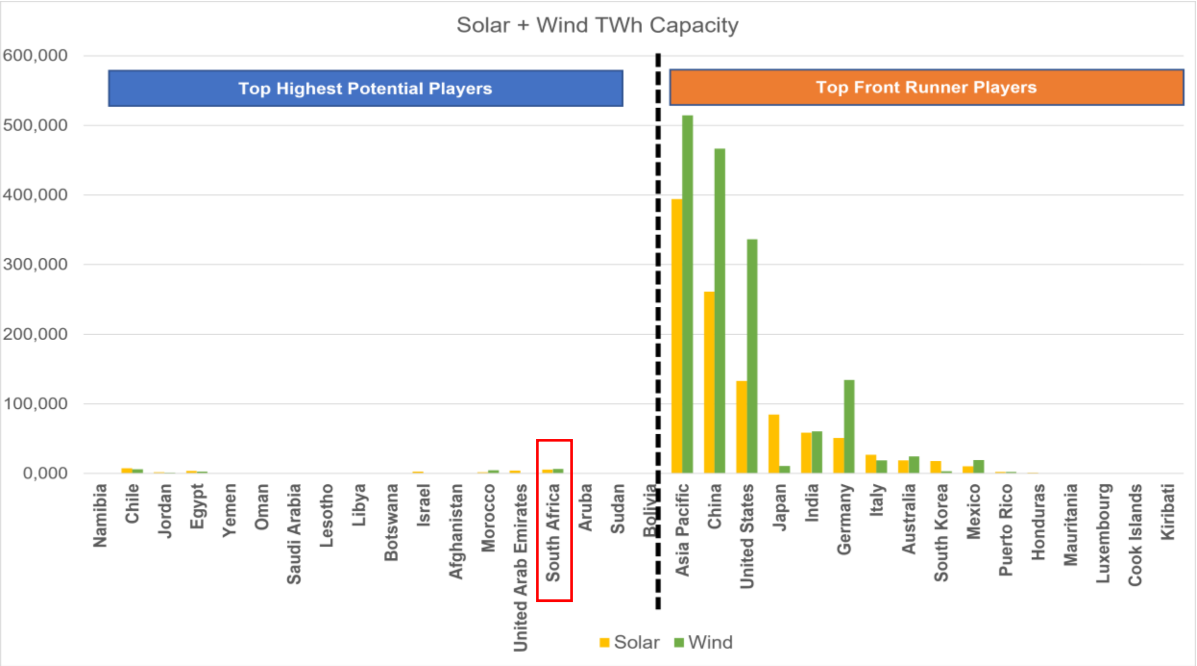


Figure 3.25 - ***Solar and Wind Generation TWh Capacity*** *(Author) (Adapted EMBER, 2020; BP p.l.c., 2021; World Bank, 2020)*

A study by the CSIR found that SA is exceptionally well situated to benefit from wind power. With appropriate turbine infrastructure, SA could reach economic viability of wind generation, as it would mean that 80% of the landmass is usable with a 30% load factor (Knorr *et al.*, 2016). Put into perspective, this would mean a wind farm with a capacity of 50GW supplying a 150 TWh annually, would take up 0.4% of SA landmass. This is equivalent to 67% of SA 2020 electricity consumption of 223 TWh (Our World Data, 2021).

Here follows one primary wind power generation technology utilised across the globe, as well as one new venture technology.

3.1.3.2.3 Wind Power solutions

As of August 2019, the biggest wind farm is the Dogger Bank, built on a drowned ice-age landmass and has a capacity of 46 080 MWh (Viens, 2019).

Put into perspective, the global average of people served on 1 MWh is 116 people, hence this farm would be enough for 6.7 million people.

SAWEA (2019) found the adoption of wind farms is more than solar, with 22 wind farms fully operational in South Africa. The two farms with the largest installed capacity of 140.3 MW, are the Khobab and Loeriesfontein two wind farms (SAWEA, 2019).

A recent study by the Stellenbosch University evaluated six sites for offshore wind farms. The results revealed how a deep water approach can provide eight times the electrical energy demand of SA (Rae and Erfort, 2020).

Hence the beneficial outcome of utilising wind energy generation is significant. However, the space usage of wind farms is not favoured. Below is an implementation that uses space for wind generation that would typically be underutilised otherwise.

Highway Turbines

The concept of harvesting wind power from traffic airflow was first patented in 2008. The concept involves placing a form of a wind turbine, usually with a vertical axis generation, in the middle or next to highway roads. The passing vehicles generate eddies and airflow currents that can turn these wind turbines and generate energy. (Chen, 2008)

The Malaysian government is the first to consider implementing this type of solution. A study from Malaysia estimates the energy lost from not harvesting moving traffic airflow at 1.2 Million Tons of Oil Equivalent (MTOE) annually (Saqr and Musa, 2011).

Put into perspective, 1 TOE amounts to 11.63 MWh, which would mean that this energy lost could have served over 120 000 peoples energy needs.

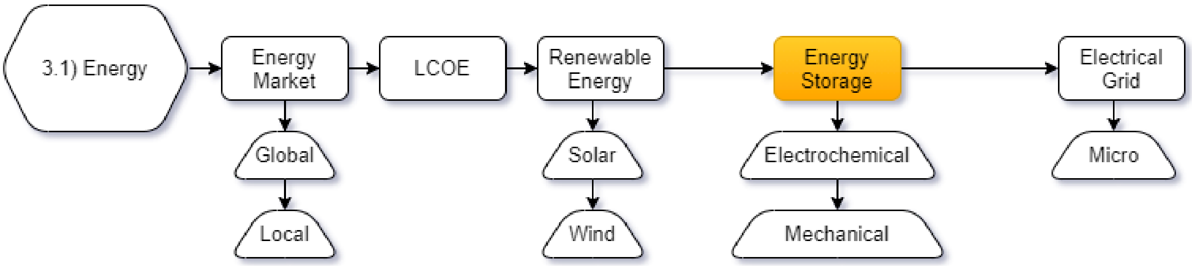
The implementation of this form of wind power generation is referred to as a Highway Vertical Axis Wind Turbine (HVAWT). The aforementioned study records an LCOE of 0.18 USD per kWh for HVAWT. The study found that the HVAWT system can generate 500MW/year, which is enough energy to power 1.7 million lamps, assuming a 300 Watt usage per lamp. (Saqr and Musa, 2011) If one considers LED street lights, this number changes to 6.9 million street lights, assuming a 73 Watts usage per light.

Sub-Section Summary

Therefore, the implementation of RE technologies such as wind and solar power present significant upside. Although solar energy is being adopted more than wind, wind still presents significant gains and varietal implementations. With the copious options available, there is a need for baseline standardisation required. The framework proposes some starting implementations in a city in section 3.2.2.

The section below discusses the mitigation technology to the most important limitation of RE.

3.1.4 Energy Storage



The most significant problem of RE is the intermittency of energy production. RE is synonymous with creating excess energy when not needed and sub-par when needed. This is because RE sources, especially solar energy, create most of their energy during the day and wind energy is highly variable (Motyka *et al.*, 2018). Figure 3.26 presents the demand curve line of South Africa's grid reduced to a similar scale and compared to California's solar- and wind energy supply curve in the USA. This shows how the grid would have to curtail the excess solar energy during the day, but then need it at night.

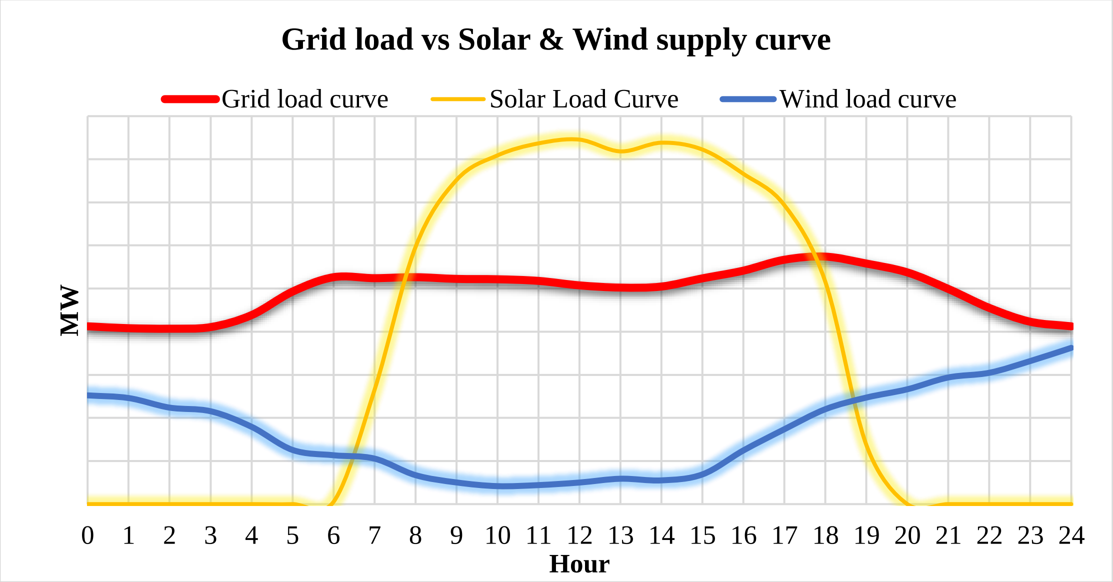


Figure 3.26 - ***Load and Supply Curve Comparison*** *(Adapted from various sources)*

Curtailment is a waste of valuable clean energy. In a review by MIT Technology news, the review shows how in April of 2020, 318 444 MWh were curtailed from the California RE supply (Temple, 2018). The solution brought to the fore by the state of California is found in infrastructure improvement and better capacity management. This leads to the next section of this research, storage.

The primary use case globally of utility energy storage is for frequency regulation, 49.7% of uses, and secondly for electric reserve supply, 9.4% use cases (Motyk *et al.*, 2018). Its other purposes include namely to alleviate the power shortage, improve grid flexibility, stimulate the economy and improve the safety of the power systems traditionally used (Järvelä and Valkealahti, 2017).

The need for energy storage is driven by modern society becoming more dependent on electrical driven solutions and technologies, both in the non-essential and essential part of surviving and living. Storage in the past was synonymous with being expensive and difficult to implement and hence today 90% of the worlds entire storage capacity is made up of pumped hydro (International Energy Agency, 2020). This research does not extensively cover pumped hydro as it does not match the scale of this concept.

To wholly understand the economic potential that can be gained from an energy storage industry, the energy storage market is presented.

3.1.4.1 Energy Storage Market

Energy storage is of concern to two major factions. The user side focusses on user revenue, and the grid side is focused on load levelling and alleviating load supply pressure (Chen *et al.*, 2018). This research focuses on the Behind the Meter (BTM) market and the Utility-scale implementation, front of meter (FOM). BTM is for all residential, commercial and industrial users who buy wholesale electricity from a utility. The utility would typically implement FOM storage for energy arbitrage, load levelling or frequency management (Henderson *et al.*, 2017).

Load levelling is a crucial challenge for RE, as the demand side is experiencing an increase from electric mobility and the supply side experiencing pressure from variable RE sources. As of 2020, 200 GWh of energy storage is implemented. The IEA states that an energy storage capacity of 10 000 GWh is required by 2040 for a sustainable development scenario (International Energy Agency, 2020).

It is, however, dependent on which analyst's report is used as to what the projected future of the energy storage market will be. Looking at the battery storage market energy report of Wood Mackenzie, it is seen how analysts have continuously had to increase their outlooks. In 2018, Wood Mackenzie projected the US energy FOM storage market at 2 535 MW by 2022. In 2019, it changed it to over 3 000 MW and now projects 7 830 MW by 2025 (Wood Machenzie, 2020).

Prescient and Strategic Intelligence cites the global 2019 energy storage market at 171 039.3 MW and projects a global CAGR of 3.3% (Prescient & Strategic Intelligence Private Limited, 2020). Despite these variances, most analysts conclude that the energy market is proliferating (Department of Energy, 2020). A report by the US energy department shows in Figure 3.27 how the energy storage market has and will grow, indicating a significant shift away from Pumped storage-hydro (PSH).

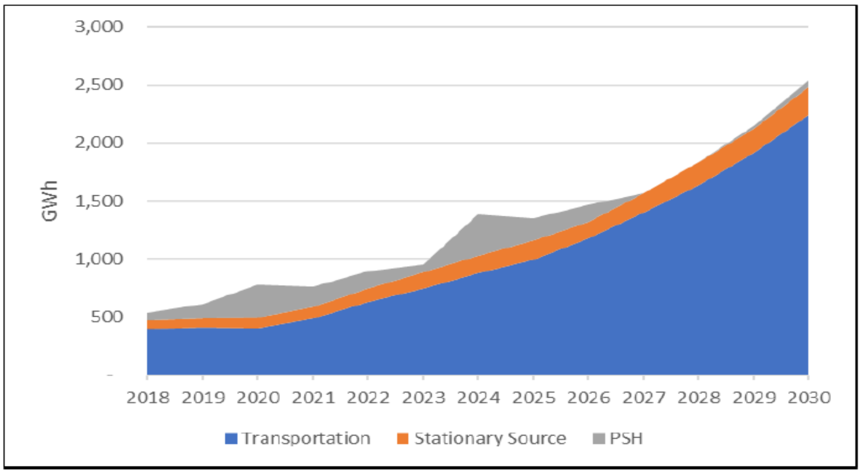


Figure 3.27 - ***Global Energy Storage Market*** *(Department of Energy, 2020)*

A wide array of energy storage technologies exist in the market, dominated in capacity by PSH (Department of Energy, 2020). Considering that in 2018 alone, 7 000 new patents were published relating to electrical storage (International Energy Agency, 2020), engineers and innovators have been devoting great effort towards developing electrical storage methods that are both commercially viable and sustainable.

Of the total International patent families (IPF), 88% is for electrochemical solutions, commonly referred to as batteries, and only 5% and 3% for thermal and mechanical solutions, respectively (International Energy Agency, 2020).

Sub-Section Summary

It can thus be seen that energy storage can improve the accessibility and usability of RE and reduce the dependency on pumped storage hydro. The market growth rate is significantly improving and focussing mainly on electrochemical solutions.

Two groups of electrical storage that apply to city infrastructure, electrochemical storage and mechanical storage, are be discussed below

3.1.4.2 Electrochemical Storage

Electrochemical storage, or batteries, is the favoured and most adopted solution for overcoming the hesitancy to implementing renewable energy. Batteries today are ubiquitous with any technology product such as phones or laptops; the Electric Vehicle market has evolved into a driving factor of the market as of recent. The utility-scale implementation of battery technology, referred to as stationary storage, is also busy experiencing disruption and mass-market adoption. (International Energy Agency, 2020)

Figure 3.28 shows the market analysis done by the IEA for use cases of electrochemical batteries.

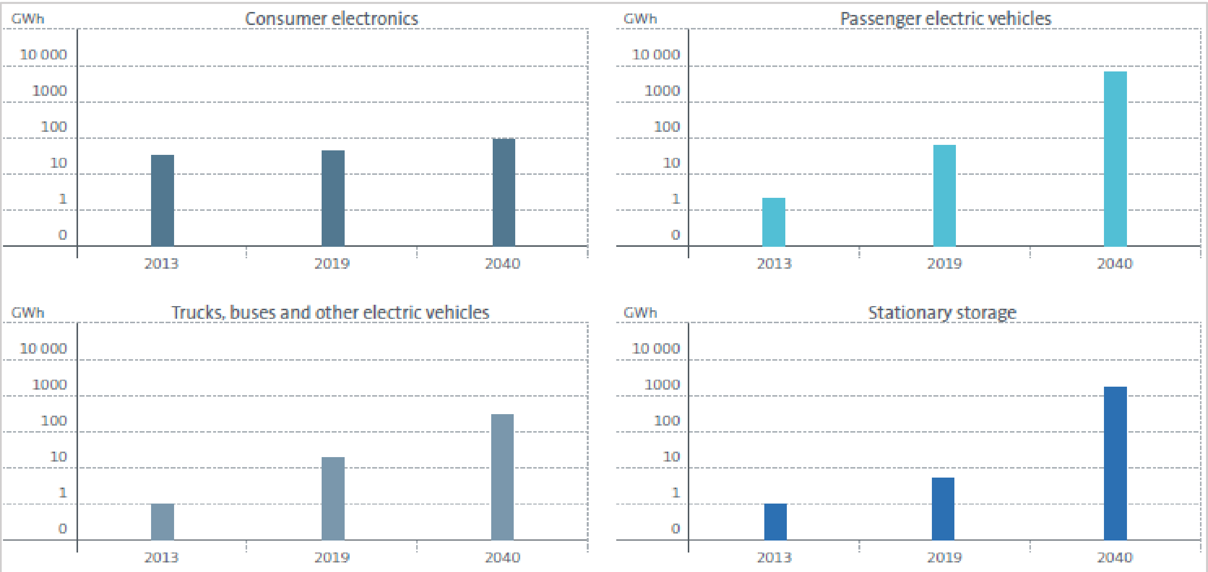


*Figure 3.28 - **Current and Future Demand for Batteries** (International Energy Agency, 2020)*

It is clear that the proliferation of electrochemical energy storage is founded in the passenger vehicle technology and stationary storage.

3.1.4.3 *Battery Market Drivers and Costs*

The market is expanding its research to not only improve and develop a specific battery type, but instead expanding to find various other chemical makeups. The rationale for this expanding scope of materials is focused on supply. Battery supply has become the limiting factor for industries, such as the EV industry (Korus, 2019).

The 2021, global semiconductor shortage (Sweney, 2021) showed the economic impact a shortage of a critical technology could have, and if urban settings are to adopt electrochemical storage on a mass scale, then various supply sources are required. Figure 3.29 shows the various battery technologies under development and its development phase and cost (Schmidt *et al.*, 2017).

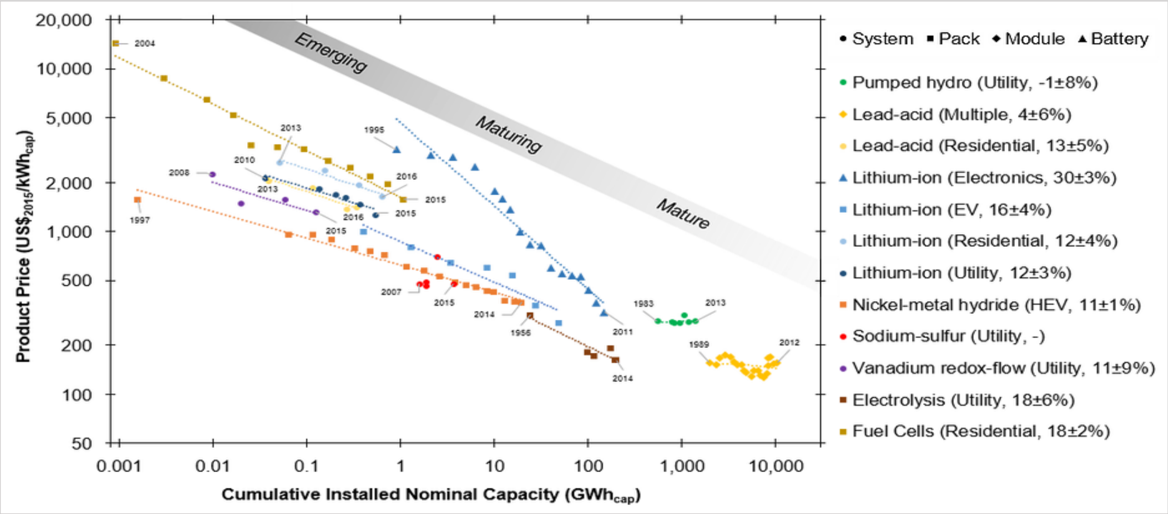


Figure 3.29 - ***Battery Technology Experience Curves***

In recent years, the market adoption rate of batteries is also less of a social dilemma with the improvements in recycling these devices (EPA, 2021). Globally there is a significant shift towards ESG driven companies that focus on sustainability and efficiency (O'Leary and Valdmanis, 2021).

Companies, such as American Mangenese, allow for the adoption of Li-ion (Lithium-ion) batteries to not have a less harmful environmental impact. They recover nearly 100% of the spent materials, which can then be used in new battery manufacturing (American Mangenese Inc., 2021). This creates a circular economy loop as alluded to earlier in this study.

Li-ion batteries, albeit the most prominent, are not the only technology available. The senior energy storage associate at BloombergNEF, Daixin Li, states that this is the cause of the wide range of battery prices (Henze, 2019). High capacity batteries are typically broken down to cell level and pack level; the battery pack typically account for 21% of the cost, and the remaining is for the cell level. This concept has recently been changed by the Battery Electric Vehicle (BEV) company, Tesla, which adopts a structural battery base that resembles one "pack".

In 2010, a Li-ion battery pack registered over 1 100 USD per kWh and since then, the price has reduced by 89% to 137 USD per kWh in 2020 (Henze, 2019). China reported a cost of 100 USD per kWh at pack level for their e-busses (Henze, 2019). A study done by MIT shows how storage could be viable at a price of 150 USD per kWh, if 5% of the grid demand is met by sources other than wind- and solar energy (Patel, 2019).

3.1.4.4 Battery Solutions

Batteries have various use cases and makeups that determine the required specifications of their operation. These different characteristics require the user to understand the specific application and prevent underutilisation, whether for power and density, the number of cycles for a lifetime, capital and operating costs or efficiency and response time (Amirante *et al.*, 2017).

This study takes advantage of the improving costs of energy storage by implementing it into the framework. Here follows some key energy storage solutions.

Li-ion Batteries:

Li-ion batteries are the dominating storage option accounting for 45% of International Patent Families (IPFs) in 2018, as it is the technology most implemented in portable electronics and e-mobility (International Energy Agency, 2020). Li-ion batteries are the name given, however, it comes in various forms where the cathode changes in material. Two common materials found in Li-ion batteries today are Cobalt and Manganese (Krivik and Baca, 2013).

South Africa holds roughly 75% of the worlds identified Manganese deposits (Ratshomo, 2013), indicating an attractive industry opportunity.

Li-ion batteries have various advantages which outweigh their disadvantages and hence the reason for their wide-scale commercial adoption. Li-ion batteries have an excellent power to energy density ratio (Krivik and Baca, 2013), which means that they can store and discharge their energy in an efficient and equal manner. Li-ion is a low maintenance, 99% charge efficiency, high energy density, and voltage battery with a comparatively low weight to other electrochemical batteries (Krivik and Baca, 2013). The disadvantages that are accepted by industry, is its relatively high cost, which is on a downward cost curve, its fragile degradation nature, its temperature output (Battery University, 2010) and its ability to form dendrites, which are small blocking crystal networks forming in the battery (He *et al.*, 2019).

The concern of the cost of Li-ion is decreasing. Figure 3.30 from BloombergNEF showing how the declining cost curve of Li-ion battery for both cell and pack level. A future development that could reduce this cost, even more, is what was announced by Tesla on its battery day in September of 2020. They stated that with various development upgrades in the entire value chain, the company can reduce battery cost up to 56% from the 2020 price tag (Tesla Inc, 2020).

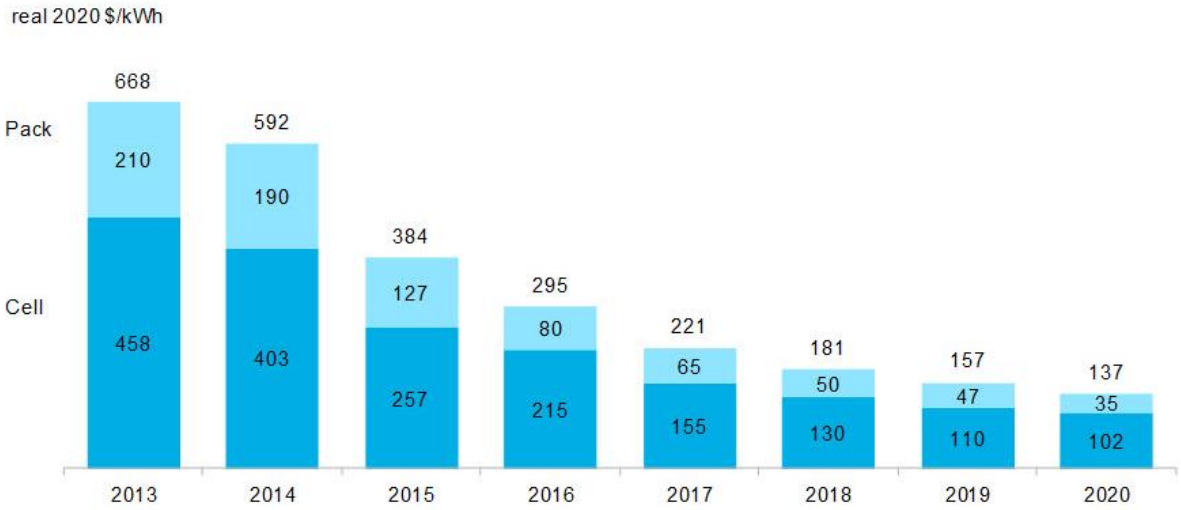


Figure 3.30 - ***Volume-weighted Average Pack and Cell Price Split*** *(Henze, 2019)*

This reduction would mean a 60.28 USD per kWh cost from the 2020 battery cost of 137 USD per kWh. This price reduction is mainly attributable to an overhaul in the manufacturing process, but also in adopting Lithium Iron Phosphate (LFP) battery technology for their heavy vehicle range.

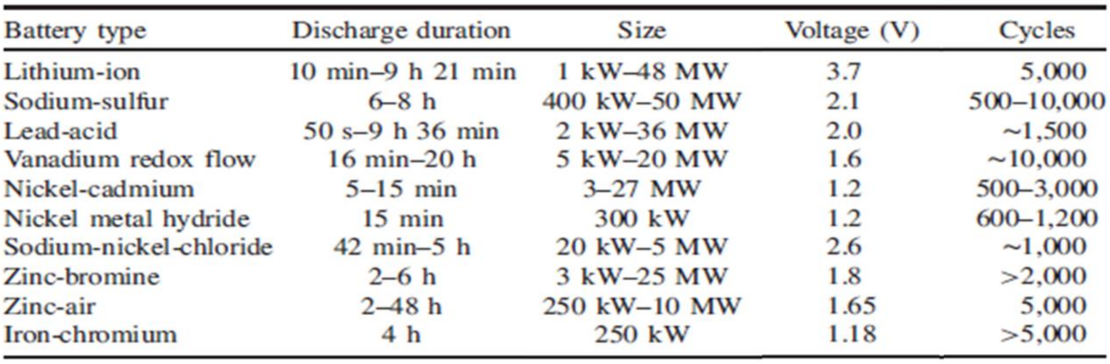
The other limitation of Li-ion batteries is their life span after a certain amount of degradation. A patent filed by Tesla in 2018 (Dahn *et al.*, 2018), protects a concept whereby the average current discharge cycles of a 1000 – 2000 is pushed to a point, where after 4000 cycles, only 10% of battery efficiency is lost. The batteries currently implemented by Tesla give a total useful mileage of 300 000 – 500 000 miles, and the average US car lifespan is only 150 000 miles. The battery lifespan can reach over a million miles with the new battery (Cohen, 2019).

Hence, this energy storage solution shows great promise for sustainable implementation with reducing cost curves, improving useful life and decreasing degradation.

Redox Flow Batteries (RFB):

NASA first developed Redox Flow Batteries in 1973 for their operations in space (VanadiumCorp, 2020). RFBs came under development again after 2006, when NASA`s patent expired. RFBs have a significant advantage over Li-ion batteries when the need for discharge time is discussed. As shown in Table 3.3, flow batteries have significantly longer discharge duration than traditional electrochemical batteries (Zhao *et al.*, 2020). Zinc-air, Zinc-bromine and Vanadium redox flow are examples of such flow batteries.

Table 3.3 - ***Battery Technology Main Characteristics*** *(Zhao, Thakur and Chen, 2020)*



Battery type	Discharge duration	Size	Voltage (V)	Cycles
Lithium-ion	10 min–9 h 21 min	1 kW–48 MW	3.7	5,000
Sodium-sulfur	6–8 h	400 kW–50 MW	2.1	500–10,000
Lead-acid	50 s–9 h 36 min	2 kW–36 MW	2.0	~1,500
Vanadium redox flow	16 min–20 h	5 kW–20 MW	1.6	~10,000
Nickel-cadmium	5–15 min	3–27 MW	1.2	500–3,000
Nickel metal hydride	15 min	300 kW	1.2	600–1,200
Sodium-nickel-chloride	42 min–5 h	20 kW–5 MW	2.6	~1,000
Zinc-bromine	2–6 h	3 kW–25 MW	1.8	>2,000
Zinc-air	2–48 h	250 kW–10 MW	1.65	5,000
Iron-chromium	4 h	250 kW	1.18	>5,000

The characteristic of discharge time plays a role in the implementation of storage as an energy storage backup to long periods of interruption to power or unavailable sources. Li-ion batteries are currently the most favoured choice of battery storage for utilities or large scale commercial applications. However, flow batteries are more equipped to handle long periods of blackouts or for night-time supply. (Amirante *et al.*, 2017)

The main advantage of RFBs, other than their minimal degradation and longer discharge times, is the detachment between power density and battery capacity (Amirante *et al.*, 2017). RFB batteries consist of two separate storage tanks containing electrolytes, and in the case of Vanadium flow batteries, the electrolyte is the same in both tanks. RFB batteries are not categorised as self-contained batteries, because the electrolyte storage tanks can simply be increased for more output potential. Vanadium flow batteries have a cost of 100 USD per kWh (Patel, 2019).

The main disadvantages of RFBs are, however, the high cost and low specific energy density. Additionally, the electrolytes used are either rare elements or highly toxic. The RFB market is experiencing a market proliferation on the long term storage side, seeing a market in 2018 valued at 130 million USD moving to a predicted 403 million USD by 2026, a CAGR of 15.2% (Yeware and Prasad, 2020).

To show the effect of constant innovation on the cost and capacity, the following research papers are presented. The University of California published a paper in April 2020 presenting a flow battery with an electrolyte made of iron sulfate, an inexpensive and plentiful waste product from mining, and Anthraquinone Disulfonic acid, which is already used in flow batteries today. The battery is organic and preliminary research shows it is half the price, 66 USD per kWh, of toxic Vanadium flow batteries. (Yang *et al.*, 2020)

Another Canadian company, Zinc8, is developing a flow battery with zinc-air, focussing on long term storage. Li-ion can, on average, hold around eight hours of capacity, where the zinc-air development claims to hold up to 100 hours. Zinc8 prices three options, an 8, 32 and 100-hour system with costs of

250, 100 and 60 USD per kWh, respectively. Zinc8 has a Levelised cost of storage (LCOS) of 180 USD per MWh for a 72-hour system, compared to a Li-ion solution of 600 USD per MWh. (Collins, 2020)

Hence Flow batteries are identified as a long-term energy storage solution for grid scale implementation with a favourable innovation improvement rate. Below is another energy storage source more commonly known for its fuel source alternative.

Fuel cell:

Fuel cell technology is the process of extracting the chemical potential from Hydrogen to generate electricity. This report focusses on the transportation, generation and storage use case of fuel cells. Fuel cells are different from conventional batteries in that they are not charged, and they do not lose capacity, unless the fuel source of Hydrogen depletes (US Department of Energy, 2020).

Hydrogen is, however, not as efficient as implementing Li-ion batteries, as fuel cells are only 35% efficient Nonetheless, Hydrogen has a high energy density which makes this limitation less impactful. (Department of Energy, 2020)

3.1.4.4.1 Electrochemical battery implementations:

In order to reach carbon zero or at least carbon neutrality, batteries need to be implemented at a city scale. Pumped hydro cannot fulfil this role as it requires an ideal geographical location, large infrastructure and extensive time frames to be built (Blakers *et al.*, 2021). Many scholars have investigated the economic viability, development and implementations methods of other energy storage solutions, such as electrochemical batteries that can supply power almost instantaneously.

Here follows some cases of battery implementations around the world with some key figures and information to show why utility scale storage is utilised.

The ideal use of batteries use has now been established to be for intermittent sources, such as solar- and wind energy. Hawaii is a case where battery storage is especially beneficial as 100% of its fossil fuels required for power generation are imported. Hawaii aims to be entirely dependent on clean energy sources by 2045. To reach this goal, the state has implemented a solar-plus-storage system on Kauai, consisting of 28 MW of solar energy capacity and 18 304 Li-ion battery modules. The solution provides enough discharge capacity for 4 hours, resulting in a saving of 14 million litres of fuel each year. (Hicks, 2020)

An impetus for the adoption of utility-scale storage is that of the implementation in Australia. Australia`s grid is restricted by its grid stability and flexibility, so much so that the one in 50-year storm in 2016/2017 caused a state-wide blackout, which resulted in rolling blackouts for an extended period after that (Gleeson, 2020).

After this critical failure, the South Australian government implemented the Hornsdale Power Project (HPR), which comprises of emergency generators, solar energy and a 100 MW discharge capacity energy storage system. The HPR system connects with a 300 MW Hornsdale wind farm. The HPR system has an overarching goal of mitigating future power failures through Fast Frequency Response (FFR); however, HPR is also a large scale feasibility test for the government.

Compared to the current six-second response time of the Frequency Control Ancillary Service (FCAS), the HPR system has a response time of 100 milliseconds (Aurecon, 2018). The FCAS savings of the system in 2019 amounted to 116 million AUD and an electricity cost saving of 150 million AUD. The French utility company owning this system is Neoen, and after the company IPO, the costs of this project was revealed, as shown in Table 3.4.

The estimate is that the HPR project saves about 90% of the grid service cost of South Australia (Lambert, 2018).

Table 3.4 - ***HPR Financials after six months of Operation****. (Adapted from Lambert, 2018)*

Financials after 6 months.	
Cost of Project	(US $ 66 million)
Grid Service Revenue	US $ 9.5 million
Energy Sales	US $ 7.9 million

Literature presents many other project case studies on the utility scale. Other notable projects are the Arizona Public Service (APS) project in Punlin Center, as well as the project of Sterling Municipal light department. The APS Punlin project was implemented after the utility found that upgrading the remote locations transmission line would cost more than a battery storage solution - more than double. The project implements a 2 MW discharge capacity or 8MWh storage capacity system. (Wamsted, 2019)

The Sterling project implements a 2MW/3.9 MWh battery storage solution and cost 2.5 million USD in 2016. The system aims to supply a 12-day supply for essential town operations, such as the police station and emergency dispatch centres. The solution saved 400 000 USD in year one and earned an additional 12 567 USD by selling power to the grid. (Wamsted, 2019)

Case studies, such as those evaluated in this research, show the promising prospect of the solar energy and storage pair. Large scale utility benefits have motivated smaller implementations to be tried by various sectors of the market. A study by NREL evaluated solar-plus-storage BTM implementations on commercial buildings and found that in more than half of the cities examined, a reduced utility cost was recorded. Some of these cases saw a cost reduction of up to 24%. (McLaren *et al.*, 2019)

Electrochemical storage solutions from literature show to be improving both in economies of scale and efficiency. Hence, it is experiencing an increased adoption.

Sub-Section Summary

It is seen that electrochemical energy storage is a crucial development and hence many variations exist with unique use cases. Li-ion and Iron Phosphate is the most adopted and developed. This led to price parity being achieved as its advantages outweigh its disadvantages. The increasing life cycles being developed furthermore improves its viability and affordability. Notably, South Africa could be a key player in the battery manufacturing industry as it holds a significant portion of a vital cathode material.

RFB batteries are seen to be advantageous for long term storage, but its high cost, rare and toxic electrolytes is a concern. Fuel Cells might have high energy potential, but its conversion efficiency is unfavourable.

A different energy storage solution that is showing promise is discussed below.

3.1.4.5 Mechanical storage

As previously mentioned in this document, energy storage can take many forms. With the recent global supply chain shortages found in various market sectors, energy storage forms other than electrochemical are being developed.

Mechanical storage is a system that harnesses the kinetic motion of physical objects and pressure to generate and store electricity. The research previously cited concerned how pumped hydro is the most implemented storage technology to date. PHS is a mechanical storage system. However, this study does not implement it in the design for reasons provided in previous sections. A mechanical storage system that is evaluated in this study, is compressed air storage as it is implementable within city boundaries.

Compressed air Energy Storage (CAES):

Compressed air energy storage (CAES) is a process whereby natural and man-made cavities are used to the advantage of storing energy. CAES is typically and most affordably implemented in large underground cavities, similar to the storage of Hydrogen in a salt cavern. CAES involves storing compressed air, compressed with excess energy supply, in large airtight voids/containers. The pressure can be released on demand for high demand energy requirements (Amirante *et al.*, 2017).

CAES is only viable for the stationary storage market. The BloombergNEF storage data hub cites four US facilities and three global facilities that implement CAES. The US in 2011 deployed a 300 MWh system in Texas and NREL estimates the US CAES potential to be at 121 GW (BloombergNEF, 2020). However, even though the US is the market leader in this space, the only successful plant in operation is the 110 MW Alabama plant built in 1991. There are plants in Ohio, Iowa and California that have been placed on hold, due to the reservoir not being adequate, due to leaks and due to uneconomical results (Department of Energy, 2020).

From the literature evaluated, the success of CAES depends on finding an underground cavity that is appropriate. For this reason, this energy storage technology is not proposed in this research framework, as it would mean that this framework can only be implemented in areas where these perfect cavities are found, which is not the aim of this research.

Gravity storage:

A mechanical storage system that does not entirely have the limitation of area-specific use, is that of gravity storage. Gravity storage involves hoisting a single or a multitude of large objects when the electricity supply is in excess and then releasing it to turn a dynamo to generate energy during high demand.

The first gravity storage method uses buoyancy forces. This method has some geographical specific limitation, and it involves raising a considerable weight, usually a cylindrical stone, using buoyancy. During excess supply, water is pumped under the weighted unit to float it, and when the energy demand is high, the unit is dropped, forcing the water back into the pump pipe connected to a turbine. (Moore, 2021)

The disadvantage of this system is similar to the CAES approach as the cavity in which the weighted unit is floated requires a non-porous wall to prevent the water from seeping away. Opposed to using buoyancy, this singular weighted unit can also be connected to a pulley system. Instead of using water to lift the weight, it can be lifted by a pulley connected to a generator (Gravitricity, 2021b).

The advantage of this approach eliminates to some extent the limitation of floating the weight, as the cavity walls need not be non-porous but just stable. This system can also be implemented in old abandoned mine shafts, gorges and cliff sides. This method, however, is still somewhat geographically constrained, to avoid excavating deep cavities into the ground.

New Energy Let's Go PTY Ltd. and Gravity Power are two companies that develop a floating energy storage system as described above (Moore, 2021). Due to water scarcity, however, these floating solutions are not explored further as it requires a significant amount of water to float these weighted units. A solution that is explored is that of the company Gravatricity.

Gravitricity configures a singular weight of up to 12 000 tonnes in a deep shaft which is hoisted up and down by multiple high tensile cables. The company focusses initially on old decommissioned mine shafts in areas such as South Africa and claims that each unit can be configured for an output of 1-20 MW peak power and a duration of 15min to 8 hours. Some key features of the system include a 50-year design life, a one second response time, 80-90% efficiency and a simple construction design. (Gravitricity, 2021a)

The company requested an independent cost analysis of the system from the Imperial College London Consultants, upon which the study found the system to have an LCOE of 171 USD per MWh in 2018 (Schmidt, 2018; Gravitricity, 2021a). As of 2021, the company only has a test site working and multiple projects in the development phase. The test rig is set up in Edinburgh and has a 50 tons combo weight hoisted up to 15 metres. The company states on its website that it will have a full-scale project in 2021 with a discharge capacity of 4MW (Gravitricity, 2021b).

A solution that removes the need for deep cavities to be found or excavated, Energy Vault proposes an above-ground gravity solution. The fundamental idea of Energy Vault`s solution is similar to that of Gravitricty, however, instead of implementing a singular unit weight, this solution implements multiple 35-ton composite blocks. These blocks are stacked via a combo crane system in a tower formation, which is picked up and hoisted down individually by an automated system during high demand periods. The system can discharge 4-8 MW of power over an 8-16 hour period (Energy Vault, 2021).The company has demonstrated these claims in their Commercial Demonstration Unit in Switzerland. The test system can store up to 35 MWh of power (Energy Vault, 2020).

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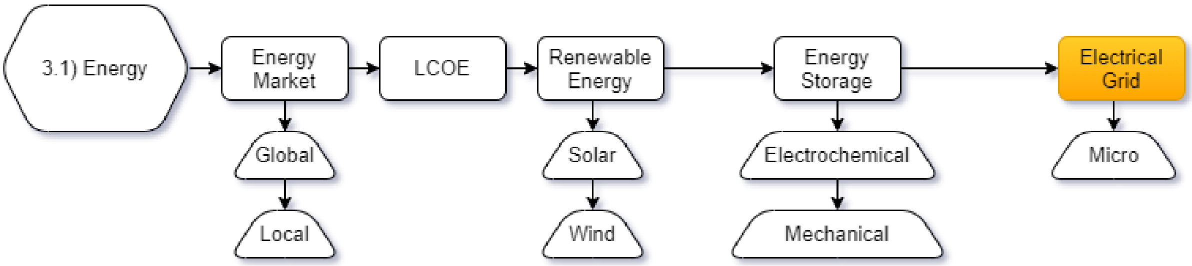
Hence, mechanical storage shows good prospect for an alternative form of energy storage that does not involve chemicals. Albeit that CAES is not the most appropriate for this framework, the pulley gravity system is favourable. The system shows good signs of reaching cost parity and is a secure and low technology solution which improves its accessibility.

This research proposes that by employing multiple of these energy storage technologies and utilisation of RE technologies, a city can improve its energy security. The section that follows looks at the method of integrating RE and storage technologies on a city scale.

3.1.5 Electrical Grid Structure



Integrating these RE solutions and battery storage systems requires a flexible, robust and efficient grid network. The electric grid is not only a generation and transmission system. The grid is a synergistic network with various shareholders, systems and government officials that create a complex ecosystem.

With a modern urban environment reliant on an inefficient and dated grid network developed over 50 years ago, the electricity grid is not on par with innovation (Martin *et al.*, 2017). This ecosystem is being pushed to do things that were not initially intended for it (Office of Electricity, 2020). The need for grid modernisation is mainly being taken up by developed countries, especially after recent storm events, which left many countries vulnerable. These countries typically initially launch smart technologies into the existing grid to determine the current situation and the best course of action forward.

An explanation of a modern city grid and how various solutions investigated in this document form part of the grid is necessary.

3.1.5.1 Grid Synergistics:

The modern grid has to be able to facilitate various use-cases of the energy market, from charging electric vehicles (EVs), supplying heating and cooling devices with power, keeping the lights on, and to ensure communication services are running. The grid was initially intended to deliver electricity for lamps only, but the industrial revolution changed this drastically. Today, almost everything is dependent on electrical energy. To provide for this high energy demand, RE and storage need to be integrated into the grid. The section that follows investigates how this integration can be done.

Renewable Energy and storage Integration:

A study by Deloitte shows how the grid modernisation efforts run coherently with battery storage growth (Motyk *et al*., 2018). Grid-connected Energy Storage Systems (ESS) typically have only one purpose, to time-shift load and generation. However, ESS in a modern grid is also used for RE integration, customer energy management and general ancillary services (Järvelä and Valkealahti, 2017). With the rapid falling of costs of solar-storage solutions, there is a growing demand for the prosumer case.

The prosumer case allows the BTM user to return excess electricity back into the grid, which is then credited against the users' bill. In some countries such as the USA and part of Europe, users can generate a nett income from this approach. The city of Cape Town, as of 2021, allow users to connect in nett metering in a hybrid manner to the grid but legislates that the user must be a net consumer (CCT, 2018).

The problem created by allowing so many feedback entry points into the grid is keeping the grid levelled and at equilibrium. Traditionally, a grid has multiple base power plants and load-following power plants, ensuring that a load levelled grid is achieved at all times. However, the inclusion of intermittent power sources, such as RE, without energy storage, typically requires more peaker power plants to be constructed to ensure grid equilibrium with supply and demand (Järvelä and Valkealahti, 2017).

Conventionally gas peaker plants are used for load levelling and FCAS, but today batteries are proving to be a much more efficient and a long-term sustainable solution. An analysis by investing analyst group, Ark-invest, shows in Figure 3.31 how batteries will become cost-comparative with gas peaker plants. The group initially made a future forecast of when battery storage reaches 150 USD per kWh (Korus, 2019), but as Henze (2019) has shown, that point has already been reached. The risk, however, is how to manage these various energy storage systems to either charge or discharge to keep the grid stable. According to the literature (Aurecon, 2018), batteries can respond on short notice as a peaker plant would, but these systems can also autonomously level the grid.

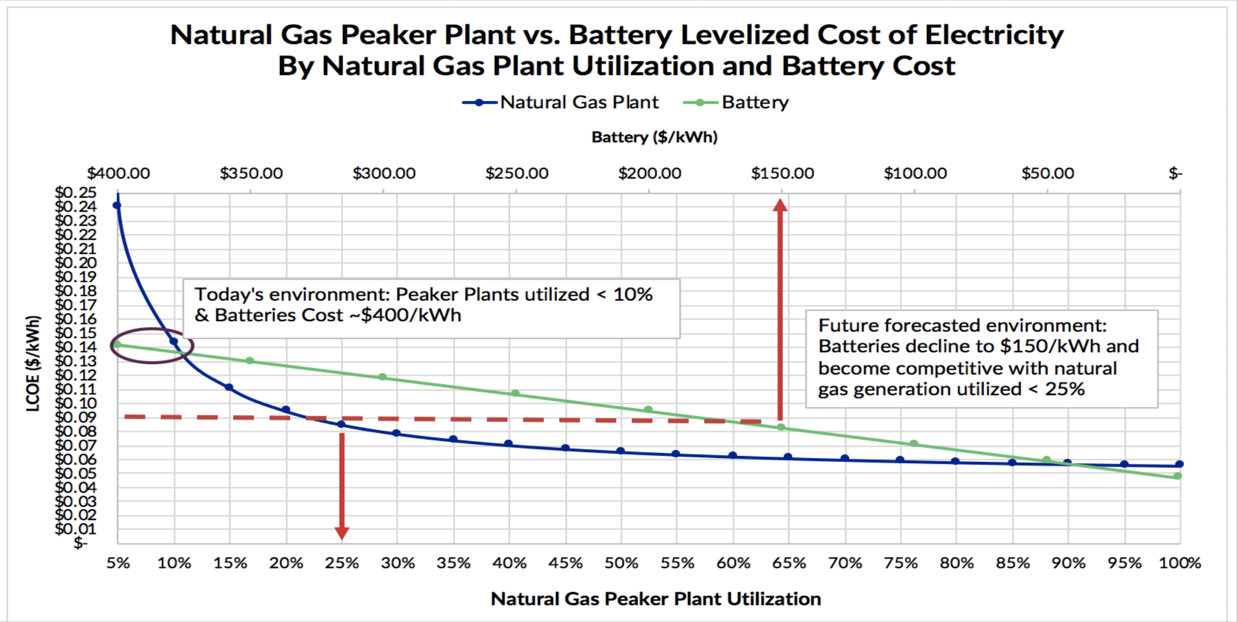


Figure 3.31 - ***Ark-invest Gas Peaker vs Battery Storage Analysis***

With the advent of IoT technologies and AI systems, innovative software systems have been developed to manage grid levelling. An example of this is a system developed by Tesla called the Autobidder. The Autobidder system leverages machine learning, predictive analytics and automated market operations to provide the most efficient system and best revenue return (De Villier, 2020).

In their study on grid modernisation, Deloitte states that prosumer participation, predictive maintenance and self-healing infrastructure is observed when the grid is digitised (Motyk *et al.*, 2018).

Grid infrastructure:

Modernising a grid using smart technologies only, is not a sustainable solution if the grid infrastructure is ageing and failing. From an interview (Electrical Products Chief, 2021), it was clear that a significant obstacle for charging network expansion is the dated grid. The interviewee highlighted that in a case, such as SA, where the distribution grid is vastly dated and aged, if mass expansion of an EV charging network had to come online, it would put too much strain on the already strained national grid and hence cause failures. Africa has a 43% reliable electricity connection rate (Trace, 2020). This ageing grid problem is made worse by the local (South African) load-shedding. During power outages, cable theft rises, which further breaks down the distribution grid. Cable theft costs the South African economy 5 to 7 billion ZAR annually (Western Cape Government, 2019a).

Italy was one of the first entities to re-evaluate the approach to improving its dated grid infrastructure. The company in charge of managing the grid, Terna, identified the best course of action to alleviate grid congestion is not the traditional way of expanding transmission lines and upgrades. Terna, in 2015, commissioned a 245 MWh renewable energy storage system that holds daily energy until the grid capacity for transmission becomes available. (Motyk *et al.*, 2018)

The incipient results of grid modernisation are being realised by those who have implemented new strategies early on. For example, since 2012, 4.8 million interruptions have been avoided since ComEd implemented its Energy Infrastructure Modernization Act in the US (Henderson *et al.*, 2017).

3.1.5.2 Micro-grid:

One solution to modernising the grid infrastructure, which incorporates the solution of implementing battery storage, is micro-grids. Micro-grids are not a new phenomenon and have been implemented for many years on university campuses, critical infrastructure and military sites, industrial sites and even remote farms or test facilities (Henderson *et al.*, 2017). The physical attributes of the grid are drastically changed by the micro-grids approach, however, the resiliency and reliability it brings are beneficial (Henderson *et al.*, 2017).

The micro-grid is a result of the significant development of inverter-based technologies and improved energy-efficient products. This solution does increase the demand for a robust grid control system, but this is a problem that is being alleviated by the advancements in machine learning and AI (Siemens Switzerland Ltd, 2020).

As depicted in Figure 3.32, micro-grids have their own generative and distributive capacity that can run entirely independent or in tandem with the national grid. The main advantage of a micro-grid is that in the event of a grid failure, the micro-grid area can sustain energy until the solution is fixed, or other micro-grids can feed energy into the grid to sustain energy until large scale facilities are brought back online (Cortese, 2018).

Figure 3.32 – ***Micro-grid Depiction*** (Cortese, 2018)

The traditional grid was structured to run as a unified singular network of power distribution, however, as climate change worsened and storms became more prevalent and destructive, the grid had to adapt (Henderson *et al.*, 2017). Interconnected grids simplistically explained are a multitude of smaller grids and microgrids working together. If one route fails, then power can flow into the area from an alternate route (The UN, 2006).

An example of the advantage of having an interconnected grid was shown in 2021 in the USA. When one of the coldest storms in history hit the state of Texas, the power grid failed due to various reasons, initially blamed on RE sources, such as wind turbines freezing up. However, the situation could have been avoided, if a micro-grid structure or even a more interconnected grid was employed. (Mehtra, 2021)

Texas grid is entirely independent of other states, meaning that when the grid failed in certain parts, the other states could not reroute power to the crippled state, as no transmission links were available. This independent grid is run by the Electric Reliability Council of Texas (ERCOT) and this method of having one unified, independent grid is how locally Eskom also operates. (Mehtra, 2021)

Micro-grids are considered the best course of action to reduce power disturbance costs to an economy. EPRI states that micro-grids will drastically reduce 100 billion USD cost of power outages of the US. In 2003, the US and Canada experienced a power outage in various states that lasted four days. The final report on the event calculated that the societal cost is around 10 billion USD per blackout event. (National Energy Technology Laboratory, 2007)

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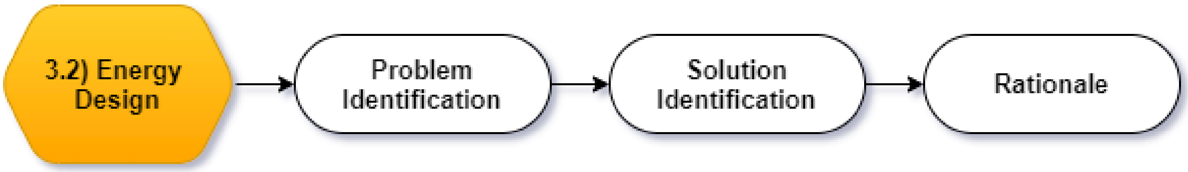
It can thus be seen that the need for a flexible decentralised grid is crucial. Grid modernisation and energy storage run parallel, and the development of load levelling technology makes the adoption of energy storage easier. It is also seen that the aging grid infrastructure can be improved through microgrids which provide reliable energy infrastructure with redundancy built in. The urgency for South Africa to adopt an interconnected grid solution is also seen as it risks the same scenario of the Texas grid failure.

Considering the literature sections discussed, the next sub-section presents the identified problems and solutions to the energy network of a city. The most prevalent identification is the effect of the energy industry on the climate, but also the significant market opportunity that can be gained from this industry.

3.2 Energy Design



The literature referred to in Section 3.1 shows the situation of the global energy demand and supply. Moreover, it presents the significant role of the energy sector in climate change. Energy is identified as the foundation of any economy, and any energy related risk is an inherent risk to global economic security and prosperity.

3.2.1 Energy Problems

Table 3.5 summarises the problems identified in Section 3.1 through the research of the energy market within the built environment. A reference is added to show the section in the document from which the problem was identified.

*Table 3.5 - **Energy Problem Identification***

Key Problem	Intricacies
Energy generation pollution *(Section 3.1)*	Many cities still rely on utilities that use fossil fuels to supply the electrical supply. Using energy generated from fossil fuels contributes to climate change and thus increases the city's carbon footprint. Furthermore, it decreases the air quality of the city, which decreases the population health and liveability.
Unreliable and high-risk energy supply. *(Section 3.1.1)*	The energy supply is heavily dependent on fossil fuels, which do not allow for an innocuous supply. The energy supply is also at risk in some areas, as one plant or entity usually supplies a significant supply. In the same context, the way renewable energy is currently utilised is also a problem. By not utilising energy storage with RE, it allows for an unreliable energy supply.
Fossil fuel *(Section 3.1.1)*	The two problems mentioned above already identify two significant risks relating to fossil fuels. Another problem is the decreasing reserves measured in the global supply of these fuels. The risk resulting from this means that countries need to import these fuels from other countries. Thus, in the event of international tensions, the country is at risk of not receiving a vital resource. This places the economy at large at risk and also civil stability. Moreover, buying fossil fuels from other countries means more money leaves the country, which could have been spent elsewhere in the local economy.
Ageing Infrastructure *(Section 3.1.5)*	The energy grid at large is ageing and is not flexible enough to adapt or grow with the increasing energy demand. The ageing infrastructure leads to power outages and cost overruns due to increased maintenance demand. A risk identified is that the grid cannot accommodate modern technology, which could hamper growth and stability. The adoption of EVs is identified as a significant risk factor to the security of an ageing grid infrastructure.
Monopolised industry *(Section 3.1.5)*	Albeit in a few, some areas have a monopolised utility or transmission network. This creates a problem where dependency for energy security is placed on a single entity. The problem with this setup is that the monopoly owning entity can increase prices for profiteering or hold entities hostage.
Not sustainable *(Section 3.1.2)*	Current methods of generation and distribution are not sustainable, if no change is made. With coal power plants becoming unprofitable and uncompetitive, it is a problem when these plants are not closed and remodelled. By not having a sustainable system, the problem is that a point of no return can be achieved.

Energy Sprawl *(Section 3.1.5)*	With the increasing population, more demand is generated. However, some cities have not planned for this expansion. This leads to haphazard and temporary fixings, which creates inefficient energy infrastructure sprawl. Moreover, this can also lead to energy poverty, whereby residents on the outskirts do not have reliable electrical connections.
Unsafe generation *(Section 3.1.3)*	The literature presented the hazardous nature of current primary utilised generation sources.
Slow implementation renewable energy *(Section 3.1.1)*	Albeit that some countries are heavily approaching RE, this study finds it not being implemented fast enough. The literature cites various sources that identify the risk of further increasing average global temperatures. The problem for adoption in some areas is that production is constrained, and in other areas, it is the governments' reluctance to adopt.
Cell constrained *(Section 3.1.4.2)*	The utility-scale storage implementation rate is currently cell constrained. This is due to high demand and low manufacturing capabilities.

3.2.2 *Proposed Energy Solutions*

This section presents a proposed framework from which cities can start reaching sustainable and secure energy infrastructure. This framework should be the essential start to any design on which more expansion can be built for case-specific scenarios. Figure 3.33 shows the logical structure of the proposals discussed below. It includes three components for efficient energy generation and supply: Solar, Wind and Storage.

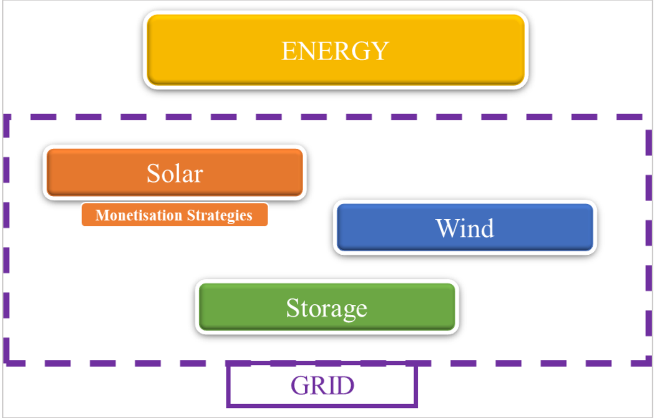


*Figure 3.33 - **Energy Solutions utilisation flow** (Author)*

Before conceptualising the exact infrastructure, the generation mix share is set out. Urban grids should strive for 100% renewable energy sources, however, realistically, there needs to be room for growth. Hence a maximum limit of 10% is advised for fossil fuel-related energy sources, to match the top performing G20 country – France (Section 3.1.2). This mainly forms part of emergency backup power, when peaker plants are required when the energy storage systems cannot discharge enough energy.

Furthermore, the framework has a goal to be completely self-sufficient on its integrated power generation, whether it be city-owned or utility-owned. In SA, where the energy sector is not yet wholly privatised, the city either runs independent from the national grid or steps into an agreement to connect the city in a hybrid setup. This hybrid connection is elaborated upon more in the micro-grid design section.

There are several options that can be considered for a city to ensure the security and flexibility of energy. There is no single solution for solving the energy crisis. Instead, it is a synergistic approach that will be the best fit.

Below are the solution options proposed in this framework that involves solar energy.

3.2.2.1 General Solar Energy Implementation:

The literature shows the potential of solar energy and the decreasing cost structure. Hence, this framework requires a heavy solar energy implementation. The setup requires the entire city to adopt hybrid connections for all properties. This way, the city has a vast array of energy sources available at its disposal. Furthermore, the solution allows net metering, allowing the user to sell power to the city as per a pre-determined monetisation strategy, which follows the guides set out in section 0.

Table 3.6 sets out the critical solar energy implementations for the framework. Furthermore, Figure 3.34 shows a 3D model of the city with location implementations of these systems.

Table 3.6 - ***Future City Solar Energy Design Implementations***

Solar Energy Proposals	Description
Building Roof-mounted *(Section 3.1.3.1.1)*	Solar panels are mounted to the roof of a set building with the option of integrating it into a native (BTM) storage system. This is implemented on commercial, industrial and residential buildings with large roof surface areas. These units would not be placed on sky-rises, such as an office block tower, as this would not be the best use-case of that space. Instead, ideal use is determined to be for warehouses, stadiums and public transport stations.
Shade Roof-mounted *(Section 3.1.3.1.1)*	Solar shade roofs implement solar panels that make up the roof of shade-providing structures. The city and private entities implement it. Where two-dimensional above-ground parking areas exist, the shaded bays have roofing made from solar panels. Where public park and walkway shading infrastructure is built, these roofs are mounted with solar panels.
Solar Roofs *(Section 3.1.3.1.3)*	Instead of traditional roof tiles, solar roof tiles are utilised. The use-case is mainly for low-density residential units.
Solar Facades (BIPV) *(Section 3.1.3.1.3)*	All high-rise buildings are required to be built with either in-pane solar glass or in-frame solar glass. All office, residential, commercial and industrial properties, where the façade gets more than three hours of sun, are required to implement BIPV. Regulations would allow ordinary glass to be installed in cases where a shade study reveals inadequate solar coverage.
Solar Street Lights *(Section 3.1.3.1.3)*	All lights within the city are solar LED lights and implement onboard storage capabilities for up to two days. The main use-case for these are public parks, above-ground roads and traffic lights
Solar Farm *(Section 3.1.3.1.1)*	A solar farm is a demarcated location with a field array of solar PV panels or a CSP plant array. If the renewable energy sources within the city boundary are not sufficient, then a solar farm can be considered in close proximity. Moreover, the solar farm can be placed on large water bodies or wide water channels.

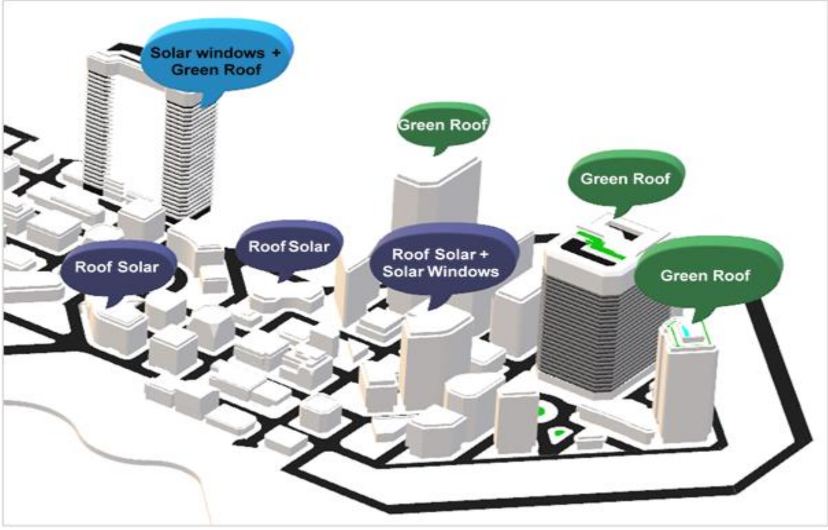


Figure 3.34 - ***Future City Roof Utilisation*** *(Author)*

3.2.2.2 Monetisation Strategy for General solar energy implementation:

Regarding monetisation strategy for general solar energy implementation, thus far, policymakers and governments have been restrictive to adopt the facilitation of solar energy implementation, as the dependency on energy revenue is significant (Janisch *et al.*, 2012).However, as the literature has shown (Section 3.1.2), the death spiral of users and revenue loss leave these entities in a worse position if no change is adopted.

Cities need to share in the capital with private and public parties, as all these entities benefit from the success of a city. Hence, this study proposes the key monetisation strategies below to allow the municipalities and government to remain stakeholders and generate appropriate revenue.

1. Self-Funded project:
    a. This strategy entails the property owner paying for the solar energy system in its entirety. The user is allowed to distribute the power generated throughout the property as they so deem fit. The user is allowed to sell excess power to the grid at an agreed-upon rate under the following conditions:
        i. Only if and when then the city grid requires additional power.
2. Partially funded by the city:
    a. This strategy entails the city contributing to the setup in an agreed-upon share. For example, suppose the city pays 40% of the system, then the following will apply:
        i. The city owns 40% of the power generated. Hence, if 10 kWh are generated, 4 kWh are fed into the grid at no charge to the city. However, if the user uses all 10 kWh, their bill will be charged with 4 kWh of energy.

3. Grid fee:
    a. Whichever party owns and manages the grid infrastructure will be owed a monthly grid connection fee, irrespective of the type of connection.
        i. If the entity is off-grid, then a yearly inspection is to be done by the city to ensure safety standards are continuously met – at the owner's cost.

3.2.2.3 Low-Income Solar Scheme.

Some governments have energy providing subsidies towards low-income users. For example, in South Africa, low-income users receive a subsidy every month ranging from anything between 50 – 100 kWh (South African Government, 2020). The proposed alternative is only plausible in this city setup, because it is built from the ground up. Because low-income housing is incorporated into the city design, these units could be equipped with solar panels fully funded by the city. Depending on the case, a 1kW-battery-inverter can be included as well. Instead of receiving 50-100 kWh units a month, these users can be allowed to use the system's energy at no cost. Any additional energy generated by the system can be pushed back into the grid and be at the city's disposal. Energy used when the system does not provide, such as at night, will be charged as per usual on their energy bill. This agreement should only be valid for as long as the system is intact on the property.

To account for water heaters using significant power and being utilised most of the time at night, installing a synapse should be required. A synapse lowers the wattage of the heating element, heating the unit over a more extended period. This way, the water heater can draw from the 1kW-storage unit at night.

3.2.2.4 Wind

The wind energy proposal in this framework is fairly limited due to size and operating method of wind turbines. Bladeless wind turbines have been investigated and can be implemented within the city boundaries, but the technology is still in its infancy and hence not yet considered an option. However, this framework is flexible and can incorporate this bladeless technology if its viability and economies of scale change. Hence, it is mentioned in this report. Table 3.7 presents the proposed options of wind technologies in this framework.

*Table 3.7 - **Future City Wind Energy Implementations***

Wind Proposals	Description
Roadway middle divider turbines *(Section 3.1.3.2.3)*	Vertical axis turbines are placed on the middle island dividers on highways. This is also done in tunnels where 2-way tunnels are implemented. Freight lines are identified to benefit significantly from this technology as these vehicles generate significant air currents.
Wind Farm *(Section 3.1.3.2.3)*	A wind farm is demarcated with a field array of wind turbines. This option is only considered if the renewable energy sources within the city boundary are not sufficient.

3.2.2.5 *Energy Storage and Grid infrastructure*

For the future city to be carbon neutral and self-sufficient on renewable energy while still protecting the climate, it needs a robust energy storage system. This research investigated the advantages of storage extending to FCAS and security. This framework proposes storage implementations as set out in Table 3.8.

Table 3.8 - ***Future City Energy Storage Implementations***

Storage Proposals	Description
Li-ion batteries BTM *(Section 3.1.4.2)*	Li-ion batteries are incentivised to be implemented by property owners. These units charge from on-property solar panels during excess supply and provide the property during low supply. Alternatively, the unit can also be charged from the grid supply. If the city grid requires power, these units can discharge into the grid and be compensated for the power. Residential, commercial and industrial buildings implement this. The ideal scenario identified is for warehouses and shops with cold storage to implement this technology, as cold storage draws significant power. Excess power can also be transferred to the city`s FOM storage units.
Li-ion batteries FOM *(Section 3.1.4.2)*	Large batteries are implemented by the city or any other private party, which provide a demarcated area with backup power. This would mainly be implemented by the city, IPP or grid management bodies. The goal is to have semi-decentralised batteries that can supply areas with backup power. An ideal use case identified is for each neighbourhood to have a battery backup system.
Redox Flow Batteries *(Section 3.1.4.2)*	Flow batteries operate in the same manner as the Li-ion FOM systems. However, they are used for scenarios of extended power outages, maintenance or climate crisis`. On the other hand, Redox Flow batteries use up more space and have toxic materials. Hence, it is only used as an extreme emergency solution until technology improves.
Gravity storage *(Section 3.1.4.5)*	The systems utilised are single weight and multiple weight pulley systems that raise and release weights to generate power. Multiple weight systems are placed on the city's outskirts, and single weighted units are in strategic positions or abandoned mine shafts nearby. These units are used in conjunction with the Li-ion and Redox solutions.

The literature evaluated, showed the synergy of energy storage with a robust distribution network. Moreover, the importance of grid robustness was emphasised in the interviews conducted (Electrical Products Chief, 2021). From the case evaluation of storm interruptions (Section 3.1.5.2) caused in various parts such as Australia and Texas of the USA, this framework presents a grid network that can adapt to innovations and adopt new technologies while being secure and reliant. The compounding factor of this flexible grid is found in micrograms of various sizes, as set out in Table 3.9. These microgrids are all hybrid connections that can feed and draw from each other.

Table 3.9 - ***Future City Grid Implementations***

Grid Proposals	Description
City Micro-grid *(Section 3.1.5.2)*	The entire city is a unified grid that consists of multiple smaller microgrids. If one had to consider multiple future cities, each city would be considered a micro-grid interconnected by the national grid. This grid has the option of implementing storage. Interconnected to the sub-micro-grids, the city grid has various service microgrids that ensure city services reliability.
Services-Micro-grid *(Section 3.1.5.2)*	A service micro-grid is a grid that represents various service chains/areas within the city.

Sector Sub-Micro-grid *(Section 3.1.5.2)*	A sector grid is a grid that encloses the ripple sector as defined in the layout section.
Area Micro-grid *(Section 3.1.5.2)*	Area micro-grids are the smallest micro-grids that can be implemented for emergency services such as police stations, hospitals and public transport. These microgrids can also be implemented in gated communities or industrial parks.

3.2.3 Rationale for Energy Proposals

This research investigated and identified problems within the energy setup of a city, and from the investigation, a baseline framework of implementations was presented. The energy framework design presented is an essential sector due to its synergistic relationship with the other sectors.

The energy framework presented would in 2019 be pushing boundaries. However, in 2021 it is now seen as a plausible way to create an efficient and cost-effective energy solution, according to the literature many countries have started to consider these features. The driver for choosing these implementations is due to climate change. Fossil fuels are known for releasing excessive GHG emissions. As the literature showed (Allen *et al.*, 2018), an increase of 1.5 °C in anthropogenic temperatures will lead to severe escalation of the climatic problems and the energy sector is a prominent role player to this.

The literature furthermore showed (Section 3.1.1) how oil and coal projections are attenuating and incorrect valuations cause a financial bubble. This is engrossed in how capacity factors have skewed the LCOE of coal-generated energy. Therefore, the framework adopts significant RE implementation as this ensures carbon neutrality and allows for an easier reach of a nett carbon effect where more GHG emissions are removed than produced.

3.2.3.1 Solar and Wind

Solar- and wind energy are focused on for their unlimited fuel source characteristic and decreasing cost curves. The technology is under rapid development and has room for improving efficiency. Moreover, the literature identified *(Section 3.1.3)* that RE is safer than conventional energy sources, protecting a valuable resource - humans. Various studies show RE's economic benefit, primarily due to its low operating costs and long useful life *(Section 3.1.3)*. Furthermore, RE is easier and quicker to implement, contributing to the ROI of these systems.

Roof-mounted solar panels are proposed, as cities take up significant surface area, but thus far, city area use has been utilised for a single purpose – it should be multi-functional. With a vertical integration approach, the vast underutilised roof space can be utilised. This framework outlines that any roof without solar PV panels or a solar geyser collecting radiant sunlight, should be carbon taxed for not implementing solar energy technologies. Because this framework presents a city built from the ground up, the added benefit is realised of building tiled roofs with solar tiles.

These *solar tiles* would typically be considered a premium product due to the cost of overhauling existing roof structures. However, these costs are reduced when the solar tiles are implemented from the start.

Another implementation to benefit from the ground-up construction process is solar windows. The attractive CAGR of *BIPV* created by the vast surface area available for utilisation is why solar glass is implemented in the framework. Making BIPV a building standard can ensure that property carbon footprint is reduced while benefiting from the implementation.

On the ground level, city lights cover a significant portion of space not utilised by buildings, and with a 25-30% city energy consumption rate, *solar LED city lights* are proposed. This framework changes the shareholder structure to benefit the city user, more so in a socio-economic factor of safety. Ensuring citizen safety while reducing energy costs and impacts to the environment makes this a salient implementation.

Moreover, *roadway wind turbines* are placed on the roadway dividers, which see a significant amount of energy going to waste due to not harvesting the airflow currents. Hence, wind turbines are placed within these traffic flow air current to harness this otherwise lost energy potential.

3.2.3.2 Energy Storage

The nascent utility-scale energy storage is allowing the primary risk of RE to be mitigated. With storage, RE intermittency is alleviated and designed for. Furthermore, storage ensures that a RE heavy generation share can be reliable and flexible. The Li-ion industry advancements are the impetus for the adoption, improvement, and development of energy storage.

Li-ion is the primary source of chemical energy storage proposed due to its modularity, efficiency, life cycles, cost curve and innovative market, which will continuously improve the technology. Li-ion is furthermore accessible to everyone and relatively easy to implement BTM (Section 3.1.4.2). Moreover, the FOM use case system allows for minimal landmass usage and optimal emergency response times.

Technologies, such as *Redox flow and gravity storage* ensure that the risk is shared amongst technologies and ensures a competitive environment. Redox flow batteries (Section 3.1.4.4) mitigate and allow for more extended discharge periods than Li-ion. Gravity based storage (Section 3.1.4.5) allows for cheaper investment costs, fewer chemicals to be used and less complex technology ensuring non-exclusion. *Fuel cells* are not implemented as a utility-scale storage system due to their inefficiency of 35%. Nor is CAES implemented due to its geographical specificness.

3.2.3.3 Grid

RE and energy storage need to work in a synergistic environment, which is in the form of *micro-grids*. The Texas shutdown showed the crippling effect of a grid that does not utilise micro-grids. Hence, this framework proposes a global city grid that consists of multiple sub-microgrids to allow for redundancy, energy security, adaptation flexibility and ease of maintenance. The first set of sub-microgrids is for the city services. These run independently to ensure the constant and efficient operation of the city.

Moreover, these micro-grids can be fed energy from other interconnected grids in emergency cases. All other sub-microgrids have energy storage incorporated into the system. A visual representation of what the grid structure looks like is shown in the layout design section of this paper.

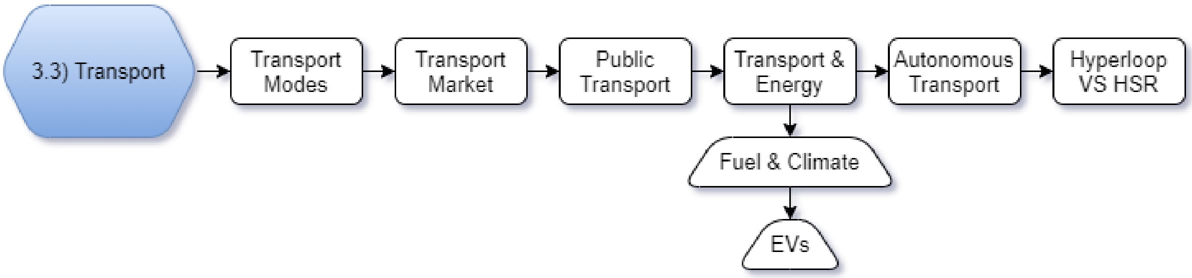
Microgrids also allow for easier monetisation of net metering and creates a favourable revenue model for the city. Each micro-grid acts as its own ledger in which records are kept, similar to blockchain technology. Allowing users to feed into the micro-grid grid storage systems ensures a charge cap, so the city does not purchase more energy than it requires, while easily keeping track of in- and outflows. Allowing users to feed back into the grid provides for FCAS, load levelling and emergency power. Additionally, it creates the opportunity for wealth sharing amongst citizens.

Many countries, especially South Africa, are living in energy poverty. With the increasing population, technology and urbanisation, cities will need to provide more energy faster and more efficiently. Energy is the foundation of the economy and the successful operation of cities. At the same time, these cities need to provide this energy supply in environmentally friendly and sustainable ways or else humanity's future is jeopardised.

With the advent of RE technology becoming cheaper and more accessible, more and more customers opt for the off-grid solution. The utilities should embed themselves into these value chains by adopting the market change. By not adapting, they risk losing more customers, resulting in a forced price increase, resulting in even more customer loss.

The fossil fuel heavy energy market significantly impacts climate change, and this needs to change. With this design, it is hypothesised that the main issues: climate change, energy shortage and lack of energy security, can be alleviated while sharing wealth across all parties and removing monopolisation. With the efficient implementation of a framework design such as this, GHG emissions can reach their peak and start their downtrend.

3.3 Transport Sector



This section presents the following key points regarding the transport sector, which were used as background to the section on transport design (Section 3.4).

- Currently used modes of transport and key market related metrics for each mode;
- Transport market, its gains and trends;
- Interdependent nature of the transport industry and the energy industry;
- Climate change impact of transport, as well as the alternative clean fuels and modes of transport available;
- Burgeoning autonomous innovation and its intricacies within the transport network;
- Implementation of Hyperloop as a public transport mode over High Speed Rail;

The importance of supplying urban mobility users with efficient transport solutions is presented in the following section. Urban sprawl and urbanisation proliferate urban distribution services demand, especially with the growing adoption of e-commerce. The mobility network affects various critical sustainable and efficient factors of the built environment. Factors affected by increased urban mobility demand are the environment – predominantly via GHG emissions – social welfare, governance, and land scarcity (Bubeck *et al.*, 2014).

The e-commerce boom has increased the need for logistics and freight use, which in its current operation is the most significant contributor to road infrastructure damage (European Parliament, 2003). The single most crucial aspect of inefficient urban mobility is traffic congestion. Traffic congestion, especially in developing countries, is of concern, as 91% of the global road crashes occur in low- and middle-income countries (WHO, 2019b). However, traffic congestion directly impacts human health when the majority of vehicles are internal combustion engine (ICE) vehicles.

Post-war town planners were forced to design cities around the motor car (Jefferson and Skinner, 2005). By 2050, the urban environment is expected to see a tri-fold increase in urban travel kilometres from the current 64% share of all kilometres driven (Lerner, 2011).

Figure 3.35 shows the historical trends in the different mobility modes.

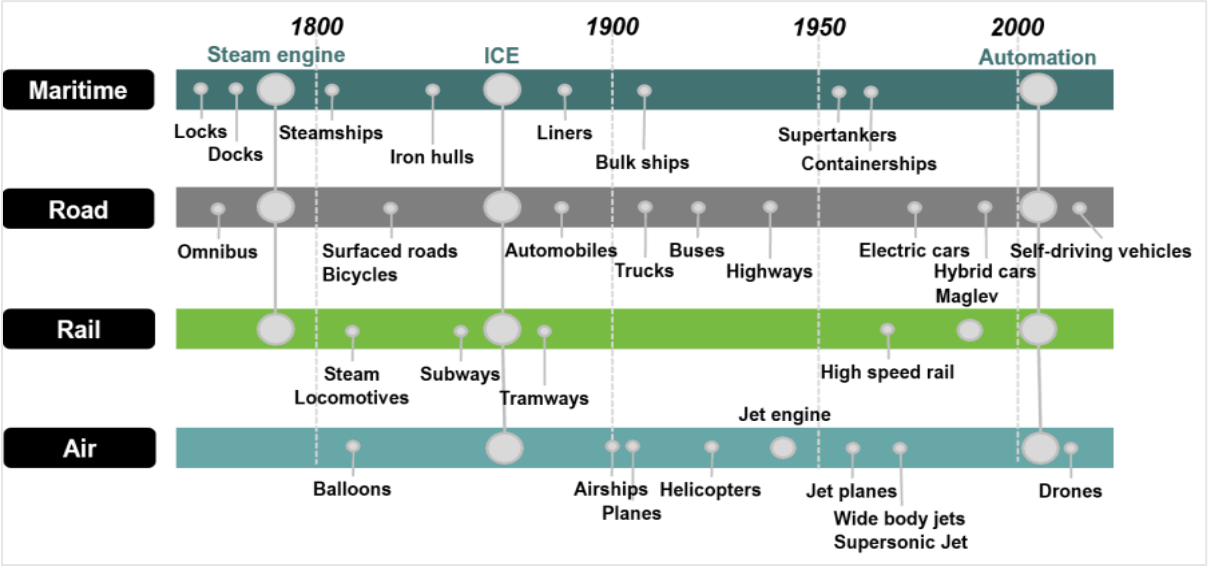


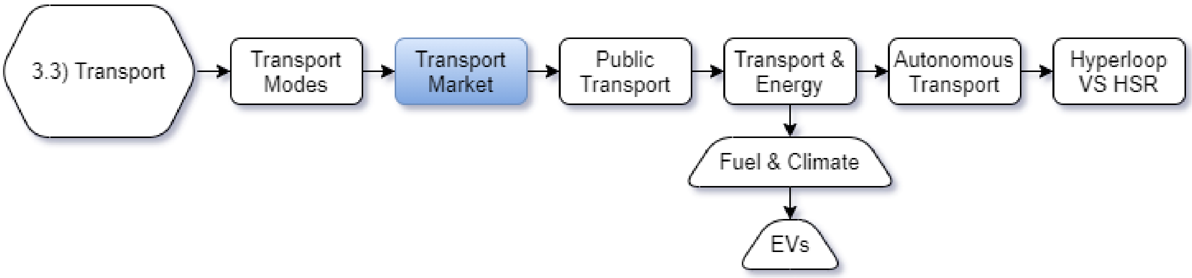
Figure 3.35 - ***Transport Mode Evolution*** (Rodrigue, 2020b)

The sub-sections below present the current transport environment and then present the new innovations explored in this research. Moreover, the contrast is presented between conventional modes of transport and new modes. These sections may help the reader understand the radical change from convention and also see the potential in economic gain that can be acquired from this industry.

Freight is the single most contributing factor to growing an economy, and it involves the movement of goods from A to B. Freight is the catalyst to growing innovation and development, allowing production and consumption to run almost end to end. (National Academies of Sciences Engineering and Medicine, 2011)

The last mile trade volume increases have created heightened levels of congestion and road damage. The EU urban areas see an 8-15% freight traffic flow, and these freight miles are predominantly powered by diesel engines which release large amounts of GHG emissions. (Jones *et al.*, 2020)

3.3.1 Transport Market:



This section evaluates the industry to identify where the public transport market can generate beneficial returns. In areas where transport infrastructure is accessible and where it links the market to valuable resources, economic opportunities are likely to arise (Rodrigue, 2020b).

Transport moves not only human resources but also physical resources and products. It is typical for the cost of sales to have a share of transport costs amounting to 10%. Transport costs are most commonly affected by the distance, which affects time and then followed by transport conditions. (Rodrigue, 2020b)

The transport market is in constant recalibration, and the industry has changed over the year, as shown in Figure 3.36. Showing that new modes of transport is bound to be developed and implemented and therefore cities of the future should be flexible enough to adopt new modes.

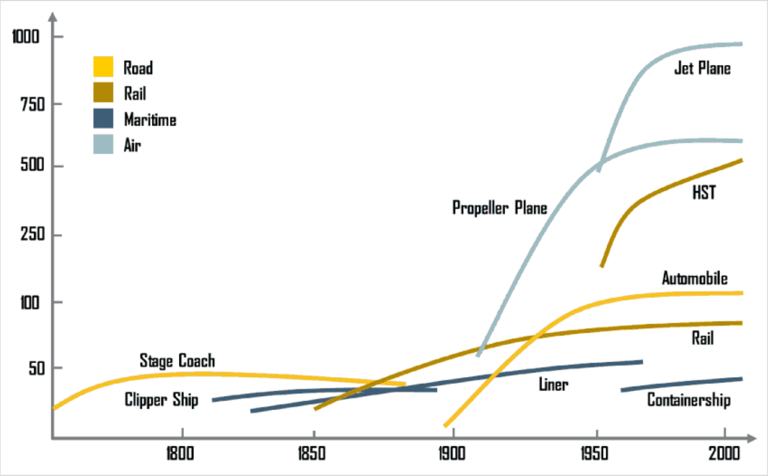


Figure 3.36 - ***Transport Mode Market Trends*** (Rodrigue, 2020b)

To avoid implementing solutions that do not align with the future market, the following section presents the global market for the transport industry. The market shows the economic potential that can or cannot be achieved from the industry parts, as well as current transport trends.

Global

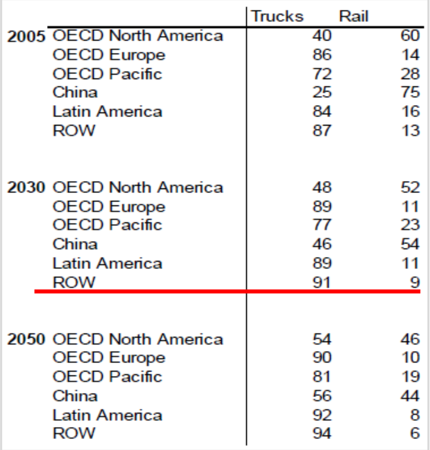
The International Transport Forum (2019) states the global GDP increased by 2.9% in 2019 and world trade volume also grew by 2.9%. The ITF states that the freight industry saw a stagnation across most sectors with a 3.2% decrease in air tonne-kilometres, a 6.3% decrease in US rail tonne-kilometres and a 1.9% decrease in the EU. However, road freight has increased by 1% and 6.3% in the EU and Russia, respectively (International Transport Forum, 2019).

With an estimated global GDP doubling by 2030, traffic will increase drastically and with transport consuming over 50% of global liquid fossil fuels, the climate effect will be far-reaching (Dayal, 2014). The global transport market is estimated by the The Business Research Company (2021) to have a 9% CAGR and reach 7500.8 billion USD by 2023.

There are significant modal differences in the transport market, especially regarding costs. This is the reason for the vast difference in approaches across the world. Transport costs include factors, such as out-of-pocket cost to the user, time costs due to inefficient operation – often referred to as Transport Time Cost (TTC) – and cost of risk and discomfort. Mobility projects are often chosen based on a portion of these costs and not the total encompassing cost. Rodrigue (2020b) finds this especially evident when motorists base their decision on short-run marginal costs, such as fuel cost only, and not considering vehicle degradation, insurance and tax.

Empirical data shows how the first and last mile stages of a transport route are often the areas where transport costs are elevated. This is especially of concern to the freight mobility sector. The freight sector is expected to have, as shown in Table 3.10, a 91% modal split for road freight and 9% rail by 2030. In 2005 the modal split for freight was 87% Road and 13% rail (Dayal, 2014). Table 3.11 shows the past and projected modal split of passenger use cases from the study done by the International Transport Forum (2011). It can be seen that road-based freight dominates the market.

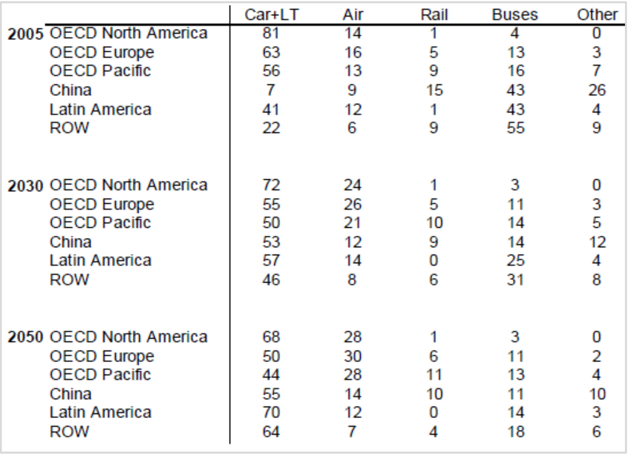
Table 3.10 - ***Freight modal split by region*** *(International Transport Forum, 2011)*



		Trucks	Rail
2005	OECD North America	40	60
	OECD Europe	86	14
	OECD Pacific	72	28
	China	25	75
	Latin America	84	16
	ROW	87	13
2030	OECD North America	48	52
	OECD Europe	89	11
	OECD Pacific	77	23
	China	46	54
	Latin America	89	11
	ROW	91	9
2050	OECD North America	54	46
	OECD Europe	90	10
	OECD Pacific	81	19
	China	56	44
	Latin America	92	8
	ROW	94	6

ROW = Rest of World

Table 3.11 - ***Passenger modal split by region*** *(International Transport Forum, 2011)*



		Car+LT	Air	Rail	Buses	Other
2005	OECD North America	81	14	1	4	0
	OECD Europe	63	16	5	13	3
	OECD Pacific	56	13	9	16	7
	China	7	9	15	43	26
	Latin America	41	12	1	43	4
	ROW	22	6	9	55	9
2030	OECD North America	72	24	1	3	0
	OECD Europe	55	26	5	11	3
	OECD Pacific	50	21	10	14	5
	China	53	12	9	14	12
	Latin America	57	14	0	25	4
	ROW	46	8	6	31	8
2050	OECD North America	68	28	1	3	0
	OECD Europe	50	30	6	11	2
	OECD Pacific	44	28	11	13	4
	China	55	14	10	11	10
	Latin America	70	12	0	14	3
	ROW	64	7	4	18	6

From the data presented by the ITF, it is predicted that the road use of car modal share for the Rest of The World (ROW) will increase. This means that for an already congested transport network, the need for decongestion is of utmost importance. For example, the most congested city in the world is Bengaluru, with a 71% congestion level (TomTom, 2021b).

Sub-Section Summary

It can therefore be seen that the global demand for mobility is increasing, especially within the logistics industry. The expected increase in travel kilometres is observed more so in developing countries as the transport market and its modes change. This increase is mainly through the mode of road based transport and rail is being underutilised.

The recent change in the mobility market is driven by the negative impacts to the environment, which this industry causes.

Local

South Africa is a country extremely dependant on its transport industry, as with any growing economy. The freight transport sector of SA is a mainstay in the economy as exports and imports account for 29% and 30% of SA`s GDP, respectively (PwC, 2012). South Africa is a country that is finding it extremely challenging to restructure a dangerous, inefficient and ineffective public transport system (Walters, 2014).

Cape Town rail transport system consists of 17 rail lines. Showing the underutilisation, only four of these meet passenger demand, and even though the original plan was to have freight moved to rail transport (Trollip *et al.*, 2011), today 89% of freight is road-based transport (PwC, 2012). The underutilisation of rail for passenger journeys is evident when only 2.2% of passenger journeys are rail-based (StatsSA, 2021).

Other than the underutilisation of the transport modes, the country records 36 daily deaths on the road network (Arrive Alive, 2020).

In context, SA has a road fatality rate of 25.1 deaths /100 000 inhabitants, which is not too distant from Thailand, which has the third-highest rate in the world of 36.2 deaths/100 000 (WHO, 2019a). On average, poor South Africans spend 20% of their income on public transport (Trollip *et al.*, 2011). When considering motorised public transport only, minibus taxi use has a stark dominance in the market (StatsSA, 2018) and the Western Cape also has an intense rail transport usage (Greencape, 2020a).

Considering road based public transport , Transaction Capital - an investment group, says that SA taxis in 2019 had a public transport share from household use of minibus for work and education, of about 69% (Transaction Capital, 2019). This figure is, however, inflated as it is only compared to motorised public transport.

The general household survey of StatsSA,2018, shows a broader scenario that considers all modes of transport within the urban environment. It shows how minibus taxis have a 15.4% share of all modes of transport in SA, whereas private vehicle use and walking have 21.35% and 42.5% share, respectively (StatsSA, 2018). These figures are more in line with the statistics shown in Johannesburg and Cape Town (Table 3.12).

Table 3.12 - ***CPT and JHB Transport Modal Share*** *(Author)*

Transport Mode	**Cape Town**	**Johannesburg**
Cars	54%	37%
Trains	24%	4%
Buses	12%	3%
Taxis	9%	23%
Non-motorised	1%	33%
Source	*(SEA, 2019)*	*(Grütter, 2011)*

The 50 billion ZAR a year minibus taxi industry (Transaction Capital, 2019) in SA is also the most prominent reason for many of the problems in the public transport network. Most notable minibus taxis are extremely unsafe.

In SA, three people die every day from taxi-related incidents (Arrive Alive, 2020), and 43% of all assassinations are taxi-related in SA (Thomas *et al.*, 2018). A survey by the South African Institute of Race relations found that 52% of interviewees witnessed accidents to the driver's fault, 47% reported seeing illegal operations, and 44% said that they have seen taxi drivers without a valid driver's license (Dawood, 2019).

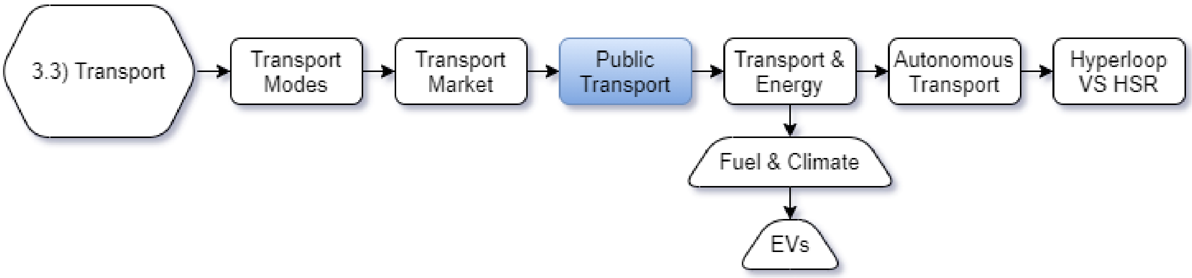
CPT has a congestion level of 32%, ranking 101 globally, and Johannesburg has a 30% congestion level which ranks 121st globally (TomTom, 2021b). In 2015 CPT commenced a congestion management program which would see it spend 750 million ZAR over five years (Deloitte, 2019).

Sub-Section Summary

It can be seen that the South African mobility industry is dangerous, underperforming and have significant congestion. The industry is dominated by private cars and minibus taxis. While the other parts of the public transport modes such as rail is underperforming. It can also be seen that the local market is significantly dependant on the freight industry.

Hence, there is a significant economic impact from the transport industry, but if utilised correctly then this industry can generate significant market potential. Below this industry is further explored by specifically focussing on the concept of public transport.

3.3.2 *Public transport and trends*



The following section identifies the main market movers and where the market is moving.

The 20th-century mobility network was designed for the automobile, which meant cities promoted automobiles. However, sustainable cities need to have a synergistic network that integrates public transport (PT).

Passenger transport in urban areas accounts for roughly 60% of energy consumption for transport activity consumption (Rodrigue, 2020b). Various factors have contributed to the dominance of private vehicle use. However, the need for a sustainable urban environment requires more affordable and safe public transport and non-motorised transport (NMT), which inherently has more efficient land use (Yazid *et al.*, 2011).

Recently the transport sector has been striving more for efficiency and sustainable energy solutions. The impetus for this move is driven by the change in climate conditions which is made worse by the emissions from the transport sector. However, with the advent of cleaner technologies predominantly in private vehicle use, the issue of congestion remains a problem. Hence, the following investigates the cause and effect of congestion and determines the solutions available to mitigate the issue.

Congestion results from two factors: an increase in the number of vehicles and, secondly, inefficient urban form or road network layout (Rodrigue, 2020b). Figure 3.37 shows the well-known picture, redone by the Cycling Promotion Fund of Australia (Makari and Tawadros, 2015), of the impact on congestion by implementing public transport. The urban layout impact on congestion is discussed in the section 3.5.

Figure 3.37 - ***Public Transport Effect on Density of Roads*** *(Makari and Tawadros, 2015)*

A study by analysis group, Arthur D. Little, shows how by 2050, an urban dweller could spend up to 106 hours per year in traffic congestion. The study cites three strategic approaches for cities to solve this problem. Firstly, to have a robust integrated transport management system that improves public transport and reduces private car use by implementing policies, such as taxation and/or road tolls for individual cars. The second approach is to rethink the system, which calls for a fundamental redesign that challenges the norm of traditional transport. The final requirement is to design a sustainable core from which growth can occur sustainably and flexibly. This third step aims to create a platform for cities to become a testbed for new technologies. (Lerner, 2011)

Congestion can attenuate an economy`s growth by increasing time spent in congestion. In the city of Cape Town (CPT), commuters can spend up to an hour in traffic on the way to work (Treiber *et al.*, 2008). This Traffic Time Value (TTV) is a cost experienced by all mobility systems around the world. The increased pollution further exacerbates this cost of congestion during congested traffic. The transport research Board of the US empirically shows in a study how average travel time is an indication of how fuel consumption scales up. This, in turn, means that when there is an increase in the number of vehicles in the system and traffic speed decreases non-linearly with more vehicles, pollution and time value cost would increase. (Treiber *et al.*, 2008)

A comprehensive study by Litman (2010) was done on congestion costs of transport in various cities in the US and Canada. The research evaluates the contribution of freight to congestion by evaluating the difference in travel speed when one truck is added to the system. A more detailed expansion of congestion cost is defined in a handbook by CE Delft (Maibach *et al.*, 2008). One report sets out an estimated urban congestion cost of 0.34 - 1.50 ZAR per vehicle-km for heavy goods vehicles and 1.50 - 2.19 ZAR per vehicle-km for interurban (Nash, 2003).

Hence, congestion can escalate cost of transport significantly therefore cities constantly try and alleviate it.

The BRT system:

Public transport solutions in some cases work and in others not. The following section investigates a brief case study to show how public transport can vary by case. This highlights the importance of making a framework that is flexible to adapt to certain scenarios.

SA implements BRT systems as a solution to public transport, even though globally, the implementation rate of this system has slowed, as shown in Figure 3.38. The underutilisation of these BRT systems implemented across SA is also, however, a concern. The Cape Town BRT phase 1A was designed for a capacity of 12 500 pax/hr/direction. However, the actual utilisation to date sits at 3 252 pax/hr/direction (Grey and Behrens, 2013).

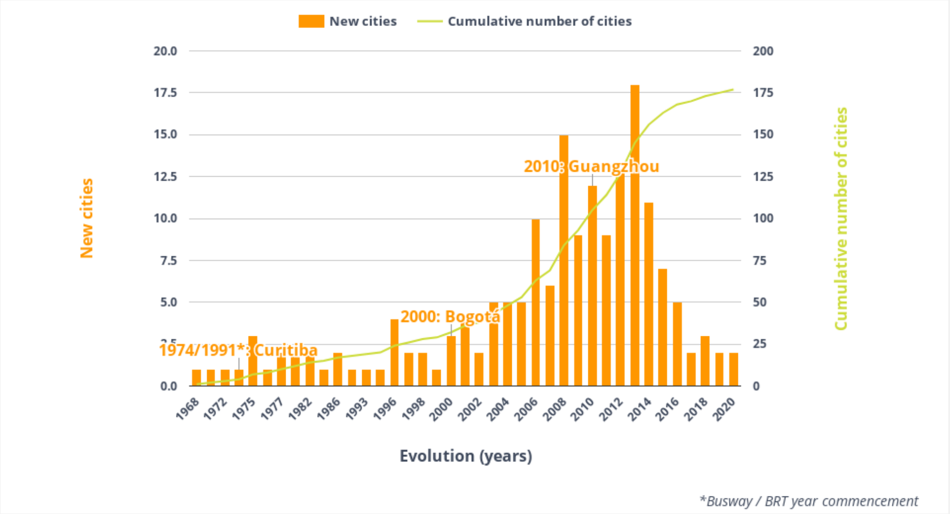


Figure 3.38 - ***BRT global deployment trend*** *(EMBARQ, 2020)*

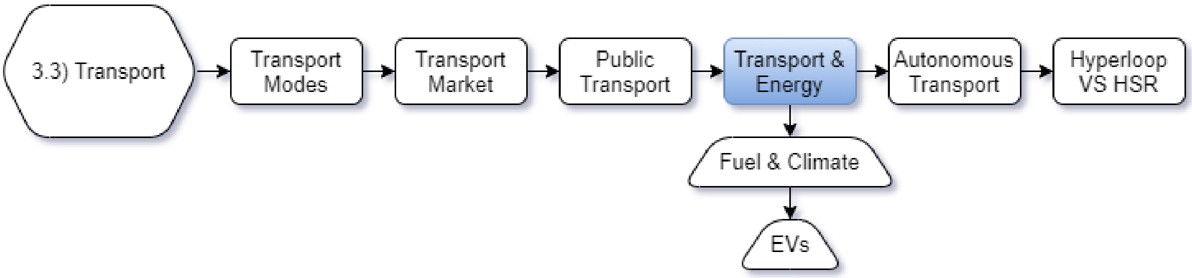
The fundamentals of the BRT system could work if implemented correctly. A somewhat successful rollout is done in Johannesburg as the study by Embraq shows how an average of 5 760 pax/hr/direction for the Rea Vaya BRT system in Johannesburg is achieved (Carrigan *et al.*, 2013). The Rea Vaya Phase 1A design capacity is the smallest BRT system capacity implemented, at 8 000 pax/hr/direction (Grütter, 2011).

A study by the University of Stuttgart investigated the potential of correctly implementing public transport and its benefits to reducing GHG. The study focussed predominantly on the Rea Vaya line showing how the current line has a performance of 90 000 passengers/day and how if expanded to a complete system in an efficient manner, it could reach a 320 000 passengers/day performance. The study also found that this system paired with the Gautrain could mitigate 1.1 to 2.7 Mt CO2e between 2014 and 2020. (Bubeck *et al.*, 2014)

Sub-Section Summary

The congestion problem observed is predominantly due to cities being designed for cars and not pedestrians. By implementing public transport correctly one can not only improve the climatic impact and economic return but also improve road safety and alleviate congestion.

3.3.3 The partnership of Transport with Energy and Climate Change



With motorised transport becoming more accessible, urban decision-makers are being forced to develop sustainable mobility solutions and frameworks that account for the uptake of motorised transport. As of 2020, the transportation of passengers and freight is responsible for roughly 25% of the global energy use annually, where 85% of this is from road-based transport (Rodrigue, 2020b).

Transport is a constant trade-off between efficiency, cost and use-case. Depending on the use-case for a specific mode of transport, the cost might be sacrificed for a better power ratio or haul weight. However, typically the lowest costing fuel is chosen. The following section presents the relationship between an efficient transport system and energy. The section presents the problems arising from the fossil heavy transport industry and investigates alternative options.

3.3.3.1 Fuel consumption and climate impact

The transport sector is dependent on various forms of energy, which in turn is generated by various fuel sources. Most of this fuel demand is covered by liquid fuel and mainly fossil fuels such as diesel, petroleum and liquid natural gas (LNG) (Ritchie, 2020). The Global Climate Data explorer by Climate Watch provides GHG emission data for all global sectors. There it can be seen how the transport sector is responsible for 36% of the global GHG emissions (The World Resource Institute, 2018).

Furthermore, the ITF transport outlook of 2021 finds that even if current commitments made by countries to decarbonise transport is met, the transport CO_2 emissions would still increase by 16% to

2050 (International Transport Forum, 2021). Figure 3.39 shows the CO_2 emission breakdown of the modal contribution within the transport sector.

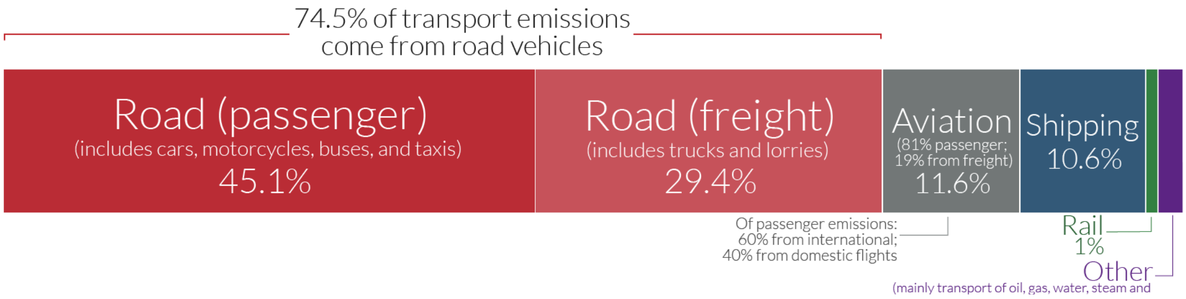


Figure 3.39 - ***Global CO_2 Emissions from Transport*** - *(Ritchie, 2020)*

The majority of the fossil fuel consumed by the transport sector comes from crude oil, demanding 61.5% of all oil consumed annually. This is because most vehicles are based on the internal combustion engine, with diesel and petrol being salient fuel sources and diesel being the most pollutive. (Rodrigue, 2020b)

The IEA forecasts a year over year growth of 3.1 mb/d in 2022, which will see gasoline increasing by 660 kb/day and diesel by 52 kb/day. Considering the adoption of RE and EVs – discussed later in the report - the IEA forecasts significant growth in oil demand post-2022 (IEA, 2021).

Contrasting to this, investment analyst group Ark-invest believes that oil demand will peak in 2023 and then follow a downward trend. The salient statistic reported by Ark-invest is a 50% drop in gasoline demand by 2030. (Korus, 2016)

Locally, CPT saw an energy usage share from the transport sector amounting to a 50% share (Euston-Brown *et al.*, 2015). Nationally across SA, the transport sector has a 41% indirect electricity consumption share (GET.invest, 2017). Overall, the local CO_2 emissions per capita in 2016 was 0.99 tons, which is just below the world average of 1.05 tons per capita (Ritchie, 2020).

The reduction of these transport-related GHG emissions can be made in various ways. A study on transport policies provides some key strategies and tools to generate an urban transport network that is low-carbon. The study highlights the dependency of GHG mitigation measures on the urban transport systems' type and development process (Nakamura and Hayashi, 2013). However, there are various modes of transport, and each emits their own weighting of CO2, as shown in Figure 3.40.

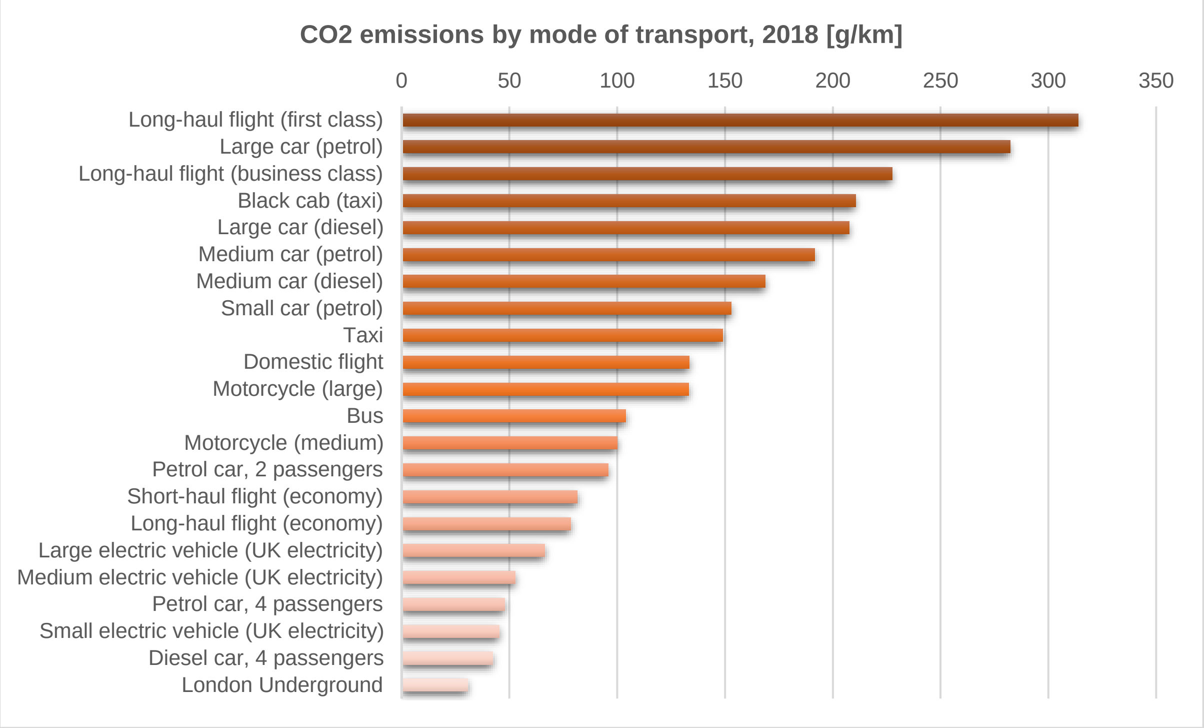


Figure 3.40 - ***CO₂ Emissions by Mode of Transport***
(Adapted from Department for Business Energy & Industrial Strategy, 2018)

Public transport is more energy-efficient due to its occupancy rate and density use of network space (Böhler-Baedeker and Hüging, 2012).

The South African economy is significantly dependant on the transport industry as the fuel levy in the country is the 4th most significant revenue stream (Greencape, 2020a). This fuel levy, however, is under increased scrutiny by the people of SA. The social impetus put on the government resulted in the government initiating, in June of 2019, a carbon tax on GHG emissions from fuel combustion.

A report released by OUTA, the civil society to protect SA from tax abuse, shows how the government's taxes and levies on fuel are unsustainable (Duvenhage, 2021). Figure 3.41 shows the extract from the report where the ballooning effect on these levies can be seen.

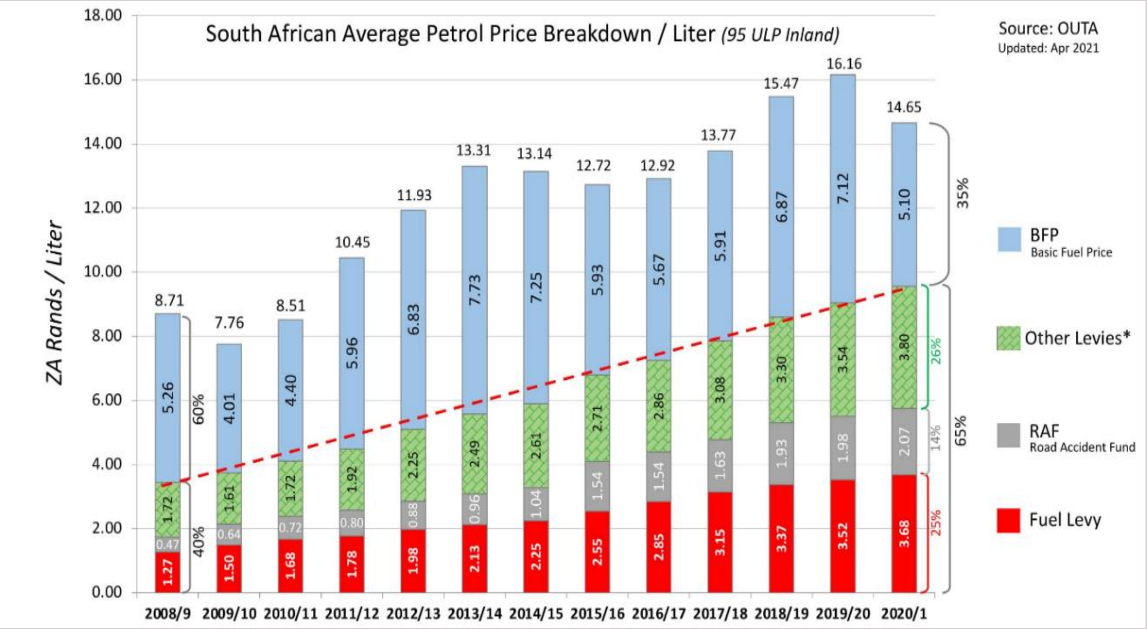


Figure 3.41 - ***South African Fuel Price Breakdown***

The ballooning of fuel prices is one of the fundamental causes for influencing innovators to explore new forms of energy other than the environmental impact. By 2050, the energy intensity of the transport industry can be reduced by 20-40% by alternative and advanced fuel technology. (Böhler-Baedeker and Hüging, 2012)

Furthermore, energy security is a part of the global supply market that is very sensitive to political and supply route changes. If disrupted, the oil supply can have a large effect on the global economy and stability, hence why sources, such as Hydrogen are also being explored as an alternative to liquid fuel.

3.3.3.1.1 Hydrogen as a transport fuel source

Hydrogen fuel cells, as previously discussed, is a viable solution for the transport industry as well. To date, it has a small market share of the total transport fuel consumption, however, its potential is being realised in heavy-duty or freight transport.

Confoundingly, 85% of Hydrogen produced is used to clean gasoline, the fuel source from which it is taking market share. Hydrogen can be produced mainly by two methods, via natural gas extraction or electrolysis. Electrolysis only accounts for 5% of production to date, as a significant amount of electrical energy is required to extract it. (Howden, 2021)

Hoffmann (2019) finds electrolyser units have a conversion efficiency of 80% and consume 45-50 kwh/kg H2 and 10-12 L of water/kg H2. Hoffman completed the study at Stellenbosch University, which evaluated a Hydrogen gas reform plant by SASOL in South Africa, finding the production has an H2 production cost of 17.89-21.47 ZAR per kg. The study excluded compression and storage costs, which is estimated by Harvego, Brien and Mckellar (2012) to add 25.05 ZAR /kg to the price. All in all, the study concludes that a 150 MWe low-temperature alkaline water electrolyser in South Africa can produce over 16 800 tonnes of H2 at a levelised cost of 63.26 ZAR/kg (Harvego *et al.*, 2012).

Hydrogen typically has an energy capacity of 33.33 kwh per kg (Systemtechnik, 2020), meaning that the LCOE of H2 would be 1.90 ZAR/kWh for the data above. However, fuel cells are only 35% efficient (US Department of Energy, 2020) at converting H2 to electrical energy, which means that the real LCOE is 5.42 ZAR/kWh.

For Hydrogen to reach cost parity with other sources of renewable transport such as Li-ion batteries, it has to reach economies of scale and higher efficiencies. Companies such as Toyota, Linde, UPS and Amazon have already implemented Hydrogen fuel cell forklifts and freight trucks (Plug Power, 2021). The reason for the freight industry favouring this technology and not the small vehicle industry is because of the way the liquid Hydrogen needs to be stored (Amirante *et al.*, 2017). The fuel needs to be compressed and stored on-board in high-pressure containers. This storage method and compression process is a costly process (Amirante *et al.*, 2017). However, the energy density of this fuel type is favoured, as shown in Figure 3.42.

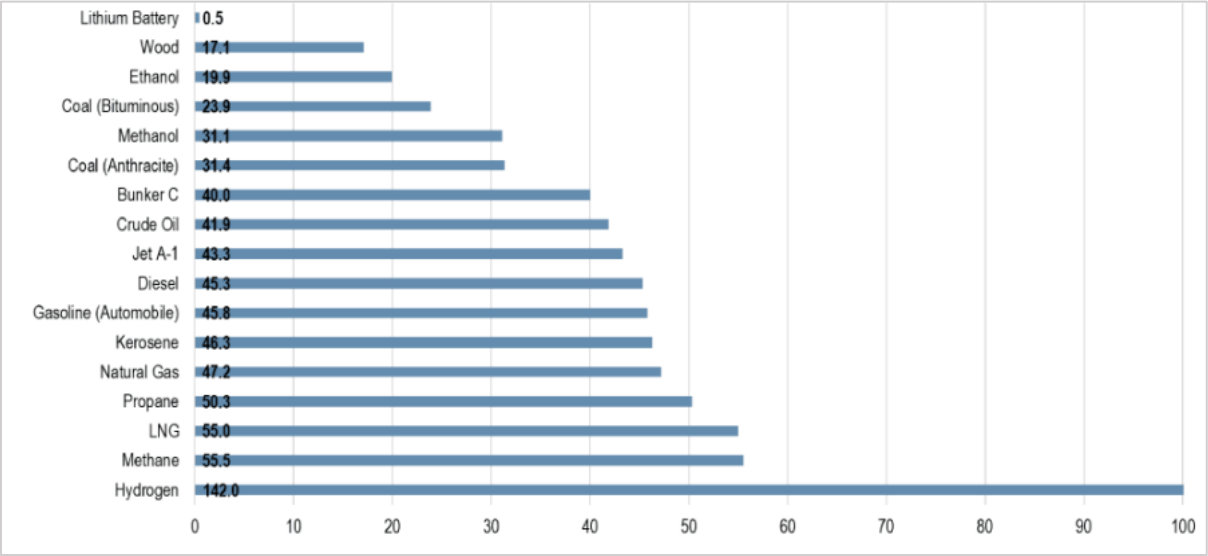


Figure 3.42 - ***Energy Content of Energy Sources [MJ/kg]*** (Rodrigue, 2020b)

Sub-Section Summary

Fossil fuels have a significant impact on energy demand and the climate, locally it also has a large impact on the economy. Considering pollution, private vehicles are the most pollutive. It is also seen how fossil fuels are at risk of supply chain changes which puts energy security at risk.

The section presents the slow adoption of the high-power fuel cell technology. This technology has a slower adoption rate due to its high cost, low efficiency, and storage method. Nonetheless, the technology is possibly favourable for the freight industry.

3.3.3.2 Electric Vehicles (EVs)

The Covid-19 pandemic has been an unlikely catalyst for the advancement of renewable technologies and fuel sources. With the global oil reserves estimated to deplete by 2072 (Ritchie, 2017), the need for alternative transport fuels is under vast development. One option which is in its incipient adoption is electric vehicles. EV sales only account for about 3.2% of the total transport market but rapidly increasing, as shown in Figure 3.43.

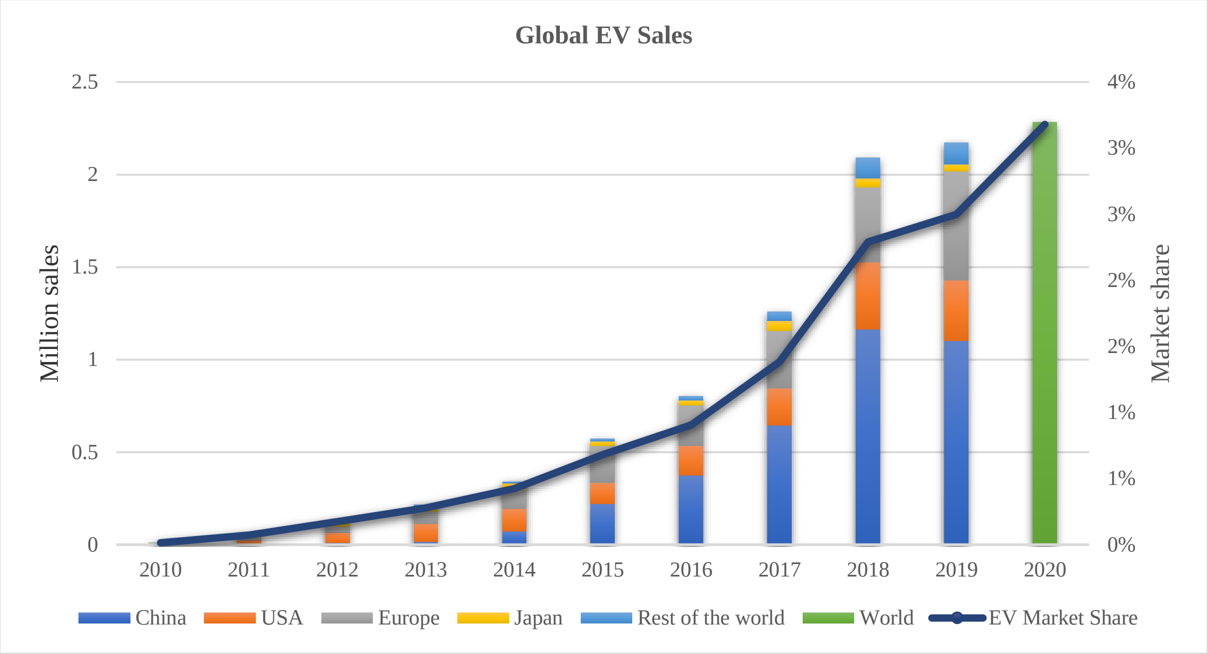


*Figure 3.43 - **Global EV Sales to Date** (Adapted from IEA, 2020a)*

Korus (2019) finds that with ever decreasing cost curves, EVs are becoming more attractive. EVs come in various forms, from battery electric vehicles (BEVs), Hydrogen electric vehicles (H2EVs) and hybrid electric vehicles (HEVs). The most adopted form of EVs is the battery electric vehicle form. Today BEVs are found in vans and trucks, passenger vehicles, bus or two/three wheel form. The EV market share of each of those types is 1%, 4%, 39% and 44%, respectively. (BloombergNEF, 2021) EVs are also the least cost heavy personal vehicle when considering the life cycle cost, as shown in Figure 3.44.

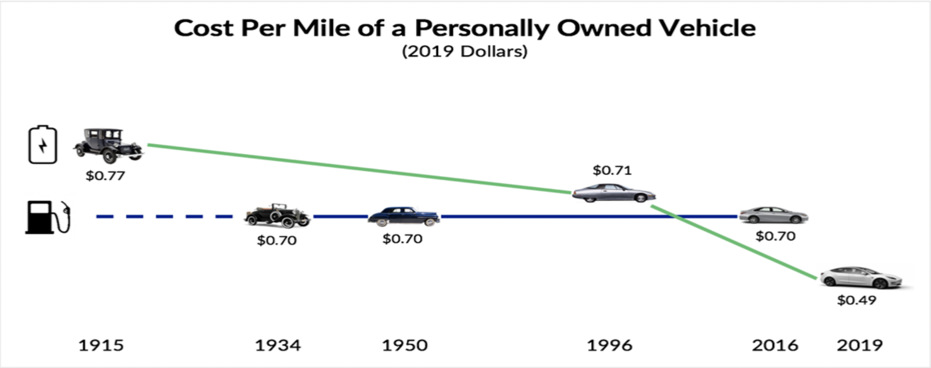


*Figure 3.44 - **Cost per mile of a Personally Owned Vehicle** (Korus, 2019)*

The displacement of oil demand is attributable primarily to the adoption of battery electric vehicles (Korus, 2016). The oil giant BP releases an annual oil forecast from which a more precise picture can be seen. Figure 3.45 shows the forecast released from 2018-2020 and how each year the forecast had to be adjusted to a lower future barrel count, peaking in 2025 (BP p.l.c., 2020a).

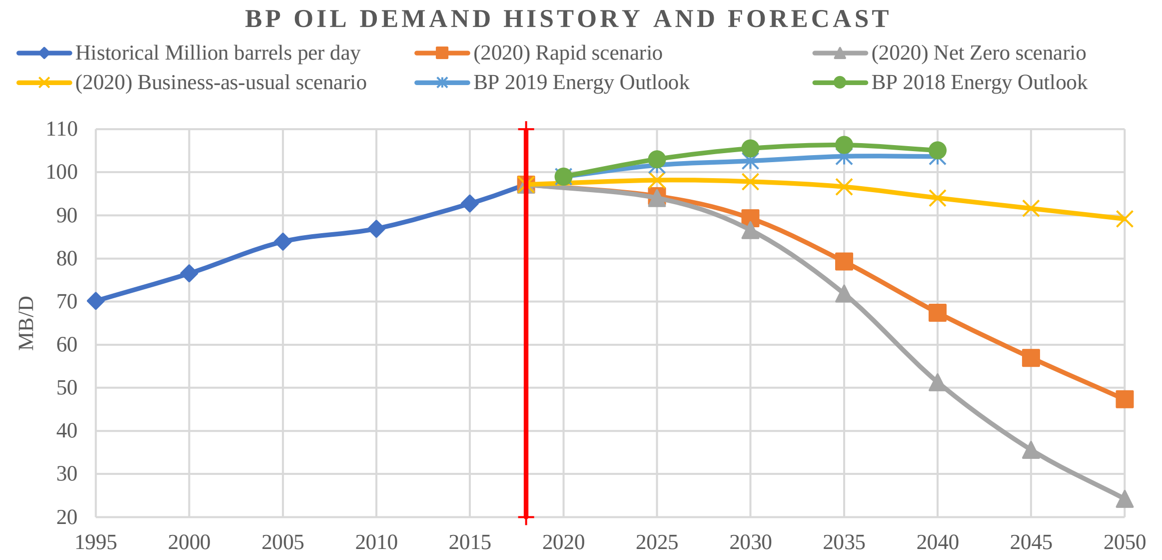


Figure 3.45 - ***BP Oil Outlook*** *(Author) (Adapted from* BP p.l.c., 2020a)

The literature has shown the considerable dependency of SA on fossil fuels. The city of CPT in 2015 recorded that 91% of liquid fuel consumed is by private cars (Euston-Brown *et al.*, 2015). No policies, subsidies or incentives exist in SA to accelerate the adoption of EVs, hence, an EV purchase in SA will cost roughly double the sticker price because of the *ad valorem*[**], VAT and import tax added onto these imports (Greencape, 2020a).

Hence, SA has not yet seen the EV growth that has been seen globally. The government is also restrictive to changing to this new adoption, because the ICE manufacturing industry is a critical economic sector for the country, bringing in 500 billion ZAR in 2017. SA imports all of its oil and an evaluation done by Greencape (2020a) shows that if SA had to deploy one million EVs, it would reduce oil imports by 6%. Greencape states this reduction will allow for over 8.1 billion ZAR of SA money staying within the country.

SA has custom-free agreements with 28 countries in ICE vehicle parts, a big part of the SA economy. However, If SA is reluctant to change its approach, this market will be lost, as most of these countries are placing bans on new ICE vehicle purchases soon. Hence, SA may have an ICE heavy manufacturing industry with no countries to export to. (Greencape, 2020a)

[**] Ad Valorem – A tax amount that is added to goods based on their value of import.

The growth of EV demand will not subside as international government policies start to align with the change in the market and incentives for consumers remain in place. There is a prediction by analysts that by 2030 the mobility storage demand will reach 0.8-3 TWh where light-duty EVs dominate the market share in the short term. (Department of Energy, 2020)

In the Ark paper, Korus (2017) states that for the urban setting, EVs' value is found with Battery Electric Buses (BEBs) and Battery electric trucks (BETs). Korus mentions how manufacturers are still sceptical of implementing the electric drivetrain due to the weight involved with batteries in heavy-duty hauling vehicles. Electric drive trains account for up to 20% of total EV cost (Korus, 2017).

One company embracing the new market is Proterra, an electric bus OEM, which gives guidance on some key metrics of BEBs. The energy consumption of a Proterra bus is at 2 kWh/mile compared to an average passenger EV of 0.33 kWh/mile. A Proterra bus has a capacity of 40, which in context, would mean a per passenger energy usage of a Proterra bus would be 0.05 kWh/pas/mile. Proterra specifies a bus range, ranging from 91-297 miles and a 3 hour full recharge time depending on the model (Proterra, 2021) . However, the goal is to have a mixed-use mix of transport modes and not strive for an unrealistic ideal case where no private passenger cars exist.

Literature shows that the single biggest concern today hindering EV adoption, is the term ‘range anxiety’ (Viola, 2021). Range anxiety is a term that describes the fear of running out of “gas” or drive capability due to loss of charge. Various mainstream publications site the range anxiety or the EPA range of these vehicles (Doom, 2013; Taub, 2017; Pevec *et al.*, 2019; Elfalan, 2021). However, the average range of the top 10 real world EPA ranked EVs are 313.5 miles or 504.53 km (Elfalan, 2021). The BET of Tesla, the Tesla Semi, has a base model range of 482 km and can reach up to 804.67 km with other models.

Consumer studies show that only 18% of driving behaviour in an average year consists of trips more than 322 km one-way. Only 0.5% of US commuters travel more than 160 km in one-way trips with personally owned vehicles (Korus, 2017). Locally a journey from Cape Town to Port Elizabeth would measure 733 km. Assuming an EV can recharge 50% in a 30-minute rest stop, one can efficiently complete this day journey. Hence, range anxiety is being attenuated in its validity as a concern.

The white paper titled, The Future of Autos and Trucks is Electric, reported results shown in Figure 3.46 of the lifetime cost of a traditional semi truck vs an electric semi showing the beneficial cost reduction potential.

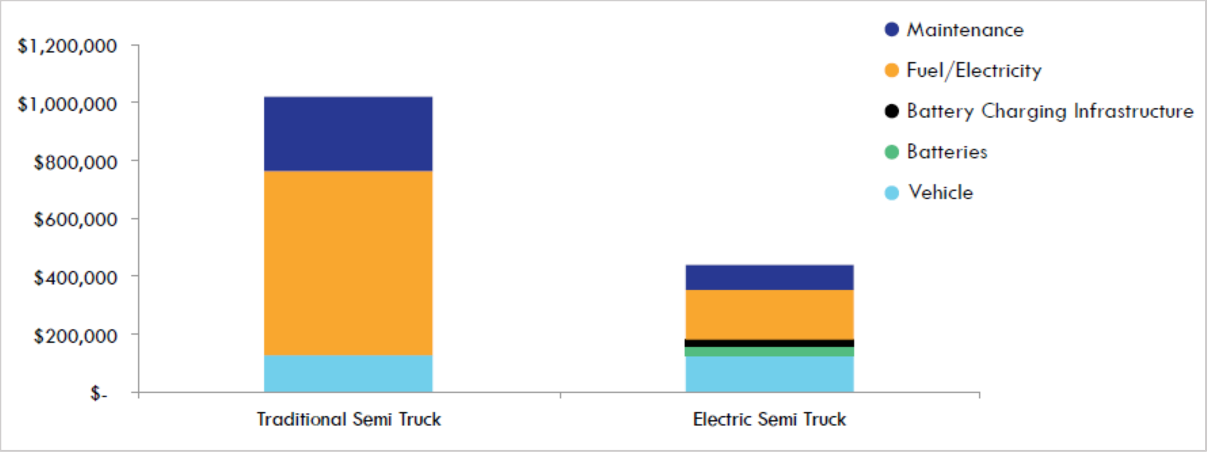


*Figure 3.46 - **Traditional vs. Electric Semi Truck Lifetime Cost Over 15 Years** (Korus, 2017)*

Sub-Section Summary

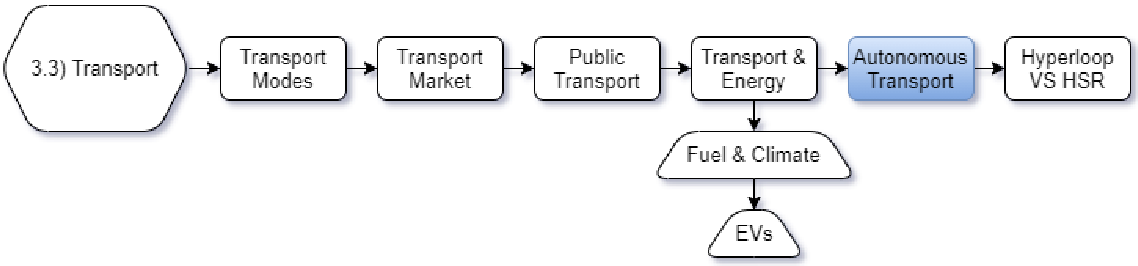
It is seen that the EV market anticipate the depletion of oil and the impacts of climate change. Hence, the adoption of EV is compounding and current EVs are less costly than ICE-vehicles. SA however, do not incentivise EV adoption as its economy is still significantly dependant on the ICE supply chain. This is a high risk as globally countries are moving away from ICE. The amount of capital SA sends out of the country for oil purchases is also unfavourable.

It is also seen that large EVs present compounding gains and that range anxiety have become a false fallacy.

Urban mobility development and management can be approached in two ways: One can either introduce a breakthrough innovation that has not yet been implemented commercially or adapt current transport systems to be more prevalent to the needs of current times (Iroshnikov, 2020). Urban planners typically opt for the latter as the legal requirements and policies for a new transport system often lag behind.

To solve the problem of congestion, energy efficiency and outdated public transport, two of the newest innovative technologies are presented in this research below.

3.3.4 Autonomous Transport



The “self-driving car” is considered by many as the future of urban mobility, but the technology has various technical problems and administrative burdens to overcome. (Wired, 2016)

Autonomous driving is set to open up various advantages to the mobility network, such as less energy use, land use, parking demand, costs, and improve reliability and delivery times. Automation reduces the number of vehicles required in a mobility network as the vehicles can at all times operate moving persons from A to B using the most efficient route and sequencing. Vehicles often spend only 10% of their life moving, and the rest is spent in storage or parking lots. (Rodrigue, 2020a)

Mobility as a service (MaaS) is a growing trend within the urban setting, also called on-demand mobility. MaaS currently exist as a taxi driver based system; however, this system is estimated to breach the autonomous market. Ark-invest refers to this autonomous MaaS as Robotaxi's in its white paper on Mobility-as-a-service (Keeney, 2017).

The analyst Tasha Keeney offers guidance on the cost per mile of this Robotaxi service reaching 3.13 ZAR/km, assuming ridesharing takes place. The average US taxi charges 31.74 ZAR/km, San Francisco Uber charges 25.94 ZAR/km (Keeney, 2017) and the SA taxi service charges on average 22.13 ZAR/km (Numbeo, 2021). In comparison, the cost per mile of ownership for a personal vehicle costs about 6.35 ZAR/km. Ultimately the primary beneficiaries of a Robotaxi system should be the consumers, as the travel costs could be reduced by roughly a factor of 10. The white paper extends the beneficiaries to the commercial industry, stating that the logistics industry will benefit from goods delivery both from land and air base mobility systems. The MaaS is expected to surpass 10 trillion USD gross revenue by 2030. (Keeney, 2017)

The literature mentions how economies have become largely dependent on auto sales, hence the risk is the effect that an autonomous vehicle adoption would have on the industry. The risk is founded on the assumption that less personal vehicle ownership will occur due to the improved on-demand mobility network.

Ark's research evaluates the NPV of the scenario mentioned above of an autonomous taxi fleet within the US. Over a period of 15 years and a discount rate of 3%, the study finds that the reduction of the traditional auto market will be 4.2 trillion USD. However, the autonomous network gain would be 11.7 trillion USD which allows for a net gain of 7.5 trillion USD. (Keeney, 2017)

A study done locally on the city of Tshwane by the Financing Sustainable cities initiative evaluates the introduction of BEBs into the city. The study found that a generic 12m BEB would be sufficient for everyday use in the city. The majority of the busses will not require charging during operation as their operational needs as per historical use data would be met by one full charge. Financially the report concludes that BEBs will reach unsubsidised cost parity with diesel busses by 2030, and the battery cost will only account for 8% of total vehicle cost. (Weston, 2018)

The most notable benefit from autonomous vehicles is the increased safety, as 90% of all vehicle accidents are caused due to human error (Rodrigue, 2020a). This figure is expected to reduce by 83%

with autonomous mobility implementation (Keeney, 2017). However, automation is not a single type entity and is non-uniform across different levels of autonomy, as shown in Figure 3.47.

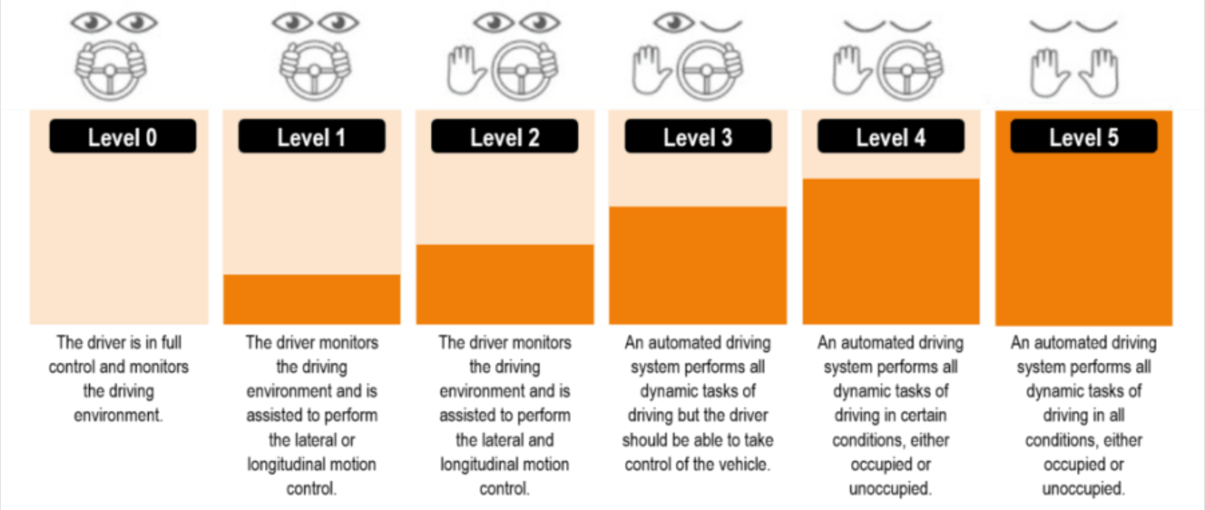


Figure 3.47 - ***Levels of Autonomy*** (Rodrigue, 2020a)

The literature often brings up the concern of appropriate infrastructure and the impact thereof. It is expected that an autonomous fleet in the USA would impact infrastructure spending by freeing up an additional 354 billion USD in annual returns by reducing parking spaces not in use (Keeney, 2017).

Autonomous vehicles are, however, not only applicable to land-based transport but also to air mobility. Within an urban setting, this typically takes the form of unmanned drones. It is currently only being implemented for goods delivery (Keeney, 2017).

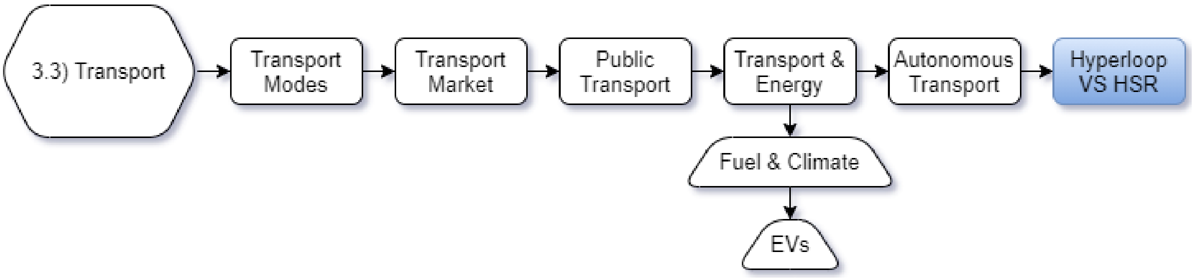
Sub-Section Summary

It is seen that Autonomous EVs could be beneficial in reducing congestion and pollution, while increasing growth and accessibility. The compounding growth potential form MaaS is especially favourable.

The prospect of an autonomous taxi fleet could be greatly beneficial, ptimarily to the consumer and also generating significant market potential. This fleet could also reduce road fatalities severely while being the most cost effective per km of vehicle travel.

The transport technology that follows should provide a similar scenario of time value cost savings but for longer distance travel and focusses on the freight market.

3.3.5 Hyperloop vs. High Speed Rail (HSR)



This section presents the rail industry as implemented today and identify the problems with this mode of transport. To this, the Hyperloop was compared and presented as an alternative solution.

3.3.5.1 Railway train

The rail industry boomed in adoption during the industrial revolution and saw it advancing trade and economic growth (Dayal, 2014). The peak of the rail industry occurred just prior to World War II, after which the depression lead to a higher adoption of the automobile. This caused the rail industry to experience revenue problems across the globe, and maintenance of these systems became costly and ill-managed. In 1976, the US federal government had to heavily subsidise the rail industry as it could not compare with the low bus fares and upkeep was costly. (Depalma, 1982)

The UK managed the rail industry downturn by partially privatising the industry. In 2019, the London Tube system was set to generate 823 million GBP in profits, but booked a nominal debt of 11.175 billion GBP. An evaluation of the Crossrail project of London shows the costly nature of the rail projects. The Crossrail project received 15.9 billion GBP from the Department for Transport, 1 billion GBP from the European Investment Bank and was set to open in 2018. Since then, the project has been delayed to open only in 2022. (Mackintosh, 2020)

The advancement of High-Speed Rail (HSR) projects was sought to solve the revenue problem of rail by allowing more trips to be completed over the life cycle. HSR reaches average train speeds in the range of 200-350 km/h (Ninno, 2018). A study by a group of consulting firms led by Dessau concluded that these HSR projects, potentially being able to cover all operating costs, will still require a significant monetary contribution from the government with no financial return to be expected. The analysis looked at an HSR line between Windsor and Quebec City in Canada and found that for the Canadian economy, the project would not result in a nett positive economic benefit. (Canada, 2009)

A paper evaluating the performance of the European railway industry, often sought to be the most efficient after China, uses statistical data to conclude the efficiency rates. The study found that the European network was not operating efficiently enough and was underperforming the network's capability. Furthermore, it concludes that the network is congested and that the current expansion and management of the railway sector is not being dealt with in the best way. It highlighted the fact that rural members are not being reached and that there is no intention of reaching them. In fact, rail tracks are being closed down due to poor maintenance, cost overruns and an unprofitable business model. This would result in more users being left stranded without adequate transport. (Fraszczyk *et al.*, 2016)

In South Africa, the article by Williams (2021) reported that the SA railway network is in a crumbling state, where most lines run hours late and lines are left inoperable due to cable theft and infrastructure degradation. In 2010 a 14 km passenger rail track was constructed in Johannesburg. The project cost 115 million ZAR, and in 2020 the track was closed with rusted tracks, electrical equipment stolen, and cables inoperable (Williams, 2021). The SA government sets out guidance on its transport government web page noting that it aims to modernise the passenger rail infrastructure via PRASA. The aim is to maintain the existing network continuously and further expand traditional rail (Department of Transport, 2020).

The inefficient, costly and slow nature of HSR implementation is one of the key driving factors that lead to Elon Musk releasing the white paper on Hyperloop (Musk, 2013). A then unproven innovation presented in the white paper called Hyperloop-alpha.

3.3.5.2 Hyperloop

Hyperloop is a transport system based on the pneumatic tube system, typically implemented in medical facilities, packing warehouses and research facilities. The concept released in the white paper sets out a tube network with a low-pressure environment, which houses steel tubes, “pods”, that move within. The difference to HSR is that the pods are supported on-air cushions instead of steel wheels (Musk, 2013). The initial concept details the transportation of passengers and goods at up to 1200 km/h. The design allows for pods with 27-30 passengers and up to 10 tons of freight (Lachaize, 2017).

Since 2013, the concept of the Hyperloop has been widely developed by various companies. For this research, three companies with working test tracks and/or tenders in progress are evaluated for data. Other feasibility studies done by independent consulting firms are also evaluated.

Virgin Hyperloop One (VHO) has a 1km test track, a licensing facility, has successfully tested their system with human passengers and is in dialogue with various parties to implement it. The VHO system is set to travel in a low-pressure environment at speeds of up to 1120 km/h. The system utilises magnetic levitation and claims to be 5-10 times more energy-efficient than aeroplanes. The system is capable of generating two-thirds of its energy needs from solar panels in certain areas. (Kelly and Daouk, 2019)

Albeit that innovation is becoming more prevalent and required within all industries, the majority of freight is still transported via air, road and rail. The best use-case for this technology is found initially in freight as it allows for a robust stress test without human loss. Hence, all literature released focuses mainly on a freight based transport system with a phased rollout to passenger travel, VHO focuses on passenger travel more.

TransPod, another considered Hyperloop leader, focus on freight. The TransPod system details a bi-directional system capacity of 5 840 000 tonnes per year. The market size for this tonnage is far greater, thus suggesting a possible full capacity utilisation. The study from Copenhagen business school calculates that this system could remove 507 341 trucks annually from the network, equivalent to 12.5% of total trucking (Lachaize, 2017).

The Copenhagen study evaluated a transport corridor between Toronto and Montreal. The study shows how 392 783 tonnes of CO_2 can be removed by implementing Hyperloop, and it will amount to roughly 15.71 million CAD (Lachaize, 2017). As the literature indicated, congestion reductions endow a project with significant value. Considering the Time Value Savings (TVS) acquired from implementing Hyperloop, the study found that the Hyperloop system can allow TVS of 175.43 million CAD per year for the freight industry and the road user using this corridor can save 2 million CAD per year (Lachaize, 2017).

The current study investigated various trusted feasibility studies from consulting companies to ensure that this technology is feasible. A brief overview of the findings from each study to show the projected benefits from the Hyperloop system is presented below.

3.3.5.3 Hyperloop Feasibility studies

To date (2021), there are no large-scale implementation of a Hyperloop system. However, various entities are in the tendering process of implementing these systems, and one such party is the United Arab Emirates (UAE). The UAE has released a Hyperloop corridor tender between Dubai and Abu Dhabi (METenders, 2020). Hyperloop Transport Technologies (HTT) is another company with 12 commercial agreements to construct 10 km tracks. These projects are to be constructed in Abu Dhabi, Ukraine and China. The China location is confirmed in the City of Tongren (Rousseau, 2018).

Additionally, various feasibility studies have been requested to test the viability of these systems in specific corridors. Below are two central feasibility studies performed by consulting firms, AECOM and KPMG, and two case studies of the TransPod project designs.

AECOM Midwest VHO study

The study evaluates an 872 km-trip between (1)Columbus, (2)Chicago and (3)Pittsburgh in the USA (Lopez, 2020). Table 3.13 summarises the hyperloop travel data compared to the other modes and also the conclusionary findings. The study projects its evaluation from 2015 and forecasts to 2040.

*Table 3.13 - **AECOM Study Corridor Travel Time and Conclusions** (Author) (Adapted from Lopez, 2020)*

Corridor	Road Trip distance	Car time	Train	Plane @ ticket cost	Hyperloop @ ticket cost
(1) – (2)	573 km	5 hrs 20 min	11 hrs 4 min	1hrs 10 min @ $100	45 min @ $60
(1) – (3)	299 km	2 hrs 56 min	3 hrs 51 min	2hrs 50 min @ $150	30 min @ $33
(1) – (2) – (3)	872 km	10 hrs 1 min	8 hrs 41 min	N/A	80 min @ $93

Findings over 30 years	
Autos shifted to Hyperloop Passengers	1.9 billion
Commercial truck hours travelled eliminated	450 million hrs
Freight Benefits	336 million USD
Auto operational cost savings	983 million USD
Commercial truck operating cost savings	150 million USD
NPV of safety benefits	845 million USD
Environmental Sustainability benefit	126 million USD
State of Good Repair (residual value)	11.1 billion USD
Total Economic Benefit	300 billion USD

KPMG Stockholm-Helsinki Hyperloop study

The KPMG study evaluated a corridor between Stockholm and Helsinki, which amounts to a 500 km journey. The network has 11 stations and incorporates a sea track section. The total trip travel time with Hyperloop will amount to 28 min, compared to a plane journey of 3 hrs 30 min. The study evaluates the system from a cost-benefit, technical and legal aspect. The total project cost consisting of Capital expenditure (CAPEX), gliding stock, risk, overheads and allowances amounts to 19 billion EUR, of which 13 billion EUR is CAPEX. This amounts to 38 million EUR per kilometre. A saving of Time Value benefits of 25 million hrs per annum was found. (KPMG, 2016)

Thailand TransPod Hyperloop study

While the AECOM and KPMG study evaluated the system of VHO as external consultants, HyperPod released its in-house findings of its system. The Thailand analysis evaluates a route between (1)Bangkok, (2)Chiang Mai and (3)Phuket. Thailand has the third-highest road traffic fatality rate in the world. (TransPod, 2019a) Table 3.14 outlines the route specifications and reported savings.

Table 3.14 - ***Thailand Hyperloop Corridor Data and Results***
(Author) (Adapted from TransPod, 2019a)

Corridor	HL Trip length	Car ticket cost	Car time	Hyperloop @ ticket cost
(1) – (2)	590 km	48.36 USD	9 hrs 22 min	52 min @ 32 USD
(1) – (3)	725 km	59.33 USD	12 hrs 3 min	58 min @ 45 USD
(2) – (3)	1315 km	107.55 USD	20 hrs 22 min	88 min @ 78 USD

Findings	
Economic Rate of Return (ERR) = 13.8% Economic output = 31 B USD GDP Increase = 4.7% & 183 780 jobs created	
Corridor revenue by year 10	1 B USD/year
Corridor revenue by year 20	1.6 B USD/year
Corridor revenue by year 30	2.7 B USD/year
Time Savings by year 10	156 M hrs
Time Savings by year 20	206 M hrs
Time Savings by year 30	252 M hrs

Societal Cost relief by year 10	552 M USD/year
Societal Cost relief by year 20	1.2 B USD/year
Societal Cost relief by year 30	2.2 B USD/year
CO_2 curbed by year 10	1 233 025 tonnes
CO_2 curbed by year 20	1 621 946 tonnes
CO_2 curbed by year 30	1 989 700 tonnes

Alberta TransPod Hyperloop Study

TransPod also did an evaluation on the implementation of Hyperloop in Alberta, Canada. The study evaluated the implementation of the system in a phased approach. The study incorporates Phase One as the feasibility study and Phase Wo as the Research and Development stage, generating 61 permanent jobs and costs 7.75 M CAD in direct GDP/year. Phase Three is a 10-km-test-track where the construction generates 152 direct jobs and has a 32.9 M CAD impact/year. The test track operations will generate 69 direct jobs and allow for a 4.97 M CAD GDP impact/year. (TransPod, 2019b)

Table 3.15 summarises the findings of Phase Four, which is the final implementation of the full-scale project, linking up (1)Calgary, (2)Red Deer and (3)Edmonton.

*Table 3.15 - **Alberta Transpod Hyperloop Analysis Data and Results**.*
(Author) (Adapted from TransPod, 2019b)

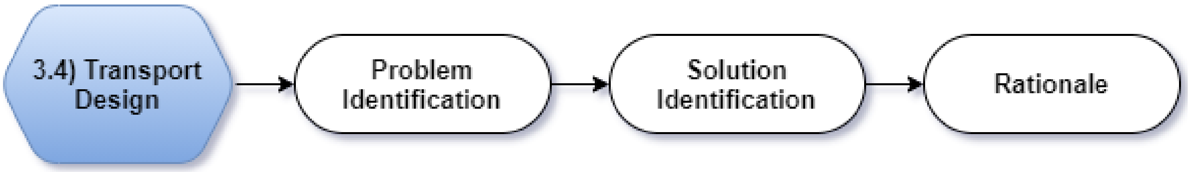
Corridor	**Trip length**	**Car time**	**Hyperloop**
(1) – (2) – (3)	301 km	3 hrs 11 min	27 min
Findings			
Construction direct jobs			14 530 jobs
Construction direct GDP impact			3.93 B CAD
Reduced CO2 emissions			400k tonnes/year
Road accidents prevention			300/year
Travel Time savings			1.5 B CAD/year
Revenues			1 B CAD/year
Possible EBITDA margin			52% for price/tonne-km
Trucks removed from network			472k trucks/year

Sub-Section Summary

From the literature it is seen that Hyperloop`s best use case is in freight and the added benefit of the system potentially running entirely from solar energy is favourable. The TVS potential of Hyperloop further improves its appeal which is evident with the increasing tenders being offered. From the case studies, it is observed that the savings and CAPEX figures suggest great prospects for this implementation.

Albeit not yet widely adopted, Hyperloop and autonomous EVs are starting to generate positive results and show good prospects of reaching economies of scale when implemented on large scale.

3.4 Transport Design



This section utilises the information and data gathered in section 3.3 to identify problems and formulate a proposal for the transport sector.

Improving transport efficiency of an urban setting can cause induced travel, a phenomenon where the improved mobility network can cause increased congestion (Rodrigue, 2020b). This is a result of the mobility network being perceived differently by the user due to its efficiency, which can lead to users wanting to use the network more, travel further or want private vehicles. There is a sensitive balance to achieve in how a city improves the urban mobility network. This framework details a design that aims to achieve sustainable transport. To define what this study details as sustainable transport, refer to Figure 3.48.

*Figure 3.48 - **Sustainable Transport Requirements** (Author)*

The transport system is categorised into a public transport network and a freight network. The challenges identified for the transport sector are summarised in the following section.

3.4.1 *Transport Problems*

The significant problems within the transport environment are summarised in Table 3.16. A section reference is added to show the point from which the problem was identified.

*Table 3.16 - **Transport Problem Identification***

Key problem	Intricacies
Pollutive modes of transport *(Section 3.3.3)*	The transport industry contributes significantly to climate change via the use of ICE vehicles. Moreover, road surfaces pollute rainwater runoffs, which then pollute rivers and also makes the harvesting of runoff water a complex and expensive task.
Congestion *(Section 3.3.2)*	The transport system experiences significant volumes of congestion that hampers economic growth and exacerbates pollution.
Underutilised Public Transport (PT) *(Section 3.3.2)*	Public transport after implementation were found to rarely meet conservative design utilisation rates. This leads to these public transport projects generating losses instead of revenues, which then requires government funding to rescue these services, such as was observed in the case of the UK railway system.
Damaged user experience of Public Transport *(Section 3.3.2)*	The problem with some public transport systems is identified to be that it is unsafe, unreliable and unprofitable. This leads to users opting to use other modes of transport, which typically result in private car use.
Public transport takes up one-dimensional space *(Section 3.3.4)*	There is a significant landmass occupied by transport infrastructure. This problem is compounded when the transport is only utilised for a short period of the day. The transport network today mainly utilises one-dimensional infrastructure.
Dated and degrading infrastructure. *(Section 3.3.5)*	The transport network infrastructure is degrading due to maintenance budget cuts and exposure to harsh climatic conditions. Moreover, the heavy-haul transport moving on the road network significantly degrades the road infrastructure.
Non-motorised transport is not being utilised. *(Section 3.3.1)*	Today's city is designed around the motorcar, and hence NMT is not provided for, nor is it incentivised.
Transport modes not part of the circular economy *(Section 3.3.3)*	ICE vehicles lose significant value over time and not enough of these vehicles are being recycled.
Significant road-based freight *(Section 3.3.1)*	A significant portion of freight is transported via the road network. Last-mile freight is not the problem; it is the intercity or port-city transport miles. By having significant road-based freight, it leads to increased congestion, pollution and road degradation.

From the identified critical focal points, the framework was able to identify the appropriate solutions presented below, both identified from the literature and inspired by research.

3.4.2 *Proposed Transport Solutions*

This framework proposes a hybrid network where both motorised and NMT transport modes are utilised. However, as synthesised from literature (Section 3.3.2), the network is designed with the pedestrian as the primary user and not designed around the motor vehicle.

Furthermore, this framework proposes a net-zero transport network that utilises clean, sustainable transport fuels. The scope stated that it does not focus in-depth on policies and regulations, which should be formed around this design. However, this framework requires a no-sale on ICE vehicles to be allowed within the city. ICE vehicles are allowed to navigate the city to ensure accessibility during the adoption phase of the city. However, these vehicles are charged a carbon penalty fee by the city. Below, the framework first outlines the freight system design and then the public transport network design.

3.4.2.1 Freight transport network

The literature presented the impetus impact that the adoption of e-commerce has had and still will have on the transport industry. With the significant increase in logistics and online purchases, the freight industry can seriously damage the transport network if not planned for properly. Rail networks are not being utilised to their full capacity as road freight is experiencing an increase due to its reduced cost and efficiency. Moving the road damaging and polluting freight to another mode requires a more efficient and cost-effective solution while still creating jobs. The proposed framework presents a hybrid solution, as it is unrealistic to demand a no road share, especially as last-mile deliveries will typically need to be done by road transport.

Moreover, this framework does not propose rail-based freight systems for urban products as this mode is identified by this research (Section 3.3.5) as not the best route for future prosperity. Table 3.17 present the solutions and their implementation methods outlined in this framework. The reasoning for these solutions is presented in the Rationale section thereafter.

Table 3.17 - ***Future City Freight Transport Implementations***

Freight Modes	Proposal
Hyperloop (HR) *(Section 3.3.5)*	HR is a high-speed, low-pressure transport mode that can run entirely on solar energy in specific locations. This allows freight shipments to be moved between cities and ports. In addition, this system is integrated with the passenger Hyperloop system.
Battery Electric Trucks (BETs) *(Section 3.3.3.2)*	BETs have to be utilised for mainly last-mile transport. However, these EVs are also allowed to do freight between cities and ports via designated transport tunnels. In addition, these vehicles are to recharge at distribution centres and strategically placed stations.
Fuel Cell Electric Semis *(Section 3.3.3.1.1)*	To ensure risk-sharing and not create a dependence on a single fuel source, this mode is implemented. Re-fuelling occurs at distribution centres and strategically placed stations.
Drones *(Section 3.3.4)*	Albeit a technology in its development phase, the technology is shown to work and be viable. The obstacle to adopting this mode is the cumbersome regulatory requirements. Drones are implemented to do last-mile deliveries only. These units are dispatched from distribution centres.

The public transport implementations that are proposed, which will move citizens in and about the urban boundaries, are presented below.

3.4.2.2 Public Transport Network

The proposed public transport (PT) network is the only transport allowed to operate above ground in the city centre inner ring, but this is discussed in more depth in the Layout Design section. Three of the most significant factors identified through the literature that hinder public transport adoption are safety, reliability, and accessibility. Public transport systems implement non-unified payment platforms, resulting in users having multiple metro cards or mobile applications, allowing a dreadful user experience and underutilisation.

Moreover, the current modes of public transport are not reliable, can be late and the statistics (Section 3.3.1) show these modes being unsafe. The issues mentioned before are alleviated by this proposed framework that focuses on TaaS. The public transport system in this framework generates revenue via an intelligent centralised system that utilises metro cards, e-tags and a scan to pay system.

The framework includes automation into the design as the technology is reaching full implementation, as research shows (Section 3.3.4) technology being close to Level 4 and 5 scale success. The modes of transport in this framework are initially implemented as Level 3 autonomy. However, the framework is flexible enough to adopt Level 4 and 5 autonomy. Table 3.18 presents the public transport solutions implemented in this framework.

*Table 3.18 - **Future City Public Transport Implementations***

Public Transport modes	Proposal
Electric BRTs *(Section 3.3.2)*	The literature showed how BRTs - if implemented correctly - can be successful and efficient. Hence this framework implements EVs. Excess energy during non-operation is allowed to be fed into the grid, and consequently these units are dual function, as they can also be used as mobile energy storage units.
Education BEBs *(Section 3.3.2)*	The literature showed significant utilisation of transport trips for educational purposes. This solution implements electric busses that transport citizens to education facilities. Excess energy during non-operation is allowed to be fed into the grid, and hence these units are dual function as they can also be used as mobile energy storage units.
Robotaxi`s *(Section 3.3.4)*	The Robotaxi fleet implemented is electric taxi vehicles that run on a centralised payment platform. Initially, most vehicles implemented in the fleet implemented are owned by the city and/or taxi industry, and dedicated drivers drive these vehicles. When Level 4 and 5 autonomy is approved, entities can contribute to the fleet by committing an autonomous vehicle to the fleet from which commission can be earned. The platform performs in a similar setup to the ride-hailing company Uber.
Hyperloop (HR) *(Section 3.3.5)*	In this instance, HR utilises passenger pods to transport passengers in the same lines as the freight network and vice versa. Thus, HR is utilised primarily for travelling within the city, but rather for inter-nodal travel. Moreover, HR passenger lines are utilised to transport users to the industrial sectors as described in the Layout section.
Autonomous district pods *(Section 3.3.4)*	Autonomous driving pods are implemented in commercial districts, business parks, or other districts with significant foot traffic. The concept is based on the same principle implemented at airports and amusement parks. It involves autonomous pods that drive below 10 km/h in a loop. Users can "hop on and off" as they want to move from A to B.
NMT *(Section 3.3.3)*	This framework includes infrastructure for NMT modes such as bicycles and walking. The goal is to allow for safe, efficient and attractive NMT routes.

3.4.3 Rationale for Transport Proposals

Throughout the literature, the study identified extensions of existing technology as a pitfall for future city transportation. Today, the transport industry uses technology already in existence for a significant period and uses historical trends to extrapolate what the future will hold. However, this extrapolated model assumes that the evaluated technology is utilised in future. Hence, the proposed design involves an extension or more extensive adoption of existing technology. Defined as an incremental change bias, this can lead to a transport network design that works based on past figures but does not work in future. This is evident when looking at the underutilisation rates found in the rail industry.

For the future city to have an effective public transport system, the system needs to have a user-friendly user interface with a good user experience that connects a great number of users to a multi-modal transport system. Furthermore, the system needs to integrate and seamlessly operated to instil trust and convenience.

3.4.3.1 Electric vehicles

Climate change is a genuine problem and engrossed in any future development design. The transport industry contributes too much to this global problem, while this framework reduces this impact. With more countries and cities starting to ban ICE-vehicle sales, it is illogical to plan for ICE vehicles in a project that will last for many years.

Moreover, EVs only have a 3% market share and hence have significant growth potential, allowing for significant economic potential to be attained. The beneficial economic potential is attenuated when considering the impact of these EVs' on the energy infrastructure. If inadequate energy infrastructure is paired with EVs, intensified grid problems can be caused. However, with efficient and well thought through infrastructure that has been designed with these technologies in mind, one can have an optimal operating system – which this framework implements.

From the literature (Section 3.3.2), it shows that the BRT system can be utilised beneficially. Making busses electric allows for the opportunity to reduce GHG emissions, improve energy security and allow for mobile emergency energy storage systems. One of the benefits of EVs is the reduced operation and maintenance costs involved, as fewer moving parts are present, no oil changes or engine services are required. This means that bus operators can more quickly and more cost-effectively resolve any breakages or issues.

The reasoning for implementing EV school busses is based on their operating times. Typically, school operating hours are from 08h00 to 14h00, creating a favourable scenario for bus to grid discharging. Peak electrical energy demand is typically founded outside these hours, which means that these units can use the excess energy on board to discharge into the grid. This bus to grid discharging allows for load demand alleviation. Moreover, EV busses allow flexibility and ensure easy transitioning over to autonomous driving.

3.4.3.2 Autonomous

The same reasoning for EVs counts for autonomous driving. The significant improvement in safety from autonomous vehicles shown in the literature (Section 3.3.4) would significantly improve the city's quality of living and safety. The implementation of automation addresses the congestion issues found in cities today. A fully autonomous system would not experience the effects of traffic jams, shockwaves and/or incident slowdowns. Moreover, implementing “Robotaxi`s” in the framework aligns the design with current and future trends. This implementation is one of the impetus factors that ensures a more democratised city.

Robotaxi’s in the scenario of full autonomy allow anyone to benefit from the revenue stream, allowing for profit sharing amongst the city residents. Robotaxi’s ensure the underutilisation of vehicles is attenuated as these units, instead of spending time in car parks, would be driving people around as part of the public transport fleet. This will also ensure fewer vehicles in the system and reduce parking space requirements.

Privately owned vehicles are disincentivised and are identified as leisure items. This, in theory, increases the accessibility of equitable transport to all at reduced costs. However, the research identified that autonomous transport is typically not favoured due to the fear of job loss. This framework identifies that up-skilling these workers is of greater importance. Moreover, autonomous transport creates an opportunity for passive income to be generated by these workers.

General efficiency and improved living implementations include the autonomous district pods, making public transport and city centres more accessible and attractive. This includes drone implementation to allow faster and more efficient last-mile deliveries from Hyperloop distribution centres.

3.4.3.3 Hyperloop

Hyperloop in this proposed design is implemented as a connection link between cities, rural areas and industrial zones. The Hyperloop system will not run extensively within city centres unless found to be viable in a circular loop of a significant circumference. Hyperloop utilisation for freight ensures that less damaging heavy-haul trucks use the road network, and freight delivery times are exponentially improved.

Literature was extensively scrutinised for the comparison of HSR and Hyperloop implementation. The rail industry has not generated confidence to build and operate a profitable system; hence, alternative routes were evaluated.

The decision to include Hyperloop instead of HSR is founded on three factors, energy efficiency, cost and operation flexibility. When considering Figure 3.49, one can see the difference in CAPEX per km of HSR vs. Hyperloop (in red box). The projects in the figure only consider tracks with no tunnelling. Hyperloop has many added case-specific benefits discussed in the Holistic Design.

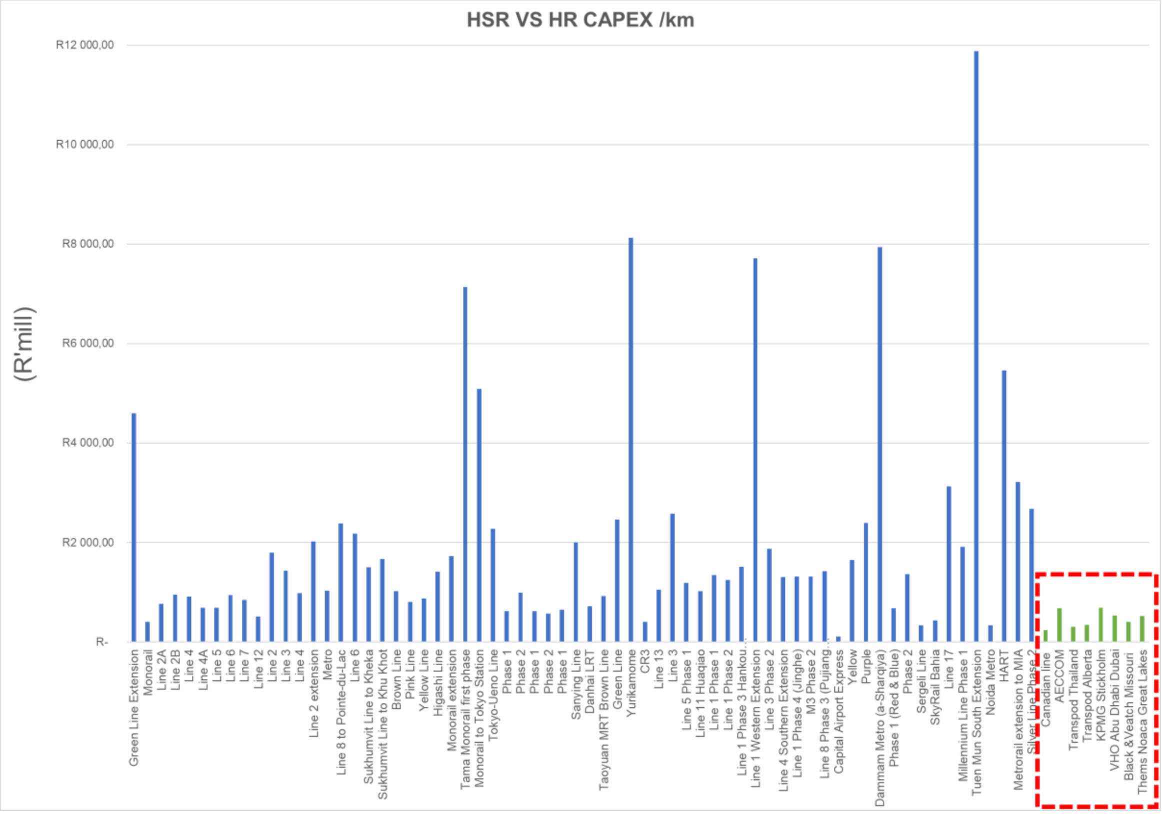


Figure 3.49 - ***HSR vs. Hyperloop CAPEX / km***

This study identifies added benefits in the energy efficiency and operation method of the Hyperloop system. Refer to the comparison matrix shown in Table 3.19, an adaptation from the TransPod feasibility study that represents various deciding factors that resulted in Hyperloop implementation in this proposed framework. One significant benefit highlighted from this system is the independence from environmental impacts. The Hyperloop system is designed to operate in any weather conditions and be tamper and disaster resilient.

*Table 3.19 - **Transport Mode Comparison to Hyperloop Matrix***
(Author) (Adapted from TransPod, 2019a)

	Passenger flights	HSR	Car	Bus	Hyperloop
Speed	Medium	Low	Low	Low	High
Frequency of departures	Medium	Medium	High	Medium	High
Fuel efficiency and sustainability	Low	Medium	Low	Medium	High
Energy efficiency	Low	High	Low	Low	High
Down Time performance	High	High	Low	Medium	High
Cost effectiveness	High	Medium	Low	Medium	Medium
Weather resistance	Low	Medium	Low	Low	High
Invasion or attack performance	Medium	Medium	Low	Low	High
Passenger comfort	Medium	Medium	High	Medium	High
Distance between stops for peak efficiency	High	Medium	Medium	Medium	Medium

	Air Cargo	HSR	Diesel Rail	Truck	Hyperloop
Freight Capacity	Low	Medium	High	Medium	Medium
GHG reduction	Low	High	Medium	Low	High
Location Flexibility	Medium	Low	Low	High	Low
Weather resistance	Low	Medium	Medium	Low	High
Reduced Cost per tonne/km	Low	Low	Low	High	Medium

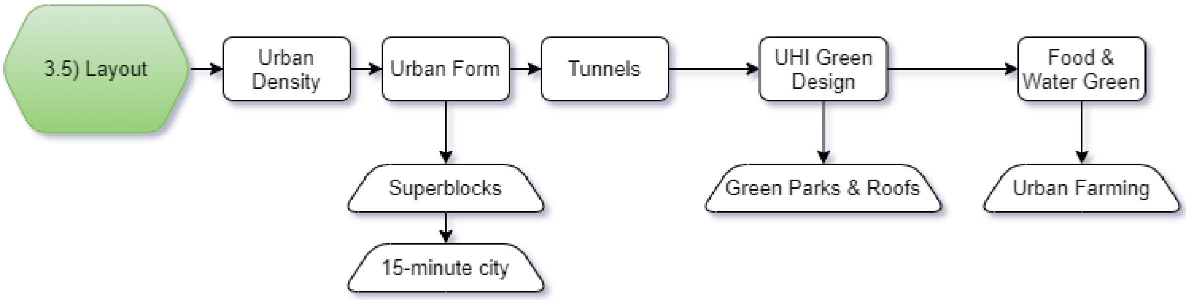
3.4.3.4 Non-Motorised Transport

NMT is proposed to be implemented as this improves living conditions, health conditions and disincentivises motorised transport. The literature (Nakamura and Hayashi, 2013; Hull and O'Holleran, 2014) showed how in locations, such as Copenhagen, Amsterdam and Asian cities, NMT could be utilised effectively, if the infrastructure supports it. A major limiting factor identified in already existing cities is that roads cannot accommodate the infrastructure for bicycles or walking paths (Hull and O'Holleran, 2014), as the roads were designed for the motor vehicle.

When NMT infrastructure is placed into existing roadways, it becomes unsafe and underutilised (Hull and O'Holleran, 2014). By building a city from the ground up, the NMT infrastructure can be designed for properly and hence utilised. NMT ensures residents stay active, resulting in improved personal health due to physical activity and reduced pollution levels. This framework incorporates areas where no vehicles are allowed, and some areas are designed as superblocks where no through traffic is allowed. Furthermore, the framework includes bicycles in the design that are safe and efficient. Walkways are demarcated for pedestrians, and pedestrians have the right of way.

By focussing on these implementations, a city design can ensure an efficient, equitable and environmentally friendly transport system. Parts of this transport network is qualitatively analysed in Chapter 8.2.

3.5 Layout Sector



This section presents the following key points regarding the layout of an urban environment:

- Effects of *urban density* on city efficiency, energy and climate change;
- Traditional and new *urban forms* implemented by cities;
- Incorporation of *tunnels* into the city infrastructure and its intricacies;
- Impact of *increasing temperatures* in urban areas due to climate change, as well as the foundational solution to this problem – *green space*;
- Utilisation of *food and water* security solutions such as urban farms;

The layout of an urban environment refers to the physical way infrastructure is built, planned and executed. This literature overview considers key urban layout concepts, such as urban density, urban geometric form, green design and coordinated design approach. The sections below present the intricacies that make up an urban environment form. The literature overview was used to gain an understanding of the layouts of current cities and how they can be improved.

3.5.1 Urban Density:

Thus far the literature has identified various urban network issues, such as congestion, inefficiency and population health. All these factors are impacted by urban density (UD). UD refers to the utilisation rate of a specific area in terms of persons per square kilometre or use-case per area (Berggren, 2017).

It is shown in this section that climate change is impacted negatively by low-density urban environments. It can be seen in Figure 3.50 that two areas of a similar population but with different densities can significantly impact the GHG emissions (Huang *et al.*, 2015).

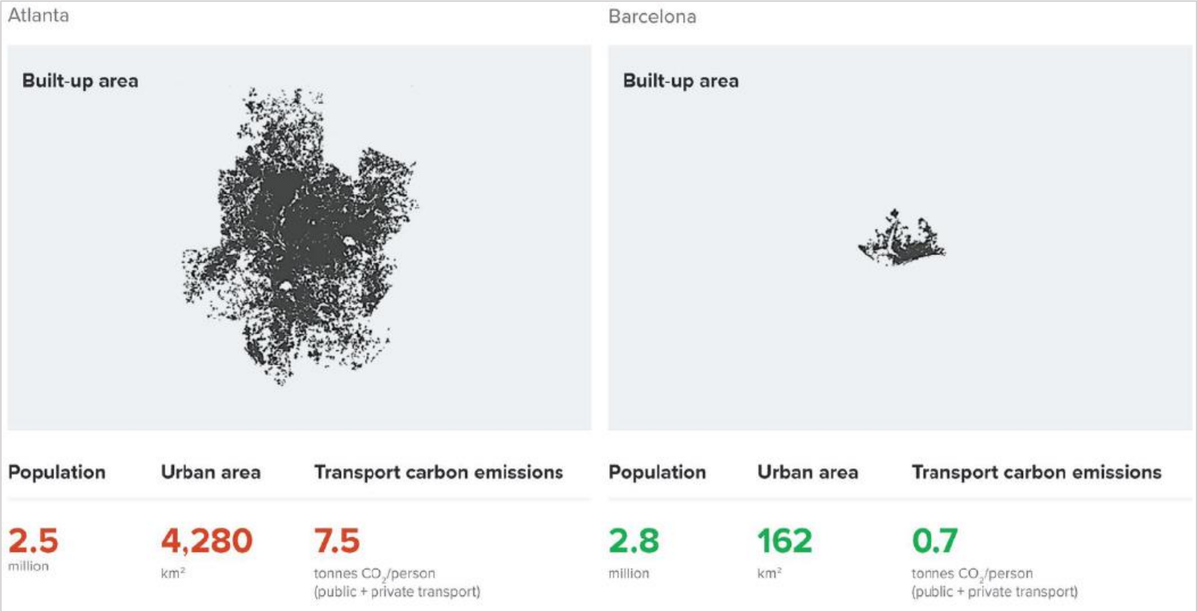


Figure 3.50 - ***Urban Populations Density Effect on GHG Emissions*** *(Huang* et al.*, 2015)*

The Chinese Development Bank capital report states how low-density urban settings have costed one trillion USD annually for the US economy (Huang *et al.*, 2015). The report concludes that urban sprawl is increased due to low density, resulting in per capita costs and per capita emissions increasing.

Huang *et al.* (2015) shows that a more densified urban setting results in an overall affordability improvement. A compact layout is identified as a vital characteristic of a sustainable city as it ensures efficient land use, protection of the environment and promotes biodiversity and food production sustainability (Huang *et al.*, 2015). In a compact city, infrastructure investment into freeways and extensive road networks are disincentivised. A compact city promotes public transport and NMT.

The City of Cape Town (CPT) is an example of how an uncoordinated approach and a disregard for dense spatial planning can create problems within the urban environment. CPT is a form of urban sprawl that has led to a spatial setup that is disproportionately set up both in terms of economic possibilities and social development. (Horn and Eeden, 2018)

It can be seen from Figure 3.51 how CPT is an example of reverse densification principles. The figure shows the difference between socioeconomic status and population density. From the figure, one can observe how almost 70% of the workforce working within the city, lives on the city's outskirts.

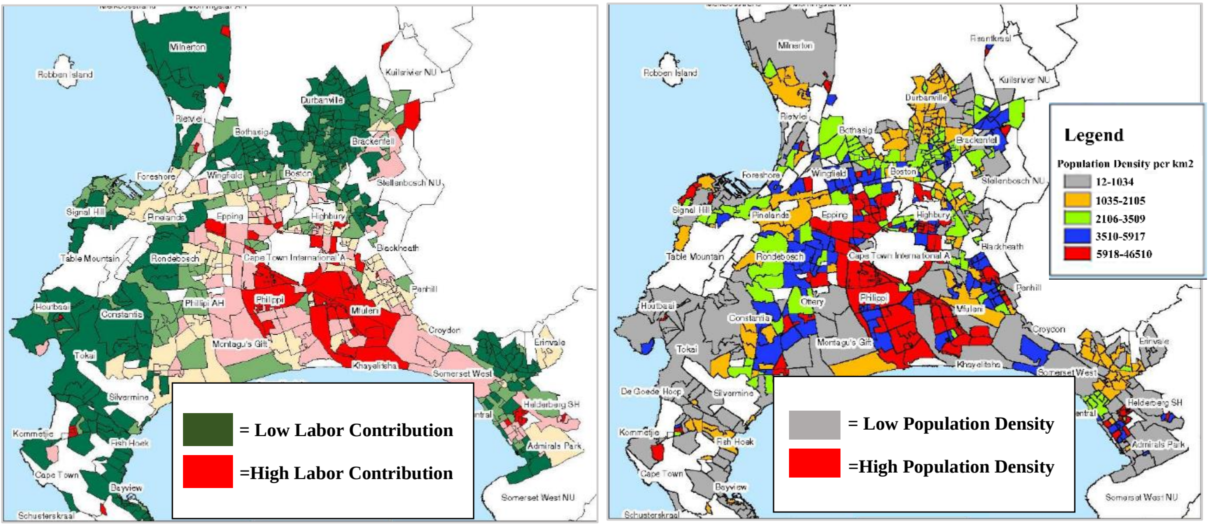


*Figure 3.51 - **CPT Socio Economic Index vs. Population Density** (Horn and Eeden, 2018)*

The report by the sustainability institute details a gross urban base density of 13 dwelling units (du) per hectare (ha) for SA, compared to the international minimum standard requirement of 25 du/ha for an efficient public transport system to operate (Ewing, 2007).

The low densification of cities affects various key metrics. Two such key metrics are the distance travelled by persons and the energy consumed.

A study from Curtin University presents a model (Figure 3.52), which shows the passenger km`s related to the density of a city, revealing how a higher density demands less passenger kms per capita (Kenworthy, 2006). Regarding the energy consumption of a city based on its density, Figure 3.53 from a report by CPT city using data from the Millenium Cities Database, shows the relationship between density and energy (Trollip *et al.*, 2011).

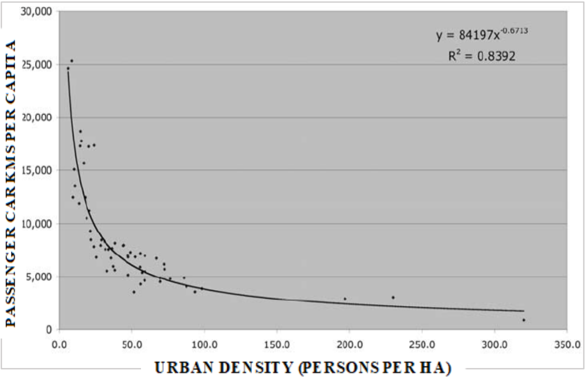


*Figure 3.52 - **Passenger kms per Capita vs. Urban Density** (Kenworthy, 2006)*

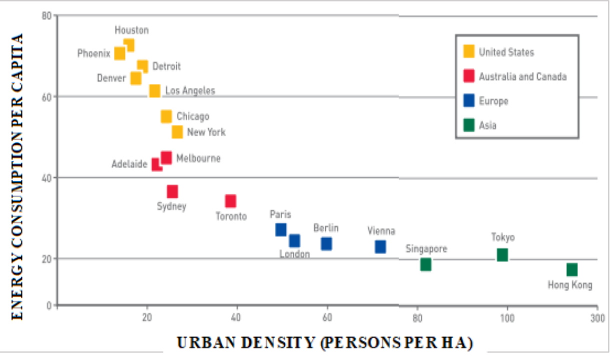
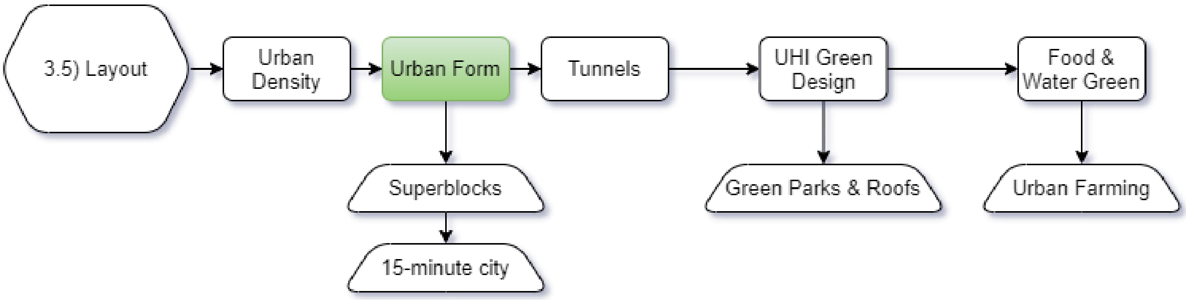


*Figure 3.53 - **Urban Energy Consumption vs. Population Density*** (Trollip *et al.*, 2011)

Sub-Section Summary

Hence, by densifying the urban area one can reduce travel distances and GHG emissions while saving energy, increasing affordability and improve accessibility to all, especially those working within the city and living outside the city.

3.5.2 Urban Form:



In the section below some components of traditional urban layout forms are kept and some new innovative urban layout forms that are proposed are discussed.

Various urban forms today exist partly in an attempt to help mitigate the density, energy and efficiency of urban settings. However, in recent years, the traditional square block system is being contested by cities as the system is just not meeting the needs of urban populations today (O`Sullivan, 2020a). Appendix D shows a collection of aerial photos of the traditional block grid system.

3.5.2.1 Traditional urban forms

The traditional outward expansion of urban areas has resulted in a low-density urban sprawl. Rodrigue (2020b) finds it concerning that large urban centres are averaging a decrease in density by 25%. This increased spread, which generates a requirement for increased travel times, makes it significantly more challenging to implement efficient and cost-effective public transport services.

The urban form of a city can vary in density, centralisation and interaction use-cases. Traditionally, the structured layout of an area is dependent on the use-case of that area. However, with the implementation of mixed-use, which is discussed later, these layouts cannot follow the same traditional layout. Figure 3.54 shows the main characteristics in which a spatial structure can be determined concerning placement and flow.

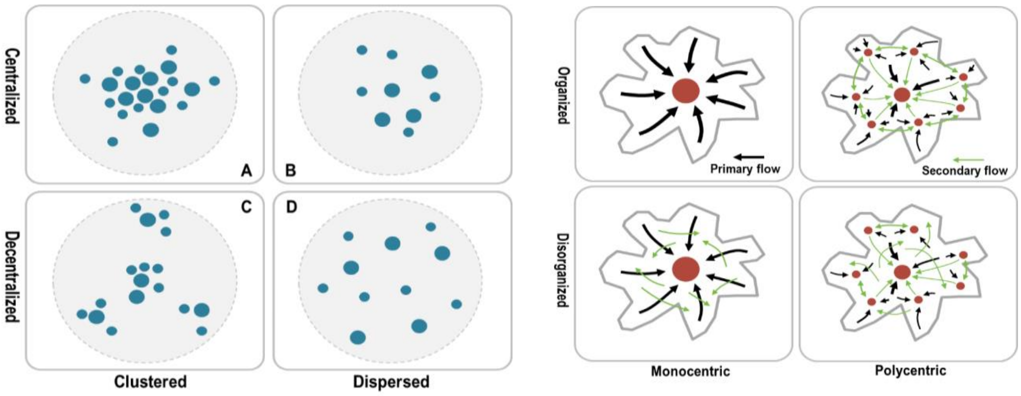


Figure 3.54 - ***Types of Urban Spatial Structures*** (Rodrigue, 2020b)

Figure 3.54 shows how urban space can vary but the core concept reverts back to working around a central node or hub. To ensure that this central point does not become a collection point for traffic congestion, one needs to efficiently plan the movement in the area.

A concept that is presented below addresses another congestion problem.

3.5.2.2 Superblocks:

Superblocks are used to redesign the spatial layout of cities. It was efficiently implemented in Barcelona and less so in China. The first working superblock introduced was in 2016 by Barcelona. The concept entails limiting specific routes for through traffic only, effectively creating a car-free environment. The concept disincentives the use of car ownership and promotes pedestrian traffic. This concept is now being considered for further expansion in Barcelona after effective test results were observed from the five neighbourhoods evaluated. (O`Sullivan, 2020a)

Barcelona implemented the superblock system after the city had severe health issues from air quality, recording deaths from air pollution amounting to 3 500 pre-mature deaths annually (Pérez *et al.*, 2009). Figure 3.55 shows the superblock system outlined in their urban mobility plan, which resulted in a liveability index increasing from 25% to 72% (Barcelona City Council, 2014).

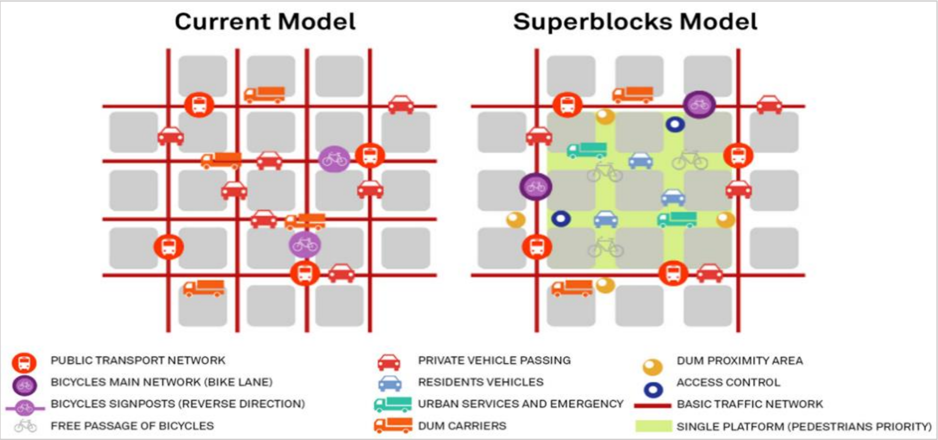


Figure 3.55 - ***Barcelona Superblock Design***

Since 2008, superblocks have been in Spain, in Victoria-Gasteiz city. The central superblock resulted in an increase from 45% to 74% in pedestrian space. Additionally, noise pollution dropped from 66.5 dBA to 61 dBA, Nitrogen Oxide (NO) emissions reduced by 42% and particle pollution by 38%. (Civitas.EU, 2013)

China also implemented superblocks, but where Barcelona utilises mixed-use areas, China only has single-use superblocks. These Chinese superblocks resulted in congested avenues due to the lack of available public transport in the area and the single use-case of residential property only. (Busch, 2013)

It is therefore clear that in order for superblocks to be implemented successfully, it has to be paired with mixed-use development.

3.5.2.3 15 – minute cities with a focus on mixed-use:

In contrast to traditional urban design is the 15-minute city (15-MC). Carlos Moreno first conceptualised the 15-MC on the principle that while the citizens traditionally had to adapt to cities, he states that cities should adapt to their inhabitants. The concept is that a city is designed in such a way that the user should be able to travel from A to B in 15 minutes via walking or via a 5-minute bicycle trip. However, within these 15 minutes, the user can access all the basic needs to survive – food, education, health, essential services and work.

The 15-MC concept, as released by Moreno, aims to rid the city centre of motorised transport entirely. Evidently, the concept is user-orientated and focuses on what resources are available locally, instead of designing the city around the motor vehicle and resources across vast distances. Moreno details critical principles of a 15-MC as ecology, proximity, solidarity and participation. (Moreno, 2020)

Figure 3.56 shows a concept of the travel distances of a 15-MC.

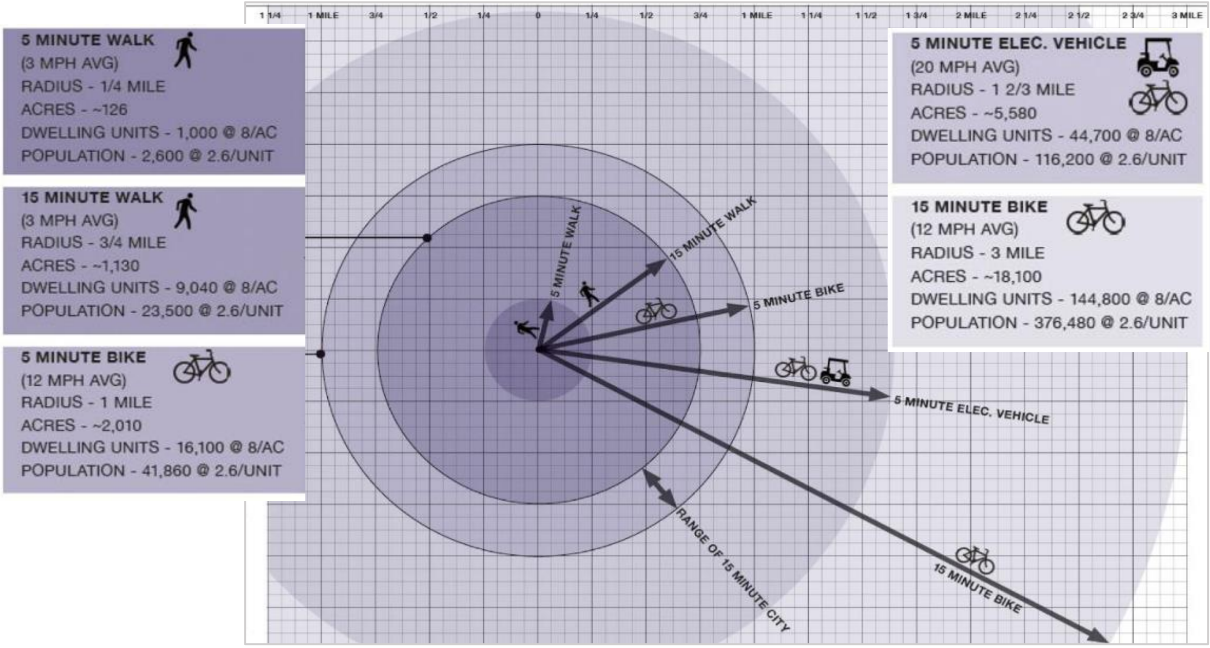


Figure 3.56 - ***15 Minutes City Travel Distances*** (Duany and Steuteville, 2021)

One of the key aspects for the viability of 15-MC is the implementation of mixed-use buildings. Mixed-use is a concept that describes the various use-cases of a singular area or building. Typically, buildings are built for one purpose, such as commercial, residential, institutional or industrial. However, mixed-use incorporates multiple of these property types into one. An example is when the ground floor is shops and the floors above are offices and residential units. Mixed-use ensures that users can comfortably achieve the 15-MC concept by having all their needs in close proximity. (C40 Cities Climate Leadership Group C40 Knowledge Hub, 2021)

A study by the Lincoln Institute of Land Policy explores the literature published on mixed-use extensively (Shen and Sun, 2020). Given the ambitious time limit of 15 minutes in Portland, Oregon, the city has set goals to change 90% of its city to have 20-minute neighbourhoods instead of an entire city. Similarly, the city of Paris aims to use 15-minute bike journeys as the limit. (O`Sullivan, 2020b)

Having the above-ground spatial form efficient and well laid out is one aspect of an urban form. However, many countries experiencing land space scarcities. One solution to this is to focus on a vertical use of space instead of horizontal.

The following section introduces the urban form proposed by the framework in this research. The concept from which the urban form is derived is presented below, an in-depth rationale is presented in Section 3.6.

3.5.2.4 Circular city

The circular economy concept was addressed in this research, however, a more literal interpretation led to conceiving this frameworks circular design as presented in Section 3.6. The circular city is a concept which is inspired by Walt Disney`s Epcot project (Figure 3.57) (Williams, 2020) which was abandoned and changed after his death. Moreover the circular concept is similar to how Baghdad city built their mosque location (Figure 3.58) (Wazeri, 2017).

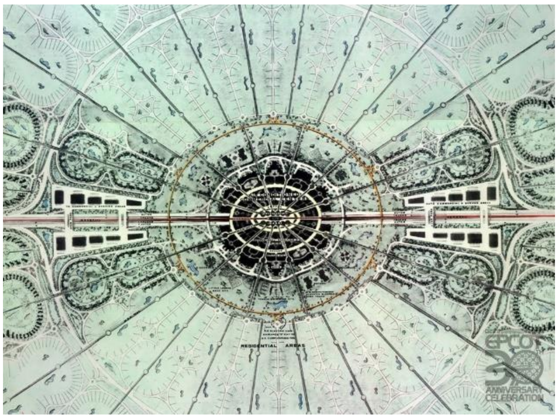


Figure 3.57 - ***Walt Disney EPCOT Project***

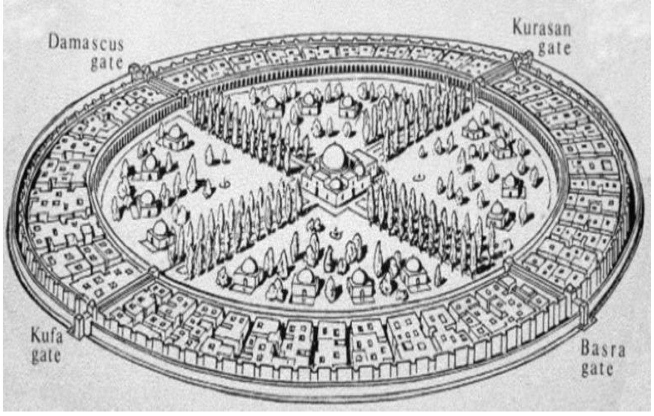


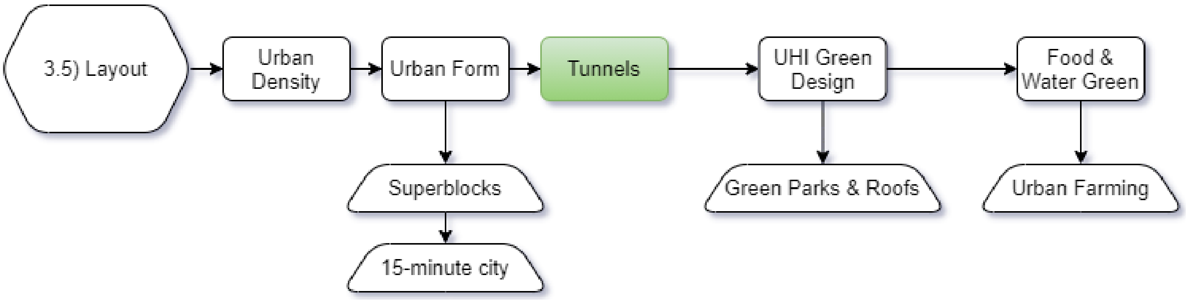
Figure 3.58 - ***Baghdad City***

Finally, concepts proposed by Helen Rosenau (Rosenau, 2013) and Ebenezer Howard (Gatarić *et al.*, 2019) represents similarities to that presented in this study. Albeit that the concepts were conceived in the late 1800s, it plays an influential role in the theoretical conceptualisation of the circular city.

Sub-Section Summary

From the traditional urban forms section, it is clear that cities naturally flow around a centre focus. From identifying the benefits of the superblock and 15-minute city approach, the circular city form is synthesised as the best housing form for these approaches. The circular city form was further investigated in Section 3.6.

3.5.3 Tunnels



Literature indicates that the population is increasing, while land surface area is diminishing. This creates a problem for urban developers aiming to protect the green environment, but also trying to provide more effective mobility while minimising land usage.

However, one solution being explored is expanding in 3-dimensions, and instead of expanding horizontally, cities could expand vertically. Cities in recent years have indeed expanded vertically upwards but not so much downwards. Tunnelling is increasing in adoption but still receives significant resistance. Tunnels are not a new concept and have been implemented for years for various use-cases. Most commonly, tunnelling has been implemented for sewage works and mining operations. (Benardos *et al.*, 2013)

Underground development is often not favoured due to its perceived high cost. This high cost, however, is only at inception. Underground structures have a less erosive and degrading operating environment than surface structures. Hence, the long term return on this large initial capital investment is suggested to be more than the solutions at surface level. (Prasad and Prasad, 2019) However, with land scarcity increasing, the hindrance of large initial CAPEX is alleviated, as there is no alternative solution than to grow vertically down and up.

Today, sub-surface construction is mainly implemented via three methods: cut and cover, drill and blast, or a mechanised boring machine. The advancement of tunnelling techniques has also been a great catalyst to the adoption increase and cost reduction. Traditionally, tunnels were constructed with manual labour. This method was time-consuming, costly and dangerous. It also had various limitations, such as tunnels not being able to be constructed in soft sand or within the water table. Hence, ideal conditions were required. (Arup North America Ltd, 2008)

With the development of the Tunnel Boring Machine (TBM), tunnelling has become increasingly more favourable, faster, safer and more flexible (Arup North America Ltd, 2008). Due to the improvements provided by the TBM machine, Herrenknecht AG – the world`s largest TBM maker – received TBM requests increasing from 20 annually to 100 projects annually in 2016 (Michaels, 2016). The President of the Metropolitan Transport Authority of Manhattan said that a 120-foot tunnel cost them 1 million USD per foot to construct manually and with the TBM a similar project three miles underground cost 19 000 USD per foot (Michaels, 2016).

The Cut and Cover method is typically used when the tunnel's roof is the ground floor or close to the surface. The TBM method is implemented for deeper excavations or when the surface has a pre-existing structure, making the cut-and-cover method unpractical. The cost of TBM Tunnelling is mainly influenced by the pipe diameter, length and soil material through which the TBM must bore (Rostami *et al.*, 2013).

Furthermore, a conference paper from GEO Montreal reduced the main influencing factors to diameter and geological properties, finding that the impact of length on per km cost is marginal, compared to these two factors (Benardos *et al.*, 2013). Figure 3.59 shows the relationship between diameter, geological conditions and cost.

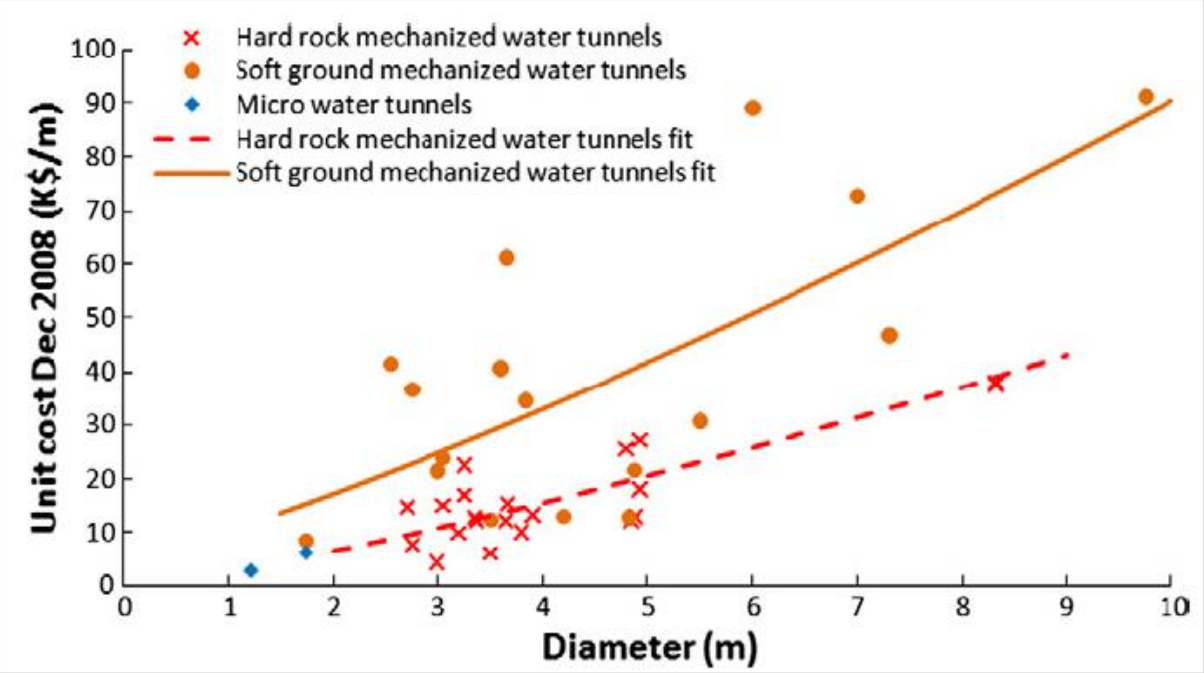


Figure 3.59 - ***Unit Cost vs. Diameter for Hard Rock and Soft Ground Mechanized Water*** - *(Rostami* et al., *2013)*

Tunnelling within an urban setting can be divided into two categories: for transport purposes and for utility services. Tunnelling frees up significant surface space and hence it is utilised in this framework.

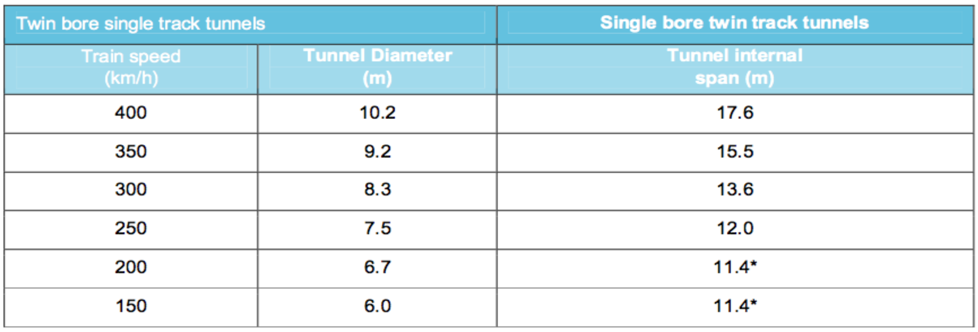
The following section investigates transport and utility tunnelling to get the largest benefit from going sub-ground.

3.5.3.1 Transport:

An analysis of California's capital city, Sacramento, shows the road pavement share of the total surface area of the city is 41% (Akbari *et al.*, 2003). This is a significant portion of the urban area which takes up space that has a single purpose. Some countries have started to see the viability of moving transport out of sight to the sub-ground. In 1863, the first London underground railway opened, advancing the exploration into sub-terranean networks. Today the implementation of sub-ground transport tunnels are becoming more accessible and more cost-effective with implementations, such as BIM, 3D technology and big data (Samsung C&T PR Manager, 2018).

Transport tunnelling is dedicated to the transportation of goods and people and typically implemented via train tunnels. However, trains require a specific diameter related to the operating speed to avoid an air block (suction plug) forming in front and around the train. The AECOM13 paper sets out guidelines for these values, as shown in Table 3.20. (AECOM, 2013)

Table 3.20 - ***Tunnel Size Requirement Based on Train Speed***



Twin bore single track tunnels		Single bore twin track tunnels
Train speed (km/h)	Tunnel Diameter (m)	Tunnel internal span (m)
400	10.2	17.6
350	9.2	15.5
300	8.3	13.6
250	7.5	12.0
200	6.7	11.4*
150	6.0	11.4*

To mitigate the cost problem of the large diameter tunnels, The Boring Co. (2020) has a potential solution to the sub-ground transport systems. The Boring company designs and implements tunnels with an inner diameter of 3.66 m. The solution is defined as an underground public transport solution. However, the company also has adaptations for freight, utility and pedestrian tunnels, all implementing the same pipe diameter. The company uses a TBM machine called, the Prufrock, and can bore - depending on soil/rock conditions - one mile per week, six times faster than the conventional TBM (The Boring Co., 2020; HS2, 2021). The public transport solution utilises autonomous driving EVs, which help reduce health and safety risks of tunnel transport and reduce the need for costly and maintenance-heavy rail infrastructure.

To date, other than its test track and R&D track, The Boring Company has one 2.8 km track built in Las Vegas, which cost 47 Million USD for the two tunnels and three stations. Compared to the closest alternative project of 6.4m diameter tube, 2.56 km in length and similar soil conditions, the bore cost alone of the Beacon Hill Tunnel costed 107.5 million USD per km. The Wesertunnel project with the exact same soil conditions, a tunnel diameter of around 11 meters costed 112.5 million USD per km to bore. (Arup North America Ltd, 2008)

However, albeit that the figures show promise, this solution and these figures challenge the norm, and hence receives significant criticism from industry experts (Farivar, 2021).

Sub-Section Summary

With the diminishing available surface area and roads taking up a significant portion of usable urban area, land is becoming more scarce. The perceived high cost of tunnels is reduced when considering the life cycle. TBM technology is rapidly improving and show possible cost reductions.

3.5.3.2 Utility

Utilities and services are typically buried in the soil sub-surface (Canto-perello and Curiel-esparza, 2013).

This means that if conduits or pipes need maintenance or replacement, the entire section needs to be excavated. With the various utilities and services used today, the complex network of cables and pipes is often referred to as "*the spaghetti subsurface problem*" (Luttikhuis and E.H.J, 1992). This spaghetti problem arose when rapid and cost-effective solutions were required during technology's advancement and increased urban populations (Canto-perello and Curiel-esparza, 2013).

This problem is intensified in European cities with narrow streets, which meant cables were buried on top of each other, increasing the meshed unorganised cable network (Canto-perello and Cano-Hurtado, 1999). This method of placing services and utilities makes it challenging to maintain and monitor. Moreover, it creates significant disruption within the urban area as roads often need to be closed off and/or traffic diverted. The open-cut method, which must be done every time, is significantly more difficult in urban centres and more costly (Stein and Stein, 2004).

A solution to this inefficient method of utility infrastructure housing can be found in utility tunnels - dedicated tunnels which host these conduits and pipes. However, to prevent a repeat of the spaghetti problem and creating an overpopulated network of utility tunnels, the Multi-Purpose utility tunnel (MUT) is implemented. A MUT is a singular tunnel that houses all the lines and allows for space to maintain, replace or add new lines (Alaghbandrad and Hammad, 2020). Figure 3.60 shows the concept of typical MUT layouts implemented.

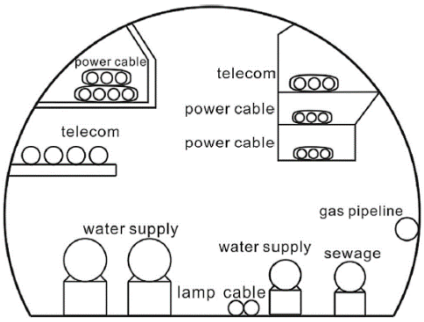


*Figure 3.60 - **Utility Tunnel Cross Sections** (Stein and Stein, 2004; Wang et al., 2018)*

Wang *et al.* (2018) found Japan and China to own the largest networks of utility tunnels. Wang also states that Japan has significant policies and laws for the appropriate implementation of utility tunnels. There is consensus in the literature that to build sustainable cities, underground infrastructure plays a vital role in the long-term view (Stein and Stein, 2004; Canto-perello and Curiel-esparza, 2013; Wang *et al.*, 2018; Alaghbandrad and Hammad, 2020).

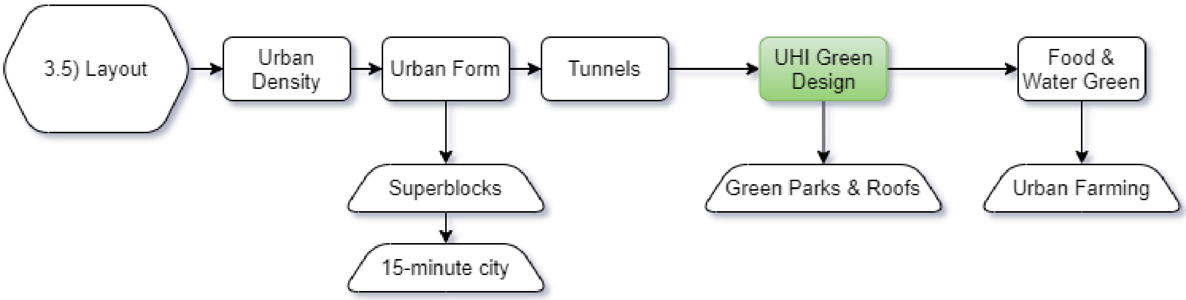
This consensus is as a result of MUTs offering protection from the natural environment, static loadings, groundwater attenuation, corrosion, theft and most of all; it provides an extended viable, useful life. The added benefit of easy maintenance and management makes it even more appealing. (Stein and Stein, 2004)

The inherent resistance to implementing utility tunnels is its initial cost, as with most of the solutions explored in the literature. The other risk often cited in literature is the regulatory framework and approvals required for this type of infrastructure. The above cited studies refer to it being easier and quicker to install buried lines. However, this framework considers a city built from the ground up, and hence these risks fall away.

Sub-Section Summary

The traditional urban form is not the best suited for how cities currently function. This is evident especially in the way utilities are still housed today. However, having the spatial form of an urban setting efficient is one aspect of the layout. With the focus on sustainability, the urban form also needs to be liveable and green in design.

3.5.4 Green Design Focusing on Urban Island Effect



Stemming from the root purpose to protect public health, city planning aims to reduce overcrowding and pollutants, however, the weakening of this purpose has resulted in cities being impacted by the effect of climate change the worst (Corburn, 2007).

Two critical parts of a liveable city are comfort and health. However, these factors have been attenuated by climate change with increasing temperatures. It is known that climate change has affected extreme highs and lows in climatic conditions. This is worsened within urban environments. A phenomenon called the Urban Heat Island (UHI) effect, is when cities experience elevated temperatures compared to surrounding areas, due to the lack of cooling sources and excess heating sources (Ruefenacht and Acero, 2017).

These heating sources are due to anthropogenic heat (AH), which is caused by human activities (Riegelbauer *et al.*, 2020). Cities are constantly heated by vehicles, electrical appliances, infrastructure surfaces and energy storing materials, while lacking the cooling effect of greenery and water bodies. Two of the most important contributors to the Urban Heat Island are dark materials (eg. asphalt) and dense materials (eg. reinforced concrete) (Akbari and Rose, 2007).

The weather-related disaster with the highest mortality rate is heat waves. Annually on average 12 000 deaths are recorded from heatwaves. The WHO estimates 260 000 deaths from heatwaves annually by 2050 ,if cities do not adapt. It is reported that during a heatwave 1°C temperature increase causes a 21% increase in the likelihood of death. (McDonald *et al.*, 2020)

Singapore is affected by UHI to the extent where temperature increases of 4-7 °C are experienced within the urban area (Ruefenacht and Acero, 2017). A study by Cooling Singapore recorded in 2016, a 171 TWh of AH of which buildings were responsible for 12% , and it is expected to increase to 28.3 TWh annually (Riegelbauer *et al.*, 2020). This increased urban temperatures cause air conditioning (AC) to be used more and at higher rates, further exacerbating the problem by increasing ambient temperatures.

In total, 60% of the 31% of electricity consumed by Singapore’s non-residential buildings is due to AC. All in all, 25% of Singapore’s electricity consumption goes towards AC (Riegelbauer *et al.*, 2020). A study conducted in Wuhan, China, showed how AC units used by residential properties caused a 2.56 °C increase in the air temperature (Wen and Lian, 2009).

The UHI effect causes severe mortality rates and with the higher temperatures, users use AC units for longer and at colder temperatures, significantly increasing pollution and energy demand from the electrical grid. On average, buildings already account for over half of the emissions of a city and typically 50% of a building’s energy use is dedicated to the HVAC system (Poon *et al.*, 2021).

The effect on energy demand and the environment from cooling within these warmer cities will be significantly more with the average summer temperature rise of 1.9°C and 4.4°C (Lombraña and Dodge, 2021).

Hence, reducing the UHI effect is of utmost importance in future cities, and some mitigation methods are already being explored as discussed below.

3.5.4.1 Green Space:

Green space is one implementation that reduces the effects of UHI. However, it also affects other factors in a positive manner. Increasing the green space within the city allows for cooling areas (Burden, 2006), increases oxygen production and CO2 absorption, improves general well being and health (Davies *et al.*, 2011), and improves property values by more than 7% (Clements *et al.*, 2013).

A study by Glatting Jackson and Walkable Communities shows how placing more trees within a city reduces the demand for air conditioning (Burden, 2006). The additional benefit green spaces can provide is reducing urban floods, as they absorb stormwater runoff. Analysis showed how increasing the tree count in Beijing reduced the government spending on rainwater control by 3.03 million ZAR in 2019 (Zhang *et al.*, 2012).

The beneficial effect on energy from green spaces within a city is put into perspective in a study of Atlanta. Reducing the need for cooling due to an increase in tree cover will reduce the CO2 content of the area, equivalent to removing 127 389 cars from the network (Frost, 2020). The beneficial impact of this improvement in air quality is presented in the C40 cities report. The report concludes that the maximum tree planting scenario, costing 3.2 billion USD annually, would reduce mortality from air quality by up to 8.7% and from UHI up to 5.6% annually. Additionally, reduce the electrical use of residential areas by up to 4.8% annually. (McDonald *et al.*, 2020)

A large body of work in the green space field that largely addresses the beneficial impacts of green space in urban settings, is that of Ebenezer Howard in his book - Garden Cities of Tomorrow (1898). The concept sets out planted or garden cities which has a goal of having urban settings where people live harmoniously with nature. The concept builds cities around a central garden and then incorporates encompassing green parks and hubs. (Gatarić *et al.*, 2019)

Green Roofs

Green Roofs is a method of placing green gardens on top of buildings. Buildings traditionally have large heat-generating HVAC systems atop together with open roof surface areas not being utilised. With green roofs, the building can utilise this surface to minimise heat absorption, delay water runoff by roughly 18 minutes and decrease the carbon footprint of the building. (Urban Espora, 2019)

A green roof study by Nadeeshani *et al.* (2021),found that the entire life cycle carbon footprint of green roofs ,construction of the roof included, amounts to 78.71 kg of CO2 per square meter per year .

Various literature sources show the benefit of green spaces, especially green roofs. In addition, the literature alludes to better health conditions; however, a study from the University of East Anglia pinpoints the critical health conditions reduced by green spaces as: heart disease, premature death, preterm birth, type II diabetes and also stress and high blood pressure (University of East Anglia, 2018).

A study focusing more on the beneficial impacts of reducing UHI through green roofs concludes that building surface temperature can be reduced by 15 to 45 °C by implementing a green roof (Ruefenacht and Acero, 2017). Further, the air temperature at ground level can be reduced up to 1.7 °C (Peng and Jim, 2013).

The concept of green roofs can be taken further by introducing vertical greenery, which is attached to the façade of the building. An evaluation in Singapore revealed that introducing green walls could reduce the energy cooling load by up to 31% (Hien and Chen, 2016).

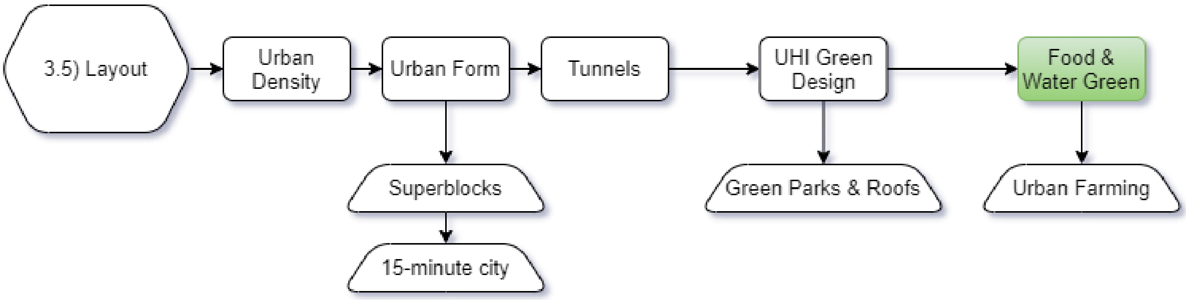
Work by Clements *et al.* (2013) shows the multiple beneficial impacts the usage of green roofs and space could have. The report also highlights the beneficial energy cost reduction generated from improved temperature insulation and anthropogenic temperature alleviation. The beneficial impact of reduced flood damage associated costs are also addressed in the report. Stormwater runoff is greatly reduced with increased porous surfaces such as green space. In turn, stormwater incident frequency is reduced and so are property damages.

Nurmi *et al.* (2013) also discusses the impacts of stormwater reduction by highlighting the alleviation of hydrological infrastructure decay by reducing the fluctuation nature of stormwater events. The study further also shows how green space can reduce pollutants in stormwater runoff, which further reduces the environmental impact of urban floods. The framework defines a goal to design a flexible framework and sewage systems are not very flexible as it is costly and time consuming to adapt the system to increasing quantities. Green space is another way to ensure a flexible city which can deal with fluctuating water flows.

Sub-Section Summary

Hence, green space is an option to reduced adverse city living conditions. Moreover, it allows for climate change alleviation ,mental health improvement and a flexible infrastructure approach.

3.5.5 *Green Design Focusing on Food and Water:*



Incorporating green into the urban environment through green parks and roofs is one way. Another way that attempts to alleviate the problem of water-, food- and land scarcity, are urban farms. More commonly referred to as Vertical Farms (VF) or Plant Factories (PF).

The world uses 50% of habitable land for agriculture, and in 2015, SA used 79.83% of its land area for agriculture (Roser and Ritchie, 2019). However, the concerning part of agriculture is the fact that in SA, 11% of the land area is arable, and of this, only 3% is truly fertile land. This results in agriculture using significant amounts of chemical fertilisers to grow produce (Greencape, 2020b). Figure 3.61 shows the historical data of arable land of SA compared to the World. Alarmingly, SA has been losing arable land.

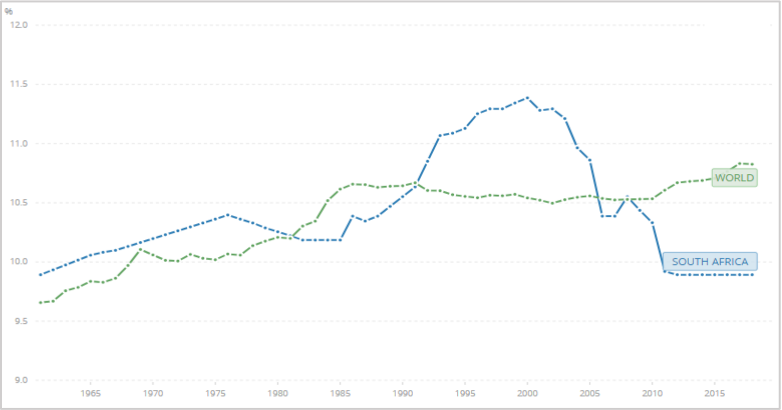
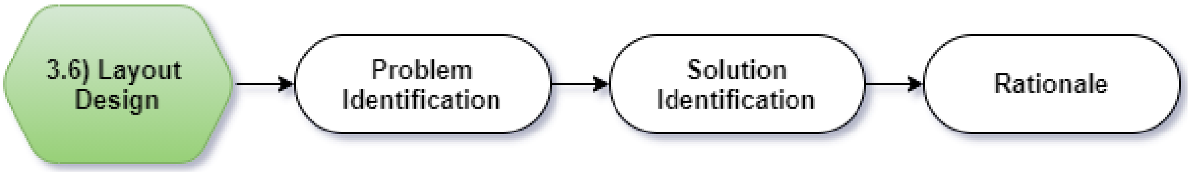


Figure 3.61 - ***Arable Land [% of land area]*** *(World Bank, 2018)*

Sub-Section Summary

The urban form is crucial to the synergistic efficiency of all its parts. The urban form houses the critical climate change alleviation tool, the green environment. Climate change can significantly be reduced via the urban form, but at the same time, urban flow can be improved while increasing liveability and economic growth.

3.6 Layout Design



As before (Sections 3.2 and 3.4), this section identifies problems from the layout literature to which solutions are proposed.

An evaluation of the literature shows that the three most critical aspects of a sustainable urban layout. Firstly, how much land a city utilises to house the population and economic practices. Secondly, how the city approaches the transport network plays an integral part in the layout. Finally, the bio-region influences the form of the city and concurrently, so is its citizens.

Hence, by implementing compact city planning, the city can plan for and incorporate green space, public transport and efficient NMT systems.

This proposed layout section of the framework is compact, efficient and designed for the pedestrian as the primary user. Moreover, the proposed framework incorporates more green space and changes the physical and structural layout of the urban form. The framework utilises UHI reducing remedies and reduces surface area wastage. The layout framework ensures a coherent design that utilises mixed-use and extends the concept to mixed societal living.

3.6.1 Layout Problems

Table 3.21 presents the layout problems identified from the literature researched. A section reference is added to show the point from which the problem was identified.

Table 3.21 - ***Layout Problem Identification***

Problem Code	**Key Problem**	**Intricacies**
P1	Car cities *(Section **3.5.2**)*	Cities are planned around the motorcar, which causes congestion, pollution, road deaths and generates wealth gaps.
P2	Low flexibility *(Section **3.5**)*	Cities are not flexible enough to adapt rapidly to market changes, pandemics and/or climate change effects. Moreover, this results in cities that are slow to adopt and implement new proven innovations.
P3	Urban sprawl *(Section **3.5.1**)*	Cities are de-densifying due to the rapid growth of urban populations. Cities are also energy sprawling due to urban sprawl. This leads to reduced energy accessibility, low density and unequal property values and segregation.
P4	Low density *(Section **3.5.1**)*	Cities with low density tend to show increased energy usage and urban sprawl leading to inefficient and wasteful land and resource use, a broken circular economy.
P5	User experience of public transport *(Section **3.5.2**)*	Public transport in current cities is inaccessible. This results from pickup and drop-off stations not being strategically placed as they were built where space was found. Public transport is unsafe and unreliable because the infrastructure is prone to attacks, vandalism or external environmental impacts.

P6	Non-Motorised Transport is not catered for *(Section **3.5.2**)*	NMT infrastructure in many cities is found to be lacking. In cases where cities do implement it, it is typically unsafe, unpractical or not utilised. This is because the location where this infrastructure is placed was not designed to accommodate such structures. This leads to, for example, bicycle lanes not being utilised as it is unsafe due to it sharing roadways with motorcars. Moreover, NMT is not always incentivised within cities, whether it be via monetary incentives or social benefits.
P7	Pollution *(Section **3.5.3**)*	Due to the majority of the transport fleet still being ICE-vehicles, air pollution and noise pollution are significant problems. This leads to reduced air quality and liveability within the city. Noise pollution becomes a significant problem in residential areas, which reduces the quality of living.
P8	Buildable area is reducing *(Section **3.5.4**)*	The rate at which urban areas are expanding reduces the land area available for infrastructure and further attenuates the natural green space available. Investigating Singapore and Germany, the significant impact of the reduced landmass is seen. This leads to the population needs not being met, such as housing due to lack thereof or elevated property prices.
P9	Parking lots not sustainable *(Section **3.5.2**)*	The amount of landmass taken up by swaths of parking lots is not sustainable for a use-case with only one function. Furthermore, parking spaces are typically one-dimensionally implemented, which utilises space inefficiently. This leads to valuable land mass loss, elevated UHI effects and green space loss.
P10	Arable land mass loss *(Section **3.5.5**)*	Due to the expansion of urban areas, agricultural area is being overtaken by the city infrastructure to accommodate the population. With the increased demand for food by the increasing population, more conventional farming takes up significant space. With the decreasing arable land available worldwide, the problem worsens when the population needs surpass the arable land available.
P11	Utility housing method. *(Section **3.5.3.2**)*	The current method implemented by the majority of cities for housing utility services is inefficient, unsustainable and not flexible. Having economic critical cabling and piping buried creates significant risks and problems. Maintenance of these services is costly and labour intensive. The method creates a disorganised and dangerous network of overlaying cables. Furthermore, the network is prone to sabotage and theft. When maintenance is done on these services in a city, it creates disruption, congestion and cost overruns.
P12	Urban Heat Island Effect. *(Section **3.5.4**)*	The UHI effect creates elevated temperatures within the city. This problem leads to an increase in energy consumption, which then leads to aggravated pollution. This leads to reduced health conditions and reduced liveability. Indirectly this affects the more significant problem at scale, which is climate change. The UHI effect is predominantly created by the lack of green spaces, excess of heat absorbent surfaces, and increased AC use.
P13	Urban floods *(Section **3.5.4**)*	Urban areas are more susceptible to flooding due to the lack of porous surfaces within a city. The problem is worsened worse by the lack of green space within the city centre. This leads to cities flooding more often, which affects health and safety.
P14	Water scarcity *(Section **3.5.5**)*	Due to the effects of climate change and the increase in consumption, water is becoming more scarce. Some cities, such as Cape Town, are coming close to running out of water. The urban environment catches significant amounts of water, but it is not harvested and utilised appropriately as would be found in a circular economy.
P15	Food scarcity *(Section **3.5.5**)*	The demand and supply of food do not meet each other and reducing arable land is a significant problem. In addition, climate change is affecting food supply chains and food security. Imports and exports of food are at risk of international tensions. Leading to increasing food prices that further amplify the inaccessibility of food. Furthermore, food supplies are increasingly at risk of diseases and pests.
P16	Food transport miles *(Section **3.5.5**)*	The time and distance to get produce to cities are significant. With an average of three days spent on the road, the fresh produce loses nutrients and lifespan. Resulting in increased food wastage and reduces ease of access to food.

3.6.2 Proposed Layout Solutions:

From the problems identified in Section 3.6.1, a framework layout design presents a solution that follows the concepts shown in Figure 3.62, all of equal importance.

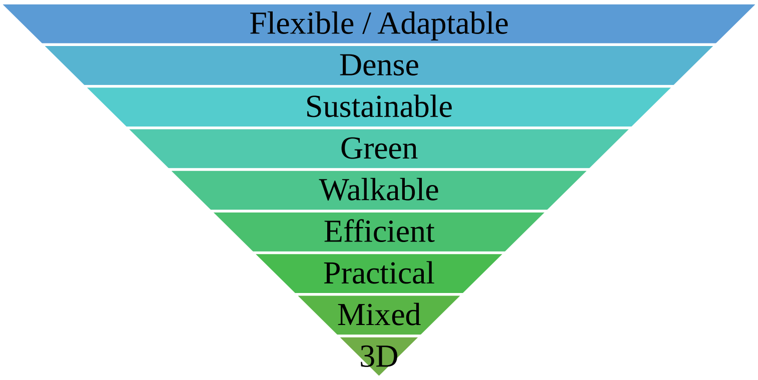


Figure 3.62 - ***Future City Layout Principles*** *(Author)*

The framework used these guidelines to choose and adapt the most appropriate solutions for the components of the framework. In Table 3.22, the solutions identified from research under section 3.5 are presented. They are divided into four main focus areas. However, the urban form implementations are difficult to conceptualise simply from the table. Hence, a more in-depth elaboration on the urban form follows in the rationale section 3.6.3.

Table 3.22 - ***Layout Future City Proposed Solutions***

Solution Code	**Layout Proposal**	**Description**
	Urban Form	
S1	Circular *(Section **3.5.2.4**)*	The city is constructed in a circular shape. The structure is made up of concentric rings with pre-defined property zone types.
S2	Central core *(Section **3.5.2**)*	The centre of the circular layout is the hub for all city offices, major commercial entities and central transport hub. Moreover, it should house leisure and entertainment facilities.
S3	Inner three zones *(Section **3.5.2**)*	These inner three zones restrict specific modes of transport or activities to occur within these zones.
S4	Sub-segments *(Section **3.5.2**)*	The circular layout is divided into segments, which on its own, can function to some extent as an independent town. These segments are to be constructed and populated to the predefined capacity, before moving to the next segment.
S5	Industrial nodes *(Section **3.5.2**)*	Industrial nodes are smaller circular nodes separated from the central city, but linked to the main city with dedicated transport lines.
S6	Repeat ring *(Section **3.5.2**)*	The repeat ring is the portion that extends to the urban development boundary line that is predetermined during planning. The city is not to be allowed to expand past the urban boundary line. However, the repeat ring could allow the inner rings to be repeated as the need demands.
	Densification	
S7	Densify *(Section **3.5.1**)*	Densify the city by planning to build within a three-dimensional space that utilises both skyscrapers and earth scrapers.
S8	Mixed-use *(Section **3.5.2.2**)*	Buildings are required to have more than one function: Commercial, residential, retail, office, leisure etc.
S9	15-min bicycle city *(Section **3.5.2.3**)*	The 15-min bicycle city is implemented in this design and is ensured to be achievable by the mixed-use approach. The framework ensures that the user can fulfil all their basic living needs within a 15-minute bicycle ride.

S10	Superblocks *(Section **3.5.2.2**)*	In residential rings, the superblock method is implemented while still utilising the mixed-use approach. The centre of each superblock should be considered a residential area (“woonerf”), which restricts traffic and utilises significant green space.
	Mobility	
S11	The mobility layout form follows the circular city design in that it is also constructed in rings. The underground mobility network can vary from case to case depending on the geological conditions. This framework proposes signalised roundabouts at all major intersections. Where traditional urban transport conditions require reasoning for implementing a roundabout over an intersection, this framework requires reasoning for when a signalised intersection is implemented over a roundabout.	
	Above Ground	
S12	Core *(Section **3.3**)*	The core includes the city centre and extends to the first green belt. The core allows mobility modes only to the following modes: • Battery Electric Busses • Autonomous Pods • Non-motorised transport • Last-mile deliveries are allowed by electric trucks between 00h00 and 04h00.
S13	Ring 1 *(Section **3.3**)*	From the boundary line of the core, this ring extends to the second green belt. Ring 1 limits mobility modes only to the following modes: • Electric busses • Non-motorised transport • Robotaxi`s • Privately owned EVs (+Congestion fee) (Phased out as autonomous Level 5 is reached) • Medium electric delivery vehicles • Last-mile deliveries are allowed by electric trucks between 00h00 and 04h00. Moreover, parking towers are placed on the outskirt where vehicles can park. The Robotaxi fleet are proposed to have dedicated parking facilities.
S14	Ring 2 *(Section **3.3**)*	This ring extends from the boundary line of Ring 1 to the initial urban boundary line for phase 1 development. Ring 2 allows mobility modes to the following modes: • Electric Busses • Non-motorised transport • Robotaxi`s • Privately owned EVs • ICE-vehicles (+Heavy carbon fee) • Electric Trucks Moreover, parking towers are placed on the outskirt where vehicles can park. The Robotaxi fleet is proposed to have designated parking facilities. In rare cases, on and off-street parking is provided.
S15	Ring 3 *(Section **3.3**)*	Ring 3 is the same as Ring 2. It does not adopt the superblock structure. This ring allows gated communities and low-density suburban areas. This ring should have significant property tax to disincentivise this low-density type of utilisation.
S16	Industrial node *(Section **3.3**)*	The industrial node utilises electric vehicles.
	Below Ground	*(These tunnels are not to be limited to a specific sector ring)*
	Parking	
S17	Core *(Section **3.3**)*	The central core is proposed to have basement parking available at a substantial fee.
S18	Rings *(Section **3.3**)*	The rings have underground parking facilities placed on the outskirts.
S19	Superblocks *(Section **3.3**)*	Superblocks have underground parking.

S20	Bicycle parking facilities *(Section **3.3**)*	Automated bicycle parking tanks can be implemented throughout the city. These systems store bicycles underground and retrieves them when the user returns. Bicycles can be rented from the system.
	Tunnels	
S21	Freight tunnels *(Section **3.5.3**)*	A freight tunnel system is proposed, which is to be used solely by freight. Large commercial buildings can have a basement delivery depot. Strategically placed inner-city distribution centres (DC) should be implemented to supply deliveries to the building without basement depots. A major distribution centre is proposed be implemented underground in the core. Medium-sized EVs can do the deliveries from the DCs during the day.
S22	Small medium vehicle tunnels *(Section **3.5.3**)*	A tunnels system is implemented solely for citizen mobility and small delivery vehicles. Both Robotaxi's and personal EVs can utilise these tunnels but no ICE vehicles are allowed.
S23	Utility Tunnels *(Section **3.5.3**)*	These tunnels are implemented throughout the city and house the critical services of the city. These include, but are not limited to, electrical cables, fibre optics, water mains, sewage pipes etc.
	Hyperloop	
S24	Core station *(Section **3.3.5**)*	The hyperloop core station is a station placed within the core hub. From here, users can utilise the hyperloop network to go and come from other cities, go to the industrial node and/or other stations.
S25	Ring 1 and 2 stations *(Section **3.3.5**)*	On the outskirts of these rings, stations can be placed to allow access to the hyperloop network. Users can utilise the hyperloop network to go to the industrial node and/or other stations.
S26	DC stations *(Section **3.3.5**)*	DC stations are utilised to insert freight pods directly into the hyperloop network.
S27	Large loop *(Section **3.3.5**)*	If the radius of the city becomes significant, a circular loop track is implemented to allow for ease of access to other parts of the city.
	Rail	
S28	Rare underground tube *(Section **3.3.5**)*	This framework proposes a last resort implementation where an underground rail tube system is utilised in cases where Hyperloop is found to be unfeasible.
	Green	
S29	Green roofs *(Section **3.5.4**)*	Roofs not covered by solar infrastructure entirely should utilise green roofs. The property owner can determine the design of the green roof, but it is advised to ensure that rainwater harvesting is incorporated. All city-owned buildings are required to implement rainwater harvesting. In addition, some properties could implement a combination of solar panels and green roofing.
S30	Green parks + belt *(Section **3.5.4**)*	The city is to implement strategically placed green parks throughout the city. Tree canopies can then cover the majority of pedestrian walkways. Moreover, a green belt is placed between each zonal ring, which is a park that completes the entirety of the circumference.
S31	Reflective surfaces *(Section **3.5.4**)*	Throughout the city, where greenery cannot be utilised, reflective materials should be used to alleviate heat capture. Preferably Titanium Oxide coatings are implemented, which helps with carbon capture. Surface roads and pathways must be either white, green or any light colour. The use of black and grey are to be restricted as far as possible.
S32	Cooling towers *(Section **3.5.4**)*	Cooling towers are tall columns placed throughout the city that extract warm air via air ducts. This warm air is mist cooled with rainwater and released via outlets placed at ground level. This should be implemented on days of sweltering temperatures. These towers operate from solar energy. This implementation can be left out in areas where temperatures do not exceed 32°C.
S33	Urban farms *(Section **3.5.5**)*	Urban farms are placed between rings 1 and 2 in each segment. These farms grow mainly leafy greens, vegetables, fruits and short grains. They have an underground DC that connects with the freight tunnelling system. They should also utilise drone deliveries when the technology gets approved for use within city boundaries.

3.6.3 Rationale for Layout Proposals

The complexities discussed previously is visually presented in the followings section. Moreover, this section provides a rationale for the implementation chosen. To summarise the proposals discussed in this section:

- A physical circular formed city
- Branching nodal zones and nodal cities with dedicated property zone types.
- Predefined development zones or “rings” which ensure efficient use case operation. Each with their own mobility requirements and restrictions.
- An urban development boundary to control urban sprawl.
- Multiple sub-sections which divide the layout up into smaller fully functional parts.

Due to the extent of the layout section, throughout the section the problems (in red) identified in Table 3.21 are referenced, as well as the respective proposed solutions (in blue) from Table 3.22, to said problems.

3.6.3.1 Circular Design: {P1 ; P2 ; P3 ; P4}

A circular city design {S1} is proposed to alleviate congestion and ease of flow in the urban network. The circular design, other than being inspired by the design of Walt Disney, is chosen based on the safety and efficiency observed when implemented as a roundabout.

The Transportation Research Board (2010) guidelines show how a roundabout has fewer conflict points than that of a conventional intersection in Figure 3.63. From this important characteristic of roundabouts, a circular city ensures efficient and safe flow.

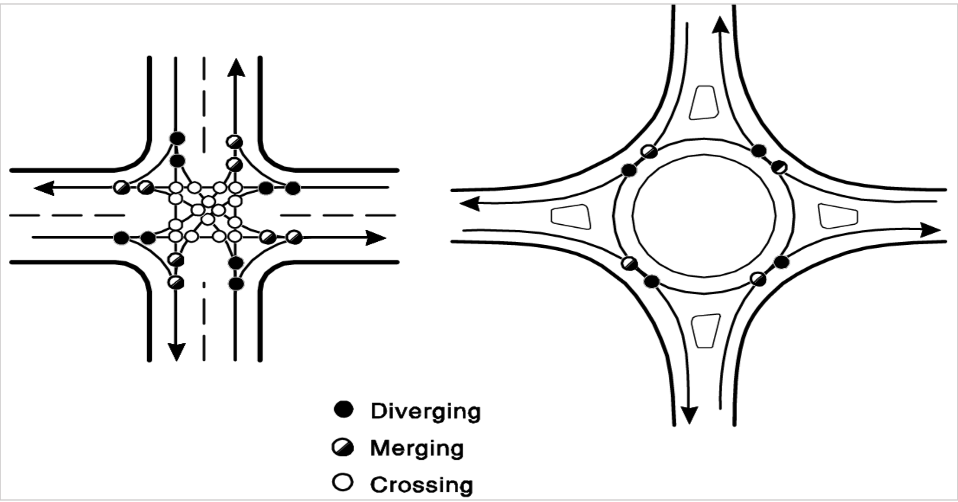


*Figure 3.63 - **Roundabout Conflict Points** (Transportation Research Board, 2010)*

A circular flow ensures reduced congestion and travel times. Refer to Figure 3.64 for a visual analysis of how this circular approach ensures faster travel times than traditional city intersections. This visual analysis is an investigation which could be done as part of a full traffic study.

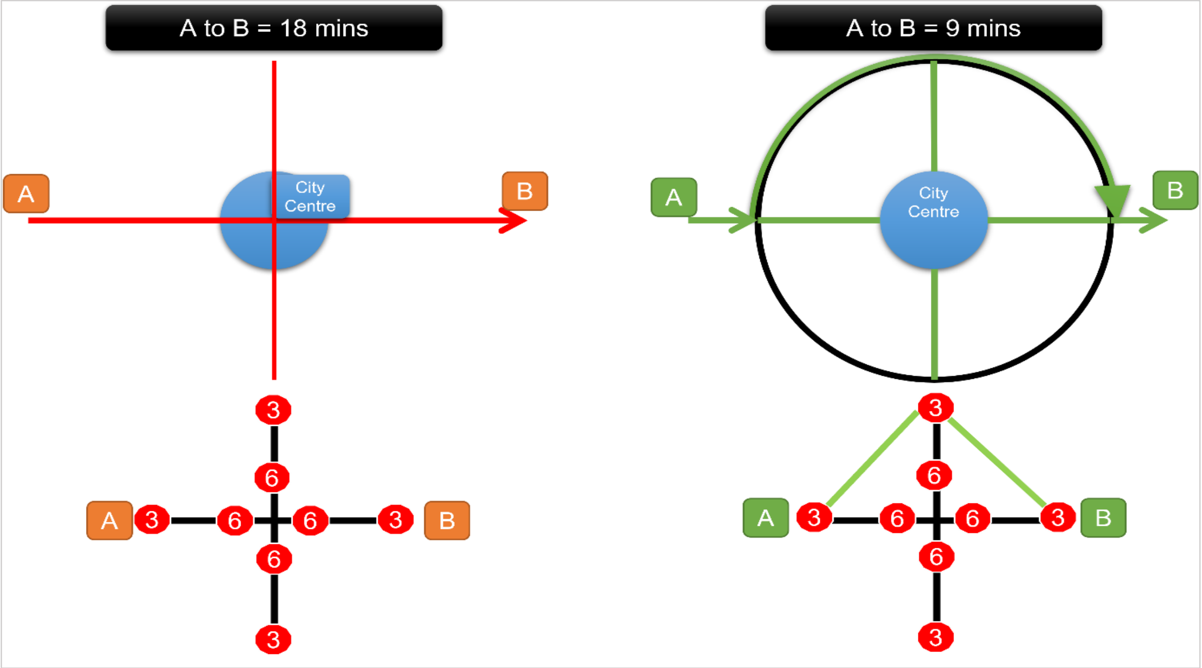


Figure 3.64 - ***Travel Time Through for Circular City Centre*** *(Author) (Method from Uchida and Kato, 2017)*

Typically, a roundabout would reach a throughput capacity point from where a signalised intersection would be more efficient. However, the Transportation Research Board (2010) shows in the roundabout guidelines, how increasing the diameter of a circle with an additional lane improves the maximum entry and circulatory flow of a roundabout. This framework ensures a significant continuous entry and flow in its network.

Moreover, this framework implements signalised roundabouts {S11} on the main roads, which can increase throughput of conventional roundabouts during peak hours.

3.6.3.2 Nodal Layout: {P2 ; P3}

The proposed framework consists of circular nodes and zones {S5} which interlink and have specific property zonal types. In the literature, it was identified how property zones become mixed with industrial zones due to urban sprawl (Section 3.5.1) in conventional city layouts. This framework avoids the overlapping of zones by defining maximum development lines and setting out industrial nodes. As a result, each Ripple City should have an industrial zone, which is restricted within a defined boundary. When more industrial land is needed, a new industrial zone can be formed. The proposed concept is shown in Figure 3.65.

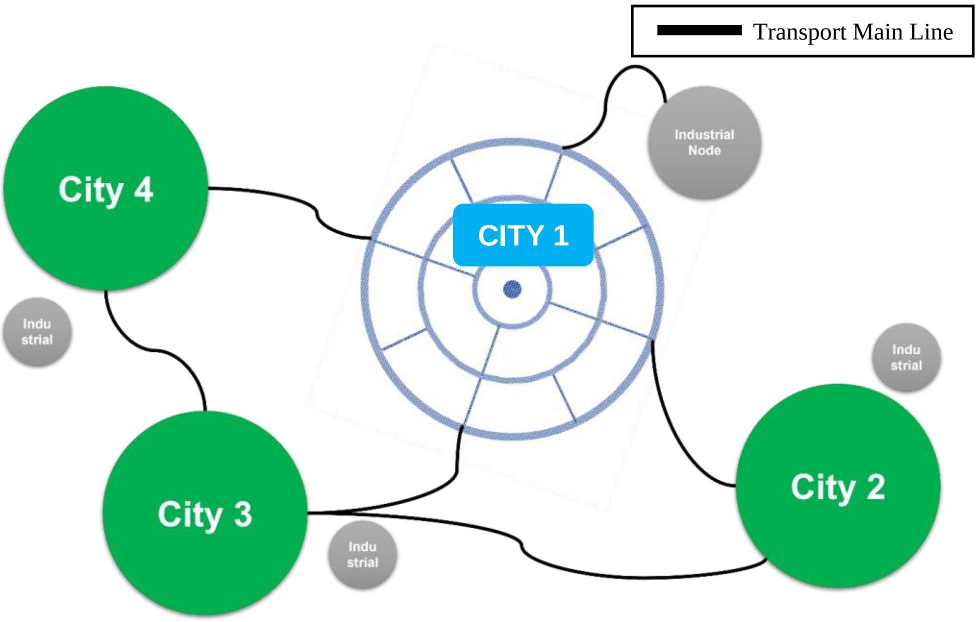


*Figure 3.65 - **Ripple City Nodes** (Author)*

New circular cities can be constructed nearby, which repeat the ripple layout. These repeat nodes are implemented when the main city reaches full development or when zones reach full development.

3.6.3.3 Development zones: {P3 ; P8}

Due to the circular nature of the framework design, the cities are divided into circular rings {S3} and a core (Figure 3.66). The core{S2} will be the central business and city management hub.

These rings should prevent urban sprawl within or beyond the urban line, as there is a fixed property type planned for future development.

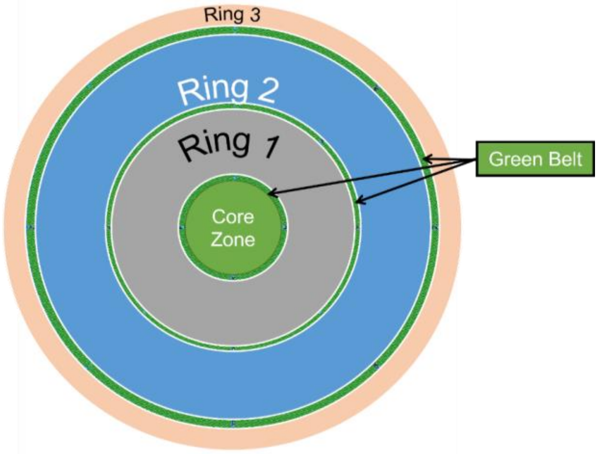


*Figure 3.66 - **Ripple City Inner Zonal Rings** (Author)*

Future expansion is planned for, for when the circle is completed. This expansion occurs within the repeat ring, as shown in Figure 3.67. This ring could be a repeat of any of the other rings to account for demand. However, the repeat ring is to be bounded by the maximum urban development line. Therefore, any development required past the urban development line should lead to the formation of a repeat nodal city.

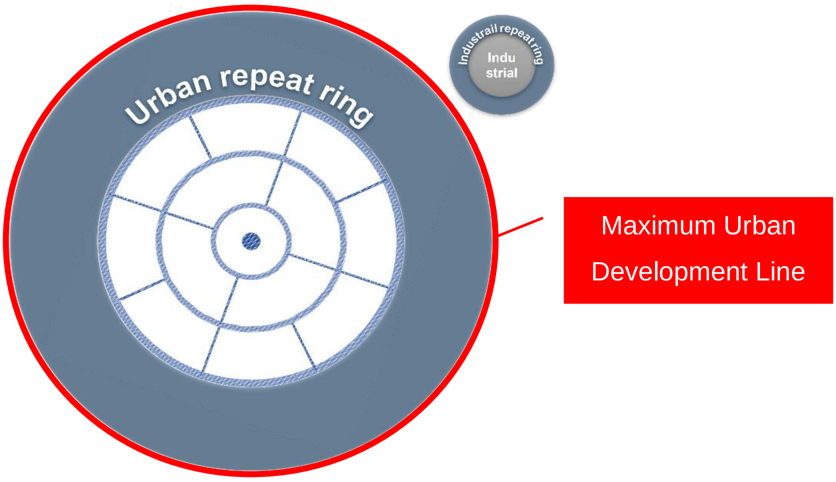


Figure 3.67 - ***Urban and Industrial Repeat Rings*** *(Author)*

3.6.3.4 Sub-Segments: {P2}

The circular city is proposed to be divided further into multiple sub-segments {S4}, as shown in Figure 3.68. For a smaller city, these segments can also be reduced as shown in Figure 3.69. The purpose of these segments is founded in their logistical and redundancy nature. These segments can operate as independent towns, with all its basic needs and requirements within the segment. Moreover, from a constructability standpoint, these segments allow for a reduced period between the end of construction and occupation. Each segment is proposed to be constructed in its entirety before expanding to the next segment. This is considered controlled urban sprawl.

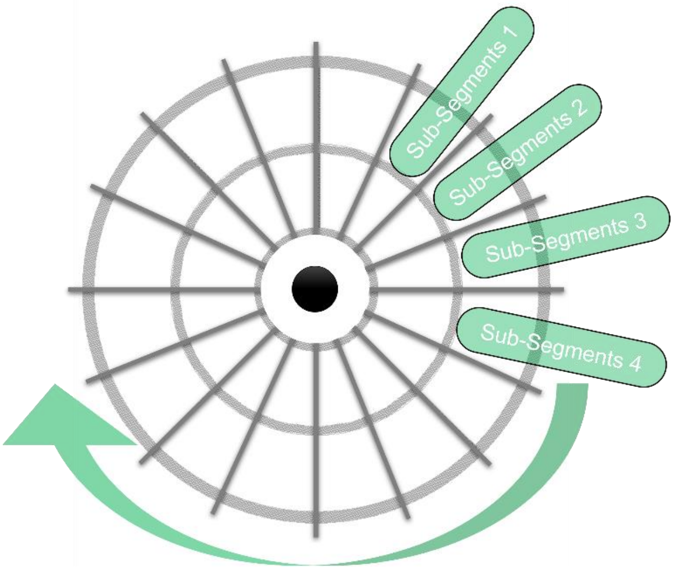


Figure 3.68 - ***Sub-Segments Large Scale*** *(Author)*

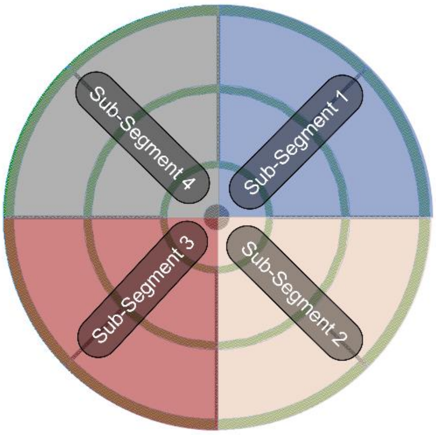


Figure 3.69 - ***Sub-Segments Small Scale*** *(Author)*

These segments improve the flexibility of these cities in the event of a pandemic where lockdown rules need to be enforced. These segments can lockdown on their own and adapt to the residents within the segment.

These segments also ensure that elevated property values are not experienced as there is a pre-defined knowledge of what each ring would house and what type of properties would be found there.

Another key logistical benefit of this approach is its adaptability nature. As the sectors expand, the following segments can quickly adopt newfound technologies and solutions without overhauling the existing city. Moreover, from research (Section 3.3.2), it was seen how construction projects often, when conceived, was achievable, but on completion, the solution was not the best fit anymore. This is because of the duration of infrastructure construction. By allowing a test segment to start operation, one can adapt the approach from lessons learnt and from the increase in data available.

As stated in the section 3.2, these segments can also behave as independent micro-grids with sub-microgrids. This allows for redundancy, flexibility and security. Moreover, it eases maintenance and renewal projects. The proposed micro-grid structure is shown for one segment in Figure 3.70. Additionally, the setup is shown for how the framework integrates the significant number of solar solutions into the grid.

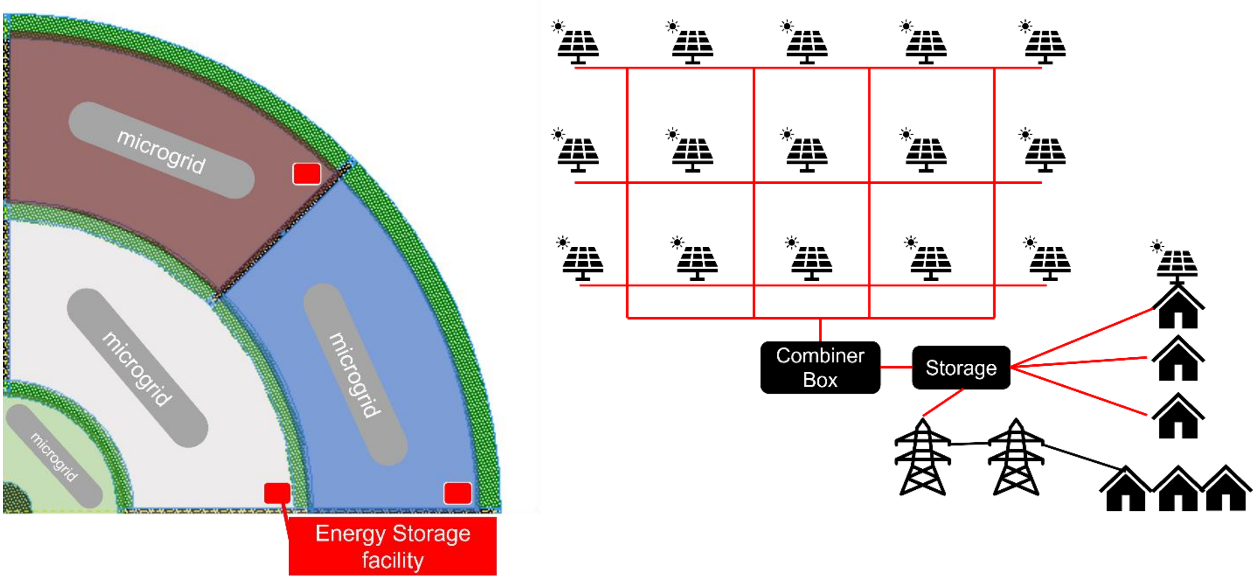


*Figure 3.70 - **Microgrids and Solar Microgrid** (Author)*

3.6.3.5 Densification: {P 3; P4 ; P7 ; P8}

In the literature (Section 3.5.1), it was identified that the density {S7} of a city affects the key aspects focussed on by this framework, namely health, energy use, mobility modes and efficiency. Resch *et al.* (2016) shows how density improves the modal share of NMT in high-density urban areas. In addition, dense cities are shown to use less energy consumption, which inadvertently creates fewer carbon emissions and has better UHI control (Riegelbauer *et al.*, 2020).

Densification can, however, not work as intended as seen from China`s superblocks (Section 3.5.2.2). Therefore, mixed-use adoption is a vital part of the success of densification. The success of the compact mixed-use approaches in Stockholm, Helsinki, Zurich and Freiburg (Kenworthy, 2006) is one of the key reasons for this framework proposing the same approach.

Mixed-use {S8} ensures that the 15-min city {S9} is achievable, as there is a more extensive mix of different property types in a set area. Hence, by implementing mixed-use buildings and superblocks {S10}, this framework ensures the most efficient land use.

The literature described a New Climate Economic Report study that stated that more dense cities can reduce capital costs by up to 15 trillion USD over 15 years, – if paired with mass public transport adoption (Zelin, 2014). This is supported by Allianz (2015) whom finds that the sustainability of future cities is founded in its compactness.

3.6.3.6 Development Zones

Table 3.23 presents a summary of the problems addressed by the solutions proposed within the development zones. The table also gives a summarised rationale for the proposals. For an expanded rationale, refer to Appendix E.

Table 3.23 - ***Development Zones Rationale Summary***

Zone	***Problem Addressed***	***Solution(s) Proposed***	**Key Rationale**
The Core	***P1***	*S8; S9; S12; S17; S20*	• Promotes NMT • Improves proximity accessibility • Places the pedestrian as the primary user and ensures their safety. • Moves vehicles out of sight • Generates revenue • Provides for decongestion
	P4	*S7; S8*	• Increases density • Makes the density liveable and practical
	P6	*S9; S12; S20*	• Promotes NMT • Ensures safe NMT trips • Increases accessibility to bicycles
	P7	*S9; S7; S12; S24; S29; S30*	• Reduces pollution from ICE vehicles • Density reduces pollution
	P9	*S12; S17*	• Above ground prevents vehicle usage • Ensure efficient use of land area for parking
	P12	*S29; S30; S31; S32*	• The prevention of heat absorption • Active cooling occurs
	P13	*S29; S30*	• Absorbs and slows stormwater runoff
Ring 1	***P1***	*S13; S18;*	• Incentivises public transport
	P4	*S8; S9*	• Ensures density is liveable and practical
	P7	*S7; S9; S13; S29; S30*	• Removes ICE vehicle emissions • Improves carbon sequestering

	P9	*S13; S18; S20*	• Safe, efficient and reduced area wastage
Ring 2	***P4; P9***	*S8; S10; S14; S19*	• Improves density, accessibility • Ensures adoption
	P10; P14; P15; P16	*S33*	• Improves food accessibility
Ring 3	***P7; P12***	*S15; S18*	*Similar to Ring 1*
The repeat ring	***P2; P3***	*S6*	• Improves accessibility and adaptability
Nodes	***P3***	*S5; S16*	• Improves accessibility • Ensures known property values

3.6.3.7 Tunnels: {P1; P8}

The framework proposes a tunnel mobility network to use landmass more efficiently, to reduce unsightly public views and to improve pedestrian safety (Section 3.3.1). Implementing a sub-surface mobility network, makes the network more adaptable and expandable (Section 3.5.3).

Tunnels are also less affected by the exposed environment's wear and tear effects, hence, mobility can continue to operate under any climatic conditions (Section 3.5.3.2). The socio-economic benefits of tunnelling include no surface disturbances from noise or vibrations, and communities are not segregated by road infrastructure above ground.

This framework sets out two methods of tunnel creation to be decided, based on the case where the city is implemented. Due to the city being constructed from the ground up, in regions where geological conditions favour the cut-and-fill method, it should be utilised. The literature (ATTINÀ *et al.*, 2018) identified a case where developing countries can pay less for a cut-and-fill option where the surface is linearly flat.

Cut-and-fill in already built cities are disruptive and expensive. This option is only proposed in the initial construction of the city. The TBM method is proposed in locations where deeper excavations need to be utilised or expansion is required.

Freight Tunnels

The framework proposes a dedicated tunnel system for freight and large haul vehicles {S21}. The rationale for this is to ensure that these vehicles do not cause delays or congestion in the other tunnels. Moreover, the infrastructure for these vehicles requires extensive maintenance and costs, which are underutilised by small vehicles if they use the same roadways. Furthermore, the ideal implementation of the freight tunnel system is an automated system that moves freight on skates as per the design of the Boring Company (The Boring Co., 2020).

Small vehicle Tunnels

The literature informed how the diameter of pipe infrastructure significantly impacts the cost per mile (Figure 3.59). Therefore, small vehicles {S22} are given their own transport network to avoid these elevated costs, that demands smaller diameter tunnels.

Utility Tunnels: {P11}

A significant problem, identified through this research in conventional city layouts, is the method of housing services (Section 3.5.3.2). The “spaghetti network” is a severe problem which this framework elimenates by proposing utility tunnels {S23}. Utility tunnels are easily accessible by operators (Wang *et al.*, 2018), which ensures fast and easy maintenance replacement or addition. Moreover, it allows for immediate problem or breakage identification.

Socio-economic benefits arising from utility tunnels are no surface disturbance, no unsightly excavations or materials leaking to where people live and work (Section 3.5.3.2). The rate at which economic expansion can occur with these tunnels is also improved. Consider the slow rollout of fibre lines (MyBroadband, 2018), which is a key role player in successful economic development. The rate at which fibre lines can be installed into these tunnels is improved by order of magnitude, mainly because municipalities, who are the main reason for causing restrictive implementation, can now generate housing revenue (Canto-perello and Curiel-esparza, 2013; Zhang *et al.*, 2019).

Furthermore, it creates an attractive revenue model for the city, which can charge utility services housing costs. Utility services are charged this fee for a safe and accessible environment. Literature showed (Stein and Stein, 2004) these services having longer viable operational lifetimes due to reduced environmental impacts and theft degradation. This allows for a better ROI over the long term.

3.6.3.8 Hyperloop system: {P1; P5; P6}

Hyperloop sub-stations {S24; S25; S26} are to be placed in each sub-segment between Ring 1 and 2 as shown in Figure 3.71. Albeit that hyperloop is better suited for long distances, lane changing has been developed for this technology. Pods can split off from the mainline and dock at stations placed closer to each other without disrupting the speed of other pods in the system (Kelly and Daouk, 2019). However, the Hyperloop network is catered to inter city travel, freight and passenger distances greater than 25km – the average work trip from outside CPT to inner CPT.

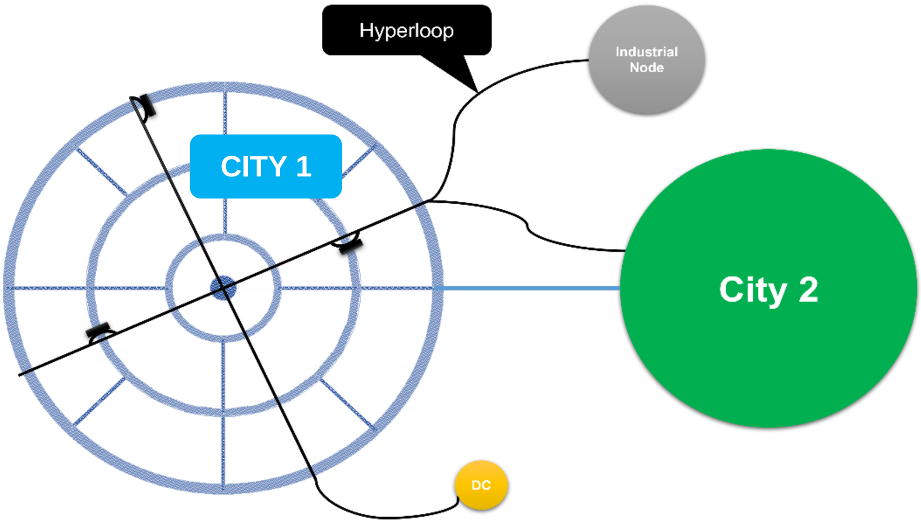


Figure 3.71 - ***Hyperloop System*** *(Author)*

The framework proposes these sub-systems to help alleviate the congestion in the central hub station while allowing for easier access to the network across the city. By combining this system with the Robotaxi system, users can easily access the stations.

Linking other nodal cities and nodes with the Hyperloop system, ensures that distance restrictions are alleviated. In addition, this ensures that the city has exponential economic growth as the time to travel is significantly reduced.

Visual summary of mobility levels

Figure 3.72 presents the cross section of traditional mobility infrastructure. Figure 3.73 presents the future city mobility cross sectional structure, as discussed in the previous sections.

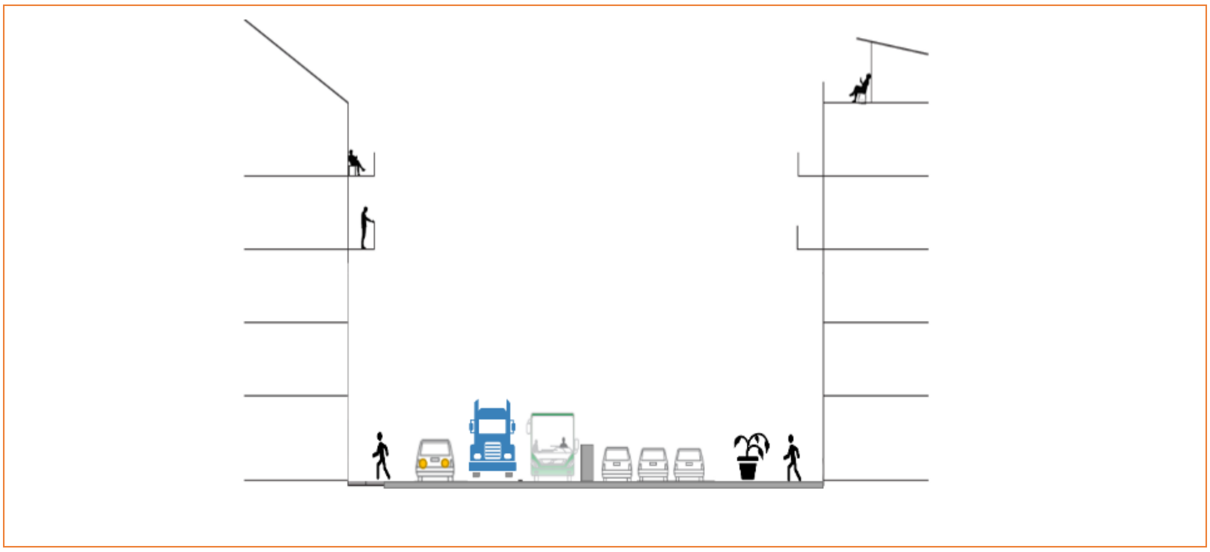


Figure 3.72 - ***Traditional mobility cross section*** *(Author)*

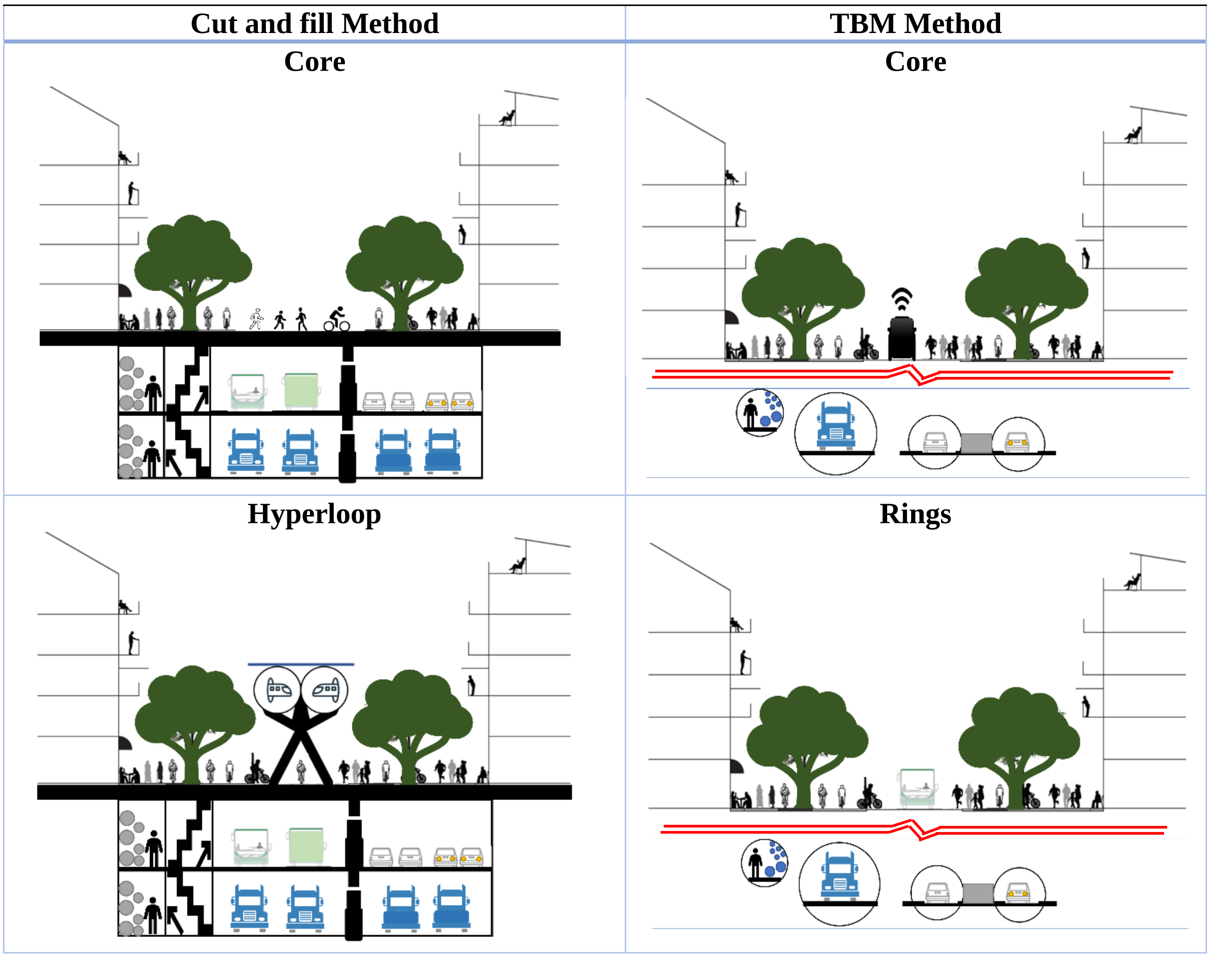


Figure 3.73 - ***Cross Section of Future City Mobility Structure*** - ***Cut and Fill VS TBM*** *(Author)*

3.6.3.9 Green Design: {P7; P12; P13; P14; P15; P16}

The major problem addressed by proposing green space in the framework is climate change, which affects: surface runoff, UHI effect, pollution, health and aesthetics. Buildings in the city are required to either implement solar solutions or a green roof {S29}. However, roofs with an area significantly smaller than the façade area are proposed to implement green roofs over solar panels. Solar panels may be hybridly integrated, but a green roof is demanded.

The framework proposes green parks {S30} to further support the benefits discussed above. This framework compounds the effect of green space by implementing a green belt which encircles the city rings. A benefit which is more so observed by green parks is the provision of community space in which residents can recreate, which leads to improved physical and mental wellness.

Green cover realistically can not alleviate the UHI effect problem on its own. There is no singular solution to the problems identified in this paper. Hence, the framework proposes reflective and light coloured surfaces {S31}. By doing this, the city will retain less heat by reflecting more heat energised photons. Moreover, by implementing cooling towers {S32} that mitigate heat the same way that transpiration from plants do, the city can ensure that heat reduction is significant. The cooling towers are only implemented in regions where high summer temperatures are experienced as these units would be underutilised in regions that do not exceed 32 °C.

The green space solution also deals with the issue of water scarcity and urban flooding. Albeit that these solutions are not as extensively investigated as the other solutions in this framework, they do play an important part in ensuring an efficient and safe urban environment.

With the ever-reducing arable farmland, excessive water consumption and unfavourable climatic conditions, this framework proposes urban farms {S33}. Hence green space impacts a significant number of aspects of equitable urban living.

4 MODEL OUTPUT ANALYSIS AND DISCUSSION

This chapter presents the methodology followed to use the intermediary calculation results to generate the final outputs of the analysis. The chapter initially discusses the outputs per major sector and then presents a holistic summary of the outputs from which clear conclusion and recommendations can be drawn.

4.1 Approach taken

It is important to note that a high-level feasibility analysis was performed and not an in-depth quantitative analysis. The presentation does not include an in-depth analysis of the various options and variables.

4.1.1 Economic analysis methods used

To evaluate the economic and socio-economic potential of the proposed solutions, two key evaluation methods were approached. Firstly, a Cost Benefit Analysis (CBA) is used with a key focus on the Nett Present Value (NPV) output of the method. Secondly, a Life Cycle Cost analysis is performed on some solutions.

The data used in the model always considers the median of a data set to ensure the probability of viability. All values considered in the model were changed to account for the current value from inflation. The values were altered to match 2021 prices using the average CPI index. For future values, costs were increased by inflation plus 1% and benefits were increased to match inflation. Inflation is calculated using the CPI index data from (Macrotrends, 2021c), Table 4.1 shows some inflation factors used. For currency conversion rates, MS Excel API was used for data after 2012. The source for data before 2012 is referenced where it is used.

Table 4.1 - ***South Africa Average Inflation Factors Used***

X	*Averages for year starting _X_ to 2021*
1977	8.928
1984	8.146
1994	5.851
2004	5.067
2005	5.341
2007	5.684
2010	5.053
2012	5.086
2014	4.896
2015	4.690
2016	4.726
2017	4.259
2018	3.951
2019	3.674

4.1.1.1 *Cost Benefit Analysis (CBA)*

Both the HM Treasury (2020) and Sartori *et al.* (2014) set out guidelines on the different approaches and methods of using a CBA. Fundamentally the CBA shows the difference between the potential benefits and human welfare gain to the costs of a project.

This study employs the NPV metric of the CBA for some evaluations. Equation 2 presents the equation for NPV:

$$NPV = PV(B) - PV\ (C) \tag{2}$$

The Present Value (PV) is defined by Equation 3.

$$PV(CB) = \sum_{t=0}^{n} \frac{CB_t}{(1+i)^t} \tag{3}$$

- t = *year of occurrence*
- i = *discount rate*
- CB_t = *Cost or Benefit in year t*
- n = *lifetime period of the project*

Typically, projects are compared to each other using the Benefit Cost Ratio (BCR), where the higher BCR is preferred. The BCR is shown in Equation 4.

$$BCR = \frac{PV(B)}{PV(C)} \tag{4}$$

- B = *Benefit*
- C = *Cost*

4.1.1.2 *Life Cycle Costing (LCC)*

Some parts of the evaluation utilise the LCC method to give a representation of what the annual costs of a project would be, excluding the benefits. The LCC is specifically used for the evaluation of coal plants to realise the LCOE value. This study uses Equation 5 to calculate the annual NPV LCC for a project.

$$NPV\ (LCC) = \frac{CAPEX + \frac{\sum_{t=0}^{n} OPEX}{(1+i)^t}}{n} \tag{5}$$

- $CAPEX$ = *Initial project Capital expenditure*
- $OPEX$ = *Operation and maintenance expenditure plus fuel cost in some cases*

4.1.2 Evaluation Process Flow

For further reference the analysis is referred to as the model, note – this does not represent a complete quantitative financial model. The process flow of the model is presented in Figure 4.1.

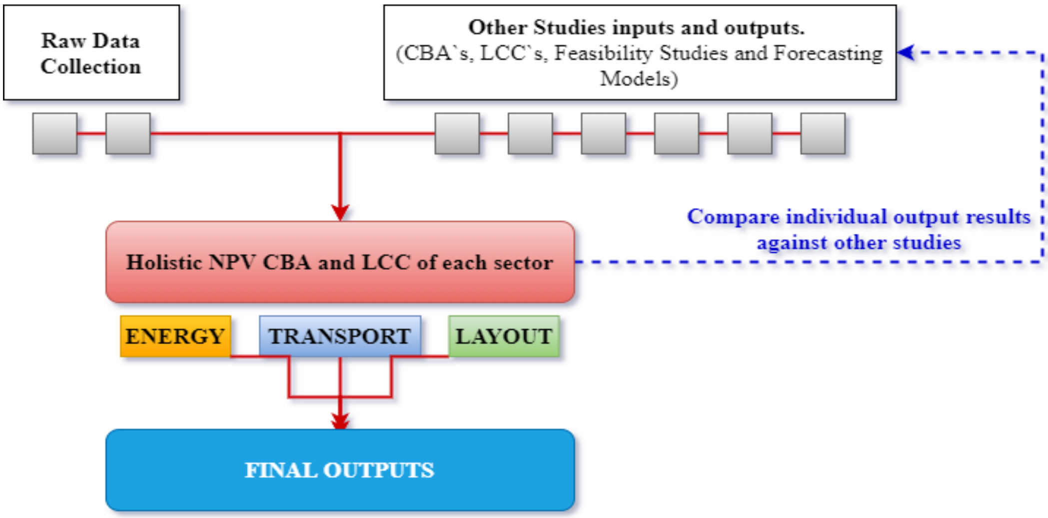


*Figure 4.1 - **Qualitative Model Process Flow** (Author)*

4.2 Comparative Scenario

As one of the objectives of this study, it outlined a focus on a South African implementation of the framework. The framework was evaluated against the city of Cape Town (CPT) in South Africa. The rationale for focussing on Africa is because according to BP`s research (BP p.l.c., 2020b) climate change is expected to have the most considerable impact on Africa’s GDP as a whole (Figure 4.2). The rationale for choosing Cape Town’s parameters for a comparitive new city is because the City of Cape Town was found to have more updated, relevant and reliable data available and moreover, the city is considered the green economic hub of SA (Williams and Boyle, 2021).

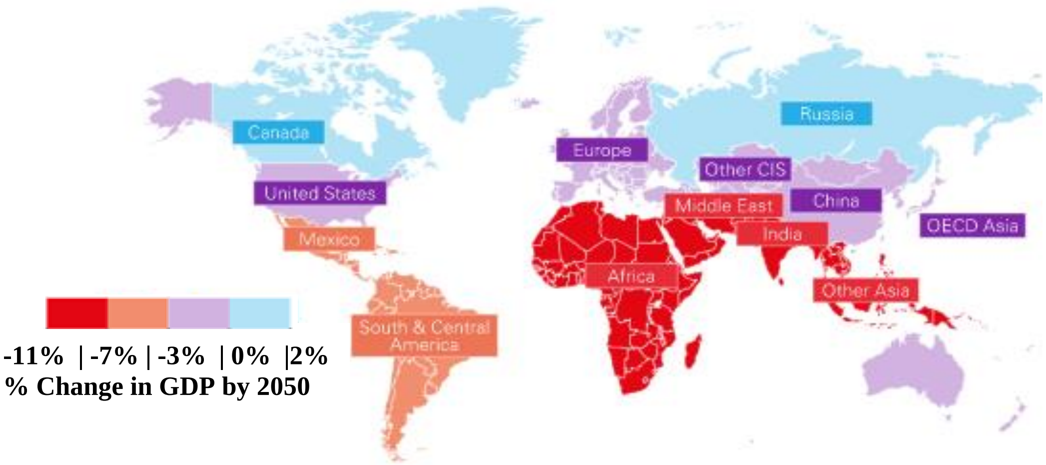


*Figure 4.2 - **Climate Change Impact on Level of GDP in 2050** (BP p.l.c., 2020b)*

Table 4.2 sets out the key scenario parameters that were used from CPT city for the Ripple City framework evaluation.

Table 4.2 - ***Base Case Scenario***

Term	***Value***	***Unit***	***Reference***
City Population	4 618 000	*people*	*(City of Cape Town, 2019)*
Road Network Length	10 302	*km*	*(City of Cape Town, 2019)*
Daily Transport passengers	2 528 000	*people*	*(City of Cape Town, 2019)*
Average Number of people per house	3.59	*people/unit*	*(de Villiers, 2019)*
Number of Households	1 286 351	*units*	*CPT Population / 3.59*
Number if new city private cars	393 623	*vehicles*	*Calculated Table 8.40*
Total Number of Autonomous taxis	7 006	*vehicles*	*Calculated Table 8.31*
Social Cost of Carbon	R 747.66	*/ton eCO₂*	(Erb, 2021)

Below in Table 4.3 is a summary of the changes made to the base case scenario in some cases of each sector to allow for the usage of validated data and appropriate scenarios.

Table 4.3 - ***Additions to Base Case per Sector***

Proposal	***Scenario***	***Rationale for change***
ENERGY		
Loadshedding	South Africa as a whole, since 2015.	As an indicator. The economic value lost from loadshedding since 2015 on both a national and regional scale.
Coal Plants	All SA coal plants are evaluated	Cape Town does not have its own Coal Plant.
Low-Income solar scheme	1 000 low-income housing units.	There is no data on how many low-income users in CPT are receiving the subsidy. The assumed number is considered conservatively low compared to the national figure of 320 000.
Preliminary GHG benefits	CPT 2012 energy data is used.	This is the most comprehensive and complete data that was available for CPT city.
New Energy Job Creation Potential	Base Case	-
BIPV	CPT city CBD	There is no data available for city window area across the city. CBD area was evaluated via google maps for an estimate.
TRANSPORT		
Hyperloop	Base Case 580 km tube	The 580 km tube length was assumed as an appropriate length as per two evaluated case studies and similar conditions to the base case.
EVS	Base Case	-
NMT	Base Case	-
LAYOUT		
Transport Tunnelling	In Base Case city but: 100 km tunnel length 50km Freight Tunnel (6m Diameter) 50km Passenger Tunnel (3.6m Diameter) 60-Year Tunnel Life	It is outside the scope of this study to forecast exactly what length of the city network is tunnelling. Hence the edge-to-edge distance of CPT municipality is used for a tunnel length.
Surface Road Transport	100 km road length.	To match the comparative case of the Tunnel equivalent.
Utility Tunnels	A 0.95km concept area is evaluated in CPT city. (Link to Evaluated Road)	The exact number of businesses, residential and traffic varies across the entirety of the road network. Hence a scenario is evaluated where mixed-use is used in CPT city. The 1km length has businesses, residential and traffic flow, which is similar to the requirement of the framework.
Green Design	Base Case	-

The sections that follow present the output values generated by the model per sector. The section also gives a summarised view in tabular form of the key values calculated. For a more in-depth and expanded elaboration on how the model calculated the values, refer to Appendix G.

4.3 Energy Output

The output section below deals with the following aspects:

- Economic value lost from loadshedding which could have been used to fund a Ripple City;
- The preliminary Ripple City GHG reduction potential and energy usage;
- The re-calculated LCOE of SA coal plants is shown as more expensive than RE sources;
- The potential financial return to be generated from the newly proposed low-income solar scheme;
- The significant benefit a small area implementation of the BIPV proposal could potentially realise;
- The significant job creation potential generated by the energy sector solutions;

Before any calculations on specific proposed solutions were done, a recalculation of the LCOE of coal was performed. The reason for this is that through literature it was identified that current LCOE values are not considering the capacity factor correctly or at all and this led to coal power being thought of as a cost-effective solution. To persuade readers and mainly governments that this is not the case, the study re-evaluated these costs. The output, furthermore, is presented to suggest that the funds lost over the evaluation period is of such magnitude, that it could be sufficient to fund a framework of this nature.

Using the hours of load shed and cost of energy, the output in Table 4.4 was generated. The R 738.91 billion ZAR lost over a period of six years is a significant loss. The framework proposed removes the possibility of loadshedding entirely for the proposed Ripple City. Instead of continuing this monetary loss every six years, these funds could be used instead to build the energy section of this framework and hence prevent future loss.

*Table 4.4 - **South Africa Load Shedding Cost***

South African Loadshedding					*Calculation*
Evaluation Date		16 August 2021			-
Total GW shed since 9 Jan 2015		7 666.23	GWh		Table 8.3
Model Total cost since 2015	**R**	**738.91**	**Billion**		*Using R96.39*
% Of 2020 GDP		***19%***			
Total Intellidex cost	**R**	**1 224.06**	**Billion**		*Used Referenced cost from Table 8.2*
% Of 2020 GDP		***32%***			
		Province Cost [R' Billion]		**pp Cost [R']**	
Western Cape Cost share	**R**	**103.45**	**R**	**15 226.37**	*Table 8.4*

The energy sector's outputs were achieved somewhat different to the other two sectors that are discussed hereafter. Cities are extremely unique in their power demand and utilisation but not so much in their approach to generating the demand. Hence the model analysed a theoretical energy consumption case based off the 2012 CPT city energy usage data. The output from this initial theoretical evaluation is shown in Table 4.5, as well as the potential GHG emissions and reductions from this approach. The GHG emissions are further calculated for each proposal in the sections that follow.

Table 4.5 - ***Preliminary Ripple City Energy Demand and GHG Volume***

OUTPUT Generated from Table 8.11	
Old energy demand [kWh]	39 193 097 500
New energy demand [kWh]	30 739 890 801
Old cost of Carbon	R 14 961 028 000
New Conservative Cost of Carbon	R 8 231 141 671
Theorised New Cost of Carbon	R 4 115 570 835
Old Cost of Electricity	R 42 018 988 701
New Cost of Electricity	R 23 916 321 068
Initial Cost of 70% solar	R 220 691 829 181

Solar- and wind energy was not analysed in a CBA, as the LCOE value gives a better view of a per unit electricity infrastructure cost. The LCOE of the wind and solar power was compared to that of the current dominating source of energy, coal. The analysis used the CAPEX and OPEX costs generated together with the appropriate capacity factor in an automatic macro-excel program that simulated the values through a Life Cycle Analyses over 30 Years.

The LCOE of solar and wind was averaged over sources that considered all the necessary parameters and capacity factors (Steyn *et al.*, 2017a; NEOEN, 2018; Lazard, 2020). The analyses produced the values shown in Figure 4.3. Refer to Table 8.6 in the Appendix for an example of the discussed automated discussion on Medupi plant. From the LCOE results, the closest viable option to consider for coal power is Matla power plant – a 42-year-old plant. Solar power reaches an LCOE of R 0.70 after 20 Years, showing that the incontrovertible solution is the adoption of Renewable Energy. Especially, when the 30 Year LCOE for the newest coal plants built (Medupi and Kusile) is more expensive than RE by a factor of five.

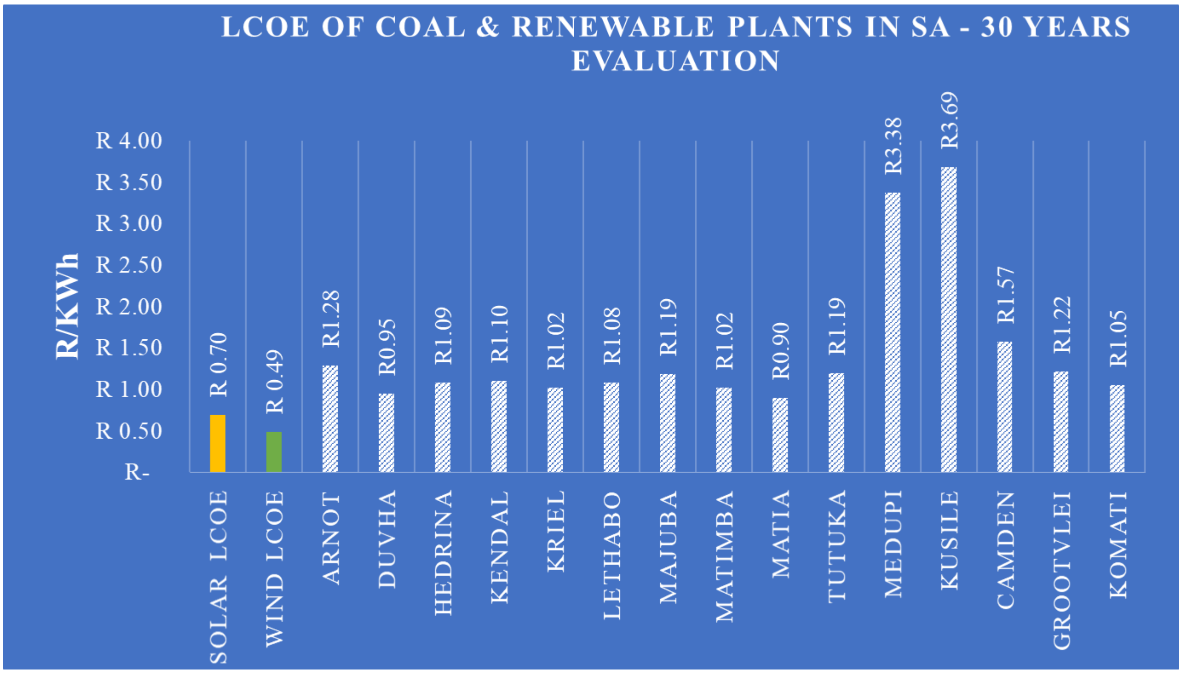


Figure 4.3 - ***Recalculated LCOE for South African Coal Power Plants***

Solar PV thus has an attractive LCOE and is easier to implement within city limits than wind. The framework proposes a low-income solar scheme that replaces an indefinitely recurring cost to city. To show the compounding beneficial impact the adoption of solar can generate, the model presented the output given in Table 4.6. The output shows how over 25 years a solar program can save 1 000 households over 72 million ZAR and the sponsor (city) could potentially save over R78 million ZAR. The framework outlined a requirement for the framework to be of benefit to its citizens on a monetary level as well. Hence, the user savings of R2 911.69 show that new approaches such as these could help ensure that citizens of future city`s save significant costs and have more money to spend in the local economy.

Table 4.6 - ***Proposed Low-Income Solar Scheme***

South African Low Income Solar Scheme				
Assume Number of Low-Income Households	1000		**Total Potential Savings over 25 Years**	
Government Total Savings per household	R 3 130.11	*NPV per year/house*	R	78 252 863.92
User Savings	R 2 911.69	*NPV per year/house*	R	72 792 220.22
		Total Potential NPV Savings	**R**	**151 045 084.14**

Another form of potential gain proposed by the framework, is the integration of BIPV in buildings. The advantage of the ground-up build approach is that buildings can be constructed with BIPV from the start. The model evaluating the CBD area of CPT city show the significant return that could be generated from implementing this technology in a small area as this. In Table 4.7 the output results are shown of the BIPV analysis. If the assumption is made that the placement between 2 streetlamps is 30m and that four LED light are placed in a single lamp pole, it would mean that by utilising BIPV in the city CBD, roughly 7 906 kilometres of road could be lit daily. Cape Town currently has 10 302 kilometres of road (City of Cape Town, 2019).

*Table 4.7 - **BIPV CBA Outputs***

BIPV 20 Year Evaluation				*Calculation*
Assumed BIPV Area		155 680.00	*m2*	*Link*
Cumulative C/B NPV	R	756 480 780.29		*Model*
LCC/year	-R	46 493 156.59		*Model*
BCR		1.81		*Model*
EV Kms supplied		87 563 010.29	*per annum*	*Table 8.16* *(1) * Area*
Lights supplied		1 054 176.00	*Lights/day*	*(2) * Area*

To further realise the potential of RE, the model shows the potential job creation in Table 4.8. Constructing a city on this scale requires significant demand and one of the key methods of drawing people to an urban area is with job opportunities. The model shows a significant number of jobs potentially being created by the adoption of the framework’s energy approach.

*Table 4.8 - **Renewable Energy Potential Job Creation for Two Local Manufacturing Scenarios***

Ripple City RE Job creation potential from Table 8.15			
	100% Local Manufacturing	**50% Local Manufacturing**	
Solar PV Job Creation Potential	190 160	158 933	*Jobs*
Wind Energy Job Creation Potential	21 839	15 580	*Jobs*
Utility scale energy storage Job Creation Potential	523 340	410 815	*Jobs*
Coal Jobs lost due to decommissioning	-200 627	-168 268	*Jobs*
Grid modernisation Job creation possibility	388 523	304 985	*Jobs*
Nett Job creation	923 235	722 046	Jobs
Confidence adjustment (85%)	784 750	613 739	Jobs

Thus, the model not only shows that South Africa especially needs to shift away from coal powered energy urgently, but it also suggests that the proposed frameworks’ energy proposals could generate significant returns.

4.4 Transport Output

The output section below deals with the following aspects:

- The lifetime costs of the Hyperloop system and also the benefits;
- The beneficial implementation of the Hyperloop system to replace some of freight tonnage and passenger travel;
- The significant benefit that could be realised by adopting the pedestrian focus approach and ensuring NMT is designed for;
- The implementation of EVs are shown together with its job creation potential and economic growth enhancing capability.

From literature it was seen how the transport network of an urban area impacts the growth, health and expansion of cities. The research indicated that the growth and efficiency of a city is seriously dependent on the transport network. The transport network currently, however, is a pollutive industry that does not have many projects generating positive returns. The Hyperloop innovation was evaluated in the model, a system that shows prospects of generating a positive return on investment. The final indicative outputs generated by the model for the Hyperloop system is shown in Table 4.9. From the results it is clear that the first best case for the Hyperloop system is for freight, which support most cited study findings. However, the dual function of freight and passenger journeys have a BCR of 2.21, which is favourable. This dual function mode is preferred as it aligns with the frameworks vision of providing efficient and fast mobility for its citizens.

Table 4.9 - ***Hyperloop Model Outputs***

Cumulative CBA values from (L_7 - Appendix I)		
	Costs	**Benefits**
Hyperloop for Freight	-R 289 756 482 288.96	R 1 832 978 940 195.92
Hyperloop for Passenger Journeys	-R 289 756 482 288.96	R 27 692 002 269.23
Hyperloop for Freight and Passenger	-R 289 756 482 288.96	R 640 578 988 943.61
	20 Year Cumulative C/B NPV [R' Billion]	**BCR**
Hyperloop for Freight	R 1 543.22	6.33
Hyperloop for Passenger Journeys	-R 262.06	0.10
Hyperloop for Freight and Passenger	R 350.82	2.21

One of the key reasons for the compounding benefit of the Hyperloop system, other than its ability to run entirely on renewable solar energy, is the cost per kilometre of construction. The results show significant reduction in CAPEX costs compared to HSR construction as shown in Figure 4.4. However, the acknowledgement is made that these results could change significantly as larger projects are built and economies of scale is reached. The cost would have to increase significantly for this project to become unfavourable.

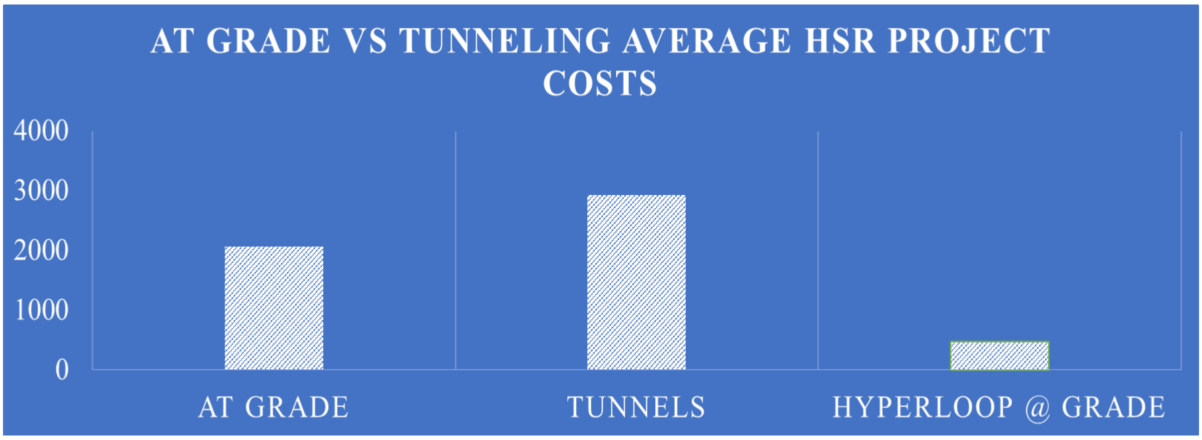


Figure 4.4 - ***Hyperloop vs. HSR Costs***

The model also calculated the LCC of each mode evaluated against the Hyperloop system to ensure that the indirect benefits, such as GHG monetary savings, do excessively overvalue the potential return of the Hyperloop system. From the results in Table 4.10 it is suggested that the overinflation of value is not a concern as the LCC of Hyperloop is far below that of the HSR and trucking mode.

Table 4.10 - ***Mass Transport LCC Outputs – From (L_7 - Appendix I)***

LCC Costs per Mode		
Mode		**LCC/year [R' Billion]**
Hyperloop	-R	14.49
HSR	-R	74.70
Trucking	-R	699.51
NMT	-R	4.20

The LCC of NMT mobility is also presented in Table 4.10. The NMT mode has a BCR of 13.92 as shown in Table 4.11, which is a high BCR. This large benefit is attributable to the lack of vehicle ownership costs and gain of health and safety benefits, especially relating to GHG reductions. The LCC of the mode is R4.2 Billion ZAR, that is still the cheapest form of transport from all modes evaluated.

Table 4.11 - ***NMT Model Outputs***

	NMT			
	20 Year Cumulative C/B NPV *[R' Billion]*	**BCR**	**Possible Injuries Prevented *annual***	**Possible Premature Deaths Prevented *annual***
NMT	R 1 085.95	13.92	4 800	9 399

As with the energy sector, the job creation potential output of the transport sector was calculated and is presented in Table 4.12. The EV job creation potential is of specific interest to the South African economy. From the literature it was identified that the SA economy is significantly dependent on the ICE auto manufacturing industry and hence, a shift in the industry to EVs poses a serious risk to the SA economy, unless the EV industry is adopted.

Table 4.12 - ***Potential Job Creation for Each Mode***

Job Creation Potential of a Ripple City similar to Cape Town	
Mode	**Job Creation Potential**
Hyperloop Job Creation =	38 000
Private EV Job Creation =	204 748
Heavy EV Job Creation =	1 814
BEB Job Creation =	3 783
Robotaxi Job Creation =	10 509
Total Ripple City jobs potential	**258 853**

In Table 4.13 the benefits discussed thus far regarding the Hyperloop system is shown in potential GDP economic return. The results suggest that the Hyperloop system could become a key growth driver for the area in which it is implemented. The table also tabulates, together with the jobs economic return, the economic growth generated from reduced fossil fuel purchases from adopting EVs. The exit of local funds to external countries for oil purchases are reduced by orders of magnitude with this framework. The fuel jobs economic return is shown separately also in Table 4.14.

Table 4.13 - ***Potential Economic Impact of Hyperloop and EVs***

GDP Output Potential of a Ripple City similar to Cape Town		
Mode		**Output [R' Billion]**
Hyperloop	R	135.20
EVs (Fuel and jobs only)	R	26.12
Total Ripple City GDP potential	**R**	**161.32**

The adoption of autonomous driving taxi’s is identified as a key instrument for the city to generate revenue and also allows its citizens to generate passive income and thus aligning with the wealth creation and sharing vision. This proposal could potentially not be favoured for adoption initially in SA as the taxi industry in SA has a large foothold in the economy. The results in Table 4.14 attempt to show that the implementation of this proposal is nevertheless a risk worth absorbing.

*Table 4.14 - **Model Outputs for EVs***

EVs				
	Cumulative 5-Year NPV **[R' Billion]**	**IRR** **[%]**	**Payback Period** **[years]**	**Cost for NPV = 0**
Robotaxi's	R 6.52	51%	2	2.79
	Total Fuel Costs kept in Local Economy **[R' Billion] per annum**	**Total annual salary potential** **[R' Billion] per annum**		
Overall EVs	R 10.25	R 15.87		

The results discussed thus far should have given the reader some confidence that the transport proposals suggested in the framework could be of beneficial gain and exponentially improve the local economy. SA has a significant potential gain from the appropriate implementation of these transport modes as shown. This is contributing to the reasoning that SA is severely dependent on the ICE manufacturing industry and by shifting towards the ICE manufacturing industry, the risk is greatly reduced of having the economy dependent on a reducing industry.

4.5 Layout Output

The output section below deals with the following aspects:

- The benefit of moving the transport network sub-ground;
- The more efficient and beneficial approach of housing utilities in multi-utility tunnels (MUTs);
- The significant benefit to the city and its citizens from implementing green space.

The layout part of the proposed framework evaluated through this model is specifically orientated around moving away from designing cities for motor vehicles and rather moves the focus to the pedestrian user and green space utilisation. The adoption of EVs in the framework still needs to be catered for and hence the framework proposed building cities three dimensionally with tunnels. The potential gain and financial returns of these tunnelling networks were evaluated in the model.

In Table 4.15 the proposed transport tunnelling results are summarised, together with the utility tunnelling proposal and green space adoption. Albeit that the BCR do not indicate as significant gain over surface roads as with other BCR calculations performed thus far, the system shows prospects of favourable returns. The tunnelling proposal value is founded in the benefit from freeing up surface space for proposals such as NMT and green space. This is evident when looking at the GHG reduction benefit of tunnelling, which includes the indirect benefits of freeing up surface space for green space implementation.

Hence, tunnelling is a key growth generator for other proposals in the framework and should be evaluated in that sense. The BCR of green space proves this approach of evaluating the tunnelling system, showing that for a relatively affordable LCC the return can seriously be improved. The utility tunnelling result is an evaluation of a 950 metre section and the results point to even more gains if the system is expanded further within the city, especially over the long term by avoiding repetitive excavation and replacements.

Table 4.15 - ***Layout Model Outputs***

Key Output Values				
	60 YEAR Cumulative C/B NPV [R' Billion]	**BCR**	**Scenario LCC/year [R' Billion]**	**LCC/year/km [R' Million]**
Transport Tunnelling	R 2 136.67	2.13	-R 31.39	-R 313.92
New Surface Road	R 22.51	1.03	-R 11.19	-R 111.88
Utility Tunnelling	R 1.21	3.26	-R 0.01	-R 8.90
Buried Utilities	-R 2.59	0	-R 0.04	-R 43.16
				LCC/year/m2 [R']
Green Space	R 30 080.05	9.48	-R 59.14	-R 295.70

The table in Appendix J is a summary of non-quantifiable items and socio-economic benefits realised through the evaluation process. Considering the results discussed in Table 4.15 and the socio-economic benefit in the appendix, it is clear that the change in urban structure could potentially be a catalyst for growth in future cities and ensure flexible, healthy and reliable infrastructure is provided.

The benefit of moving from Buried utilities to MUT is especially singled out as a proposed crucial implementation. The method of burying utilities not only solves serious disruption issues in the city and does not only prove to be more financially sound than the buried method, but it also creates an opportunity for favourable revenue to be generated by the city while ensuring flexible and efficient infrastructure.

4.6 Final Holistic View

The two tables, Table 4.16 and Table 4.17, show a holistic summary of all the results discussed. The Figure 4.5 shows the summary of equivalent tonne CO_2 avoided by some proposals.

*Table 4.16 - **Final Outputs of Model w.r.t. Economic Output***

Value/Cost to Economy			
-	**Valuation Frame**	**Value** ***[R' Billion]***	
SA Loadshedding	6 Years	-R738.91	total
WC Loadshedding	6 Years	-R103.45	total
		[R' Million]	
Low Income conventional Scheme			
Sponsor Cost	1000 Houses - 25 Years	-R39.57	total
User Energy Cost		-R187.99	total
Low Income Ripple City Scheme			
Sponsor Cost	1000 Houses - 25 Years	R 78.25	total
User Energy Cost		R 72.79	total
EVs GD Contribution (Fuel and jobs)	City Life	R 26.12	per annum
Hyperloop nett GDP Contribution	20-Years - 580 km	R 135.20	total

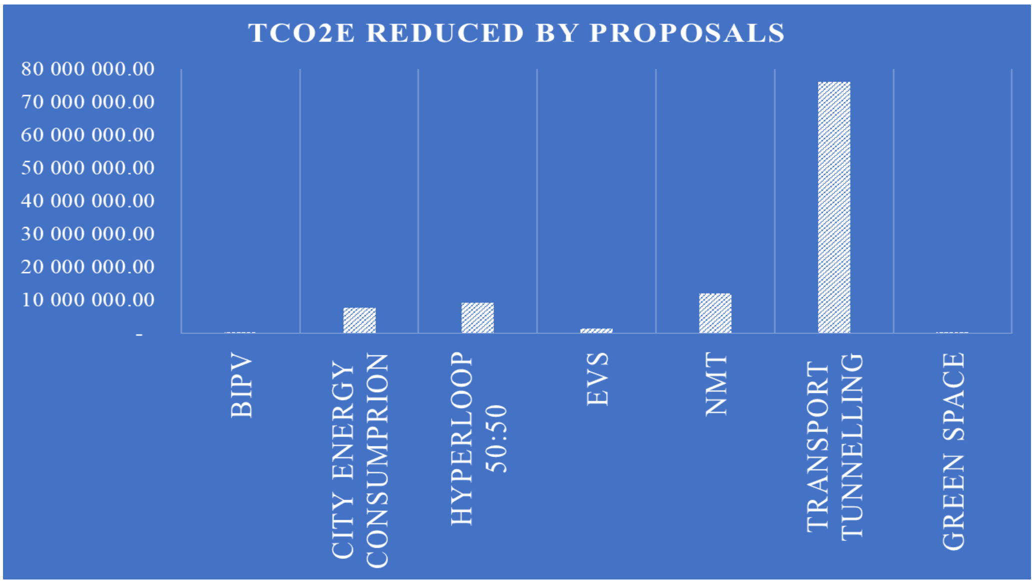


*Figure 4.5 - **GHG reduction Potential from Each Proposal.***

*Table 4.17 - **Summarised Model Final Outputs for Each Sector***

Key Output Values					
Evaluation	**Valuation Period**	**CB NPV**	**BCR**	**LCC/year**	**Job Potential (50% Local manufacturing)**
		[R' Million]		***[R' Million]***	**[Total]**
Energy					
BIPV	CPT CBD - 20-Year	R 756.48	1.81	-R46.49	-
Solar PV	City Life	-	-	-	158 932.99
Wind Energy	City Life	-	-	-	15 580.36
Utility Storage	City Life	-	-	-	410 815.47
Coal Jobs Lost	City Life	-	-	-	168 267.89
Grid modernisation	City Life	-	-	-	304 985.25
Nett Energy Jobs (85% confidence)					**613 739.26**
Transport		***[R' Billion]***		***[R' Billion]***	
Hyperloop for Freight	20-Years - 580 km	R1 543.22	6.33	-R14.49	38 000.00
Hyperloop for Passengers	20-Years - 580 km	-R262.06	0.10		
Hyperloop for Freight & Passengers	20-Years - 580 km	R350.82	2.21		
HSR	20-Years - 580 km	-	-	-R74.70	-
Trucking	20-Years - 580 km	-	-	-R699.51	-
EVs					
Robotaxi's	5-Year City Wide	R6.52	2.79	-	10 509.00
Overall EVs	City Life	-	-	-	210 344
NMT	20-Year - City Life	R1 085.95	13.92	-R4.20	-
Layout		***[R' Billion]***		***[R' Billion]***	
Transport Tunnelling	60-Year - 100km	R2 136.67	2.13	-R31.39	-
Surface Road	60-Year - 100km	R22.51	1.03	-R11.19	-
Utility Tunnelling	60-Year - 1km	R1.21	3.26	-R0.01	-
Buried Tunnels	60-Year - 1km	-R2.59	0.00	-R0.04	-
Green Space	60-Year - City Wide	R30 080.05	9.48	-R59.14	-

5 CONCLUSION AND RECOMMENDATIONS

This chapter provides conclusions and recommendations regarding the proposed framework evaluated in this thesis. The conclusions made are overarching and considers all the sectors together and how they could benefit each other in ensuring this framework reaches proven viability.

5.1 Conclusions

The thesis provides a holistic view of key areas of innovation for the future of cities. The objective of the study was to develop a baseline framework from which future cities can be designed from. Three sectors were identified as the foundational structure of this framework and a number of proposals form part of the framework.

The urban environment is where most development, growth and monetary operations occur. This thesis investigated the problem of how future cities should be designed and where the market is moving towards. The major problems identified result from two key issues, urban sprawl and climate change.

How the objectives were met, that were set out in Chapter one, are discussed as follows:

- Perform a literature study to obtain a fundamental understanding of the urban environment. Furthermore, identify various solutions to urban problems.

The thesis conducted a literature review to ensure that a fundamental understanding was achieved of how cities of today are built and operated. Once the fundamental understanding was achieved, it was easier to identify the most pressing problems and hence, find the most viable possible solutions to these problems. It was clear that cities are growing exponentially, and that urban sprawl is attenuating efficient and constructive growth. The impact of climate change on and by cities was identified as one of the single most important risks of the prosperity of future cities.

Some main solutions identified was the implementation of the Hyperloop system, an underground tunnelling system, green roofs and space and also renewable energy solutions such as solar PV. The framework also proposed utility scale energy storage paired with microgrids to improve the reliability and security of the energy supply. Congestion is addressed primarily by the implementation of Non-Motorised Transport and autonomous electric vehicles (EVs).

- Determine the main sectoral problem areas of an urban environment and focus on them.

By completing a word mining analysis and a frequency hit analyses, the main impacting sectors of a city were identified. The two methods initially identified four major sectors but sector four, the living sector, was absorbed by the other three as it had an impact on each. The final three sectors used for evaluation was the energy, transport and layout sector. These sectors were focussed on to reduce the scope of the study to an achievable volume.

- Evaluate the solutions available to the main problems within main sectors. From where, the study is to conceive and construct the best route forward for a baseline framework that attempts to solve or alleviate these sectoral problems.

AND

- Develop a framework for South Africa which will also be relevant internationally.

Instead of focussing a quantitative analysis on a single solution, this thesis looked at various solutions from a bird's eye view and implemented a top-down approach. Various extensive analyses have been done on key problem areas in cities. These past studies were collectively used and represented. By bringing together these various literature findings, their findings could be realised in partnership with others. Using the researched proposed solutions, a baseline framework was developed and presented from which an indicative financial model was developed with a specific focus on South Africa.

The framework developed is an attempt to solve some of the key issues of urban areas. The framework especially focusses on being flexible and future looking. A significant problem identified throughout all three sectors is that urban environments have not been designed correctly for many years and that the rapid rate of growth is hampering current cities from evolving to change.

The research further concludes that the transport and energy industry could potentially generate significant economic growth in cities if implemented correctly. Dated modes of transport, such as rail, should not be expanded on as is, but rather newer or adaptive modes should be pursued as it aligns with future trends. New innovations such as the Hyperloop system already show prospects of being less costly, as the LCC costs of rail is -R74.7 billion ZAR vs. the Hyperloop system cost of -R14.49 billion ZAR per annum for a city as big as Cape Town.

- Use the data collected from literature and data banks, and evaluate the indicative financial feasibility of the proposed framework per sector. Implement cost-benefit analysis, life cycle evaluations, and forecasting models to achieve the outcomes.

The various findings and data were used to generate a model that could suggest the viability of implementing these solutions together in an urban environment. The model had the intention of motivating future research and entities to further investigate the frameworks approach.

The study concludes, that from the model outputs, it is clear that the suggestive potential benefit of the proposed framework is significant. By orders of magnitude the proposals generate significant upside from sustainable and environmentally beneficial practices. The transport modes such as Hyperloop and Non-Motorised Transport could not only generate favourable returns but can also greatly improve living conditions by alleviating pollution. Moreover, the job creation potential generated from the electric solutions could be a key economic grower.

Isolating the concern of job loss from adopting new innovative solutions, the results generated attenuate this false fallacy by showing the job creation is significantly more than the job loss potential. The energy improvements for example showed a job loss potential of 200 627 but a nett job creation potential of 784 750.

- Measure the outcomes against existing solutions and urban settings.

This thesis attempted to fill gaps in research and furthermore, modelled the data to be appropriate to a case specific scenario in South Africa. Cape Town city was evaluated as a base case and used as a validation check for the solutions proposed. The findings of this model are presented and discussed. The end results showed some key proposed solutions compounding its return significantly. Throughout the analyses development, the figures used, and sub-outputs generated were compared to past studies results.

From the results it is clear that the best approach to this evaluation is looking at the long term. Short term views make some proposals seem unfavourable and lead to a missed opportunity of implementing an effective solution. The competitive industry founded within many of the mentioned solutions is the result of an increased demand for change and innovation. These factors have led to costs decreasing and efficiency rates increasing.

The results, furthermore, suggest significant gain could be generated from implementing renewable energy technology together with green infrastructure. The layout section results showed prospects of being an aid to flexibility of adopting the technologies proposed in the energy and transport sector. The layout sector also showed that moving the mobility network sub-ground would be beneficial.

The study concludes that instead of overhauling current dating cities, this framework should first and foremost be used as the starting baseline for a city built from the ground up. The results of the evaluated scenarios suggest that, for a city with the population of Cape Town, by building this Ripple City framework from the ground could potentially reduce Greenhouse Gas Emissions emission by 124 222 086.19 tons per annum. The results indicate possible Benefit Cost Ratio (BCR) of 6.33 for the Hyperloop system, a BCR of 13.92 for adopting non-motorised transport, a BCR of 9.48 for adopting green space and a 2.79 BCR of adopting the autonomous EV. Furthermore, just over 1.9 million jobs could be generated, more than R32 trillion Nett Present Value (NPV) benefit could be realised from the layout proposals over 60 years and over R 1.4 trillion NPV in transport benefits over 20 years.

5.2 Recommendations

Due to the broad nature of this study and the evaluated sectors, the possible outcomes of the implementation of this framework are significant. This thesis recognised this and hence proposed a baseline framework, rather than a definitive framework, from which future city development can start the planning and design from.

5.2.1 Future Work

The main recommendation of this thesis is that further in-depth quantitative analysis is required on the proposed framework as a whole in case specific implementations. A quantitative analysis could enhance, prove or disprove the findings of this study and motivate governments to more rapidly adopt these solutions or search for others. The list below identifies some key evaluations the study suggests should be started with.

- The framework, as is, should be quantitively and statistically evaluated with reliable data purchased from reputable sources.
- The utilisation of the various energy storage systems together with microgrids, should further be quantified and evaluated, especially with the utilisation of modular gravity-based storage systems.
- The framework should be adapted to incorporate urban farms which address the significant food and land shortage in many countries.
- A study should be performed to identify appropriate locations in South Africa where this Ripple City could be built.

Finally, a recommendation is made to evaluate the quantitative feasibility of this framework as an adaptation to existing cities and not merely as a green fields city.

5.2.2 Proposed Monetisation Strategy

To ensure the success of this framework, this paper recommends some funding schemes to be implemented to help fund a city such as this. Funding this framework design also needs to incorporate a scheme that ensures wealth sharing to the city's people. Table 5.1 presents the monetisation schemes implemented by this framework.

*Table 5.1 - **Monetisation Strategies***

Strategy	Description
Public-Consumer-Private Partnership (PCPP)	The PCPP takes the fundamentals of the PPP agreement one step further. The PCPP brings the consumer into the investment structure, allowing the user to benefit from the implementation. 70% of the project is funded per the traditional PPP, but the other 30% is opened to the consumer. The 30% is gathered via crowdfunding via fractional shares, which are bought on an online platform. This way, the investment can compensate the users via dividends of the profit sharing. An example of this is where the Hyperloop system is funded using a PCPP which returns a portion of ticket sale profits to all shareholders.
Segmental allocation	Companies are allowed to take control of a portion of a segment within the city. The company's responsibility would be to develop and manage the area and the compensation for this is a reduced property levy or sole operation in the area. Furthermore, companies that utilise local manufacturing gets preference, which will ensure more job creation. Finally, allowing private companies segmental control will ensure accountability and the immediate care of the area to ensure better corporate governance. An example of this is allowing a large logistics company to set up its head office and warehouse in a sector at reduced fees. The company and the city will enter into a PPP with joint profit share and management of the sector.

Tax benefit	A tax benefit is advised for companies setting up head courters in the city, albeit not up to the city. Furthermore, a tax incentive should be provided for local manufacturing utilisation.
Data monetisation	The city can leverage special usage data gathered by city operations for improvements and moreover sell the data to corporate for betterment. Due the centralised payment and management platform implemented by this framework, users can opt in to allow the city to leverage their usage data. While aligning with global data protection policies, users can opt into this scheme and then be compensated for data sharing their special use data.

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7 GENERAL APPENDIX

7.1 Appendix A

(Numbeo, 2021)(GlobalPetrolPrices.com, 2021)(Our World Data, 2021)(TomTom, 2021b)

	Units	Higher value evaluation	Joburg	CPT	Durban	Tshwane	Ahmedabad	Bengaluru	London	New York	Copenhagen	Singapore	Reference
Population density	*persons/hectare*	*Better*	20.9	12	14	9.5	134	207	57.01	101.94	44	78.04	(The World Bank, 2019)
Transport Time Index	*min/one way trip*	*Worse*	40.8	43.2	26.59	45.13	37.65	53.08	43.81	33	22.67	30.09	(Numbeo, 2021)
Average Trip Length	*Major mode km/one way trip*	*Worse*	22.63	15.9	19.55	26.39	5.5	9	19.22	14.92	6.51	16.21	(Numbeo, 2021)
Carbon Footprint	*CO2 tons/capita/annum*	*Worse*	7	8	6	9	0.05	0.12	1.2	6.1	2.5	8.56	(The World Bank, 2019)
Population	*mill*	*NA*	5.6	4.5	3.12	1.4	5.571	8.444	8.982	8.5	1.21	5.18	(Our World Data, 2021)
Unemployment Rate	*%*	*Worse*	24.50%	19.40%	21%	25.80%	3.40%	29.80%	5%	4.30%	5.80%	1.90%	(The World Bank, 2019)
petrol price	*Rand/L*	*Worse*	R 17.44	R 16.60	R 16.60	R 17.44	R 16.72	R 17.84	R 20.98	R 12.11	R 24.80	R 20.77	(GlobalPetrolPrices.com, 2021)
GDP per capita	*Rands/person*	*Better*	R 111 171.00	R 97 664.00	R 66 254.00	R330 065.43	R49 992.60	R43 892.83	R604 624.79	R932 676.23	R 1 207 831.70	R931 766.08	(Our World Data, 2021)
Congestion Level	*%*	*Worse*	30%	32%	19%	25%	30%	71%	23%	37%	22%	32%	(TomTom, 2021)
Traffic Index	*unitless*	*Worse*	201.63	213.49	122.85	228.02	140.24	248.87	155.35	163.91	87.16	147.46	(Numbeo, 2021)
Traffic Inneficiency index	*unitless*	*Worse*	249.39	251.09	127.44	312.57	141.03	279.78	188.61	190.4	109.4	148.09	(Numbeo, 2021)
Transport CO2 emission Index	*g*	*Worse*	10404.91	10497.03	6317.52	11169.07	3439.7	7483.39	1886.34	3050.43	1619.71	2460.85	(Numbeo, 2021)
Cost of Living Index (Excl Rent)	*% of NY*	*Worse*	46.0%	42.2%	39.9%	44.7%	26.7%	28.2%	85.6%	100.0%	97.5%	85.6%	(Numbeo, 2021)
Pollution Index	*unitless*	*Worse*	61.62	38.8	52.12	55.93	71.83	83.23	58.86	57.58	21.06	33.16	(Numbeo, 2021)
Crime Index	*unitless*	*Worse*	80.65	73.78	80.84	81.94	30.45	54.11	52.81	46.96	27.54	32.98	(Numbeo, 2021)
Quality of Life Index	*unitless*	*Better*	123.44	142.27	134.92	131.06	113.95	133.51	128.09	137.67	182.71	143.82	(Numbeo, 2021)

Description of metrics	
Traffic Index	A composite index of time consumed in traffic due to job commute, estimation of time consumption dissatisfaction, CO2 consumption estimation in traffic and overall inefficiencies in the traffic system.
Time Index	An average one way time needed to transport, in minutes.
Innefficiency Index	An estimation of inefficiencies in traffic. High inefficiencies are caused by people that drive a car instead of using a public transport or long commute times.
CO2 Emission index	An estimation of CO2 consumption due to traffic time.
Cost of Living Index (Excl. Rent)	A relative indicator of consumer goods prices, including groceries, restaurants, transportation and utilities. Excludes accommodation expenses such as rent or mortgage. If a city has a Cost of Living Index of 120, it means Numbeo has estimated it is 20% more expensive than New York (excluding rent).
Pollution index	An estimation of the overall pollution in the city. The biggest weight is given to air pollution, than to water pollution/accessibility. Small weight is given to other pollution types.
Crime Index	An estimation of overall level of crime in a given city. Crime levels lower than 20 considered as very low, levels between 20 and 40 as low, levels between 40 and 60 as moderate, levels between 60 and 80 as high and finally crime levels higher than 80 as very high.
Quality of Life Index	An estimation of overall quality of life by using an empirical formula which takes into account purchasing power index (higher is better), pollution index (lower is better), house price to income ratio (lower is better), cost of living index (lower is better), safety index (higher is better), health care index (higher is better), traffic commute time index (lower is better) and climate index (higher is better).

7.2 Appendix B

1 Circular layout	26 Building proprietary water filtering
2 Block structure layout	27 Salt water Desalination
3 Centre Island heat cooling tower	28 Vertical Farming
4 Hyperloop	29 Building roof wind turbines
5 Tunnels	30 Tubular natural light source in buildings
6 Off grid power solutions	31 UV luminesant building materials
7 Green Space	32 Smart Parking system
8 Pneumatic Tube systems	33 Subterranean parking and storage spaces
9 Carbon Sequestering	34 District heating and cooling
10 3D printing	35 Prefabricated modular road.
11 Kinetic pathways	36 Sky Tunnel Roadways
12 Solar Roadways	37 Artificial Intelligence
13 Heat capturing	38 Hydrogen Fuel
14 Omniled lights	39 Renewable Energy Solutions
15 Smart grid system	40 Energy Storage solutions
16 Gym equipment energy regeneration	41 Recycling
17 Traffic wind turbines	42 Small Hydropower
18 CO2 consuming building materials	
19 High Speed Rail	
20 Utility Tunnels	
21 Alternative cement	
22 Wood infrastructure material	
23 Bicycle infrastructure	
24 Waste to energy	
25 Nuclear Power	

7.3 Appendix C

	GHG Commitment	Carbon-free energy commitment	Due date	*Source Used:*
Saudi Arabia	-	50% RE Capacity	2030	*2*
South Africa	26% reduction	7% RE Capacity	2030	*2&8*
Indonesia	29% reduction	23% RE Capacity	2030	*1*
Mexico	22-36% reduction	43% RE Caoacity	2030	*2*
Australia	26-28% reduction	50% RE Capacity	2030	*2*
India	33-35% reduction	40% RE Capacity	2030	*2*
Japan	50% reduction	50% RE Capacity	2030	*3*
Argentina	25.7% limitation	20-25% RE Capacity	2030	*4*
China	60-65% reduction	40% RE Capacity	2030	*5*
South Korea	30% reduction	20% RE Capacity	2030	*2*
United States	50-52% reduction (by 2030)	100% RE Capacity	2050	*3*
Russia	25-30% reduction	4.5% RE Capacity	2030	*2*
Turkey	21% reduction	38% RE Capacity	2030	*6*
Italy	33% reduction	55% RE Capacity	2030	*7*
Germany	55% reduction	65% RE Capacity	2030	*2*
United Kingdom	40% reduction	87% RE Capacity	2030	*8*
Europe	40% reduction	32% RE Capacity	2030	*9*
Canada	40% reduction	90% RE Capacity	2030	*10*
Japan	50% reduction	50% RE Capacity	2030	*3*
France	50% reduction	40% RE Capacity	2030	*6*

Source number	Source link
1	https://www.iisd.org/publications/getting-23-cent-strategies-scale-renewables-indonesia
2	https://climateactiontracker.org/countries/
3	https://www.nrdc.org/
4	https://newclimate.org/wp-content/uploads/2020/12/Impact-of-Cost-Progressions-on-Argentinas-NDC-Technical-Analysis.pdf
5	https://www.reuters.com/article/us-china-climatechange-renewables-idUSKBN2AA0BA
6	https://www.climate-transparency.org/wp-content/uploads/2019/11/B2G_2019_Turkey.pdf
7	https://www.ifri.org/sites/default/files/atoms/files/memo_lombardini_italy_necp_in_an_european_context_fev_2021.pdf
8	https://www.climatechangenews.com
9	https://www.eceee.org/policy-areas/2030-policy-framework/#:~:text=The%20Clean%20Energy%20Package%20sets,target%20of%20at%20least%2032%25&text=For%20the%20electricity%20market%2C%20it,the%2010%25%20target%20for%202020.
10	https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/powering-future-clean-energy.html

7.4 Appendix D

Figure 7.1 - ***Block Grid Urban Form*** - *(Google Maps, 2021)*

7.5 Appendix E

The Core

Above ground, the core is the central economic hub which is the fundamental concept of the 15-min bicycle city approach. The core is pedestrian orientated and focuses on incorporating significant amounts of green space. This ensures a safe, attractive and healthy pedestrian orientated environment.

Bus stations should have solar mounted roofs to help contribute to public energy and energy storage capabilities. This theoretically increase the number of RE sources that supply the city with reliable energy.

Moreover, significant NMT infrastructure is provided by means of bicycle lanes, pedestrian bridges and bicycle parking bays. By ensuring efficient, safe and clean NMT zones, the city can reduce GHG emissions in the city centre (Section 3.4.1).

Furthermore, commercial, leisure and entertainment buildings can be found in the central hub. The primary hyperloop port is proposed to also be housed in this facility. This can ensure that visitors to the city can have easy access from other cities while being strategically located to move to their required location of interest. From the core, any point in the city is reachable.

Below ground level, the core connects with the major mobility tunnel network. The central hub should have basement levels which house a distribution centre, public transport parking bay and an underground public transport station. Moreover, the core hub needs to have a basement parking lot for privately owned vehicles that utilise the underground tunnel transport network, which offer charged parking at a steep rate. By allowing underground parking for the core, the framework ensures universal accessibility while preserving the pedestrian orientated approach above ground. At the same time, it generates favourable revenue for the city.

Electric delivery trucks are allowed to utilise the above-ground transport routes during the early morning hours. This allows large haul deliveries to reach businesses that do not have basement freight delivery stations that connect with the tunnelling system. Moreover, allowing these vehicles to only deliver during these hours ensures that the pedestrian orientated approach of the core is not compromised. The benefit of utilising electric trucks is that low noise pollution is created because electric engines are significantly less loud than ICE vehicles (Iversen and Skov, 2015; Hahad *et al.*, 2018; Williams, 2018).

Fundamentally this framework`s core setup allows for a decongested city centre while still driving economic growth, potential and activities.

Ring 1

Ring 1 houses high-density mixed-use buildings that supply more residential units and office units. Moreover, Ring 1 houses emergency services and recreational facilities, as this ring is easily accessible..

This ring allows smaller vehicles to operate above ground to allow for better accessibility to residential and commercial buildings. However, the framework proposes only Robotaxi`s to operate in this ring. Hence, a systematic phase-out approach is implemented where privately owned EVs is to be banned above ground once the sub-sector is fully developed. This further incentivises NMT mobility and less private vehicle ownership.

While privately owned EVs are allowed, they must be charged a congestion fee for operating in this ring. Medium EV delivery vehicles are included to operate in this ring to ensure the e-commerce industry is catered for.

Above ground, parking bays are not allowed in this ring unless in the form of parking towers placed on the outskirt. Placing parking towers on the outskirts allows users travelling from outside the ring to reach the city centre while still ensuring the city centre keeps the pedestrian at the focus. From these towers, users can use the public transport network such as the BEBs or robotaxis to navigate the inner city.

These parking towers extend to basement levels which connect with the underground tunnel mobility network. This is to ensure easy access for all and ensure adequate parking for the Robotaxi fleet. Underground distribution centres (DCs) can also be implemented in this ring which connect with the freight tunnels. Furthermore, underground bicycle storage bays are implemented. This ensures safe, efficient and reduced area wastage for bicycle utilisation.

Ring 2:

Ring 2 implements the mixed-use superblock structure to densify the city further while allowing for a more community atmosphere. This ring should implement low-, middle- and high-income superblocks in each sub-sector. These superblocks restrict through traffic through its centres. Moreover, this ring is proposed to house the urban farms to improve accessibility to food.

The above-ground mobility network allow all forms of transport. ICE vehicles are heavy carbon taxed. ICE vehicles are allowed to ensure easier adoption and attractiveness of the city while at the same time incentivising the shift towards EVs. In rare cases where the city gives approval, off-street parking is allowed. One such case is for medical clinics.

This ring also uses parking bays on the outskirts for the same reasons as in Ring 1. In addition, the superblocks are allowed to implement basement parking for residents, but basement distribution centres are not allowed in these cases.

The urban farms utilise underground distribution centres and plan for expansion to drone deliveries from the roof, to align with the 4th industrial revolution and e-commerce trends.

Ring 3:

Although ring 3 goes against the goal of the city to densify, the framework needs to be attractive and accessible to all. Residents living in this ring should be expected to pay the premium fee for living in low-density. This ring is limited in size and is not allowed to expand outwards. Off-street parking is implemented in this ring, but no underground parking.

The repeat ring:

The repeat ring sets out an area that ends at the maximum urban development line. In this ring, it is to the discretion of city management for its utilisation. The framework proposes to repeat Ring 1 and 2. Moreover, in the absolute rare case, slums are catered for, but this framework proposes to avoid slums by helping those who would have otherwise lived in slums to move them into low-income housing.

The industrial and DC node:

The industrial node is separated from the city to ensure that these property zones never mix with other zones as is the case in cities currently (Section 3.5.1). These industrial nodes have dedicated hyperloop lines that transport workers and freight to and from the city to the industrial sector. The same principle accounts for the distribution centre. These nodes are also accessible by the underground mobility network.

By having these industrial districts outside the main city it ensures that property values are not degraded and community disturbance is not generated, moreover any industrial pollution does not impact the residents health.

Green Design:

The literature (McDonald *et al.*, 2020) showed the benefits of water retention in an urban setting to reduce flooding and the carbon sequestering capabilities of these roofs. In addition, green roofs ensure improved air quality, which affects residents' health, resulting in cost savings on medical expenses. The socio-economic benefit of green roofs is founded in a more aesthetically pleasing city while experiencing better living conditions due to a reduced centre island temperature.

Green Parks:

Various studies throughout the literature (Section 3.5.4.1) show the beneficial impacts of trees: carbon sequestering, erosion protection, shade cover and reduced energy consumption. By implementing various green space solutions, the city ensures that the city's energy consumption is reduced due to the mitigation of the UHI effect. Furthermore, evidence suggests that greater access to green spaces improves property values, reduces segregation, and promotes healthy living.

Urban Farms:

These urban farms use a fraction of the space of conventional farms and less than 10% of conventional farming water needs. Moreover, this solution reduces food miles, improves food quality and ensures the security of food supplies. Urban farms also ensure equitable access to produce while generating local jobs and up-skilling.

The implementation of urban farms aligns with the shift towards plant-based foods, which can increase the demand for plant growth. Moreover, with the increasing average age of conventional farmers, there is a severe risk of the security of farming. Hence, by creating technology-driven jobs for the urban farmers, this risk is reduced.

7.6 Appendix F

Thus far, this paper has presented various identified problems within the urban built environment and solutions to some key issues. The model uses the proposals and evaluates a case-specific implementation within the context of South Africa. Figure 7.2 shows a holistic view of the physical nature of the framework design (not to scale or proportion).

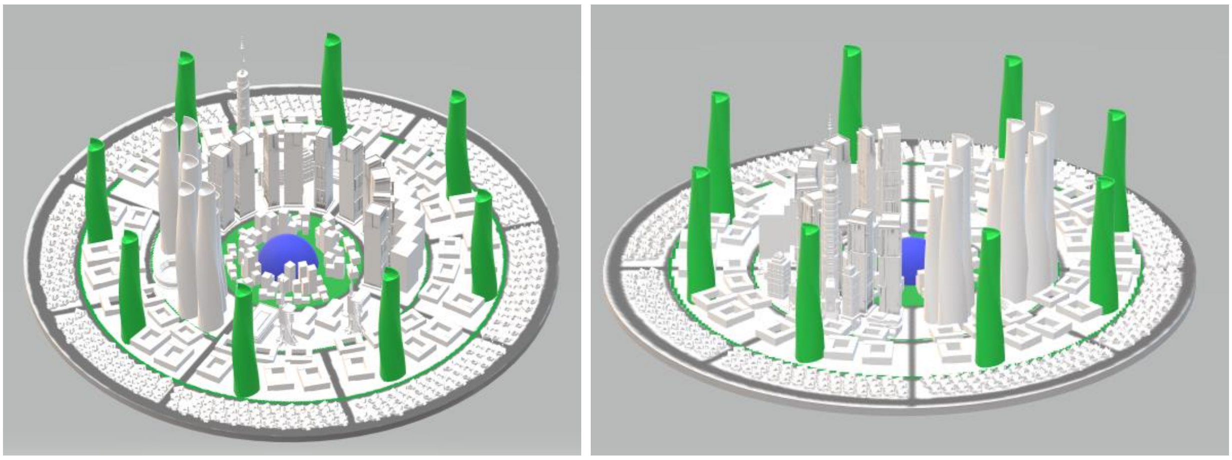

Figure 7.2 - ***Ripple City Holistic Rendering*** *(Author)*

By presenting the solutions in a case-specific view, the overwhelming information provided in this document is made easier to conceptualise. The purpose of this is to show the significant above and over benefits achievable by the South African market if they had to implement this framework. The umbrella problem that is affected by each and every implementation is climate change.

The research (Section 3.5.2) identified various issues that are significantly affected by the urban setting within south Africa. Some of these include the significant number of people living in informal settlements, the underutilisation of public transport, unreliable and pollutive energy generation mix, segregation and more.

However, with the expected share of the global urban population being at 25% for Africa alone, the urban sprawl trend is an emerging problem in Africa. Sub-Saharan Africa is expected to be 60% urbanised by 2050. This research focuses on South Africa, as it is the most significant contributor per capita, in Africa, to GHG emissions with 8.86 metric tons per capita (European Union Energy Initiative, 2018).

To ensure the city level economic growth, the pressure on the natural resources, efficiency, jobs and climate need to be alleviated. However, these issues are addressed individually below. First the Ripple City principles are given, which are geared specifically for the African Ripple City.

7.6.1 Benefits that South Africa can observe from this framework.

Generally, the benefits of building a city from the ground up are founded in the logistical nature of the concept. Engineers and developers have a better understanding of what cities require to operate and what humanity needs. Compared to cities of the past, which were built as the need arose, this new framework is endowed with its planning for success approach.

The Sub-Sharan region is expected to urbanise rapidly, and below in Table 7.1 are some key benefits that this area would see compared to other countries.

*Table 7.1 - **From the Ground Up Added Benefits In SA***

Advantage	Elaboration
Coordinated planning *(Section 3.5.1)*	The setup in SA lacks the centralisation of urban land, which leads to suburbanisation or urban sprawl. However, by planning a coordinated implementation from scratch, this issue can be planned for, ensuring that equitable housing is provided. An example of this is guaranteeing that low-income housing is not situated in high flood risk areas, hindering accessible infrastructure.
Efficient design disconnected from past inefficiencies	Innovations require significant time frames and capital to be implemented into existing urban infrastructure that has been built 50 years ago. African cities can now plan and design for flexibility and innovation inclusion. By constructing a city from the ground up will ensure that the basic requirements of a city are now incorporated.
Starting from 1st-principles	SA is especially more segregated than other countries due to the colonisation and apartheid regimes that were in the country. This framework allows the opportunity to build a city that is completely separated from the historical injustices and ensure an equitable city for all.
Does not hamper economic growth or day to day operations. *(Section 3.5.3)*	Overhauling cities with existing infrastructure is disruptive and expensive both in project cost and cost to the economy. This framework ensures fast, efficient and no disruption deployment. An example of this is the cut and fill method, which can be utilised for tunnels. Traditionally, a cut and fill construction in an existing city would require a temporary roof road to be constructed to resume traffic flow while construction proceeds - which is costly. This temporary roof is not required in a city built from scratch.
Work around restrictive policies.	Existing cities have copious restrictive policies and regulatory requirements for construction projects within the city. This framework potentially could have reduced regulatory obstacles due to the method of construction. For example, a traditional city overhaul project would have requirements, such as an EIA, a traffic impact analysis for the construction period, a robust public safety plan, and would be required to operate only certain hours under certain conditions. However, the from-scratch approach would only require an EIA. A practical example of this would be where a crane would not be allowed to operate over or near certain buildings in an already built city. The framework would not have that problem.
Job creation	South Africa has an extremely high expanded definition unemployment rate of 44.4% (Statistics South Africa, 2021). By implementing a project of this magnitude that is built over a long period, it generates a significant number of long term jobs.
Draws investment. *(Section 3.1.1)*	South Africa specifically is rated an uninvestable country by many credit rating agencies. However, this framework creates the opportunity for extensive international investment attraction due to the scale of this project. Furthermore, the project in itself creates some security for investors for extended term contracts. An example of this is the benefit that this city creates for local solar panel manufacturing due to the significant number of solar panels required for this framework.
Space available	Finally, Sub-Saharan Africa has the added benefit of having expansion landmass available compared to other countries such as Singapore, Germany and Canada. Hence, this framework setup should especially be able to be constructed on green fields in SA.

From the discussion above, it is clear that SA benefits mainly from the ground up approach due to the magnitude of the proposal and the opportunity of planning for success. Building the city from scratch also extends its benefits into the sectors discussed below.

Energy

In the energy sector specifically, South Africa is a constant dichotomy where corruption often undermines a sound approach. Nevertheless, below (Table 7.2) are some key added benefits that SA can collect from this framework.

*Table 7.2 - **Added Benefits in the Energy Sector in SA Context***

Advantage	Elaboration
Significant potential to utilise RE *(Section 3.1.1)*	SA has an increasing energy demand but a diminishing energy supply, with a 1000 MWs being decommissioned each year on average. Moreover, the country is not adopting RE fast enough while it is endowed with a significant potential to benefit from solar energy. SA can benefit from solar energy implementation more than most other countries. All the raw resources to manufacture solar panels can be found within the borders of SA. SA has the added benefit of generating significant economic returns from locally manufactured solar panels.
Local manufacturing industry growth and up-skilling *(Section 3.1.3.1)*	Compounding the benefits mentioned above, the significant job creation and skills development that can be achieved from a SA solar industry is significant. An industry shift or manufacturing expansion to renewable energy equipment is fundamental to reduce the dependency of the South African GDP on ICE vehicle manufacturing.
Local energy storage manufacturing industry *(Section 3.1.4)*	SA is exceptionally well situated to benefit from the large scale adoption of battery energy storage. This is because one of the key materials in energy storage is Magnesium and iron, both of which SA has in abundance. This allows SA to become a key player in the RE supply chain.
Recycling industry gain	SA can benefit significantly from the Li-ion and Iron battery manufacturing industry due to the already settled battery recycling industry within the country. SA has a lead-acid battery manufacturing industry, which can aid in the shift to more current and future battery technologies. (ESI Africa, 2013)
Increased access to reliable electricity *(Section 3.1.1)*	SA currently has a monopolised and centralised energy supply and distribution setup. This creates a network of issues and limits accountability and redundancy. It has resulted in poor energy access as identified in the literature. Permitting hybrid nett metering connections in this framework allows for wealth sharing while ensuring a reliable and secure energy network.
Load-shedding removal *(Section 3.1.5)*	Currently, SA is a country whose economic growth is significantly crippled by load-shedding. Load-shedding is removed entirely by utilising the energy storage design presented in the framework, paired with the microgrid structure. Furthermore, this framework allows SA to become an energy exporter to other countries in sub-Saharan Africa.
Kerosene use reduction	SA has another benefit from implementing microgrids. With a congested and ageing grid infrastructure to benefit from microgrids, SA also has the added benefit of moving 17-20 million households from kerosine paraffin use to electric lighting. Kerosene related fires cause injury and damage to over 200 000 people in SA annually (Foreign & Commonwealth Office, 2017).
More economical low-income energy aid plan	This framework creates a better revenue model for the low-income energy grant. SA supplies low-income users with a 50-100 kWh energy grant monthly indefinitely. This is a recurring cost. This framework allows a benefit for the grant provider where a point is achievable where the initial investment of the solar system is worked back. After this point, the provision of equitable power to low-income users come at no high cost. The city can generate "free" power after the ROI period is achieved from unconsumed power from these systems.

Figure 7.3 illustrates the revenue streams that the city and its interested parties have with the new energy grid proposed in this framework. This figure shows how all current parties can remain in the monetary structure while allowing for wealth sharing and a de-monopolisation of the electrical industry.

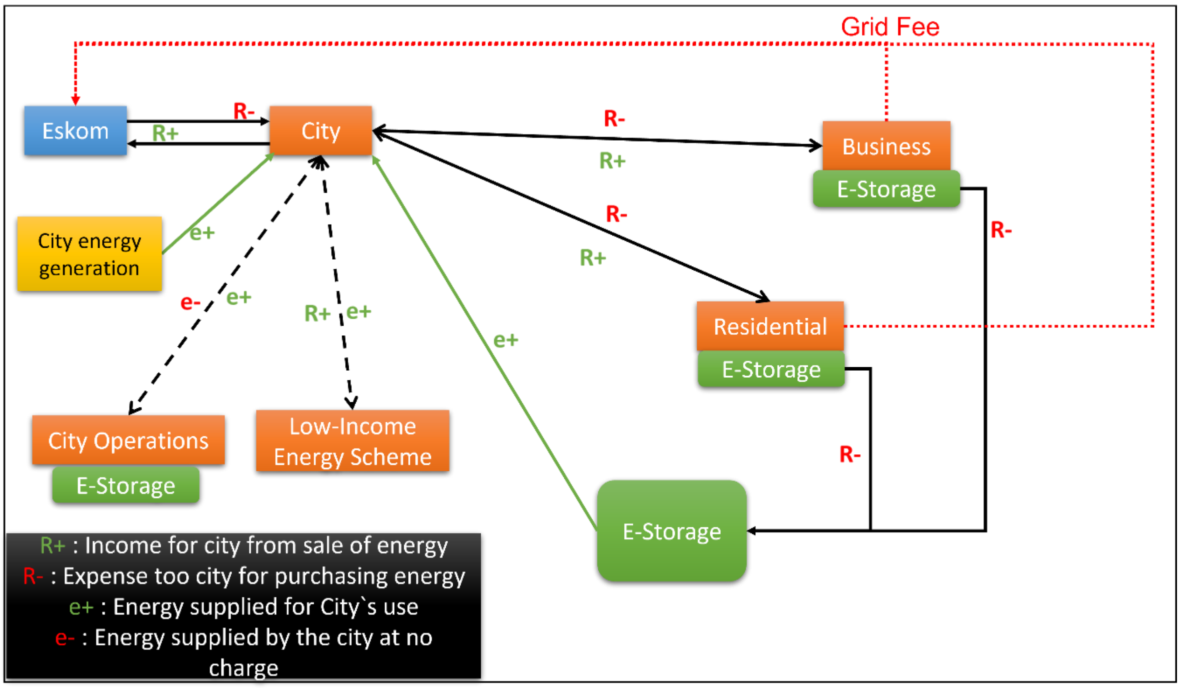

Figure 7.3 - ***Monetisation Structure for the Electrical System*** *(Author)*

Hence, SA can significantly benefit from an energy infrastructure overall, both in terms of energy security and wealth redistribution.

Transport

Locally technologies that are unproven on a large scale are avoided. However, as per the literature previously cited (Section 3.3.2), SA has established that even with proven technologies, the system can still fail. Hence, new technologies that are proven on a small to medium scale are considered in this framework.

SA does not have a successful public transport network, especially in the rail mode (Williams, 2021). Table 7.3 provides some of the key benefits that a South African implementation of this framework could generate.

Table 7.3 - ***Added Benefits in the Transport Sector in SA Context***

Advantage	Elaboration
Generate new brand confidence with innovation	The rail industry and public transport sector in SA has a tainted reputation. Consumer studies show that SA is a brand-based market (GeoPoll, 2021). This means that it would take significant improvement to convince users to adopt these traditional modes of transport. Hence this framework implements new innovative technologies that are not bounded by the tainted brand of the traditional modes. Implementing modes such as the Hyperloop, creates the opportunity for a new trusted and reliable brand to be formed if implemented correctly.
Price parity to an underutilised system *(Section 3.3.5.1)*	SA has a decaying rail infrastructure that is being underutilised, as shown in the case of the Western Cape, where only 4 of the 14 rail lines are being utilised. Data shows rail passenger trips decreasing YoY. This attenuation is as a result of an unreliable, unsafe and inefficient rail implementation. The hyperloop system implements a premium product at prices equivalent to or lower than that of rail.
Reduced theft and vandalism *(Section 3.3.5)*	The SA rail industry is susceptible to cable theft, vandalism and boycotts. The Hyperloop system experiences an added benefit in SA with being near tamper-proof. It does not have easily stolen infrastructure, as in the case of cables being accessible above rail tracks. The security of the Hyperloop system is improved in that it is placed on pylons, making it harder to access for vandalism. Furthermore, the system is more secure because there are only controlled entrances and exit points, unlike rail, which is highly exposed. This benefit is especially realised when considering the monetary savings that can be achieved by making it near impossible for infrastructure to be a victim of arson, as is commonly observed in rail cars.
Benefit more from solar energy *(Section 3.1.3.1)*	SA is considered a solar energy superpower. The Hyperloop system can theoretically run entirely self-sufficient on solar energy in SA.
Job creation	Some of the largest employers in SA is the transport entities such as Transnet. Hence, implementing new innovative transport technologies creates more jobs and creates an opportunity for innovation and up-skilling.
EV manufacturing industry *(Section 3.3.3.2)*	SA is to a large extent dependant on auto manufacturing. The risk of countries banning ICE vehicles, identified through the research, presents a serious problem for the local manufacturing industry. By pivoting to EVs, it can create the demand for local EV manufacturing which in turn could shift the industry to a more reliable future industry.
Reduction of road mortality *(Section 3.3.2)*	The benefit of implementing autonomous driving technology is salient in safety improvement and congestion reduction. For example, SA records some of the highest road fatalities, which can now be reduced with autonomous technology.
Improve equitable access *(Section 3.5.1)*	Another benefit that SA can realise with autonomous transport is better access to jobs and resources. Due to SA’s high unemployment rate, people often have to travel to the country's economic hubs for work, while they and their families live far away. Hyperloop improves equitable accessibility and reduces these travel times, resulting in the betterment of economic growth and opportunities.
Education access and energy security improvement *(Section 3.3.2)*	Implementing electric school busses can help improve education access and further cater to the significant education trips recorded in the country. The utilisation of these vehicles as mobile energy storage units allows for a more secure energy supply and can even be used for humanitarian solutions.

South Africa can significantly benefit from a safer, more reliable and more accessible transport network. As a developing nation, transport is a key economic driver and, with the implementations discussed above, the economic growth could see significant upside.

Layout

SA cities are inefficiently laid out due to urban sprawl, but also because of the apartheid regime. The lack of skills in the urban planning environment leads to inefficient planning and execution. Table 7.4 provides some key benefits that can be experienced by the SA market when this framework is implemented.

*Table 7.4 - **Added Benefits in the Layout Sector in SA Context***

Advantage	Elaboration
Community growth *(Section 3.5.4.1)*	The benefit of having more access to green spaces that are evenly spread throughout the city, allows for more community orientated living. This way, all residents can connect in a neutral environment.
Reliable property value stability	The framework sets out a predetermined property scheme that ensures that property values are not unknowingly inflated or damaged due to development forming that were not planned for. A practical example of this is a sewage plant being constructed next to a residential development, which negatively affects the property value. The framework ensures that development occurs, knowing what the area will be utilised for in the future.
Improved air quality *(Section 3.5.4)*	The implementation of green space improves air quality. SA struggle especially with Tuberculosis, which is adversely affected by attenuated air quality. By having a cleaner air quality in this framework, the health conditions of residents are improved, and the medical expenses of residents are reduced.
Climate impact on water reserves *(Section 3.5.5)*	The layout framework plans for the UHI effect, which affect climate change. The city of Cape Town in SA was the first city that almost ran out of water. The risk of natural disasters is reduced by improving the climatic conditions, reducing the UHI effect and improving water utilisation and catchment.
Reduction in poverty *(Section 3.5.5)*	Other than being susceptible to droughts and flooding, SA has a high poverty rate. Implementing urban farms in the cities of SA improves access to food, reduces water wastage, reduces food wastage and improves the economies of scale for food, which reduces food costs. In addition, SA has a significant agricultural industry that is at risk of being attenuated due to reducing arable land.
Low-income housing provision	The magnitude of this framework can attenuate the significant unemployment rate of SA. This framework implements low-income housing, which can be given to the builders and their families as an employment benefit. The builders of this city are ensured an extended work period due to the magnitude of this project that ensures job security.

South Africa’s urban layouts have been adversely impacted by the apartheid regime and as of late the lack of change to the approach. Hence, by adopting this framework, the layout can be redesigned entirely and planned for success.

8 APPENDIX G

Qualitative Evaluation Appendix

This Appendix presents the processes followed to qualitatively evaluate the framework proposed in Chapter 3. It is explained how key parts contributing to the success of the framework are calculated and evaluated. Additionally, the key input values used are supplied and referenced. For more expanded and elaborate tables, interactive links – referenced with a (**L_0**) – are provided that point to Appendix and back. Figure 8.1 provides visual schema of the various parts of the model and their categorisation.

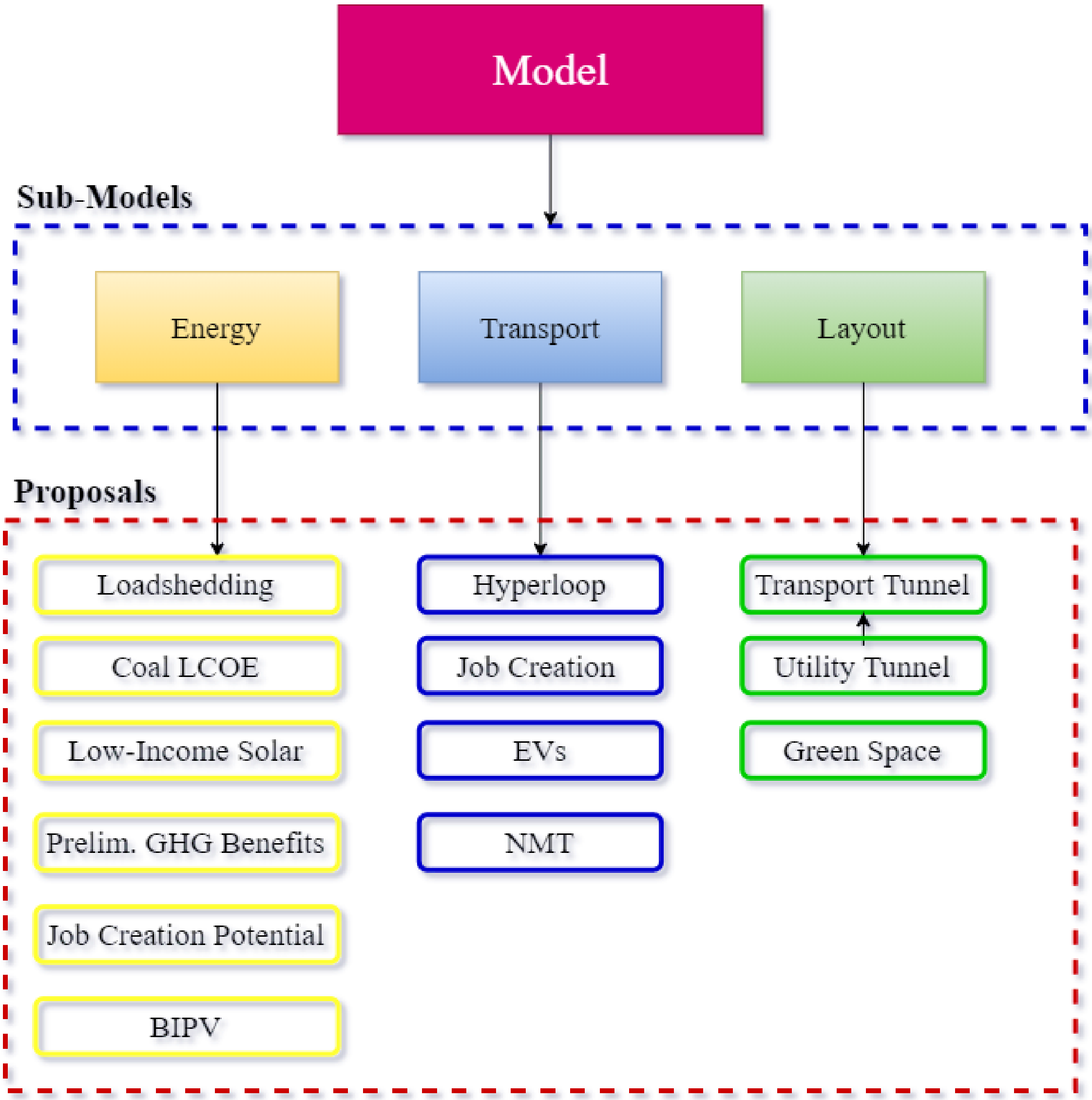

Figure 8.1 - ***Qualitative Model Schema***

8.1 Energy Sector Sub-model

Section 8.1 presents the economic analysis done on the energy sector of the proposed framework. Refer to Appendix for a summary of all the key values from each sectoral evaluation.

8.1.1 Scenario(s) used.

Table 8.1 shows the scenario used for each proposal, and if it differs from the base case scenario presented in sub-section 4.2, why and how it differs.

Table 8.1 - ***Energy Scenarios Evaluated***

Proposal	***Scenario***	***Rationale for change***
Loadshedding	South Africa as a whole, since 2015.	As an indicator. The economic value lost from loadshedding since 2015 on both a national and regional scale.
Coal Plants	All SA coal plants are evaluated	Cape Town does not have its own Coal Plant.
Low-Income solar scheme	1 000 low-income housing units.	There is no data on how many low-income users in CPT are receiving the subsidy. The assumed number is considered conservatively low compared to the national figure of 320 000.
Preliminary GHG benefits	CPT 2012 energy data is used.	This is the most comprehensive and complete data that was available for CPT city.
New Energy Job Creation Potential	Base Case	-
BIPV	CPT city CBD	There is no data available for city window area across the city. CBD area was evaluated via google maps for an estimate.

Considering the scenarios evaluated, Table 8.2 summarises key additions to the base scenario used in the energy model. The summary table includes frequently used key values as well.

Table 8.2 - ***Energy Sector Additions to Base Case and Recurring Key Values***

TERM	VALUE	UNIT	REFERENCE
Intellidex Cost/Stage/Day	R 300.00	*Million*	(BusinessTech, 2019)
Electricity Inflation Rate	6.8%	-	*Derived*
Coal O&M Growth Rate	2.00%	-	*Assumed*
Coal Discount Rate	8.00%	-	*Calculated from (IndexMundi, 2020)*
2020 Coal Cost Per MWh	R 101.79	*per MWh*	*Calculated from (IndexMundi, 2020)*
Average KWh Solar Per Month	1 026.67	*KWh*	*Calculated from (SA Department of Energy, 2020)*
tCO_2e Per Capita	5.5	Per cap	*(Euston-Brown et al., 2015)*
Households Receiving Free Basic Electricity	*[i]*320 000.00	Households	*(Euston-Brown et al., 2015)*
Average Energy Consumption Per Capita (Excl. Marine and Aviation)	36.80	*Gj/capita*	*(Euston-Brown et al., 2015)*
Low Income Energy Contribution Per Month	100.00	*kwh*	*(Euston-Brown et al., 2015)*
GHG Emissions Per Capita (Excl. Marine and Aviation)	5.21	*tCO2e/capita*	*(Euston-Brown et al., 2015)*
Cost Per kWp Of Solar	R 12 162		*(Sklar-Chik, 2017)*
LCOE Of Fossil Fuels	R 3.38	Per kwh	*Calculated in Section 8.1.3*
CPT Income Class Energy Consumption Breakdown			
Low-Income Not-Electrified	4%	-	(Borchers and Ndlovu, 2015)
Low-Income Electrified	20%	-	(Borchers and Ndlovu, 2015)
Mid-Income	30%	-	(Borchers and Ndlovu, 2015)
High Income	36%	-	(Borchers and Ndlovu, 2015)
Very High Income	10%	-	(Borchers and Ndlovu, 2015)
New City Energy Mix			
New City Energy from Solar	70%	-	
New City Energy from Wind	20%	-	
New City Energy from Eskom	10%	-	

8.1.2 Loadshedding Intermediary Calculations and Outputs

The value of unserved energy was calculated to be R96.39 per KWh. This cost was calculated using the average of four cited resources (L_1- Appendix). This value was used to calculate the total cost of the lost energy volume up until the 16th of August 2021. The energy volume lost, since 9 January 2015, was derived from the open-source data provided by the loadshedding application used in SA, EskomSePush (Maritz, 2021). Table 8.3 shows the results of the calculations performed, showing the total national energy lost. This national loss is further broken down in Chapter 4 to an equivalent regional figure.

Table 8.3 - ***Loadshedding Energy Loss from 2015-2021***

Ref	*Stage*	*Total [hrs]*	*Total MW shed*

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[i] This is a national value which is adapted in the model to fit the base case scenario

Calculated from (Maritz, 2021)	1	1076.00	1 076 003.06
	2	2658.24	5 316 483.33
	3	118.01	354 036.67
	4	224.02	896 100.00
	5	0.00	-
	6	3.93	23 603.33
	Total	**4 080.22**	**7 666 226.39**

Item	Value	Unit
Total Hours of Loadshedding	4 080.22	hrs
Annual hours of Loadshedding	680.04	hrs/year
Total unserved energy	7 666.23	GWh
Total unserved energy cost	R 738.91	Billion

Table 8.4 continues to allocate the loadshedding cost up into provincial costs by using two different metrics namely, the GDP contribution of each province and the population number of each province.

*Table 8.4 - **Loadshedding Provincial Cost Allocation Using GDP and Population Numbers***

COST DEVIDED TO PER PROVINCE BASED ON GDP CONTRIBUTION

	% Contribution	Average Cost (R' Billion)		Intellidex Cost (R' Billion)	
GP	34%	R	251.23	R	416.18
KZN	16%	R	118.23	R	195.85
WC	14%	R	103.45	R	171.37
EC	8%	R	59.11	R	97.93
MP	8%	R	59.11	R	97.93
LP	7%	R	51.72	R	85.68
NW	6%	R	44.33	R	73.44
FS	5%	R	36.95	R	61.20
NC	2%	R	14.78	R	24.48
SOURCE:	(Stats SA, 2019)				

COST DIVIDED TO PER PERSON BASED ON PROVINCE POPULATION

	Population (2019)	Average Cost pp		Intellidex Cost pp	
GP	15055000	R	16 687.53	R	27 644.11
KZN	11363000	R	10 404.49	R	17 235.80
WC	6794000	R	15 226.37	R	25 223.59
EC	6519000	R	9 067.82	R	15 021.50
MP	4605000	R	12 836.73	R	21 264.97
LP	5933000	R	8 718.02	R	14 442.02
NW	3997000	R	11 092.03	R	18 374.75
FS	2917000	R	12 665.65	R	20 981.57
NC	1246000	R	11 860.58	R	19 647.91
SOURCE:	(Statista, 2019)				

The loadshedding values are used to calculate the monetary loss which could be avoided in future by the framework and moreover could have been used to fund the city instead of being lost.

8.1.3 SA Coal Plant LCOE

The literature identified a shortfall in how conventional energy LCOE is being calculated. This section re-calculates the LCOE of coal in SA to show the stark difference in LCOE between coal and RE sources when the capacity factor is correctly utilised.

The LCOE is calculated as per Equation 8 defined Section 3.1.2, however, the inclusion of the capacity factor is considered in this analysis. The calculation is performed over 15 and 30 years, but for the purposes of this explanation, the 30-year analysis is discussed. The calculation follows an LCC model approach.

The first data value acquired was the Capital Expenditure (CAPEX) of each coal plant. Some plants construction cost data was not readily available, but the CAPEX per MWh of the generative capacity could be found. Hence, in these cases where project costs were lacking, per MWh prices were used.

The second parameter acquired was the coal fuel cost. The 2020 cost of coal calculated per MWh (R 101.79) **(**L_2 **-** Appendix **)**, was then used to calculate year 1 fuel cost for each plant. Table 8.5 shows an extract from the calculation table. The expanded calculations for all coal power plants are shown in the link (L_3 **-** Appendix). The product of the installed capacity of each plant and the turbine efficiency was taken to calculate the maximum actual capacity of the plant for a year. The average produced energy units of each plant for one year could also be calculated from data available which gave the average last 3 years production values. This led to the actual one-year production capacity factor being calculated for the plant.

*Table 8.5 - **Coal Plant Fuel Cost Calculation Extract***

(Eskom, 2020)		***Eqn.***		***Arnot***	***Duvha***
Downtime percentage	(1)		*%*	**8%**	**10%**
Installed capacity	(2)		*MW*	2100	3600
Turbine efficiency rate	(3)			35.60%	37.60%
Distributed Production last 3 yrs.	(4)		*MWh*	9 675 000	22 798 000
Average Distributed Production 1 year	(5)	= (4) / 3	*MWh*	3 225 000	7 599 333
Max actual capacity	(6)	(2) * (3) * 24 *365	*MWh*	6 548 976	11 857 536
1 Year Capacity Factor	(7)	= (5) / (6)		49%	64%
Gj of energy	(8)	= (2) * 3.6	*Gj*	23 576 314	42 687 130
Fuel Cost for year 1 production		**= *(6)* * R 101.79**		**R666 592 200.00**	**R1 206 927 771.43**

As previously discussed, the capacity factor should represent the actual units of energy **sold** to the grid. Due to the lack of sales data available, this production capacity factor is used as the actual capacity factor. Hence, this calculation shows an overestimated sales margin and hence gives the absolute minimum LCOE of these coal plants. Where the average 3-year production data was not available, a conservative 60% capacity factor was assumed.

The final parameter acquired was the Operating Expenditure (OPEX) of each coal plant (L_4). The OPEX includes water usage, fixed O&M costs and variable O&M costs. A plant with lacking OPEX data was calculated using the ratio of installed capacity to that of a similar plant with available data.

The calculated input costs used to calculate the LCOE of each coal plant are summarised in Table 8.6. The inputs were placed in an automated LCC model of which an extract up to year 3 for Medupi is shown in Table 8.7. The output results of each plant LCOE is discussed in Section Table 4.2.

*Table 8.6 - **SA Coal Plant Cost***

Coal Plant	***Fuel Cost***	***CAPEX (2020)***	***CAPEX Source***	***OPEX (2020)***	***1st Capacity Factor***
Arnot	R 666 592 200.00	R 2 676 738 624.49	*(Carbon Tracker Initiative, 2020)*	R 1 843 949 642.30	49%
Duvha	R 1 206 927 771.43	R 1 600 000 000.00	(Eskom, 2020b)	R 3 353 437 486.76	64%
Hedrina	R 609 883 714.29	R 2 793 056 070.67	*(Carbon Tracker Initiative, 2020)*	R 1 755 135 526.27	60%
Kendal	R 1 295 510 706.00	R 6 027 164 551.04		R 3 813 305 722.45	60%
Kriel	R 935 957 507.14	R 5 176 291 247.51		R 2 688 794 767.24	65%
Lethabo	R 1 130 724 406.29	R 3 340 431 219.24		R 3 365 328 921.76	60%
Majuba	R 1 253 311 032.86	R 11 900 000 000.00	(Eskom, 2020a)	R 3 770 205 536.10	60%
Matimba	R 1 266 525 180.00	R 4 492 889 305.98	*(Carbon Tracker Initiative, 2020)*	R 3 693 675 271.10	64%
Matia	R 1 206 927 771.43	R 4 930 712 317.51		R 3 353 437 486.76	71%
Tutuka	R 1 238 063 940.00	R 6 839 883 977.51		R 3 420 459 841.36	54%
Medupi	R 1 460 061 612.00	R 208 700 000 000.00	(Donnelly, 2019)	R 5 772 419 337.57	60%
Kusile	R 1 463 720 914.29	R 239 400 000 000.00		R 5 786 886 553.96	60%
Camden	R 460 462 204.29	R 16 199 188 110.90	(Eskom, 2020a)	R 1 385 546 735.36	60%
Grootvlei	R 365 930 228.57	R 4 800 000 000.00	(Bigala, 2011)	R 1 060 470 274.17	60%
Komati	R 286 645 345.71	R 80 000 000.00	(Eskom, 2020a)	R 867 448 694.62	60%
Single Source	*(Eskom, 2020a)*	*NA*	*NA*	(Steyn *et al.*, 2017b)	*NA*

Table 8.7 - ***LCOE Extract Calculation for Medupi Plant – Using Table 8.6***

Assumptions (in 'mill)	
Initial Investment Cost (R)	208 700
Operations and Maintenance Costs (R)	5 772
O&M Growth Rate (%)	2.00%
Annual Fuel Costs (R)	1 460
Annual Electricity Output (kWH)	14 344
Project Lifespan (years)	30
Discount Rate (%)	8.00%
Entry Date	2020/12/31

Total Costs	Implementation	Construct Completion	Operate year 1	Operate year 2	Operate year 3
Date	2020/12/31	2020/12/31	2021/12/31	2022/12/31	2023/12/31
Year Frac (From Start Date)		-	1	2	3
Cost Of Fuel Increase			*1*	*1.0385*	*1.0367*
Initial Investment	208 700	-	-	-	-
O&M Costs	-	-	7 232	7 377	7 525
Fuel Costs	-	-	1 460	1 516	1 572
Discount Factor		100.0%	92.6%	85.7%	79.4%
Present Value of Costs	208 700	-	8 049	7 625	7 221
NPV of Total Costs	**R 329 374.71**	**mill**			

Total Energy Output	Entry	-	1	2	3
Yearly Output	-	-	14 344	14 344	14 344
Capacity Factor	-	100.0%	60.0%	51.4%	47.6%
Actual Output	-	-	8 607	7 379	6 832
NPV of Total Output	**97 530 kWH**				

LCOE	**R3.38/kWH**

8.1.4 *Low-Income Solar Scheme*

To replace the continuous cost expense solution of providing monthly free electricity units to low-income users, the low-income solar scheme is validated in the section below. Table 8.8 presents the solar system setup per dwelling proposed by the framework, together with the input costs used in the model. The systems costs are calculated with respect to the sponsor (the city) and the user. The analysis calculates the costs to both parties in the conventional scheme vs. the new proposed solar scheme (**L_5**).

The model evaluates a household using 300 KWh a month and assumes that the user uses 50% of the solar units generated. This includes the solar units stored in the storage unit as most energy is typically used at night. The model accounts for the favourable return of 50% of the power for its use. Finally, the evaluations account for the electricity bought by the user when not utilising the solar capacity.

Table 8.8 - ***Solar Setup per Dwelling***

Ref	***Item***	***Value***	***Unit***
	System Life Cycle	**25 years**	
	System repayment period	**20 years**	
	System Size	5	*kW*
	Battery Size	1	*kW*
Derived From: (SolarAdvice, 2021)	1 kW Inverter storage Cost (Bought every 8 years)	R 3000.00	
	System Cost	R 78 825.00	
	Number of panels	6	
	Panel Wattage	390	*W/panel*
	Inverter Size	5	*kW*
	Daily production	10.30	*kWh*
	Monthly production	308.88	*kWh*

The analysis accounts for the increase of the electricity tariff by using equation 6, derived from the historical price of electricity.

$$y = 1 * (10^{-79}) * e^{0.0903} \tag{6}$$

The intermediary output NPV per scheme is shown in Table 8.9.

Table 8.9 - ***Intermediary Low-Income Energy Scheme Outputs*** - *(L_5).*

Conventional Scheme	25-Year NPV Value
*[ii]*Sponsor Cost	-R 39 572.25
User Cost	-R 187 994.94
Proposed Solar Scheme	
Sponsor Savings	R 38 680.62
User Cost	- R 115 202.72

8.1.5 *Preliminary Estimated GHG Benefit of Ripple City Energy Volume*

Before the model calculated the GHG impact of key technologies. A preliminary forecasted benefit was calculated from the city`s perspective. The energy consumption data of the year 2012 of the City of Cape Town was used *(Euston-Brown et al., 2015)* to determine what the proposed decreases and increases in the energy consumption would be in the Ripple City. The analysis assumed reduction factors from various sources as shown in Table 8.10 and applied these to the 2012 data of energy consumed and GHG emitted.

[ii] Sponsor = The entity paying for the solar system, which in this case is the city.

Table 8.10 - ***GHG Impact Assumptions***

Ref	***Assumption***	***Value***
(Euston-Brown et al., 2015)	CBD solar PV energy GHG impact	5.00%
	Industrial solar PV energy GHG impact	24.75%
(Borchers and Ndlovu, 2015)	Reduction of paraffin from new energy	48.00%
	General confidence ratio	0.85
(Hien and Chen, 2016)	Better building efficiency energy load reduction	31.00%
(Sudarmono *et al.*, 2018)	LED street lights energy reduction	78.40%
(Rodrigue, 2020b)	ICE vehicle energy loss	64.00%
(Euston-Brown et al., 2015)	Old city energy from fossil fuel source	95.00%

The reduction of paraffin rate was calculated by taking the summation of the share of low-income users total energy utilisation (Borchers and Ndlovu, 2015). The rate thus includes low-income users with access to electricity and without access to electricity. The rate is then multiplied by a factor of two to account for the higher energy potential of parrafin.

The assumptions applied to the 2012 data were calculated in the model and the output results were summarised in Table 8.12. The expanded calculations are shown in Table 8.11 and not via a link to allow for ease of reading with reference to the assumptions presented above in Table 8.10. The CPT energy data was given in Gj and the conversion to kWh required values to be multiplied by a factor of 278.

Table 8.11 - ***Expanded Preliminary GHG and New Energy Calculations*** *– CPT Data from* (Euston-Brown et al., 2015)

		Conventional city		**Ripple City**			
		CPT 2012 [kwh] energy consumption Source	**CO2 emissions [tCO2e]** Source	**Demand Assumption**	**New City Energy Consumption [kwh]**	**GHG Assumption**	**new CO2 Emsission [tCO2e]**
Service Sector							
	Wastewater treatment works	125 766 930	129 540	unchanged	125 766 930	24.75% reduction	97 473
	Buildings	135 114 966	139 168	31% reduction	93 229 327	5% reduction	132 210
	Bulk water supply	19 039 860	19 611	unchanged	19 039 860	24,75% reduction	14 756
	pump stations	44 426 340	45 759	unchanged	44 426 340	24,75% reduction	34 431
	municipal street lighting	98 235 794	101 183	78,4% reduction	21 218 932	78,4% reduction	21 856
	Eskom street lighting	25 225 139	25 982	78,4% reduction	5 448 630	78,4% reduction	5 612
	Traffic Lighting	1 668 780	1 719	78,4% reduction	360 456	78,4% reduction	371
	TOTAL	449 477 809	462 962		**309 490 475**		**306 709**
Service Transport							
	Electric vehicles	0	0	increase by new veh consumption (1378 BEBs + 7006 Robotaxis) = 90% increase Other Evs calculated seperately	15 196 453	10% increase	2 034
	Diesel service vehicles	9 999 489	27 019	95% reduction	499 974	95% reduction	1 351
	Petrol Service Vehicles	5 996 777	13 655	95% reduction	299 839	95% reduction	683
	TOTAL	15 996 266	40 674		**15 996 266**		**316 760**
	Sub TOTAL	465 474 075	503 636				
Residential							
	Electricty	4 464 862 191	4 598 808	increase by parrifin reduction	4 486 467 154	5% reduction	3 908 987
	Parrafin	45 010 339	115 992	48% reduction	23 405 376	48% reduction	60 316
	LPG	22 800 404	36 982	unchanged	22 800 404	unchanged	36 982
	Coal	1 702 472	708	unchanged	1 702 472	unchanged	708
	TOTAL	4 534 375 406	4 752 490		**4 534 375 406**		**4 006 993**
	Sub TOTAL	4 999 849 481	5 256 126				
Industrial							
	Electricty	1 552 354 502	1 597 647	increase by parrifin and coal reduction	1 729 026 935	24,75% reduction	1 202 151
	Parrafin	44 699 620	11 199	0.85	37 994 677	48% reduction	5 823
	LPG	338 476 676	73 965	unchanged	338 476 676	unchanged	73 965
	Coal	1 133 116 602	471 335	0.85	963 149 112	0.85	400 635
	TOTAL	3 068 647 400	2 154 146		**3 068 647 400**		**1 682 574**
	Sub TOTAL	8 068 496 881	7 410 272				
Commercial							
	Electricty	5 272 127 664	5 417 747	increase by parrifin and coal reduction	5 286 306 957	24,75% reduction	4 076 589
	Parrafin	94 440 492	23 661	0.85	80 274 418	48% reduction	12 304
	LPG	169 238 338	36 982	unchanged	169 238 338	unchanged	36 982
	Coal	88 126	37	0.85	74 907	0.85	31
	TOTAL	5 535 894 620	5 478 427		**5 535 894 620**		**4 125 906**
	Sub TOTAL	13 604 391 501	12 888 699				
Transport							
	Electricity	0	-	increase by parrifin and coal reduction + decrease by better efficiency of Evs	14 096 389 982	increase by 10%	285 131
	Petrol	13 574 127 566	3 250 903	95% reduction	678 706 378	95% reduction	162 545
	Diesel	9 610 724 378	2 451 725	95% reduction	480 536 219	95% reduction	122 586
	TOTAL	23 184 851 944	5 702 628		**15 255 632 579**		**570 263**
	Sub TOTAL	36 789 243 445	18 591 327		28 720 036 746		11 009 204
	Other						
	Low-income contribution	384 000 000	5 985 248				
	Total City electricity consumption	12 997 976 535	13 379 712		25 922 877 955		
	Total City excl aviation and mar	***39 193 097 500***	***20 010 470***		***30 739 890 801***		

Table 8.12 - ***Ripple City Preliminary GHG Costs and Energy Costs***

Term	Value	Calculations
CPT energy demand [kWh]	39 193 097 500	Table 8.11
Ripple energy demand [kWh]	30 739 890 801	Table 8.11
Cost of Energy Carbon		
CPT cost of Carbon	R 14 961 028 000	= Social cost of carbon x CO_2 emission = 2010470 x R747.66 (Table 8.11)
Ripple Conservative Cost of Carbon	R 8 231 141 671	= Social cost of carbon x CO_2 emission = 11009201 x R747.66 (Table 8.11)
Theorised Ripple Cost of Carbon	R 4 115 570 835	= 50% of Ripple Conservative, as the framework sets out a goal to achieve carbon neutrality
Cost of Energy Infrastructure		Table 8.11
CPT cost of Electricity	R 42 018 988 701	= (95% of Total City Consumption x LCOE of fossil energy) + (5% of Total Consumption x LCOE of wind energy)
Ripple Cost of Electricity	R 23 916 321 068	= (10% of Total City Consumption x LCOE of fossil energy) + (20% of Total Consumption x LCOE of wind energy) + (70% of Total City Consumption x LCOE of solar energy)
Initial Ripple Infrastructure Cost of 70% solar	R 220 691 829 181	= 70% of Total City Consumption x CAPEX for solar energy per kWp

8.1.6 *Energy Potential Job Creation Potential*

The literature often suggests the industry potential attainable by the proposals. The section below presents the calculation method used to calculate the Job creation potential of the energy proposals in the framework. Specifically, those of solar, wind, utility-scale energy storage and grid modernisation together with micrgrids. Figure 8.2 shows the visual representation of the formula used to calculate the job potential of each technology.

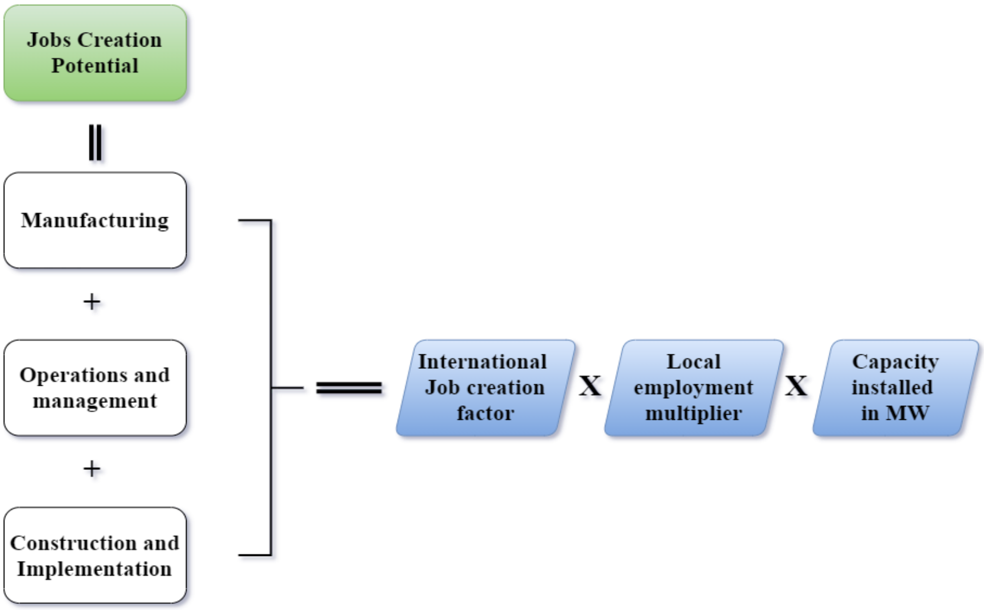


Figure 8.2 - ***Job Creation Potential Formula***

The formula utilises available American energy manufacturing and construction job statistics and applies a region-specific modifier to these values to align them with the region's market trends. The job creation factors generated, shown in Table 8.13 for per MW of energy, was then used to calculate the jobs potential of the new Ripple City, using the new city energy consumption calculated in Section 8.1.5.

Table 8.13 - ***Annual Energy Potential Job Equivalent Creation Factors***

	USA figures				***Africa figures***		
Job creation multipliers	**Manufacturing**	**O&M**	**Construction and implementation**	Regional adjustment multiplier	**Manufacturing**	**O&M**	**Construction and implementation**
	[Jobs/MW]	[Jobs/MW]	[Jobs/MW]		[Jobs/MW]	[Jobs/MW]	[Jobs/MW]
Calculations:	(1)	(2)	(3)	(4)	= (1) * (4)	= (2) * (4)	= (3) * (4)
Solar	6.7	0.7	13	4.5	30.15	3.15	58.5
Wind onshore	4.7	0.3	3.2		21.15	1.35	14.4
Utility scale battery storage (prosumer case)	16.9	0.8	21.6		76.05	3.6	97.2
Coal	5.4	0.14	11.2		24.3	0.63	50.4
Ref	(Rutovitz *et al.*, 2015; US Department of Energy, 2017)						

From the calculations performed in Table 8.11, the Ripple City energy usage is determined to be 2 959.23 MW. The storage capacity is calculated to be 71 021.58 MWh - 2 959 MW - for a reliable capacity for 24 hours. For Grid modernisation, it is derived that 74% of the utility-scale storage potential factors are appropriate to be used for grid modernisation (US Department of Energy, 2017). The grid factors are shown in Table 8.14.

Table 8.14 - ***Grid Modernisation Potential Job Creation Factors***

	Manufacturing	***O&M***	***Construction and implementation***
	[Jobs/MW]	[Jobs/MW]	[Jobs/MW]
Grid Modernization and microgrid Job creation	56.46	2.67	72.16

Using the calculated capacities, the resulting optimal potential job creation from the new Ripple City is presented in Table 8.15.

Table 8.15 - ***Intermediary Output of Energy Job Creation Potential Considering Two Local Manufacturing Scenarios***

Job Category	100% Local	50% Local	Unit	From
Solar PV Job creation possibility	190 160	158 933	*Jobs*	*Table 8.13*
Wind creation possibility	21 839	15 580	*Jobs*	*Table 8.13*
Utility scale energy storage jobs	523 340	410 815	*Jobs*	*Table 8.13*
Coal Jobs lost due to decommissioning	-200 627	-168 268	*Jobs*	*Table 8.13*
Grid modernisation Job creation possibility	388 523	304 985	*Jobs*	*Table 8.14*

8.1.7 BIPV Intermediary Calculations and Outputs

To perform the Cost Benefit analysis (CBA) on the BIPV proposal made in the framework, a smaller sample scenario had to be evaluated. The rationale for considering the CBD area is that it was relatively easy to estimate the glass façade area, as there is no other data available on the total viable glass façade area. BIPV is a significant compounder to optimising previously underutilised surface area and that is why this model performed a CBA on this technology. Google Earth (Google and Keyhole Inc, 2021) was used to evaluate and estimate the glass façade area in CPT CBD that is optimal for solar radiation. Figure 8.3 shows the evaluation area and buildings considered. The assumed scenario has a viable radiated façade area of 155 680 m^2.

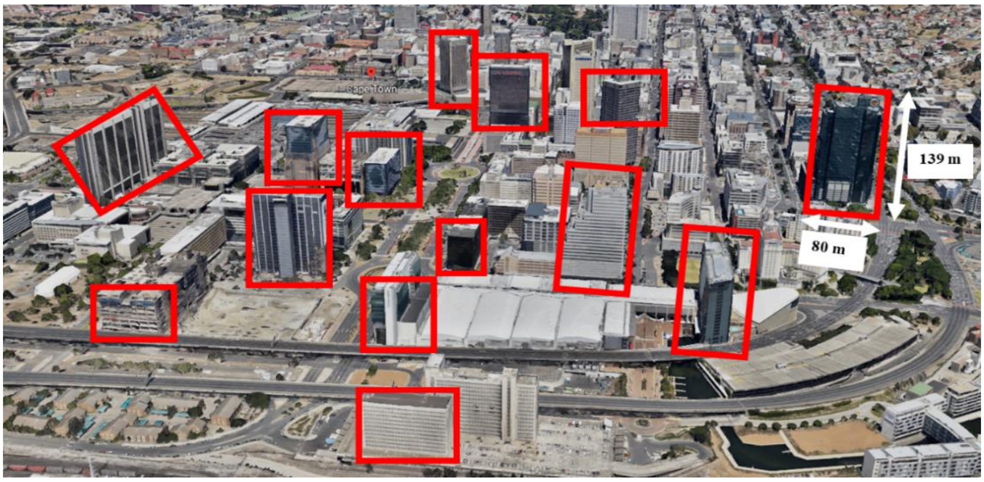


Figure 8.3 - ***Cape Town CBD Solar Viable Building Glass Area Estimation***

Key metrics were derived (**L_6 -** Appendix) from seven BIPV feasibility studies performed by Onyx Solar (2020). Table 8.16 shows the summary of the averaged outputs from the seven evaluated cases.

Table 8.16 - ***BIPV CAPEX and Benefits from Scenario Case***

Calculated from: (Onyx Solar, 2020)		***35-Year Life***			***Per annum per m2***
Average CAPEX	R	4 143.01	*per m2*		-
Average Peak Power		92.74	*Wp per m2*		
Environmental Benefits					
Average Energy Generated		3 423.57	*kWh per m2*		97.82
Average CO2 avoided		2 975.07	*Kg per m2*		85.00
Average EV kms supplied - (1)		19 685.93	*Km per m2*		562.46
Average Light points fed - (2)		6.77	*every day per m2*	-	
Economic Benefits					
Average Value of energy	R	16 482.57	*per m2*	R	470.93
Average Benefit	R	19 064.00	*per m2*	R	544.69
Average times of ROI		10.01	*times*		0.29
Average IRR		37.65%	-		1.08%
Average PBP		2.34	*Years*		0.07
Average Building Value increase	R	5 656.86	*per m2*	R	161.62

The estimated façade area of 155 680 m^2 was then used in the model together with the key metrics to generate the preliminary costs and benefits shown in Table 8.17.

Table 8.17 - BIPV Costs and Benefits

BIPV Costs				**From**
CAPEX	R	644 984 464.00	*once off*	*Table 8.16*
BIPV Benefits				
Direct Benefit	R	84 796 672.00	*per annum*	*Table 8.16*
Indirect Benefit	R	9 893 872.79	*per annum*	*Table 8.16*

8.2 Transport Sector Sub-model

Section 8.2 presents the economic analysis done on the transport sector of the proposed framework. Refer to Appendix for a summary of all the key values from each sectoral evaluation.

8.2.1 Scenario(s) used.

All projects in the transport model use the base case scenario. Table 8.18 summarises additional parameters and changes to the scenario used for the transport projects. Some projects have further scenario assumptions which are discussed later.

Table 8.18 - ***Transport Scenario Additions to Base Case and Recurring Key Values***

TERM	VALUE	UNIT	REFERENCE
Number Of Trucks Replaced by Hyperloop	201 380.00	*trucks*	*Calculated*
Scenario Annual Freight Tons	5 840 000.00	*tonnes/year*	*(Lachaize, 2017)*
Number Of Daily Private Vehicles	1 071 872	*vehicles*	*Calculated Table 8.28*
% Of Private Trips Moved to Hyperloop	3%	-	*Assumed*
% Of Public Transport Trips Moved to Hyperloop	3%	-	*Assumed*
% Road Accidents Avoided	3%	-	*Assumed*
% Of Rail Passenger Trips Moved to Hyperloop	50%	-	*Assumed*
Number Of Households	1 286 351	Houses	*CPT Population / 3.59*
Sa Household Vehicle Ownership Rate	30.60%	-	*(de Villiers, 2019)*
Ripple City Private Cars	393 623	Vehicles	*Calculated Table 8.41*
Total Number Of BEB	1378	Busses	*Calculated Table 8.42*
% Taxi Replacement by Robotaxi	50%	-	*Assumed*
Number Of Robotaxi's	7 006.00	Vehicles	*Calculated Table 8.44*
Number Of Initial Robotaxi Drivers	10 509.00	Drivers	*Calculated Table 8.44*
Total Number of Small EVs	400 629	Vehicles	*Calculated Table 8.44*
Ripple City Minimum NMT Goal	50%	-	*Framework*
Ripple City Number of NMT Users	2 309 000	Users	*Calculated Table 8.46*
% Of Ripple NMT Users Utilising Walking	80%	-	*Assumed*
CPT Congestion Level	32%	-	*(TomTom, 2021a)*
Number of Bus Stations	42	stations	(Whitehead *et al.*, 2015)
SA Manufacturing Industry 2014 Employment	1 749 000	-	*(Department of Transport: RSA, 2014)*

8.2.2 Hyperloop Intermediary Calculations and Outputs

Hyperloop is an innovation with a few small-scale implementations as of 2021. The prospects of this new innovative technology are of interest and this section evaluates the proposed implementation of a 580km Hyperloop system in a Ripple City framework in South Africa. The 580km length was chosen from the Transpod feasibility study (TransPod, 2019b) and the Quebec City case study (Canada, 2009), as it is based in a similar setting as the base case. The length accounts for inter-city travel and an extensive inner-city network that also links with the proposed industrial nodes.

8.2.2.1 Hyperloop Costs

Due to no large-scale project being implemented yet, there is a lack of data from a project that has reached economies of scale. Nonetheless, there are several feasibility studies evaluated in this model, as well as some real small scale project costs.

The Hyperloop was evaluated against two scenarios which in the end became a dual 50:50 function. The first scenario looks a purely freight usage and at replacing a portion of the CPT region truck freight tonnage. Truck freight tonnage is considered only as this is the status quo of freight usage. The second scenario evaluated the Hyperloop system against the passenger rail usage. From literature it was identified that if the rail mode is implemented, then High Speed Rail (HSR) is the most efficient. Considering that the Hyperloop system is a high-speed mode of transport and the evaluated scenario length includes longer than normal trips, the evaluation only looks at the HSR case. The CPT slow rail passenger statistics are used for passenger counts as there is no HSR implementation in the city.

The CAPEX cost for the model was adapted from Lachaize (2017) and amounts to R 192 517 763.87 per km. The OPEX costs shown in Table 8.19 were also acquired from Lachaise's report based on his 5 840 000 tonnes per year estimation. The expenditure values were used from this report due to its in-depth evaluation of these costs in the report. The figures in the report were adjusted to match real-world data and the O&M values were based on a variety of railway project costs which suggest conservatism as Hyperloop is expected to have reduced O&M requirements than that of rail.

Table 8.19 - ***Hyperloop O&M Costs for 580 km Scenario***

Adapted from Source: (Lachaize, 2017)	***Annual Cost***
Labour	R 2 384 696 948.31
Materials and services	R 1 430 818 173.36
Energy (Including Solar Energy Contribution)	R 317 959 595.30
Decrepitation and amortisation	R 843 069 466.38
Equipment Rent	R 211 973 059.88
Miscellaneous	R 105 986 535.41
Total	*R 5 294 503 778.64*

Furthermore, the CBA model for Hyperloop considers an additional cost of trucking revenue loss. The Hyperloop system is expected to reduce the number of trucking utilised by freight drastically and hence this would be a short term cost to consider. Moreover, by considering the jobs lost in the trucking industry and the jobs gained by the Hyperloop system.

The model first determined what amount of freight trucking is present in the City of CPT to ensure that there is enough tonnage demand to be utilised by the system. To take over the entire truck freight tonnage of CPT, calculated in Table 8.20, more than three of these 580km systems would be required. Hence, the model assumes that the Hyperloop system will operate at full tonnage capacity. The model averages five freight truck types, from dual-axle to 7-axle rigs. These seven include a dual axle semi, tridem-axle semi, end tridem tip semi, tridem reefer Semi and a taut-liner interlink. They are focussed on as they are the most expensive, large haul and generate the most damage to the road network.

To ensure a conservative approach, the model calculates the number of trucking jobs available in the Western Cape (WC) region and assumes that all these equivalent jobs are lost to the Hyperloop system. Table 8.20 shows the intermediary values used in calculating the total revenue lost in the trucking industry. The key value of interest is that 201 380 trucks are replaced by the system.

Table 8.20 - ***Freight Trucking Volume and Revenue loss***

Ref	***Term***		***Value***	***Unit***	**Calculation**
(Statistics SA, 2020)	Total SA Freight per Year		217 987 000	*tons*	(1)
(Western Cape Government, 2019b)	WC 2016 freight share		16.30%		(2)
Calculated	**Freight tonnage for WC**		**35 531 881.00**	***tons***	**(3) = (1) * (2)**
(Booley *et al.*, 2019)	CPT GDP contribution		9.80%		(4)
Calculated	**Freight tonnage for CPT**		**21 362 726**	***tons***	**(5) = (1) * (4)**
(Lachaize, 2017)	Hyperloop max capacity		5 840 000	*tonnes/year*	(6)
(Braun, 2019)	Average Tonnage Benchmark *(Dual axle semi; Tridem-axle Semi; End Tridem Tip Semi; Tridem Reefer Semi; Taut-liner Interlink)*		29	*tons*	(7)
Calculated	**Average number of trucks removed by Hyperloop**		**201 380**	***trucks***	**(8) = (6) / (7)**
(Economic Research Institute, 2020)	Average Labour salary per annum	R	225 761	*/driver*	(9)
(Statistics SA, 2020)	Income/tonne	R	204.57	*/tonne*	(10)
Calculated	**Service Revenue lost**	**R**	**1 194 663 577**	***/year***	**(11) = (6) * (10)**
(Singh, 2020)	Total local SA trucking jobs		44 021	*drivers*	(12)
Assumed	CPT share to trucking jobs		9.80%		(13)
Calculated	**Trucking jobs lost**		**4315**	***drivers***	**(14) =(12) * (13)**
Calculated	**Trucking Salary theoretically lost**	**R**	**974 158 715**	***per year***	**(15) = (9) * (14)**
	Nett Trucking loss	**R**	**2 168 822 292**	***/year***	**(16) = (11) + (15)**

Table 8.21 presents the intermediary outputs that were used to generate the final CBA of the Hyperloop system for the case of freight utilisation. Due to South Africa moving the majority of its freight via road-based transport, the analysis only considers trucking freight and not rail freight.

Table 8.21 - ***Intermediary Hyperloop Cost Output***

Hyperloop Costs				**From**
CAPEX	R	111 660 303 043.89	*once off*	*8.2.2.1*
OPEX	R	5 294 503 778.64	*per annum*	*Table 8.19*
Cost of Trucking Reduction	R	2 168 822 291.53	*per annum*	*Table 8.20*

8.2.2.2 Trucking Costs

From Braun (2019) the average CAPEX cost for the five trucks is R 1 846 025.57 per veh. Braun also sets out the OPEX costs as R3042293.13 per veh/year. Using the total trucks replaced by the Hyperloop system, the costs in Table 8.22 were calculated.

Table 8.22 - ***Intermediary Trucking Cost Output***

Trucking Cost			
CAPEX	R	371 752 629 429.52	*once off*
OPEX	R	612 656 991 294.13	*per annum*

8.2.2.3 High-Speed Rail Costs

Hyperloop is furthermore evaluated against the case of being utilised for passenger journeys also. This model specifically considers the replacement of rail-based passenger journeys due to the rail mode being identified as an underperforming mode of public transport in conventional cities. HSR is specifically chosen as the mode of rail-based transport.

To evaluate rail transport in a CBA against the Hyperloop mode, the first data point calculated was the CAPEX of rail. Table 8.23 shows the per km cost of the network infrastructure costs. The train sets CAPEX costs are shown in Table 8.24. The same resource for the train acquisitions costs was used to derive the OPEX costs and is also shown in Table 8.24. From the passenger volume available during the 230 work days in a year, the calculation determines that about 88 trains are required, this is 16 more trains than what CPT had in 2013 (Lewis, 2013).

Table 8.23 - ***Railway Infrastructure Costs***

Adapted from Source: (Carter *et al.*, 2018)		***2021 ZAR Value***	***Unit***	***Calculation***
Railway single Track (diesel)	R	11 193 366.42	*per km*	*(1)*
Railway single Track (electric)	R	14 924 488.56	*per km*	*(2)*
Railway signalling	R	5 223 571.00	*per km*	*(3)*
Rebalasting a railway	R	44 773.47	*per km/year*	*(4)*

Table 8.24 - ***HSR Equipment Cost and O&M Cost***

Adapted from Source: *(Barrón et al., 2009)*	***2021 ZAR Value***	***Unit***	***Calculations***
Total Maintenance cost	R 830 989.26	per km	*(A)- From Source*
Total Operation Cost	R 724 281 574.92	per train	*(B)- From Source*
Average seats per train	518.5	seats	*(1) From Source*
CPT Daily public transport passengers (City of Cape Town, 2019)	2 528 000	Pax/day	*(2)*
Share of public transport Metrorail CPT trips (City of Cape Town, 2019)	18%	-	*(3)*
Work days	230	days	*(4)*
Total passengers (similar to Hyperloop) per year (Work days only)	**104 659 200.00**	**passengers**	***(5) = (3)*(4)*(2)***
Seats required per day	455 040.00	passengers per day	*(7) = (6) / (4)*
Seats required per work day hour (10 work hours per day)	45 504.00	per peak hour	*(7) = (6) / 10*
Number of trains required	87.76		*(8) = (7) / (1)*
Train acquisition Cost	R 612 384 169.70	per train	*(9) From Source*
Total Train Acquisition Cost req.	**R 53 743 354 402.88**		**(10) = (8) * (9)**

Considering the same scenario length as the Hyperloop system, the intermediary costs used in CBA is shown in Table 8.25. The CAPEX was calculated according to Equation 7. And the OPEX according to Equation 8.

$$CAPEX_{HSR} = 580 * \left(\frac{\text{Table 8.23 (1)} + \text{Table 8.23 (2)}}{2} + \text{Table 8.23 (3)}\right) * \text{Table 8.24 (10)} \qquad (7)$$

$$OPEX_{HSR} = (580 * \text{Table 8.24 } (A)) + (\text{Table 8.24 (8)} * \text{Table 8.24 } (B)) \qquad (8)$$

Table 8.25 - ***Intermediary HSR Cost Output***

HSR Costs			
CAPEX	R	64 347 203 525.12	*once off*
OPEX	R	64 045 539 410.11	*per annum*

8.2.2.4 Hyperloop Benefits for Freight vs. Trucking

The calculation process for the benefits used in the CBA is discussed in the following sections. These benefits are specifically related to the freight trucking replacement.

The first benefit calculated was the positive reduction in GHG emissions as the Hyperloop system is entirely electric and replaces fossil fuel trucks. The total CO_2 tons avoided are shown in Table 8.26, together with the cost of carbon of these avoided GHG emissions. To calculate these figures the average CO_2 emitted by the sample trucks were multiplied by the average kilometres driven of 100 000 kms per annum per truck.

*Table 8.26 – **Hyperloop GHG Reduction Benefit***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.20	Trucks removed	201 380	trucks	*(1)*
(Ambel, 2015)	Kg of CO2 per km	0.9	kg	*(2)*
(Ambel, 2015)	Assume 100 000 km pa	90	tonne CO2/year/truck	*(3)* *= [(2) * (10^5)] / 1000*
Calculated	Gross CO2 reduced	18 124 200	tons/year	*(4)* *= (3) * (1)*
(Sklar-Chik, 2017)	Social Cost of Carbon	R 747.66	/ton of eCO_2	*(5)*
	Total Cost of CO2 removed	**R 13 550 739 372.00**	**/year**	**(6) = (4) * (5)**

Paired with the GHG emission reduction from fossil fuels, is the saved amount of money spent on fossil fuels. SA was identified through the literature to import 100% of its crude oil. By using the Hyperloop system, which operates on electricity, the total sum of money leaving the country's economy for crude oil is now kept within the country – to spend in the local economy.

To calculate this value of money kept within the local economy, the fuel savings were calculated as shown in Table 8.27. By first calculating the average useful life kilometres of a truck per annum and the average fuel consumption of these trucks, the total consumption of fuel could be calculated for the trucks removed. The September 2021 price of Diesel was used to calculate the total cost of fuel.

*Table 8.27 - **Hyperloop Fuel Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.20	Trucks removed	201 380	trucks	*(1)*
(Braun, 2019)	Average truck useful life (4-12 years)	8	years	*(2)*
(Braun, 2019)	Average useful life per truck km/year	95 000	km/year	*(3)* *= Source / (2)*
(Nylund and Erkkilä, 2005)	Average fuel consumption of sample trucks	0.26	L/km	*(4)*
Calculated	Total one truck consumption in year 1 of useful life	24 700	L/truck/year	*(5)* *= (3) * (4)*
Calculated	Total trucking removed fuel usage	4 974 086 000	L/year	*(6)* *= (1) * (5)*
(GlobalPetrol Prices.com, 2021)	Cost of Diesel	R 17.44	/L	*(7)*
	Total cost of Fuel of trucks removed	**R 86 748 059 840**	**per annum**	**(8) = (6) * (7)**

The local economy not only benefits from money kept within the country but also from improving the efficiency of economic generators. Each person generates value for the economy in some way and therefore people have a monetary value linked to their time. Companies form part of this time value as they generate money over a specific time period. The quantifying metric for this value is called the Time Value Money (TVM) or also referred to as Value of Time (VOT) or Time Value Savings (TVS). TVM is not to be confused with inflation in this case.

The Hyperloop system shows prospects of improving travel times significantly and promises to be more efficient and adaptive. Hence, by using the Hyperloop system, it theoretically can reduce congestion, time travelled and therefore costs. To quantify this TVM cost saving, the methods discussed below were followed.

For trucking congestion reduction, the model conservatively only considered the 4 peak hours of a working day as these are the hours with the largest impact from congestion. The total annual kilometres driven by the recorded 200 trucks in a CPT peak hour was calculated by using the average travel speed of 60km/hr. Thereafter, the total kilometres driven were multiplied by the average cost of trucking congestion during peak hours.

The congestion delay savings from private vehicle travel was calculated using the TVM of car work trips. Based on the TomTom (2021a) congestion hours lost per vehicle per annum and the traffic data available for CPT, the total hours lost due to congestion was calculated. The model assumes 3% off these hours spent in congestion is alleviated by the Hyperloop system. The method for calculating the public transport congestion delay cost is the same.

The summarised results of delay cost savings are shown in Table 8.28.

Table 8.28 - ***Hyperloop Delay Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(TomTom, 2021a)	Cape Town average time lost in congestion	163	*hours/year/veh*	*(1)*
(City of Cape Town, 2019)	Daily passengers	2 528 000	pax	*(2)*
(City of Cape Town, 2019)	% of trips in morning peak for public transport	38%	-	*(3)*
(TomTom, 2021a)	Travel time index time	21	*min*	*(4)*
(City of Cape Town, 2019)	% of peak trip vehicles with one passenger	80%	-	*(5)*
(City of Cape Town, 2019)	% of total traffic private cars	53%	-	*(6)*
Calculated	Number of daily private vehicles	1 071 872	*veh*	*(7)* *= (2)*(5)*(6)*

(Pienaar and Nel, 2009)	SA free-flow volume of traffic 2009	1600	*veh/lane/hour*	*(8)*
(TDA Cape Town, 2018)	number of peak hour trucks in CPT system (N1)	200	*trucks/hour*	*(9)*
Ref	**Term**	**Value**	**Unit**	**Calculation**
Derived	% of trips driven during peak hours	70%	-	*(10)*
(TomTom, 2021a)	CPT Congestion	32%	-	*(11)*
	Congestion Trips (Trucks)			-
Derived: *(Rensburg and Krygsman, 2020)*	Average Truck Congestion Cost Peak (2021 value)	R 12.03	*per vkm*	*(12)*
(Rensburg and Krygsman, 2020)	Average speed of trucks during congestion	60	*km/hr*	*(13)*
Calculated	Total truck kms during peak hour	12000	*kms/peak hour*	*(14)* *= (9) * (13)*
Derived	Number of peak hours	4	*hrs*	*(15)*
Calculated	Annual 230 working year truck kms driven in peak	11 040 000.00	*kms/year*	*(16)* *= (14) * (15) * 230 work days*
	Trucking congestion cost reduced	**R 132 756 205.96**	***annual***	***(17)*** ***= (16) * (12)***
	Congestion Trips (private)			
Derived: *(Hayes and Venter, 2016)*	Average Car TVM - Work trips (2021 value)	R 87.27	*per hour*	*(18)*
Calculated	Private vehicle share (during congestion)	300 124	*private veh for peak hours per day*	*(19)* *= (2)*(6)*(10)*(11)*
Calculated	Hours lost annually by private vehicles	48 920 238	*hours*	*(20)* *= (1) * (19)*
	Hyperloop congestion trips reduced	**R 128 083 448.14**	***annual***	***(21)*** ***= (18) * (20) * 3%***
	Congestion Trips (PT)			
Derived: *(Hayes and Venter, 2016)*	Average public transport TVM - Work Trips (2021 value)	R 31.02	*per hour*	*(22)*
Calculated	Public transport share (during congestion)	960 640	*daily public transport passengers for peak hours*	*(23)* *= (2) *(3)*
Calculated	Hours lost annually by public transport trips	156 584 320	*hours*	*(24)* *= (23) * (1)*
	Hyperloop congestion trips reduced	**R 145 723 074.21**	***annual***	***(25) = (24) * (22)***
	Total Delay Savings	**R406 562 728.31**	**annual**	**(26) =** **(17) + (18) + (25)**

From the literature, it was evident that the transport network is dangerous and fatal. SA has a significant road mortality rate and the Hyperloop system can improve the transport safety statistics significantly. To calculate the savings from reduced transport related fatalities, injuries and damages, the CPT road safety statistics were assumed to be avoided by 3% through the adoption of Hyperloop. The safety transport statistics of CPT show the number of incidents determined together with its cost, which were then back analysed for per incident cost and used to calculate the model results shown in Table 8.29.

Table 8.29 - ***Hyperloop Safety Benefit***

Ref	***Term***	***Value***			
(Invest Cape Town, 2019)	**CPT City**		**Cost per incident**		**Number of annual incidents**
			(1)		*(2)*
	CPT Fatalities	R	4 119 437.00		1 634
	CPT Severe Injuries	R	445 857.00		7 649
	CPT Slight Injuries	R	75 055.00		29 901
	CPT Property damage	R	1 141.00		3 066 258
	Ripple City	*Avoided 3%*			
Derived			**Number of incidents avoided**		**Annual Cost avoided (2017)**
			*(3) = 3% * (2)*		*(4) = (1) * (3)*
	Fatalities		49	R	201 978 000.00
	Severe Injuries		229	R	102 312 000.00
	Slight Injuries		897	R	67 326 000.00
	Property damage		91 988	R	104 958 000.00
	Total Savings (2021)	***R***	***563 087 951.13***	***annual***	

Swarts et al. (2012), state the cost of noise pollution is estimated to amount to 0.15% of a country`s GDP and that the possible reduction of noise pollution from EVs are 33% at minimum. By using Swarts statistics, the noise cost reduction was calculated, again assuming a 3% alleviation by Hyperloop. The noise cost savings are shown in Table 8.30.

Table 8.30 - ***Hyperloop Noise Benefit***

Ref	***Term***		***Value***	***Unit***	***Calculation***
(Swarts et al., 2012)	Cost of Noise		0.15%	*Of GDP*	*(1)*
(Swarts et al., 2012)	Noise discount due to Electric		33%		*(2)*
(City of Cape Town, 2020)	CPT 2019 GDP	R	489 000 000 000.00		*(3)*
Calculated	Noise Cost reduced by Electric (2019)	R	233 986 500.00		*(4) = (1)*(2)*(3)*
3%	***Noise Cost reduced by hyperloop (2021)***	***R***	***7 544 891.92***	***annual***	***(5) = (4) * 3% * inflation adjustment***

A cost per tonne/km was acquired from literature which was used to quantify the cost of the total freight kilometres travelled in the Hyperloop system. To calculate the total kilometres the maximum tonnage travels in the system per annum, the model assumed that freight on average travels 50% of the track length. The resulting potential annual freight revenue is shown in Table 8.31.

Table 8.31 - ***Hyperloop Freight Revenue Benefit***

Ref	***Term***	***Value***		***Unit***	***Calculation***
(Braun, 2019)	Total Tonnage per Year	5 840 000		*Tonnes*	*(1)*
	Cost per tonne per km (75% Load) (2021)	R	1.02	*per tonne/km*	*(2)*
	Annual Revenue made from 50% network travel	***R***	***1 722 038 862.07***	***Annual***	***(3) = (1) * (2) * 0.5 * 580km***

The damage road based freight imposes on the infrastructure is also accounted for as a cost reduction. CPT records a road network damage cost from freight in 2015, which is used in Table 8.32 to calculate a 3% reduction due to Hyperloop in 2021 ZAR value.

Table 8.32 - ***Hyperloop Infrastructure Cost Reduction***

Ref	***Term***	***Value***		***Unit***
(Mazaza *et al.*, 2016)	Infrastructure Maintenance Cost on CPT road network (2015)	R	713 000 000.00	per annum
	Road network cost avoided (2015)	R	21 390 000.00	per annum
	Road network cost avoided (2021)	***R***	***28 160 013.39***	***per annum***

The summarised estimated benefits of Hyperloop implementation are presented in Table 8.33. These values are used in the CBA of the model.

Table 8.33 – ***Hyperloop vs Trucks Intermediary Output Benefits***

Hyperloop Benefits [Trucking Freight]				**From**
Environmental benefits	R	13 550 739 372.00	*per annum*	*Table 8.26*
Trucking Fuel Cost Reduced	R	86 748 059 840.00	*per annum*	*Table 8.27*
Delay Savings / Congestion Reduction	R	406 562 728.31	*per annum*	*Table 8.28*
Safety Benefits	R	563 087 951.13	*per annum*	*Table 8.29*
Noise cost reduction	R	7 544 891.92	*per annum*	*Table 8.30*
Revenue - Hyperloop freight moving revenue	R	1 722 038 862.07	*per annum*	*Table 8.31*
Infrastructure damage	R	28 160 013.39	*per annum*	*Table 8.32*

8.2.2.5 Hyperloop Benefits for passenger travel vs. HSR

The GHG benefit is calculated similarly to that of the trucking method. The rail emission factor is used in tandem with the rail work trip kilometres travelled to determine the emission tonnage shown in Table 8.34, which is then used to calculate the cost of carbon.

Table 8.34 - ***Hyperloop GHG Benefit for Passenger Rail Case***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(Miller, 2020)	Average passenger rail emission factor (diesel and electric)	0.06	*kg CO2/ passenger km*	*(1)*
(The Climate Change Observation Team, 2018)	Passenger train emission	0.04	*kg CO2/ passenger km*	*(2)*
	Ave Passenger train emission	0.05	*kg CO2/ passenger km*	*(3)* *= [(1)+(2)]/2*
(City of Cape Town, 2019)	Daily Metrorail Passengers	128 728	*Pax/day*	*(4)*
	Total rail passenger-km (Assume average trip length of 30 km)	888 223 200	*annual work day kms*	*(5)* *= (4)*(30)*230 work days*
	Gross CO2 reduced	23 169 835.91	*kg of CO2 annually*	*(6)* *= (3)*(5) *50% adoption*
	Total Cost of CO2 removed	***R 17 323 159.52***		***(7)***

The Safety benefit of Hyperloop with regards to rail mode replacement is calculated similarly to the trucking method. However, the rail based safety incidents are used instead of road based. Added to this cost-benefit is a benefit somewhat unique to SA, cable theft. Hyperloop reduces cable theft damages due to the system being enclosed in a steel tube and having fewer unsupervised access points. The cost of cable theft reduction was determined by using the average cost per kilogram of cabling and multiplying it by the share of cables stolen in Cape Town.

Table 8.35 - ***Hyperloop Safety Benefit for Passenger Rail Case***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(RSR and Poya, 2017)	WC share of Rail safety occurrences	19%		*(1)*
	WC operational safety occurrences	784	*occurrences*	*(2)*
	CPT operational safety occurrences	25	*occurrences*	*(3)*
	Total cost of occurrences in 2016	R 962 000 000.00		*(4)*
Calculated	**CPT share of occurrence cost**	**R 5 828 443.88**	***annual***	***(5)*** ***= (1)*(2) (3)*(4)***
	Rail cable theft			
(Western Cape Government, 2019a)	Metrorail cable theft cost annually	R 70 000 000.00	*annual*	*(7)*
	Assume WC occurrence rate equals CPT cable theft share	***R 13 300 000.00***	***annual***	***(8)*** ***= (7) * (1)***

To calculate the passenger revenue generated by the Hyperloop system an average distance from Khayelitsha to CPT CBD was used for work trips of 10km. A 10% share of the total work trips volume was used and the cost of the work trip was valued at the same rate per kilometre as the SA taxi rate. The revenue shown in Table 8.36 only considers workdays (230).

Table 8.36 - ***Hyperloop Passenger Revenue***

Ref	***Term***		***Value***	***Unit***	***Calculation***
Calculated	Total Hyperloop passengers per year (Workdays only)		104 659 200		*(1)*
(Taxi-Calculator.com, 2013)	SA Taxi fare per km	R	10.00	*per km*	*(2)*
	Average annual work trips (assume 10% of trips are 10km trips)		10 465 920		*(3)* *= (1) * 0.1*
	Annual revenue from 10km work trips	***R***	***1 046 592 000.00***	**Annual**	***(4)*** ***= (2)* (3)***

To determine the delay benefit of Hyperloop rail passenger journeys, the difference in total travel time of the two modes were compared. The model assumes 10% of peak travel hour trips are moved from rail to Hyperloop. The total hours saved by moving the journeys to Hyperloop, as shown in Table 8.37, is calculated and monetised by using the TVM of public transport users.

Table 8.37 - ***Hyperloop Delay Benefit for Passenger Rail Case***

Ref	***Term***		***Value***	***Unit***	***Calculation***
(Hitge and Vanderschuren, 2015)	Trip time for rail		122	*min*	*(1)*
Calculated	Trip time for hyperloop		35.9	*min*	*(2)*
Calculated	Time saved		1.435	*hrs*	*(3)* *= ([1)-(2)]/60*
(City of Cape Town, 2019)	Share of Metrorail public transport trips in CPT		18%		*(4)*
(City of Cape Town, 2019)	Daily passengers		2 528 000	pax	*(5)*
Calculated	Number of passengers during peak moved to hyperloop (Assume 10% adoption)		45 504	*daily*	*(6)* *= (4)*(5)*0.1*
Calculated	Total hours saved annually		15 018 595	*hrs*	*(7)*
	Total TVM saved	**R**	**465 895 065.97**		**(8)** **= (3)*(6)*230 work days**

The summarised benefits used in the CBA for the comparison of HSR to Hyperloop is shown in Table 8.38. The Noise cost is considered the same as the freight scenario, as HSR is typically also electric.

Table 8.38 – ***Hyperloop vs HSR Passenger Case Intermediary Output***

Hyperloop Benefits [HSR]				**From**
Environmental benefits	R	17 323 159.52	*per annum*	*Table 8.34*
Safety Benefits + Cable theft reduction and occurrence cost	R	19 128 443.88	*per annum*	*Table 8.35*
Revenue public transport	R	1 046 592 000.00	*per annum*	*Table 8.36*
Delay Savings / Congestion Reduction	R	465 895 065.97	*per annum*	*Table 8.37*
Noise cost reduction	R	7 544 891.92	*per annum*	*Table 8.30*

8.2.3 Job Creation Intermediary Calculations and Outputs

The job creation potential of the transport proposals is significant due to the potential manufacturing industry gain. The jobs potential is not calculated the same way as with the energy sector, as the job factors used in energy could not be found for transport modes evaluated.

8.2.3.1 Hyperloop Job Creation Potential

To quantify the Job creation potential of the Hyperloop system was difficult due to lacking long term data availability. Hence, the jobs potential from the Alberta case study was used and adapted for this scenario as shown in Table 8.39.

Table 8.39 - ***Hyperloop Job Creation Potential Calculation***

Ref		***Jobs [FTE-years]***	***Total FTE work hours***	***Annual 2021 ZAR Value***
(TransPod, *2019b*)	**Hyperloop Job Creation**	38 000	1 520 000	R 29 804 876 220.00

The annual GDP potential impact of Hyperloop job creation is R 105 398 695 342.50, this could lead to a total annual potential GDP output of R135 203 571 562.50. The model shows that the Hyperloop system is not only a monetary benefit but also a job creating benefit.

8.2.3.2 EV Job Creation Potential

There is significant job creation potential to be realised from the EV industry. This model calculates the potential jobs generated from the implementation of Robotaxi`s, private EVS, BEBs and Electric Semis.

First, the Robotaxi potential of creating jobs was calculated as shown in Table 8.41. Two methods were used to determine the most appropriate number of vehicles. To calculate the output of method 1, an assumption was made that 20% of the public transport trips are utilised by Robotaxi trips in the new Ripple City. After the average number of passengers a Robotaxi can transport per day was calculated, the number of Robotaxi’s required to meet the 20% demand was calculated.

Method 2 assumed that 50% of the number of WC taxis are replaced by Robotaxi’s. The output of method 2 was used as it aligns more with the framework's view of having majority EVs in the system. This method is a 12.5% increase over the number of vehicles in method 1 which is not a stark difference. Finally, the number of drivers were calculated using a global average ratio of taxi drivers. The results of these calculations are shown in Table 8.40.

Table 8.40 - ***Robotaxi Job Creation Potential***

Ref	**Term**	**Value**	**Unit**	**Calculation**
	Method 1			
Assumed	% of CPT public transport Utilising Robotaxi network	20%	-	*(1)*
(City of Cape Town, 2019)	Daily passengers	2 528 000	pax	*(2)*
Calculated	New city Robotaxi trips	505 600	*trips*	*(3) = (1)*(2)*
(Mkentane, 2020)	SA Daily passengers taxi industry	16 500 000	*pax*	*(4)*
(BusinessTech, 2018)	SA total taxis	200 000	*vehicles*	*(5)*
Calculated	Average passengers per Robotaxi per day	83	*daily pax*	*(6) = (4)/(5)*
Calculated	**Number of Robotaxi's in system**	**6 128**	***taxis***	***(7)= (3)/(6)***
	Method 2			
(BusinessTech, 2018)	Number of taxis in Western Cape	14 012		*(8)*
	Assume % replacement	50%		*(9)*
Calculated	Number of Robotaxi's in system	7 006	*taxis*	*(10) = (8)*(9)*
(UITP Advanced Public Transport, 2020)	Global average driver to taxi ratio	1.5		*(11)*
	Number of initial Robotaxi drivers	***10 509***	***drivers***	***(12)= (10)*(11)***

To calculate the other EV job creation potentials, the model evaluated two areas of potential. The manufacturing jobs of the actual cars and then the entire value chain potential of EV charging infrastructure. The whole value chain of EV charging infrastructure is considered as it is a long term creator of continuous jobs as can be seen with the current shortage of EV charging infrastructure in the Northern and Western countries.

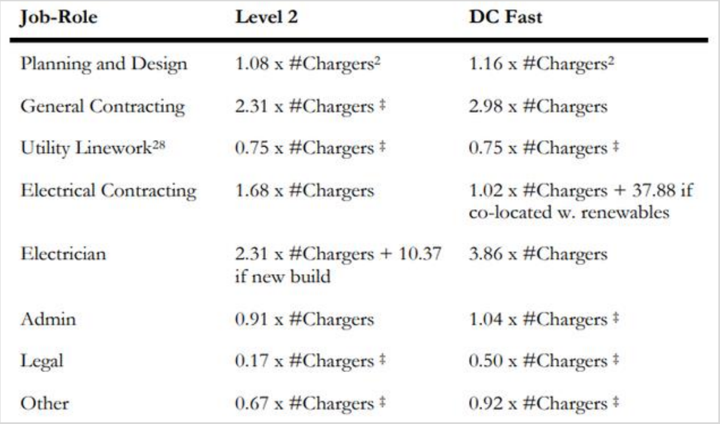
In Table 8.41 the calculated result for the manufacturing potential of the EVs are shown. To get this output, the model evaluated the two largest purely EV companies by production volume. A Jobs per car factor was generated and used to calculate the new Ripple City potential. The number of car units were determined by taking the product of the SA car ownership proportion of 30.6% and the assumed number of households.

Table 8.41 - ***Vehicle Manufacturing Job Creation Potential***

Vehicle manufacturing		***Number of jobs 2020***	***Number of veh produced***	***jobs per car***	***Calculated number of car sales for new city***	***Jobs created***
		(1)	*(2)*	*(3) = (1)/(2)*	*(4)*	*= (3)*(4)*
(Carlier, 2021)	Tesla	70 757	510 000	0.139	393 623	54 611
(Macrotrends, 2021a; Nio Inc., 2021)	NIO	7763	43728	0.178		69 880
		Total Vehicle Manufacturing Jobs				***62 245***

The second area of potential gain that was evaluated is the EV charging infrastructure value chain. For private EVs, two checks were performed, that was averaged out in the end for a more conservative value. Check 1 involved using the manufacturing share of the EU for EVs (4%) and translating it to the SA industry in two ways. Firstly, by translating it into the current total of vehicle manufacturing jobs and secondly into the CPT population.

Check 2 uses equations that implement factors for Level 2 chargers and DC fast chargers as shown in Figure 8.4. The number of chargers is determined by using ratios acquired from sources that give the per number of EVs charger requirement.



Job-Role	**Level 2**	**DC Fast**
Planning and Design	1.08 x #Chargers[2]	1.16 x #Chargers[2]
General Contracting	2.31 x #Chargers ‡	2.98 x #Chargers
Utility Linework[28]	0.75 x #Chargers ‡	0.75 x #Chargers ‡
Electrical Contracting	1.68 x #Chargers	1.02 x #Chargers + 37.88 if co-located w. renewables
Electrician	2.31 x #Chargers + 10.37 if new build	3.86 x #Chargers
Admin	0.91 x #Chargers	1.04 x #Chargers ‡
Legal	0.17 x #Chargers ‡	0.50 x #Chargers ‡
Other	0.67 x #Chargers ‡	0.92 x #Chargers ‡

Figure 8.4 - ***Charging Infrastructure Job Creation Equations***

Using the equations as stated and the required number of chargers for the scenario, the job creation potential is summarised in Table 8.42. The total number of busses are the summation of the 1 000 Golden Arrow busses and 42 Myciti busses (Whitehead *et al.*, 2015) currently in CPT.

Table 8.42 - ***EV Charging Infrastructure Job Creation Potential***

	Small Vehicle Charging Infrastructure Check 1			***Calculation***
(Pek et al., 2020)	Reported nett jobs created by 100% EV uptake in EU	1 200 000	*Considers ICE veh jobs lost*	*(1)*
(Eurostat, 2021)	EU28 manufacturing jobs 2018	29 900 000		*(2)*
Calculated	Share of jobs for EV infrastructure manufacturing in EU	4.0%		*(3)* *= (1) / (2)*
	As % of SA manufacturing jobs			
(Department of Transport: RSA, 2014)	*SA manufacturing industry jobs*	*1 749 000*	jobs	*(4)*
Calculated	Theoretical 100% adoption EV infrastructure manufacturing jobs	70 194	jobs	*(5)* *= (4) * (3)*
	As % of city population			
(de Villiers, 2019)	*CPT population*	*4 618 000*	people	*(6)*
Calculated	Theoretical 100% adoption EV infrastructure manufacturing jobs	185 338	jobs	*(7)* *= (3) * (6)*
	Vehicle Charging infrastructure Check 2			
	Ripple City Private Car Count		393 623	*(8)* Table 8.41
(Wood et al., 2017)	Number of DCFC stations required per 1000 EVs	3.4	Small Vehicles	*(9)*
	Number of Level 2 stations required per 1000 EVs	40		*(10)*
Calculated	Number of new city DCFC chargers required	1 338		*(11)* *= (9) * (8)*
Calculated	Number of new city Level 2 chargers required	15 745		*(12)* *= (8) * (10)*
(TDA Cape Town, 2018)	Number of peak hour EV trucks	200	trucks	*(13)*
(Carr *et al.*, 2021)	Level 2 stations required per truck	0.783	Heavy Vehicles	*(14)*
	DCFC stations required per truck	0.089		*(15)*
	Number of new city DCFC chargers required	18		*(16)* *= (13)*(14)*
	Number of new city Level 2 chargers required	157		*(17)* *= (13)* (15)*
(Lowell et al., 2020)	Number of chargers per bus	0.133	Busses	*(18)*
Calculated from *(Whitehead, Whittle and Hugo, 2015)*	Total number of Busses	1 378		*(19)*
	Number of busses per station	9		*(20)*
Calculated	Number of Chargers per station	2		*(21)* *= (18) * (20)*
	Number of Ripple City bus stations	153		*(22)* *= (19) / (20)*
	Number of new city DCFC chargers required	306		*(23)* *= (21) * (22)*

	Job-Role	**Level 2 Factor**	**Number Of Jobs from Level 2**		**DCFC Factor**	**Number Of jobs from DCFC**		
			Small Vehicle	Heavy Vehicle		Small Vehicle	Heavy Vehicle	Bus
	Calculations	*(24)*	*(25) = (12)*(24)*	*(26) = (17)*(24)*	*(27)*	*(28) = (11)*(27)*	*(29) = (16)*(27)*	*(30) = (23)*(27)*
Factors from: (Carr *et al.*, 2021)	Planning and design	1.08	17 005	169	1.16	1552	21	355
	General Contracting	2.31	36 371	362	2.98	3988	53	913
	Utility Linework	0.75	11 809	118	0.75	1004	13	230
	Electrical Contracting	1.68	26 451	263	1.02	1403	56	350
	Electrician	2.31	36 381	362	3.86	5166	69	1182
	Admin	0.91	14 328	153	1.04	1392	18	318
	Legal	0.17	2 677	27	0.5	669	9	153
	Other	0.67	10 549	105	0.92	1231	16	282
	Total Jobs		**155 570**	**1 558**		**16 406**	**255**	**3 783**

8.2.4 EV Economic Intermediary Calculations and Outputs Potential

The framework proposes that the Robotaxi's are implemented by the city. To show the potential beneficial return from the city funding this proposal, the calculations are shown in Table 8.43 were done. The result shows the NPV of a single Robotaxi bought and used as an autonomous passenger transporter. To calculate the value an NPV was performed on a single car considering all equipment costs, maintenance and operation costs.

*Table 8.43 - **Robotaxi NPV Calculation Parameters***

Ref	***Robotaxi Inputs***	***Value***	***Units***
(Keeney, 2017)	Price of 250-mile range EV in 2019	R 697 827.09	
	Price of Autonomous Technology 2019	R 77 536.34	
	Passenger utilization rate (% of day occupied)	53%	
	Total utilization rate (% of day driving)	58%	
(Western Cape Government, 2019c)	Average km/h of Autonomous vehicle	60	
(Keeney, 2017)	Total max possible kilometres in a given year	525 600	
(Keeney, 2017)	Expected % accident reduction	83%	
	Depreciation	straight line over 5 years	
(Keeney, 2017)	Insurance	R 0.18	*/km*
(Du Toit, 2021)	Electricity Cost	R 0.85	*/km*
(Keeney, 2017)	Maintenance & Repair	R 0.21	*/km*
	Tire costs per km	R 0.08	*/km*
	Remote operator network cost	R 0.39	*/km*
	Remote operator labour cost	R 0.13	*/km*
	Cost of parking	R 6 978	*/year*
Calculated	**Cost to consumer for SAV**	R 4.02	/km
Calculated	**Cost to consumer for personal vehicle**	R 11.21	/km
	5-Year NPV per Robotaxi	***R 931 261.58***	***Per veh***

Similar to the Hyperloop CBA, the EV benefit for fossil fuel money kept within the local economy is calculated. The Hyperloop CBA already accounted for trucking fuel savings and this section accounts for busses and passenger vehicles. The model calculated these fuel cost savings by calculating the total kilometres driven by these modes in the evaluated scenario per annum. The fuel consumption rates were used to get the volumetric consumption which was then used to monetise the volume. The resultant fuel cost savings that could be kept within the local economy is shown in Table 8.44.

Table 8.44 - ***EV Fuel Money Kept in Country***

Ref	***Term***	***Value***	***Unit***	***Calculations***
(Merven et al., 2012)	Average passenger km driven	16 630	*km*	*(1)*
(Merven et al., 2012)	Commercial vehicle average km driven in Sa	50 000	*km*	*(2)*
Table 8.42	Total number of Private EVs	393 623	*veh.*	*(3)*
Table 8.42	Total number of Robotaxi`s	7 006	*veh.*	*(4)*
Calculated	Total number of small EVs	400 629	*units*	*(5) = (3) + (4)*
Table 8.42	Total number of BEB	1 378	*units*	*(6)*
(Natural Resources Canada, 2019; Paoli, 2020)	Passenger vehicle fuel consumption average	0.081	*L/km*	*(7)*
(Zhang et al., 2014)	Bus average fuel consumption	0.326	*L/km*	*(8)*
Calculated	Small veh fuel consumption	1 347	*L/annum/veh*	*(9) = (1) *(7)*
Calculated	Total small vehicle fuel consumption	539 659 818.43	*L/annum*	*(10) = (5) * (9)*
Calculated	Commercial veh fuel consumption	16 300	*L/annum/veh*	*(11) = (2) * (8)*
Calculated	Total commercial vehicle fuel consumption	22 461 400	*L/annum*	*(12) = (6) *(11)*
(AA, 2021)	Price of Diesel (wholesale)	R 15.52	*/L*	*(13)*
	Price of petrol	R 18.34	*/L*	*(14)*
	Total Fuel Cost	***R 10 245 961 998.02***	***per annum***	***(15) = [(12)*(13)] + [(10)*(14)]***

Using the EV jobs calculated in Section 8.2.3.2, the jobs value is monetised in Table 8.45 using industry appropriate salaries and expressing the total as an economic value creation figure.

*Table 8.45 - **EV Jobs Salary Economy Output***

Ref	***Term***	***Value***	***Unit***	***Calculations***
Calculated Table 8.42	Number of jobs potential	220 853		*(1)*
(World Economic Forum, 2020a)	Ration of engineer to factory worker	0.025		*(2)*
Calculated	Number Of engineers	5 521		*(3)* *= (1) * (2)*
Calculated	Number Of factory workers	215 332		*(4)* *= (1) – (3)*
(Payscale, 2021)	Average factory worker salary	R 65 664	*per annum*	*(5)*
	Average Automotive manufacturing salary	R 314 000	*per annum*	*(6)*
	Total annual salary potential	***R 15 873 263 978.60***		***(7) = [(3)*(6)] + [(4)*(5)]***

8.2.5 NMT Intermediary Calculations and Outputs Potential

The final mode of transport evaluated in the model is the Non-Motorised Transport Mode. NMT shows significant CBA promise due to the GHG benefit and the lack of continuous expensive vehicle management and ownership costs. The following section presents the calculations steps taken to generate output values used in the NMT CBA shown in Chapter 5.

8.2.5.1 NMT Costs

The first calculation that was performed for NMT was the facility cost. The minimum goal set out by the proposed framework is that at least 50% of the city population makes use of NMT modes such as walking or bicycling. Other modes of NMT are not evaluated in this model to prevent the model from becoming quantitative. The calculated number of people using NMT in the scenario is shown in Table 8.46.

*Table 8.46 - **NMT Facility Costs***

Ref	***Term***	***Value***	***Unit***	***Calculations***
(de Villiers, 2019)	CPT population	4 618 000	people	*(1)*
(Litman, 2021)	NMT infrastructure cost	R 1 602.41	*Per annum/capita*	*(2)*
(City of Cape Town, 2019)	CPT current share of NMT utilisation	9%		(3)
	Cap	415 620	pax	(4) = (1) * (3)
	Cost	**R 665 992 795.14**		**(5) = (5) * (2)**
	Ripple City NMT minimum goal	50%		(6)
	Cap	2 309 000	pax	(7) = (1) * (6)
	Cost	**R 3 699 959 972.99**		**(8) = (7) * (2)**
	Conservative average NMT users	30%		(9)
	Cap	1 362 310	pax	(10)
	Cost	**R 2 182 976 384.07**		**(11) = (10) * (2)**

The equipment cost is included in the cost equation to ensure conservatism in the calculations. Typically, this cost would be covered by the user, but this framework suggests covering these costs to promote usage of NMT. The model assumes 20% bicycle share of NMT trips and the rest for walking. The 20% could be significantly higher but requires appropriate analysis and a suggested bike-sharing program to improve accessibility and adoption rate. In Table 8.47 the calculation used the number of users of each mode and calculated the distance travelled using average movement speeds for each mode and a 20-min journey.

Table 8.47 - ***NMT Equipment Costs***

Ref	Term	Value	Unit	Calculations
(Stamatakis et al., 2018)	Average walking speed	78	m/min	(1)
Calculated	20-min city walking distance	1.56	km per 20 min trip	(2) = [(1) * 20]/1000
(Road-Bike.co.uk, 2021)	Average bicycle speed	0.322	km/min	(3)
(Litman, 2021)	Urban Peak Bicycle Equipment Cost	R 1.28	Per km	(4)
Calculated	20-min city cycle distance	6.43	km	(5) = (3) * 20
Table 8.46	Ripple City NMT Users	2 309 000	pax	(6)
Assumed	Share utilising walking	80%	-	(7)
Calculated	Number of walkers	1 847 200	pax	(8) = (6) * (7)
Calculated	Annual km walked (workdays only considered)	662 775 360	kms	(9) = (2) * (8)
	share utilising bicycles	20%	-	(10)
Calculated	Number of bicycle riders	461 800	pax	(11) = (6) * (10)
Calculated	Annual km biked (workdays only considered)	683 310 066.67	kms	(12) = (11) * (5)
	Annual cost of NMT equipment	**R 875 953 190.41**	**annual**	**(13) = (4) * (12)**

To ensure the adoption of the NMT mode in the new Ripple City is rapid and lasting, the CAPEX includes a cost for security improvements of the NMT network. A Cost per capita was used to calculate the total cost shown in Table 8.48.

Table 8.48 - ***NMT Security Improvement Cost***

Ref	Term	Value	Unit	Calculation
Table 8.46	Ripple City NMT Users	2 309 000	pax	(1)
(WSDOT, 2020; Weinberger, 2021)	Security improvement	R 1 121.49	annual per capita	(2)
	Total Improvement Cost	**R 2 589 520 410.00**	**annual**	**(3) = (1) * (2)**

Table 8.49 shows the OPEX calculated for the use of Bicycles in the network.

*Table 8.49 - **NMT Bicycle OPEX***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.47	Annual km biked (workdays only considered)	683 310 066.67	*kms*	*(1)*
(Litman, 2021)	Average cost per km for cycling	R 1.68	per km	*(2)*
	Operating Bicycle cost	**R 1 150 487 687.44**	**annual**	**(3) = (1) * (2)**

There was lacking data available for NMT OPEX costs other than bicycle costs. This model assumed that the additional NMT OPEX to be considered equals the maintenance cost of a Cape Seal Road as shown in Table 8.50.

*Table 8.50 - **Other NMT OPEX***

Ref	***Term***	***Value***	***Unit***	***Calculations***
(City of Cape Town, 2019)	CPT city roads length	10 302	km	*(1)*
(Carter et al., 2018)	Western Cape estimated per km road maintenance cost	R 218 685.62	per km	*(2)*
	NMT OPEX Cost	**R 2 252 899 305.50**		**(3) = (1) * (2)**

Table 8.51 shows the condensed CAPEX and OPEX used in the CBA for NMT. An extract of the analysis is shown in Appendix I (L_9).

*Table 8.51 - **Intermediary NMT Costs Output***

NMT Costs				**From**
CAPEX	R	7 165 433 573.40	*once off*	*Table 8.46 + Table 8.47 + Table 8.48*
OPEX	R	3 403 386 992.94	*per annum*	*Table 8.49 + Table 8.50*

8.2.5.2 NMT Benefits

The following section discusses the calculations done to generate the benefits relating to NMT utilisation. The health and safety benefits are calculated in Table 8.52. To calculate the average, two case studies were evaluated and slightly adjusted with current prices and figures and one data point was used. The average of these three sub totals was taken as the potential benefit figure. Case Study 1 utilises a NMP-PAT tool which is ideal to use as a calculation tool. However, this research could not attain access to it and resolved to using a similar study that used the tool for this evaluation.

Table 8.52 - ***NMT Health and Safety Benefits***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(Cooke et al., 2017)	**Case Study 1**			
	CBD Area Death Savings	R 634 393 298.00	*Per annum*	*(1)*
	CBD Area Injury Savings	R 338 592 800.00	*Per annum*	*(2)*
	Metro Area Death Savings	R 38 084 195 065.00	*Per annum*	*(3)*
	Metro Area Injury Savings	R 911 596 000.00	*Per annum*	*(4)*
	Death and Injuries reduced SARF Study	**R 39 968 777 163.00**	***Per annum***	***(5) = (1) + (2) + (3) + (4)***
	Case Study 2			
(Mulley et al., 2013)	Walking Health Benefit 1	R 21.77	*per km*	*(6)*
(New Zealand Transport Agency, 2013)	Bicycle Health Benefit 1	R 14.52	*per km*	*(7)*
	Walking Health Benefit 2	R 25.18	*per km*	*(8)*
	Bicycle Health Benefit 2	R 13.43	*per km*	*(9)*
	Average Cases Benefit	R 18.73	*Per km*	*(10) = [(6)+(7)+(8)+(9)] / 4*
Table 8.47	Annual Kilometres NMT	1 346 085 426.67	*kms Per annum*	*(11)*
	Per km data points average	**R 25 207 602 043.37**	***Per annum***	***(12) = (10) * (11)***
	Case Study 3			
Table 8.46	Ripple City NMT Users	2 309 000	*pax*	*(13)*
(Grabow et al., 2012)	NMT Health Benefit for pax	R 3 033.00	*Per person/year*	*(14)*
	Per person data	**R 7 003 199 658.16**		***(15) = (13) * (14)***
Average Health and Safety Benefit		**24 059 859 621.51**	**Per annum**	**(16) = [(5)+(12)+(15)] / 3**

Using the NMP-PAT tool, the GHG reduction and travel time savings as shown in Table 8.53 was generated through the study by Cooke et al. (2017).

Table 8.53 - ***NMT GHG Savings Using the NMP-PAT Tool***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(Cooke et al., 2017)	**NMP-PAT Tool Results**			
	CBD CO2 savings	164 012.00	tons	*(1)*
	Metropolitan CO2 savings	11 754 699.00	tons	*(2)*
	Social cost of carbon	R747.66	per ton	*(3)*
	Total GHG savings	**R122 625 211.92**		**(4) = [(1)+(2)] * (3)**
	CBD Travel Time Savings	-R1 028 965.00	tons	(5)
	Metropolitan Travel Time Savings	R212 987 676.00	tons	(6)
				(7) = (5) + (6)

A significant benefit calculated in the model is the vehicle ownership cost reduction value shown in Table 8.54. The cost is significant primarily due to fuel cost and maintenance cost, which are not needed for NMT modes.

*Table 8.54 - **Vehicle Ownership Cost Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.47	Annual Kilometres NMT	1 346 085 426.67	*kms Per annum*	*(1)*
(Litman, 2021)	Cost to consumer	R 11.21	Per km	*(2)*
	Cost to consumer	R 15 091 123 900.72	Per annum	*(3)* *= (1) * (2)*
	Vehicle ownership Cost	R 33 579.66	pp/annum	*(4)*
Table 8.42	Total number of Private EVs	393 623	*veh.*	*(5)*
	Ownership cost saving	R 13 217 738 153.07	Per annum	*(6)* *= (4) * (5)*
	Total ownership cost savings	**R 28 308 862 053.79**	**Per Annum**	**(7) = (3) + (6)**

The cost reduction potential of parking was calculated taking the average scenario resultant value of three different sources. The averaged amount is shown in Table 8.55.

*Table 8.55 - **NMT Vehicle Parking Cost Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.42	Total number of Private EVs	393 623	*veh.*	*(1)*
Table 8.47	Annual Kilometres NMT	1 346 085 426.67	*kms Per annum*	*(2)*
Table 8.46	Ripple City NMT Users	2 309 000	*pax*	*(3)*
(Litman, 2021)	Cost of Parking1	R 6 977.73	Annual	*(4)*
	Parking cost saving 1	R 2 746 599 099.48	Annual	*(5) = (1) * (4)*
(Litman, 2009)	Parking Cost Saving 2	R 40.30	Per trip	*(6)*
	Parking Cost saving 2	R 93 042 509.74	Annual	*(7) = (6) * (3)*
(Munro, 2011)	Cost of Parking 3	R 0.21	Per km	*(8)*
	Parking Cost Saving 3	R 289 286 944.25	Annual	*(9) = (8) * (2)*
Average Parking Cost saving		**R 1 042 976 184.49**	**Annual**	**= [(5)+(7)+(9)] /3**

Roadway cost savings and accessibility cost savings are extensively analysed by Litman (2009), hence the cost per km of the study was used to calculate the output in Table 8.56 and Table 8.57.

*Table 8.56 - **NMT Roadway Cost Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.47	Annual Kilometres NMT	1 346 085 426.67	*kms Per annum*	(1)
(Litman, 2009)	Shift benefit from Car to NMT	R 0.44	*per km*	(2)
	Total cost savings	**R 593 562 722.40**	**Per annum**	**(3) = (1) * (2)**

Table 8.57 - ***NMT Accessibility Cost Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.47	Annual Kilometres NMT	1 346 085 426.67	*kms Per annum*	(1)
(Litman, 2021)	Accessibility improvement	R 0.69	per km	(2)
	Total Accessibility Benefit	**R 922 102 134.80**	**Per annum**	**(3) = (1) * (2)**

Noise Pollution cost savings is extensively analysed by Munro (2011), hence the cost per km of the study was sued to calculate the output in Table 8.58.

Table 8.58 - ***NMT Noise Pollution Cost Savings***

Ref	***Term***	***Value***	***Unit***	***Calculation***
Table 8.47	Annual Kilometres NMT	1 346 085 426.67	*kms Per annum*	(1)
(Munro, 2011)	Noise pollution	R 1.22	per km	(2)
	Total Noise Pollution	**R 1 645 319 495.43**	**Per annum**	**(3) = (1) * (2)**

The summarised NMT benefits used in the CBA of NMT in shown in Table 8.59. An extract of the analysis is shown in Appendix I (L_9).

Table 8.59 - ***NMT Intermediary Benefit Outputs***

NMT Benefits				**From**
Health and Safety	R	24 059 859 621.51	*per annum*	*Table 8.52*
GHG reduction	R	8 911 143 466.26	*per annum*	*Table 8.53*
Travel Time Savings	R	211 958 711.00	*per annum*	*Table 8.53*
Vehicle ownership cost savings	R	28 308 862 053.79	*per annum*	*Table 8.54*
Parking Cost savings	R	1 042 976 184.49	*per annum*	*Table 8.55*
Roadway Cost Savings	R	593 562 722.40	*per annum*	*Table 8.56*
Accessibility	R	922 102 134.80	*per annum*	*Table 8.57*
Noise pollution	R	1 645 319 495.43	*per annum*	*Table 8.58*

8.3 Layout Sector Sub-model

Section 8.3 presents the economic analysis done on the Layout sector of the proposed framework. Refer to Appendix for a summary of all the key values from each sectoral evaluation.

8.3.1 Scenario(s) used.

*Table 8.60 - **Layout Scenarios Evaluated***

Project	*Scenario*	*Rationale for change*
Transport Tunnelling	In Base Case city but: 100 km tunnel length 50km Freight Tunnel (6m Diameter) 50km Passenger Tunnel (3.6m Diameter) 60-Year Tunnel Life	It is outside the scope of this study to forecast exactly what length of the city network is tunnelling. Hence the edge-to-edge distance of CPT municipality is used for a tunnel length.
Surface Road Transport	100 km road length.	To match the comparative case of the Tunnel equivalent.
Utility Tunnels	A 0.95km concept area is evaluated in CPT city. (Link to Evaluated Road)	The exact number of businesses, residential and traffic varies across the entirety of the road network. Hence a scenario is evaluated where mixed-use is used in CPT city. The 1km length has businesses, residential and traffic flow, which is similar to the requirement of the framework.
Green Design	Base Case	-

*Table 8.61 - **Layout Scenario Additions to Base Case and Recurring Key Values***

TERM	VALUE	UNIT	REFERENCE
Number Of Trucks (100km single lane)	14 154	*Per annum*	*Calculated Section 8.3.2.2*
Number Of Busses (100km single lane)	3 538	*Per annum*	*Calculated Section 8.3.2.2*
Number Of Passengers (100km single lane)	2 830 769	*Per annum*	*Calculated Section 8.3.2.2*
Average Fuel consumption of sample trucks	0.26	*L/km*	*(Nylund and Erkkilä, 2005)*
Average Fuel consumption of passenger car	0.081	*L/km*	*(Natural Resources Canada, 2019; Paoli, 2020)*
Bus average Fuel Consumption	0.326	*L/km*	*(Zhang et al., 2014)*
Cost of Diesel	R 17.44	*/L*	*(GlobalPetrolPrices.com, 2021)*
Cost of Petrol	R 18.34	*/L*	*(GlobalPetrolPrices.com, 2021)*
VOT Private Car travel	R 87.27	*Per hour*	(Hayes and Venter, 2016)
VOT of Pedestrian walking	R 41.58	*Per hour*	(Hayes and Venter, 2016)
No. of Trees	1 214 950	*trees*	*Calculated Section 8.3.4.2*
CPT Municipality Area	400 000 000	*m2*	(REN21, 2021)
Derived Urban Roof Area	20%	-	(Akbari and Rose, 2007)
Assumed Green Roof Area	50%	*Of Urban Roof Area*	-
Assumed Urban Pavement Area	40%	-	-
Assumed Urban Floor Green Area	40%	-	-
Total Green Space (incl. green roofs)	200 000 000	*m2*	-

8.3.2 Transport Tunnelling Intermediary Calculations and Outputs

Transport tunnelling is a proposal in the framework that aligns with the pedestrian and prevents a city from being designed for the motor vehicle but still allows it to operate within the city. Tunnelling is often considered too expensive as a solution. The following section presents the calculations that show the beneficial gain is more than that of conventional surface roads.

The two modes of tunnelling primarily evaluated in these calculations are the TBM and Cut-and-fill method. It was identified that the two largest cost influencing factors are geology and tunnel diameter.

Hence, throughout the model calculations, projects of similar geological conditions and tunnel diameters are used. Furthermore, sources that correlate and adjust data to comparable values are used as far as possible.

8.3.2.1 Tunnelling Costs

This section discusses the calculations performed in the model that generated intermediary output values used in the CBA of tunnelling.

The results in Table 8.62 show the project costs for TBM transport tunnelling projects. The First set of data is a representation of the BoringCo costs, however, this companies costs is often doubted as the projects undertaken thus far are not considered of significant length. The cost shown for BoringCo is actual cost nonetheless averaged from their existing projects. The other conventional full boring projects cost is a collection of various projects evaluated to get an accurate average per km cost. For an expansion on the projects averaged for the conventional boring projects, refer to L_13 in Appendix I.

*Table 8.62 - **TBM Tunnelling Project Costs***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(McBride, 2020)	**BoringCo Tunnelling Project Cost**			
	Average BoringCo Cost for Tunnelling Project	R 580.00	*M/km*	*(1)*
	Other Conventional Full Boring Projects	**Cost per km**		
(Arup North America Ltd, 2008)	Single Bore project	R 3 380.08	*M/km*	*(2)*
	Twin Bore Project	R 7 004.03	*M/km*	*(3)*
	Triple Bore	R 54 321.63	*M/km*	*(4)*
(Membah, 2016)	Average TBM Project Cost from additional source 1	R 5 150.09	*M/km*	*(5)*
(Naghashian, 2014)	Average TBM Project Cost from additional source 2	R 4 820.03	*M/km*	*(6)*
(Levy, 2018)	Average TBM Project Cost from additional source 3	R 4 915.05	*M/km*	*(7)*
	Average per km (Single, twin)	**R 5 053.85**	***M/km***	***(8) = [(2)+(3)+(5)+(6)+(7)] / 5***

The CAPEX costs discussed above only relate to passenger tunnels. In order to get an accurate estimation for similar freight tunnels, excavation equations were utilised which only consider boring costs. The equations consider the geological conditions as well as the method, diameter and length. Once a freight and passenger cost per km for excavation was acquired, a price increase ratio was calculated for freight vs. passenger. It was assumed for the evaluated scenario where the tunnel diameters do not vary significantly, this ratio could be used to estimate total project cost of freight projects. The freight increase over passenger ratio generated is 1.261.

Using the ratio and project costs from Table 8.62, the costs calculated in Table 8.63 were generated.

*Table 8.63 - **Transport Tunnel CAPEX Cost***

Ref	***Excavation Cost equations***			***USD 2013***	***ZAR 2021***		***Calculation***
(Rostami et al., 2013)	Highway Conventional	Cost (M$) = 10^[1.51 + 1.02 log(L) + 0.374 log(D)]					*(1)*
	Hard rock Subway Mechanised	Cost (M$) = -97.2 + 11.7L + 28.3D					*(2)*
	Soft ground Subway Mechanised	Cost (M$) = 10^[1.23 + 1.05 log(L) + 0.636 log(D)]					*(3)*
	Freight	L	D	**Cost per km**	**Cost per km**		
	Highway Conventional	50	6	$ 68.39	R 974.55	*M/km*	*(4) = Using (1)*
	Hard rock Subway Mechanised	50	6	$ 13.15	R 187.41	*M/km*	*(5) = Using (2)*
	Soft ground Subway Mechanised	50	6	$ 64.54	R 919.71	*M/km*	*(6) = Using (3)*
	Freight Boring Cost Eq				**R 693.89**	***M/km***	***(7) = [(4)+(5)+(6)] /3***
	Passenger	L	D	**Cost per km**			
	Highway Conventional	50	3.66	$ 56.85	R 810.06	*M/km*	*(8) = Using (1)*
	Hard rock Subway Mechanised	50	3.66	$ 11.83	R 168.54	*M/km*	*(9) = Using (2)*
	Soft ground Subway Mechanised	50	3.66	$ 47.13	R 671.62	*M/km*	*(10) = Using (3)*
	Passenger Boring Cost Eq				**R 550.07**	**M/km**	***(11) = [(8)+(9)+(10)] /3***
	Freight increase over passenger cost				**1.261**		*(12) = (7) / (11)*
	Total CAPEX for project if Boring Co						
	Passenger			R	29 000.00	M	*(13) = Table 8.62(1) * 50km*
	Freight			R	36 582.20	*M*	*(14) = (12) * (13)*
	Average Boring Co CAPEX			**R**	**32 791.10**	***M***	***(15) = [(13)+(14)] /2***
	Total CAPEX for project if TBM project average						
	Passenger			R	252 692.67	M	*(16) = Table 8.62(8) * 50km*
	Freight			R	318 760.44	M	*(17) = (16) * (12)*
	Average TBM CAPEX			**R**	**285 726.56**	**M**	***(18) = [(16)+(17)]/2***

The approach taken to calculate the O&M costs of these tunnelling projects involved averaging out three data sets of tunnelling projects. The three output values are summarised in Table 8.64 together with the averaged output to be used in the CBA.

*Table 8.64 – **Transport Tunnel O&M Costs***

					Calculation
(Lyon, 2012)	**Data Set 1**				
	Cost/km Bored tunnel (2012)	GBP	2.39	*M annual/km*	*(1)*
	Cost/km Bored tunnel (2021)	**R**	**48.79**	*M annual/km*	*(2)- adjusted for inflation and ZAR conversion*
(Zahed *et al.*, 2018)	**Data Set 2**				
	Cost/km Bored tunnel (2021)	**R**	**467.30**	*M annual/km*	*(3)*
(Hatch Mott MacDonald, 2004)	**Data Set 3**				
	Case Project Length		19.991	*km*	*(4)*
	Total estimated O&M 1	$	5 483 062.00	*annual*	*(5)*
	Cost/km Bored tunnel 1 (2004)	**$**	**274 276.52**	*per km*	*(6) = (5) / (4)*
	TBM Bored Tunnel calculated O&M	$	6 800 000.00	*annual*	*(7)*
	Cost/km Bored tunnel 2 (2004)	**$**	**340 153.07**	*per km*	*(8) = (7) / (4)*
	2004 USD/ZAR	6.5			
	Average O&M (2021)	**R**	**4.63**	*M per km*	*(9) = [(6) + (8)] /2*
	Total average O&M	**R**	**173.57**	**M per km**	**(10) = [(2)+(3)+(9)] / 3**

The CAPEX of the BoringCo and conventional projects are summarised in Table 8.65, as well as the OPEX cost calculated. These cost consider the total 100 km scenario length of 50:50 Freight and passenger tunnelling. The values were used in the CBA shown in the extract in Appendix I (L_8).

*Table 8.65 - **Intermediary Transport Tunnel Costs Output***

100km Transport Tunnelling Costs [R' Million]				**From**
Boring Co. CAPEX	R	32 791.10	*once off*	*Table 8.63*
TBM project average CAPEX	R	285 726.56	*once off*	*Table 8.63*
Average CAPEX used	R	318 517.65	*once off*	*Table 8.63*
OPEX	R	17 357 295 100.27	*annual*	*Table 8.64*

8.3.2.2 Tunnelling Benefits

The following section deals with the potential benefits generated by the proposed tunnelling scenario. Before calculating the benefits, the model generates a volume count for each major mode of motor transport using a 6.5km case study tunnel as a reference. The study from Zahed, Shahandashti and Najafi (2018) is extrapolated to a 100km track. The impact of the addition of large vehicles is incorporated using Figure 8.5, to adjust the free flow volume of the evaluated system. The resulting flow was 14 154 trucks, 3 538 busses and 2 830 769 passenger cars.

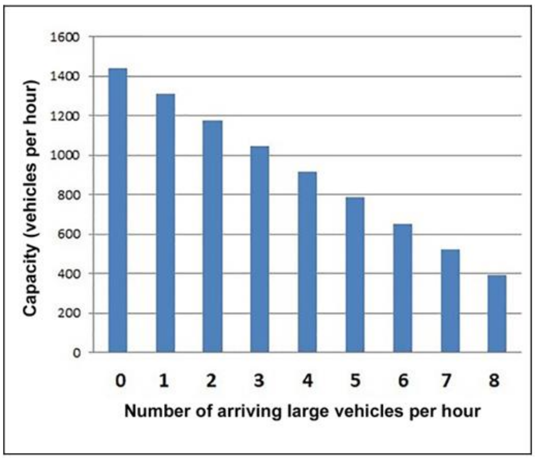


Figure 8.5 - ***Impact of a Large Vehicle Addition to Free Flow Volume***
(Zahed, Shahandashti and Najafi, 2018)

The benefit calculated in Table 8.66 is a generalised benefit from using a tunnel system vs a surface road. The benefit is derived for per major modal use, using the calculated volume per mode over a year in the 100km tunnel system.

Table 8.66 - ***Tunnel Vehicle Travel Benefits – for 100km Scenario***

Ref	***Mode***			***unit***
(Upchurch, 2020)	Truck	R	2 111 257.36	Per annum
	Bus	R	2 149 464.69	Per annum
	Car	R	117 007 777.61	Per annum
	Total (100 km Benefit)	**R**	**121 268 499.65**	

Using the same method thus far used in this model to calculate fuel cost, the output values in Table 8.67 were generated.

Table 8.67 – ***Transport Tunnel Fuel Cost Savings***

	Based on Annual peak hour work days traffic volume				***Calculations***
(Nylund and Erkkilä, 2005) (Zhang et al., 2014) *Table 8.44*	Average fuel consumption of sample trucks		0.26	L/km	*(1)*
	Bus average fuel consumption		0.326	L/km	*(2)*
	Average Fuel consumption of passenger car		0.081	L/km	*(3)*
	Cost of Diesel		R 17.44	/L	*(4)*
	Cost of Petrol		R 18.34	/L	*(5)*
		km	**Litres**	**Fuel Cost**	
		(6)	(7) = [(1) or (2) or (3)] * (6)	(8) = (7) * [(4) or (5)]	
	Busses	176 923	57 677	R 1 005 885.54	*(9)*
	Trucks	707 692	184 000	R 3 208 960.00	*(10)*
	Cars	141 538 462	11 464 615	R 210 261 046.15	*(11)*
	Total Fuel Cost			**R 214 475 891.69**	**(12) = (9)+(10)+(11)**

Table 8.68 summarises the benefits derived from a source that extensively evaluated the external benefits of 4 transport tunnelling projects. Projects 1 and 2 are of similar diameters and Projects 3 and 4 are of similar diameter. The values were average and summarised. The conversion factor for 2016 USD to 2021 ZAR used is equal to 18.34 (1).

*Table 8.68 - **Transport Tunnel External Cost Benefits***

Source: (Zahed *et al.*, 2018)	*Project 1*	*Project 2*	***Average ZAR 2021 value per km***	*Project 3*	*Project 4*	***Average ZAR 2021 value per km***
Tunnel Diameter [m]	4.27	4.27	4.27	3.05	2.13	2.59
Tunnel Length [km]	402.34	6.44		24.14	24.14	
Costs [M/km]						
	(2)	*(3)*	*(4) = [((2) + (3))/2] * (1)*	*(5)*	*(6)*	*(7) = [((5) + (6))/2] * (1)*
Maintenance of Tunnel	$ 15.17	$ 15.17	R 278.23	$ 9.77	$ 6.84	R 152.29
Tunnel Construction	$ 28.96	$ 28.95	R 530.98	$18.65	$ 13.04	R 290.63
Administration	$ 0.45	$ 28.12	R 261.95	$ 13.20	$ 13.20	R 242.14
Benefits [M/km]						
Air Pollution Reduction	$ 48.46	$ 48.44	R 888.58	$ 16.90	$ 10.18	R 248.30
Noise Pollution Reduction	$ 0.77	$ 0.77	R 14.06	$ 0.27	$ 0.16	R 3.93
Water Pollution Reduction	$ 0.13	$ 0.13	R 2.36	$ 0.04	$ 0.03	R 0.66
Congestion Reduction	$ 6.02	$ 13.88	R 182.46	$ 2.10	$ 1.27	R 30.86
Infrastructure damage reduction	$ 1.41	$ 1.41	R 25.80	$ 0.49	$ 0.30	R 7.21
Accident Reduction	$ 7.94	$ 7.94	R 145.59	$ 2.77	$ 1.67	R 40.68

The Crossing cost in tunnelling is entirely removed due to it being underground. This benefit relates to the reduced ROW costs often observed in tunnelling projects, not calculated in this model due to lacking data. The calculated results in Table 8.69 account for urban separation cost savings.

*Table 8.69 - **Transport Tunnel Crossing Cost Saving***

Ref	***Term***	***Value***	***Unit***	***Calculations***
(The State of Queensland (Department of Transport and Main Roads), 2011)	Urban Separation (passenger veh)	R 0.08	*Per km travelled*	*(1)*
	Urban Separation (passenger bus)	R 0.25	*Per km travelled*	*(2)*
	Average freight Separation cost	R 5.52	*Per 30-tonne-km*	*(3)*
Table 8.67	Busses	176 923	*Km*	*(4)*
Table 8.67	Trucks	707 692	*Km*	*(5)*
Table 8.67	Cars	141 538 462	*km*	*(6)*
	Cars separation savings	R 10 864 485.91	*per annum*	*(7) = (1) * (6)*
	Bus separation savings	R 43 503.98	*per annum*	*(8) = (2) * (4)*
	Trucks average separation savings	R 3 907 071.69	*per annum*	*(9) = (3) * (5)*
Total annual urban separation cost savings		**R 14 815 061.58**	**per annum**	**(7) + (8) + (9)**

Table 8.70 shows the urban landscape cost savings generated from implementing tunnels.

*Table 8.70 - **Transport Tunnel Landscape Cost Saving***

Ref	***Term***	***Value***		***Unit***	***Calculations***
(The State of Queensland (Department of Transport and Main Roads), 2011)	Urban Landscape (passenger veh)	R	0.01	*Per km travelled*	*(1)*
	Urban Landscape (passenger bus)	R	0.25	*Per km travelled*	*(2)*
	Average freight Landscape cost	R	3.52	*Per 30-tonne-km*	*(3)*
Table 8.67	Busses		176 923	*Km*	*(4)*
Table 8.67	Trucks		707 692	*Km*	*(5)*
Table 8.67	Cars		141 538 462	*km*	*(6)*
	cars	R	92 0719.16	*per annum*	*(7) = (1) * (6)*
	bus	R	43 503.98	*per annum*	*(8) = (2) * (4)*
	trucks average	R	2 490 084.93	*per annum*	*(9) = (3) * (5)*
Total annual urban separation cost		**R**	**14 815 061.58**	**per annum**	**(10) = (7) + (8) + (9)**

The benefits calculated are summarised in Table 8.71, that are used in the CBA of transport tunnels.

*Table 8.71 - **Intermediary Transport Tunnel Benefits Output***

100km Transport Tunnelling Benefits [R' Million]				**From**
Vehicles travel benefits	R	121.27	*per annum*	*Table 8.66*
Noise pollution reduction	R	899.54	*per annum*	*Table 8.68*
Fuel savings	R	214.48	*per annum*	*Table 8.67*
Congestion Savings	R	10 666.32	*per annum*	*Table 8.69*
GHG pollution reduction	R	56 844.12	*per annum*	*Table 8.68*
Accident reduction	R	9 313.68	*per annum*	*Table 8.68*
Water pollution reduction	R	150.95	*per annum*	*Table 8.68*
Infrastructure damage reduction	R	1 650.68	*per annum*	*Table 8.68*
Crossing Cost Reduction	R	14.82	*per annum*	*Table 8.69*
Landscape Cost Saving	R	3.45	*per annum*	*Table 8.70*

8.3.2.3 Surface Transport Road Costs

For an accurate realisation of the proposed tunnels utilisation, the transport tunnelling proposal is compared to a road surface project of the same length and use.

The CAPEX of the surface road was relatively simplistic to calculate due to the availability of local data. In Table 8.72 the calculated cost is shown for a 2-lane single road, as well as the temperature adjustment for the CAPEX. The temperature adjustment is a cost added due to degradation from the external heat environment imposed on surface roads.

Table 8.72 - ***Surface Transport Road CAPEX – 100km road***

			New Total Road construction cost per km *(Nkabinde, 2019)*	***Resurfacing Cost*** *(Tsamboulas, 2014)*	***Higher Temp adjustment (assume PG-52)*** *(Tsamboulas, 2014)*
			per km	**per km**	**per km**
	Dual Carriageway	R	140 000 000.00	NA	NA
	4-Lane undivided	R	100 000 000.00	R 14 249 457.37	R 1 870 241.28
	2-Lane Single	R	50 000 000.00	R 712 472.87	R 1 870 241.28
(Nkabinde, 2019)	**CAPEX 2-lane single**	**R**	**5 000 000 000.00**	**Once off**	**(1)*100km**
	Heat CAPEX increase	**R**	**187 024 128.04**	**Once off**	

The OPEX costs are summarised in Table 8.73 for a 14mm + 7mm double seal, as the road compared is a high-volume traffic road. The summary includes the recurring maintenance costs over the 20-year serviceable life of the road.

Table 8.73 - ***Surface Transport Road O&M***

Ref	***Item***		***14mm + 7mm double seal***	***Unit***
(Carter et al., 2018)	WC estimated per km road maintenance cost	R	218 685.62	*Per km*
	Routine Maintenance Cost (4-years)	R	118 153.31	*Per km*
	Minor Rehab every 10 years	R	1 358 763.05	*Per km*
	Major Rehab every 20 years	R	2 156 297.89	*Per km*
	Reseal every 20 years	R	5 021 515.64	*Per km*

The summarised CAPEX and OPEX costs calculated are presented in Table 8.74. An extract of the analysis is shown in Appendix I (L_10).

Table 8.74 - ***Intermediary Surface Transport Road Cost Output***

100km Transport Surface Road Costs [R'Million]				**From**
CAPEX	R	5 187.02	*Once off*	*Table 8.72*
General Annual OPEX	R	21.87	*Annual*	*Table 8.73*
Urban annual crossing Cost	R	14.82	*Annual*	*Table 8.69*
Landscape Annual Cost	R	3.45	*Annual*	*Table 8.70*
Maintenance every 4 years	R	11.82		*Table 8.73*
Minor Rehab every 10 years	R	135.88		*Table 8.73*
Major Rehab every 20 years	R	215.63		*Table 8.73*
Reseal every 20 years	R	502.15		*Table 8.73*

8.3.3 Utility Tunnelling Intermediary Calculations and Outputs

Utility tunnels are a significant improvement proposed by the framework from a logistical view. The ease of access and improved ease of control provided by these tunnels are of great benefit. From a physical space usage perspective, using the horizontal space usage equations of Zhang *et al.* (2021), it is calculated that for the same 5 utilities, buried utilities use 60 m^2 and a MUT tunnel uses 20 m^2.

8.3.3.1 Buried Utility Costs

The conventional method of housing utilities is by burying them. In Table 8.75 the CAPEX and OPEX of buried utilities are calculated by averaging out three evaluated cases.

Table 8.75 - ***Buried Utilities CAPEX and OPEX***

	Utility		*CAPEX*		*OPEX*	*Calculations*
Data Source 1			*ZAR/km*		*ZAR/km*	*(1)*
(Alaghbandrad and Hammad, 2020)	Municipal	R	63 899 902.98	R	1 956 631.42	*(2)*
	Gas	R	2 842 968.73	R	12 575.96	*(3)*
	Electricity	R	48 551 216.52	R	2 132 226.55	*(4)*
	Telecom	R	51 454 389.29	R	2 132 226.55	*(5)*
	Total	**R**	**166 748 477.53**	**R**	**6 233 660.46**	***(6) = sum((1) - (5))***
Data Source 2			*ZAR/km*			
(Matthews *et al.*, 2015)	**Open Cut**	**R**	**46 453 959.12**			***(7)***
Data Source 3	**Open Cut Cost**		*ZAR/km*			
(Hunt *et al.*, 2014)	100mm steel pipe	R	4 445 378.88			*(8)*
	150mm steel pipe	R	4 778 669.96			*(9)*
	200mm steel pipe	R	4 941 695.48			*(10)*
	300mm steel pipe	R	5 462 728.03			*(11)*
	Total	**R**	**19 628 472.35**			***(12) = (8) + (9) + (10) + (11)***
	Average Cost	***R***	***77 610 303.00***	***R***	***6 233 660.46***	***(13) = [(6) + (7) + (12)] / n***

The disadvantage of buried utilities identified by the framework is the continuous excavation and replacement (E&R) cost impact. Every time an E&R occurs the cost increases as shown in Figure 8.6. The graph was evaluated and an average increase factor per E&R was derived for 5 utilities. The resulting factor is summarised in Table 8.76 together with the CAPEX and OPEX costs previously calculated.

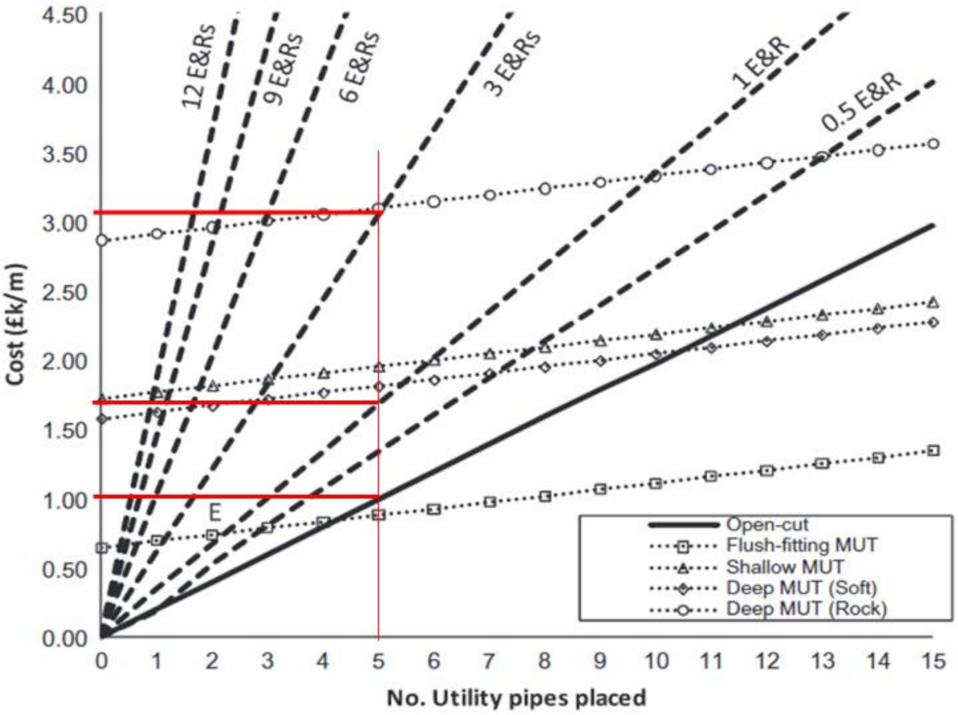


Figure 8.6 - ***Buried VS. MUT Costs Considering Excavation and Replacements*** (Hunt *et al.*, 2014)

Table 8.76 - ***Intermediary Buried Utilities Cost Output***

1 km Utility Buried Cost				**From**
CAPEX	R	77 610 303.00	*per km*	*Table 8.76*
OPEX	R	6 233 660.46	*annual per km*	*Table 8.76*
Cost increase per ER (Limit 4)	1.2		factor	*Figure 8.6*

8.3.3.2 MUT Tunnelling Costs

The proposed solution to the exacerbated continuous cost of buried utilities is the MUT tunnels. Below in Table 8.77 the CAPEX and OPEX costs of MUT tunnels are averaged over 4 data sets covering various MUT project costs. CAPEX costs from these studies are calculate using an equation that allocates the space usage area to a specific utility. It thus takes the total cost of the tunnel and devides it between the utility types. This is a method used to ensure that utilities pay appropriately for the utilisation and benefit from the MUT tunnels. This study however uses the total CAPEX values to evaluate the tunnel cost as a whole, as the specific utility type cost is not of concern for this evaluation.

*Table 8.77 - **MUT CAPEX and OPEX Costs***

Ref	***Utility***	***CAPEX***	***OPEX***	***Calculations***
Data Source 1 *(Alaghbandrad and Hammad, 2020)*		*ZAR/km*	*ZAR/km*	
	Municipal	R 96 710 304.04	R 1 249 367.69	*(1)*
	Gas	R 12 969 155.08	R 145 827.57	*(2)*
	Electricity	R 93 757 228.81	R 976 643.37	*(3)*
	Telecom	R 52 980 695.59	R 825 731.91	*(4)*
	Total	**R 256 417 383.52**	**R 3 197 570.54**	***(5) = sum((1)-(4))***
Data Source 2 *(Wang et al., 2018)*		ZAR/km	*ZAR/km*	
	Water	-	R 707 987.34	*(6)*
	Reclaimed Water	-	R 589 768.92	*(7)*
	Heating	-	R 884 651.87	*(8)*
	Power	-	R 1 976 299.00	*(9)*
	Telecom	-	R 1 415 974.68	*(10)*
	Total	**R 75 608 528.22**	**R 5 574 681.81**	***(11) = sum ((6)-(10))***
Data Source 3 (Matthews *et al.*, 2015)		*ZAR/km*		
	Micro tunnel	**R 104 653 331.13**		***(12)***
Data Source 4 (Hunt *et al.*, 2014)		*ZAR/km*		
	Deep MUT	**R 104 980 445.97**		***(13)***
	Shallow MUT	**R 56 235 066.48**		***(14)***
	Average	**R 119 578 951.06**	**R 4 386 126.18**	**(15) = [(5) + (11) + (12) + (13) + (14)] / n**

Table 8.78 shows the CAPEX and OPEX values used in the CBA for MUTs in Chapter 5. An extract of the analysis is shown in Appendix I (L_11).

*Table 8.78 - **Intermediary MUT Cost Output***

1 km Utility Tunnel Cost			
CAPEX	R	119 578 951.06	*per km*
OPEX	R	4 386 126.18	*annual per km*

8.3.3.3 MUT Tunnelling Benefits

The MUT tunnelling proposal has two time zones of benefits. One set of benefits during construction and another annually by avoiding continuous excavation and disruption costs.

The calculated during construction benefits are shown in Table 8.79. The evaluated stretch of road has a travel time of 2 min by car under normal conditions and 4 min under peak traffic. The evaluated length is 950m. The peak traffic time is used for the disturbed travel time during buried utility construction. The undisturbed walking time is 11 min and the disturbed is 16 min by the same principle. Both construction builds take a 100 days as per advisory of Matthews, Allouche and Sterling (2015)

To calculate the travel delay benefit the product of the delayed travel time, project duration, free flow volume and Value of Time (VOT) of a private car is taken. The pedestrian disruption cost is calculated similarly by taking the product of the delayed travel time, the project duration, the number of pedestrians per hour and the VOT of pedestrians. Furthermore, vehicle operating cost is calculated the same way but instead of using the VOT metric, the operating cost allowance data point is used.

The Road damage avoided by the continuous excavation of buried utilities is accounted for by taking the product of the scenario road length with the damage cost value per unit length.

The model also accounts for business revenue that would have been lost along the construction length if buried utilities were the case. The evaluated road has 5 restaurants, residential flats and offices placed. The revenue of the restaurant, Rocomamas, was used as the benchmark for all 5 restaurants. The impact factor of 30% was applied to the weekly revenue to calculate the lost revenue.

The above explained metrics are all summarised in Table 8.79, together with some other benefits summarised by Matthews, Allouche and Sterling (2015).

Table 8.79 - ***MUT During Construction/Interruption Benefits***

Ref	***Item***	***Value***	***Unit***	***Calculations***
	Travel Delay			
Table 8.61	VOT private car	R 82.27	*Per hour*	*(1)*
Table 8.28	Free flow veh count	1600	*Veh/hr*	*(2)*
	Delayed travel time	0.033333333	*hr/veh*	*(3)*
	Project Duration (14 hours a day)	1400	*hrs*	*(4)*
	Delay Cost	**R 6 859.40**	***Per m***	***(5) = [(1) * (2) * (3) * (4)] / 950***
	Pedestrian Disruption Cost			
Table 8.61	VOT pedestrians	R 41.58	*Per hour*	*(6)*
	Number of pedestrians	40	*persons/hr*	*(7)*
	Delayed travel time	0.083333333	*hr/person*	*(8)*
	Project Duration (Data averaged for 24-hour days)	2400	*hrs*	*(9)*
	Disruption Cost	**R 350.15**	***Per m***	***(10) = [(6) * (7) * (8) * (9)] / 950***
	Decreased road surface value			
(Matthews *et al.*, 2015)	**Damage cost**	**R 1 872.46**	***per m***	***(11)***
	Vehicle operating Cost			*(12)*
	Increased travel distance	0.05	*km*	*(13)*
(Litman, 2021)	Operating Cost allowance	R 11.21	*per km*	*(14)*
	Project Duration (14-hour days)	1400	*hrs*	*(15)*
Ref	**Item**	**Value**	**Unit**	**Calculations**

	Veh Operating Cost	**R**	**1 321.73**	***Per m***	***(16) = [(12) * (13) * (14) * (2)] / 950***
(Matthews *et al.*, 2015) *(Geldenhuys, 2017)*	**Lost Business Revenue (5-businesses)**				
	Impact factor		30%		*(17)*
	Roccomamas turnover per week	R	179 634.70		*(18)*
	Project Duration		14.29	*weeks*	*(19)*
	Revenue Cost	R	4 051.91	***Per m***	***(20) = (18) * (19) * (17) * 5***
(Matthews *et al.*, 2015)	Dust control	R	214.29	***Per m***	***(21)***
	Parking meter revenue loss	R	435.16	***Per m***	***(22)***
	Parking ticket revenue loss	R	947.81	***Per m***	***(23)***
	Worker safety	R	2 077.51	***Per m***	***(24)***
(Zhang et al., 2021)	Annual MUT benefit from recurring disruptions in same year.	R	7 869 465.26	***Per km***	***(25)***

In Table 8.80 the summarised benefits is shown, that is used in the CBA of the MUT proposal. An extract of the analysis is shown in Appendix I (L_11).

*Table 8.80 - **Intermediary MUT Benefit Output***

1km Utility Tunnel Benefits [R' Million]			
During Construction Benefits			
Travel Delay	R	6 859 403.53	*per km*
Pedestrian Disruption Cost	R	350 147.37	*per km*
Decreased road surface value	R	1 872 457.13	*per km*
Vehicle operating Cost	R	1 321 731.92	*per km*
Lost Business Revenue	R	4 051 910.60	*per km*
Dust control	R	214 288.85	*per km*
Parking meter revenue loss	R	435 162.78	*per km*
Parking ticket revenue loss	R	947 811.04	*per km*
Worker safety	R	2 077 506.02	*per km*
Recurring Benefits			
Benefit from reduced recurring disruption works	R	7 869 465.26	*per km/year*

8.3.4 Green Space Intermediary Calculations and Outputs

The following section presents the calculations performed to generate the output values to be used in the Green space CBA. The model researched various green space implementations, however, one system that has data present in the model but is not used explicitly in the calculations, is the permeable pavements. The rationale for not including it, is because it is unclear what percentage of these permeable pavements are from green material and what percentage is from permeable building materials. Furthermore, the green material typically used in permeable pavements is simply grass and low height shrubbery, which does not sequester significant GHG emissions in comparison to the other forms evaluated hereunder.

The Green space area is determined from the base case area available of 400 000 000 m^2, as shown in Table 8.81.

Table 8.81 - ***Green Space Area Allocation from Assumptions***

Area or Assumption	*Result*	*Calculations*
Base Case area available	**400 000 000 m^2**	**(1)**
Derived share of roof area (Akbari and Rose, 2007)	20%	*(2)*
Roof Area	80 000 000.00 m^2	*(3) = (1) * (2)*
Assume Share of Green Roofs	50%	*(4)*
Green roof area	40 000 000.00 m^2	*(5) = (3) * (4)*
Pavement Share Area	40%	*(6)*
Pavement Area	160 000 000.00 m^2	*(7) = (1) * (6)*
Assumed Total Ground Green Space Area	40%	*(8)*
Green Space Area ground level	160 000 000.00 m^2	*(9) = (1) * (8)*
Total Green Space Including roof area	***200 000 000.00 m^2***	***(10) = (5) + (9)***

8.3.4.1 Green Space Cost

This section discusses briefly the CAPEX cost involved in the two evaluated green space implementations namely tree space and green roofs. The CAPEX for Green roofs were derived from a 685 m^2 area, quantified by Van der Walt (2018). The cost per m^2 for Green Roofing amounted to R 2134.06. The per tree CAPEX in Table 8.82 were calculated by averaging out the five US green parks data supplied by McPherson *et al.* (2005).

Table 8.82 - ***Tree Costs*** *- McPherson et al. (2005)*

Project	*Ft Collins*	*Cheyenne*	*Bismarck*	*Berkley*	*Glendale*	***(6) Total trees***
Street trees + park trees	30 943	17 010	17 821	36 485	21 481	**123 740**
						Average per Tree
	(1)	(2)	(3)	(4)	(5)	**(7) = sum ((1)-(5)) / (6)**
Planting	R 1 581 610.26	R 653 896.12	R 83 743.37	R 1 352 996.57	R 300 507.66	**R 32.11**
Pruning	R 5 772 937.27	R 1 205 975.69	R 1 350 860.26	R 10 966 393.22	R 1 259 169.81	**R 166.12**
Removals	R 1 858 404.87	R 332 367.17	R 712 972.22	R 996 944.84	R 181 016.70	**R 32.99**
Im/litre/gm waste	R 1 344 365.87	R 1 393 444.04	R 544 630.97	R 2 777 203.48	R 937 313.29	**R 56.55**
Infrastructure and liability	R 1 028 277.39	0	R 306 062.07	R 15 125 077.40	R 42 726.21	**R 133.36**
Admin	R 2 622 833.69	R 1 084 248.72	R 1 511 339.89	R 2 563 572.44	R 1 216 286.94	**R 72.72**
Total Costs	***R 14 208 429.35***	***R 4 669 931.74***	***R 4 509 608.77***	***R 33 782 187.95***	***R 3 937 020.62***	***R 493.84***

The green space urban maintenance cost is given by Tempesta (2014) as R19.56 per $m^2/annum$. Whereas the green roof OPEX is given by Van der Walt (2018) as R55.43 per $m^2/annum$. The CAPEX and OPEX cost are thus summarised in Table 8.83. An extract of the analysis is shown in Appendix I (L_12).

Table 8.83 - ***Intermediary Green Space Cost Output***

Green Infrastructure Cost Base Case Scenario			
CAPEX	R	85 962 437 736.82	*Once Off*
OPEX	R	7 499 247 944.31	*Annual*

8.3.4.2 Green Space Benefits

The section below covers the potential benefits that could be gained from implementing green space. The model generated an estimated number of trees that could be implemented by this framework. To keep the estimate conservative, the number of trees are calculated using the average current trees per capita. The average trees per capita were derived from the McPherson *et al.* (2005) study. The total minimum tree to be implemented is calculated to amount to 1 214 950 trees.

The first benefit calculated is the potential energy reduction savings that could be generated by planting trees. Trees help alleviate the UHI effect which in turn reduces the need for cooling. To calculate the potential energy savings generated from the scenario tree number, the trees had to be assumed and divided into 3 size ranges as shown in Table 8.84. From the number of sized trees, the energy savings were calculated using averaged KWh savings derived from case studies found (Clements *et al.*, 2013).

Table 8.84 - ***Tree Energy Benefits***

Ref	***Energy Savings***	***Spread [m]***	***Average kWh/yr***	***2021 ZAR Savings – (1)***		***Unit***
(Clements *et al.*, 2013)	Small tree	6.40	72.67	R	159.87	*Per tree*
	Medium Tree	8.23	140.33	R	308.73	*Per tree*
	Large Tree	11.28	221.00	R	486.20	*Per tree*
Calculations	Minimum number of trees – (2)		1 214 950	trees		
		(3)	*(4) = (3) * (2)*	*(5) = (4) * (1)*		
	% Small	20%	242 990	R	38 846 001.33	*per year*
	% Medium	50%	607 475	R	187 547 781.67	*per year*
	% Large	30%	364 485	R	177 212 607.00	*per year*
			Tree Total	***R***	***403 606 390.00***	***per year***

Similar to the tree energy savings, the green roof energy savings were calculated as shown in Table 8.85. The potential energy reduction potential was derived by averaging out 4 data sets of green roof energy savings and then applying the average value to the square meters set out in the scenario for green roofs.

Table 8.85 - ***Green Roof Energy Benefit***

Ref	***Case***	***Value***	***Unit***	***Calculations***

(Clements *et al.*, 2013)	Energy savings – Case Study 1 – Retail Centre	R 16.31	*Per m2/year*	*(1)*
	Energy savings – Case Study 2 – Apartment Building	R 38.67	*Per m2/year*	*(2)*
	Energy savings – Case Study 3 – Medium Sized Office Building	R 7.47	*Per m2/year*	*(3)*
(Nurmi et al., 2013)	Data set 4 heating reduction potential	R 63.50	*Per m2/year*	*(4)*
	Data set 4 cooling reduction potential	R 36.56	*Per m2/year*	*(5)*
	Average Green Roof Energy Savings	**R 32.50**	***Per m2/year***	***(6) = sum ((1)-(5)) / 5***
Total Green roof energy reduction potential		**R 1 299 981 630.48**	**per year**	**(7) = (6)*** Table 8.81 **(10)**

The Carbon sequestration potential of green space provides a significant potential benefit. This sequestration benefit is calculated for three types namely, ground green space (excluding trees), trees and then green roofs. To calculate the green floor space benefit for sequestration, the model used a predetermined kg per square metre factor and multiplied it with the calculated ground green space area. The green roof space was calculated in the same manner.

For the calculation of the tree sequestration potential, a more in-depth analysis was approached. Using the survival rate factors set out by Groth *et al.* (2008) together with the moderate sequestration rates, the sequestration potential was generated over a 59-Year tree life. The assumption was that the division of hardwood trees to Conifer trees are 50:50. To calculate the per year carbon sequestered, the appropriate survival factor is multiplied with the sequestration rate, multiplied by the total relevant trees. The results of the three green forms of sequestration is summarised in Table 8.86.

Table 8.86 - ***Green Space Carbon Sequestration Potential***

Ref	***Term***	***Value***	***Unit***	***Calculation***
(Davies et al., 2011) Table 8.81	Parks Sequestering capability (less trees)	0.90	*kg/m2*	*(1)*
	Area of Green Floor Space	160 000 000.00	m^2	*(2)*
	Total Ground Green Space Sequestration	**144 000 000**	***kg/year***	***(3) = (1) * (2)***
(Getter et al., 2009) Table 8.81	Green Roofs Sequestering Capability	0.375	*kg/m2*	*(4)*
	Area of Green Roofs	40 000 000.00	m^2	*(5)*
	Total Green Roof Sequestration	**15 000 000.00**	***kg/year***	***(6) = (4) * (5)***
	Total Green Space Sequestration	**159 000 000.00**	***kg/year***	***(7) = (3) + (6)***
Calculated from*: (Groth et al., 2008)*	INPUT number of trees -Table 8.84	1 214 950.00	*Trees*	*(8)*
	Share of Hardwood	50%	-	*(9)*
	Share of Conifer	50%	-	*(10)*
	Total Tree Sequestration	**5 715 158.14**	*kg/year*	*(11) Calculated in (L_14)*
	Grand Total	**164 715 158.14**	***kg/year***	***(12) = (7) + (11)***
Total Social Cost of Carbon sequestered		**R 123 150 935.13**	**annual**	***(13) = (12) * Social cost of Carbon***

From evaluating case studies where green roofs have been implemented, the average increase in rental income in shown in Table 8.87, as well as the average increase in retail revenue.

Table 8.87 - ***Green Space Increase in Revenue***

Ref	*Term*	*Value*	*Unit*	*Calculation*
(Clements *et al.*, 2013)	Increased rental income	R 1 688.26	Per m2/year	*(1)*
	Increased rental income	R 738.54	Per m2/year	*(2)*
Average rental increase from green roofs		**R 1 213.40**	***per m2/year***	***(3) = [(1) + (2)] /2***
Table 8.81	Green Roof Space	40 000 000	m2	*(4)*
Total Rental Revenue increase				***(5) = (4) * (3)***
(Clements *et al.*, 2013)	Increased retail sales	R 5 496.85	Per m2/year	*(6)*
Table 8.81	Ground level Green Space Area	160 000 000	m2	*(7)*
(Burden, 2006)	Treescape street shops increased income	12%	-	*(8)*
Total Potential Increase in Retail Revenue		**R105 539 582 115.00**	**Per annum**	**(9) = (6)*(7)*(8)**

The health and safety benefit achievable by green space is calculated in three main categories namely, GP visits, mortality from heat and mortality from Particulate Matter (PM). To calculate the health benefit of visiting the GP less frequently in areas of green space, the NHS savings data per person is used. The mortality reduction from heat is calculated when the AH temperature reduces by 0.5°C, that results in a 17% death reduction. Finally, the PM-related death reduction is calculated using an 8% mortality reduction rate to the share of SA deaths of PM. The results are shown in Table 8.88.

Table 8.88 - ***Green Health and Safety Benefit***

Ref	*Term*	*Value*	*Unit*	*Calculation*
(Ball et al., 2018)	NHS savings pp	R 62.56	*Per person*	*(1)*
(de Villiers, 2019)	CPT population	4 618 000	people	*(2)*
	Improved Health Total	**R 288 920 475.27**	***Annual***	***(3) = (1) * (2)***
(WHO and UN, 2015)	Projected death rate from heat related stress	50	*per 100 000*	*(4)*
(European Commission DG, 2014)	Death reduction from 0,5 °C reduction	17%	-	*(5)*

	Mortality reduction from Heat (projected value used)	381	*annual deaths reduced*	*(6) = [(2)/100 000] * (4) * (5)*
(Macrotrends, 2021b)	SA death rate 2021 (excl. Covid-19 deaths)	9.44	*for every 1000*	*(7)*
	Theoretical CPT Total Deaths 2021	43 599	*people*	*(8) = [(2)/1000] * (7)*
(Keen and Altieri, 2016)	SA death rate share due to PM	7.40%	-	*(9)*
	Deaths from PM in 2021	3 227.00	*deaths*	*(10) = (9)* (7)*
	Assume % increase in Greenery over CPT	20%	-	*(11)*
(Rojas-Rueda *et al.*, 2019)	10% Green space increase leads to energy reduction of	4%	-	*(12)*
	Reduction rate from Greenery	8%		*(13) = [(11)/10%] * (12)*
	Mortality reduction from PM	259.00	*annual deaths reduced*	*(14) = (13) * (10)*
	Total Possible Deaths reduced	**640.00**		*(15) = (6) + (14)*
(Keen and Altieri, 2016)	Cost to economy per PM related death	R 12 609 138.91	*per death*	*(16)*
	Total Cost to economy of mortality	**R8 069 848 903.07**		**(17) = (15) * (16)**

An indirect benefit of increased green space is the ability to terrain and slow stormwater runoff. The results in Table 8.89 show the potential benefits attainable from reduced stormwater management fees due to the green space reducing the risk.

Table 8.89 - ***Green Space Stormwater Cost Savings***

Ref	***Term***	***Value***	***Unit***	***Calculations***
Table 8.18	Number of Houses	1 264 849	houses	*(1)*
(Tasca *et al.*, 2018)	SA Stormwater fee per unit	R 1 056.29	Per annum	*(2)*
	Total Stormwater cost	R 1 336 048 087.65	Per annum	*(3) = (1) * (2)*
(Clements *et al.*, 2013)	Assume the increase in stormwater cost is equal to the reduction in new city	6%	-	*(4)*
Total annual stormwater cost reduction		**R 80 162 885.26**	**annual**	***(5) = (3) * (4)***

As an additional indication of the value of Green space, the Willingness To Pay (WTP) data from the study done by Ball et al. (2018) was adapted to align with the scenario case and the resultant values are summarised in Table 8.90. For a more detailed analysis this WTP factor should be reconsidered for a case specific evaluation, however, for the scope of this study the average is used.

Table 8.90 - ***Willingness to Pay for Green Space***

Ref	***Term***		***Value***	***Unit***	***Calculations***
(Ball et al., 2018)	Lower socio-economic groups	R	62.56	*pp/month*	*(1)*
	BAME communities	R	88.01	*pp/month*	*(2)*
	Urban Residents	R	77.81	*pp/month*	*(3)*
	Total WTP for Green Space	**R**	**913.51**	***pp/annum***	***(4) = [((1)+(2)+(3)) / 3] * 12***
(Ball et al., 2018)	**Total WTP for Green Space Maintenance**	**R**	**617.72**	***pp/annum***	***(5)***
(Borzino *et al.*, 2020)	**Total WTP for Green Space for Heat Reduction**	**R**	**4 084.23**	***pp/annum***	***(6)***

The key problem alleviated by green space is the effects of climate change and the UHI effect. As an additional value realisation, Table 8.91 summarises the attainable heat reduction values from utilising EVs. Hence if used in parallel to green space, then the compounding positive effects could significantly improve urban living conditions.

Table 8.91 - ***EV Anthropogenic Heat Reduction Potential***

Ref	***Term***	***Value***	***Unit***	***Reduction % from Base***
(Ivanchev and Fonseca, 2020)	Heat Flux max in Singapore midday	147.2	W/m2	-
	Averaged Heat flux over a day	60	W/m2	Base
	EV or AV only heat flux max	13	W/m2	78%
	EV and AV heat flux max	5.9	W/m2	90%

The summarised benefits of Green space is shown in Table 8.92.

Table 8.92 - ***Green Space Intermediary Benefits Output***

Green Space Benefits Base Case Equivalent Scenario				**From**
Energy Savings	R	1 703 588 020.48	*annual*	*Table 8.84 + Table 8.85*
Carbon Sequestering	R	123 150 935.13	*annual*	*Table 8.86*
Increased rental Revenue	R	48 536 171 815.99	*phased in annually*	*Table 8.87*
Increased Retail Revenue	R	105 539 582 115.00	*phased in annually*	*Table 8.87*
Improved Health	R	288 920 475.27	*annual*	*Table 8.88*
Reduced mortality	R	8 069 848 903.07	*annual*	*Table 8.88*
Storm water costs reduction (6% increase annual)	R	80 162 885.26	*annual*	*Table 8.89*
Willingness To Pay				
WTP for green space	R	4 218 604 661.10	*annual for population*	*Table 8.90*
WTP for green maintenance	R	2 852 632 540.67	*annual for population*	*Table 8.90*
WTP for heat reduction from green	R	18 860 982 173.01	*annual for population*	*Table 8.90*

8.4 Appendix H

8.4.1 Energy:

Term	Value	Unit
Total GW shed since 9 Jan 2015	7 666.23	*GWh*
Unserved Energy Cost to economy	R 96.39	*/kwh*
Intellidex Cost/stage/day	R 300.00	*Million*
Number of stages since 2015	4080	
Assumed Electricity Inflation Rate	6%	
Coal O&M Growth Rate	2.00%	
Coal Discount Rate	8.00%	
Coal Cost per MWh	R 101.79	*per Mwh*
Average kwh solar per month	1 026.67	*KWh*
tCO2e per capita	5.5	
CPT Number of households	1 068 573.00	
Ave household size	3.59	
Households receiving free basic electricity	320 000.00	
NMT portion of all work trips	16%	
Private-vehicle transport share	42%	
Public vehicle transport share	46%	
Number of light passenger vehicles	794 796.00	
Average energy consumption per capita (excl marine and aviation)	36.80	*Gj/capita*
Low income energy contribution per month	100.00	*kwh*
GHG emissions per capita (excl marine and aviation)	5.21	*tCO2e/capita*
Social cost of Carbon	R 747.66	
LCOE of fossil fuels	R 3.38	
LCOE of Solar PV	R 0.64	
LCOE of Wind	R 0.49	
Cost per kwp of solar	R 12 162.00	
CPT income class energy consumption breakdown		
Low-income Not-electrified	4%	
Low-income electrified	20%	
Mid-Income	30%	

8.4.2 Transport

Term	Value	*Unit*
Trucking Salary	R 225 761.00	*/driver*
Freight Income	R 204.57	*/tonne*
Truck GHG emission rate	0.9	*kg CO2/km*
Social Cost of Carbon used	R 747.66	*/ton of eCO2*
Average truck service life	8	*years*

Truck useful life km	95 000.00	*km/year*
Truck Fuel Consumption average	0.26	*L/km*
Cape Town average time lost in congestion	163	*hours/year/veh*
Daily passengers	2 528 000.00	*passengers*
% of trips in morning peak for public transport	38%	
CPT congestion level	32%	
% of peak trip veh with one passenger	80%	
% of total traffic private cars	53%	
SA free-flow volume of traffic 2009	1600	*veh/lane/hour*
number of peak hour trucks in CPT system (N1)	200	*trucks/hour*
Average Truck Congestion Cost Peak (2021 value)	R 12.03	*per vkm*
Average speed of trucks during congestion	R 60.00	*km/hr*
number of peak hours	4	*hrs*
Average Car TVM - Work trips (2021 value)	R 87.27	*per hour*
Average public transport TVM - Work Trips (2021 value)	R 31.02	*per hour*
Road Deaths per 100k population	36.2	*per 100 000*
Road Fatalities Avoided	49	*per annum*
Road Severe Injuries Avoided	229	*per annum*
Road Slight Injuries Avoided	897	*per annum*
Road Property Damage Avoided	91988	*per annum*
Cost of Noise Pollution	0.15%	*of GDP*
Noise discount due to Electric	33.00%	
Total Hyperloop passengers per year (Work days only)	104 659 200.00	*per annum*
Cost of freight move (75% Load)	R 1.02	*per tonne/km*
SA Taxi fare per km	10	*per km*
Infrastructure Cost on CPT road network	R 713 000 000.00	*per year*
% of trains delayed	32%	
% of trains on time	50%	
% of trains cancelled	18%	
Daily 2019 Metrorail passengers	128728	*passengers*
Average passenger rail emission factor (diesel and electric)	0.05	*kg CO2/ passenger km*
WC share of Rail safety occurrences	19%	
WC operational safety occurrences	784	
CPT operational safety occurrences	25	
Stolen Cable recovered	7592	*kg*
Cost per kg of cable	R 138.46	
Share of Metrorail public transport trips in CPT	18%	
Important Units Used: HSR		
Railway single Track (diesel)	R 11 193 366.42	*per km*
Railway single Track (electric)	R 14 924 488.56	*per km*
Railway signalling	R 5 223 571.00	*per km*

Reballisting a railway	R	44 773.47	*per km/year*
Train acquisition Cost	R	612 384 169.70	*per train*

Important Units Used: EVs

Term		**Value**	***Unit***
EV Jobs per car (Tesla)		0.139	
EV Jobs per car (NIO)		0.178	
ICE Jobs per car (VW)		0.074	
ICE Jobs per car (GM)		0.023	
Share of jobs for EV infrastructure manufacturing in EU		4%	
Number of DCFC stations required per 1000 EVs		3.4	
Number of Level 2 stations required per 1000 EVs		40	
Number of new city DCFC chargers required		1 338	
Number of new city Level 2 chargers required		15 745	
Level 2 stations req. per truck		0.783	
DCFC stations req. per truck		0.089	
Number of EV trucks (peak traffic hour CPT trucks)		200	
Number of new city DCFC chargers required		18	
Number of new city Level 2 chargers required		157	
Number of chargers per bus		0.133	
Number of Golden Arrow Busses in CPT		1000	*busses*
Number of My citi busses		378	*busses*
Number of taxis in Western Cape		14012	
Global average driver to taxi ratio		1.5	
Number of initial Robotaxi drivers		10509	
Price of 250 mile range EV in 2019	R	697 827.09	
Price of Autonomous Technology 2019	R	77 536.34	
Passenger utilization rate (% of day occupied)	R	0.53	
Total utilization rate (% of day driving)	R	0.58	
Average km/h of Autonomous vehicle	R	60.00	
Total max possible kilometres in a given year	R	525 600.00	
Expected % accident reduction	R	0.83	
Depreciation		straight line over 5 years	
Insurance	R	0.18	*ZAR/km*
Electricity Cost	R	0.85	*ZAR/km*
Maintenance & Repair	R	0.21	*ZAR/km*
Tire costs per km	R	0.08	*ZAR/km*
Remote operator network cost	R	0.39	*ZAR/km*
Remote operator labour cost	R	0.13	*ZAR/km*
Cost of parking	R	6 977.73	*ZAR/year*
Cost to consumer for SAV	R	4.02	
Cost to consumer for personal vehicle	R	11.21	
Cost to consumer for average minibus taxi	R	10.00	
Robotaxi Discount Rate		10%	
Corporate Tax Rate		28%	

Average passenger km driven	16 630	*km*
Commercial veh. average km driven in Sa	50000	*km*
Passenger veh. fuel consumption average	0.081	*L/km*
Bus average fuel consumption	0.326	*L/km*
Price per L of petrol	R 18.34	
Price per L of Diesel (wholesale)	R 15.52	
Ration of engineer to factory worker	0.025	
Average factory worker salary	R 65 664.00	*per annum*
Average Automotive manufacturing salary	R 314 000.00	*per annum*
Important Units Used: NMT		
NMT infrastructure cost	R 1 602.41	*annual per capita*
CPT current share of NMT utilisation	9%	
Average walking speed	78	*m/min*
20-min city walking distance	1.56	*km*
Average bicycle speed	0.322	*km/min*
20-min city walking distance	6.433	*km*
Total NMT km	1 346 085 426.67	*kms/annum*
Vehicle ownership cost	R 33 579.66	*annual*
NMT roadway cost saving	R 0.44	*per km*
NMT Parking Cost Saving	R 0.21	*per km*
Veh. operating cost savings	R 4.70	*per km*
Accessibility improvement	R 0.69	*per km*
Average cost per km for cycling	R 1.68	*per km*
Urban peak Equipment cost	R 1.28	*per km*
Upper bound infrastructure cost for pedestrians	R 1 602.41	*annual per capita*
NMT safety improvement Cost	R 1 121.49	*annual per capita*
Western Cape estimated per km road maintenance cost	R 218 685.62	*per km*
Cost per death	R 4 119 437.00	
Average injury cost	R 260 456.00	
Noise Pollution Cost	R 1.22	*per km*

8.4.3 Layout:

Important Units Used: Transport Tunnelling

Term	**Value**	**Unit**
Average Bore only Cost	R 661.05	*M/km*
Average Boring project cost	R 5 053.85	*M/km*
Assumed free flow traffic volume	1440	*passenger cars per hour*
Assume Number of large veh. per peak hour	5	*large veh*
Reduced free flow speed from large vehicles entry	800	*passenger cars per hour*
Total annual trucks for 100 km scenario	14 154	
Total annual busses for 100 km scenario	3 538	
Annual work day passenger car flow	2 830 769	
Benefit Value of Truck using Tunnel	R 149.16	*per veh/peak hr*

Benefit Value of Bus using Tunnel	R	607.46	*per veh/peak hr*
Benefit Value of Car using Tunnel	R	41.33	*per veh/peak hr*
Average fuel consumption of sample trucks		0.26	*L/km*
Bus average fuel consumption		0.326	*L/km*
Cost of Diesel	R	17.44	*/L*
Average Fuel consumption of passenger car		0.081	*L/km*
Price per L of petrol	R	18.34	
Urban separation (passenger veh)	R	0.08	*per km*
Urban separation (passenger bus)	R	0.25	*per km*
Freight separation (light veh)	R	10.12	*per 30 tonne-km*
freight separation (heavy veh)	R	0.92	*per 30 tonne-km*
Urban Landscape (passenger veh)	R	0.01	*per km*
Urban Landscape (passenger bus)	R	0.25	*per km*
Important Units Used: Utility Tunnelling			
Value of Time private car	R	-	*per hour*
Value of Time pedestrians	R	41.58	*per hour*
Number of pedestrians		40	*persons/hr*
Decreased road surface value	R	1 872.46	*per m*
Operating Cost allowance	R	33 579.66	*per km*
Lost Business Revenue Impact Factor		30%	
Important Units Used: Green Space			
Total economic value of green space pp	R	598.71	*per person/year*
Average increase in retail sales from Green space	R	5 496.85	*per m2/year*
Average rental increase from green roofs	R	1 213.40	*per m2/year*
Average NPV of green roof	R	1 397.75	*per m2/year*
Average Energy Savings green roof	R	32.50	*per m2/year*
Net Green benefit per city m2	R	0.13	*per m2/year*
Net Green Benefit per tree	R	393.84	*per tree/year*
Average Stormwater Green Benefit	R	42.22	*per m2/year*
Value of Rainwater reduction from permeable pavements	R	4.26	*per m2*
Green Space Maintenance Cost	R	19.56	*per m2/year*
Capex of Permeable pavement	R	825.25	*per m2*
OPEX of Permeable pavement	R	9.66	*per m2/year*
LCC average of permeable parking lot	R	1 190.45	*per m2*
LCC average of asphalt parking lot	R	1 726.69	*per m2*
Green Tree cost	R	493.84	*per tree*
Green Roof CAPEX	R	2 134.06	*per m2*
Green Roof OPEX	R	55.43	*per m2*
Green Tree Benefit	R	891.92	*per tree*
Healthcare savings pp from reduced GP visits	R	62.56	*pp/year*
Wellbeing value per visit	R	312.23	*pp/visit*
WTP for green space	R	913.51	*pp/year*
WTP for green maintenance	R	617.72	*pp/year*

WTP for heat reduction from green	R	4 084.23	*pp/year*
Green Buildings reduction of water		1.12	*m3/m2/year*
Average trees per capita		0.263090069	*tree pp*
Public Tree cover Carbon Capture Rate		28.86	*kg/m2*
Domestic Vegetation Carbon Capture Rate		3.16	*kg/m2*
Storm water Fee South Africa	R	88.02	*per dwelling / month*
Global mortality rate from PM25		4.7	*deaths per 10 000 people*
CO2 sequestering ability of Parks in Rome		319.7	*kg/m2/year*
Social Cost of Carbon	R	747.66	

8.5 Appendix I

Loadshedding Cost of Unserved Energy (L_1)

Ref	*Data Source*	*Cost of Unserved Energy*	
	Data source	**2021 ZAR Value per KWh**	
(AfriSam, 2015)	AfriSam	R	106.80
(BusinessTech, 2019b)	NERSA	R	80.10
(SAWEA, 2019b)	SAWEA	R	96.12
(Minnaar and Crafford, 2017)	CIGRE SA	R	102.52
	Average	***R***	***96.39***

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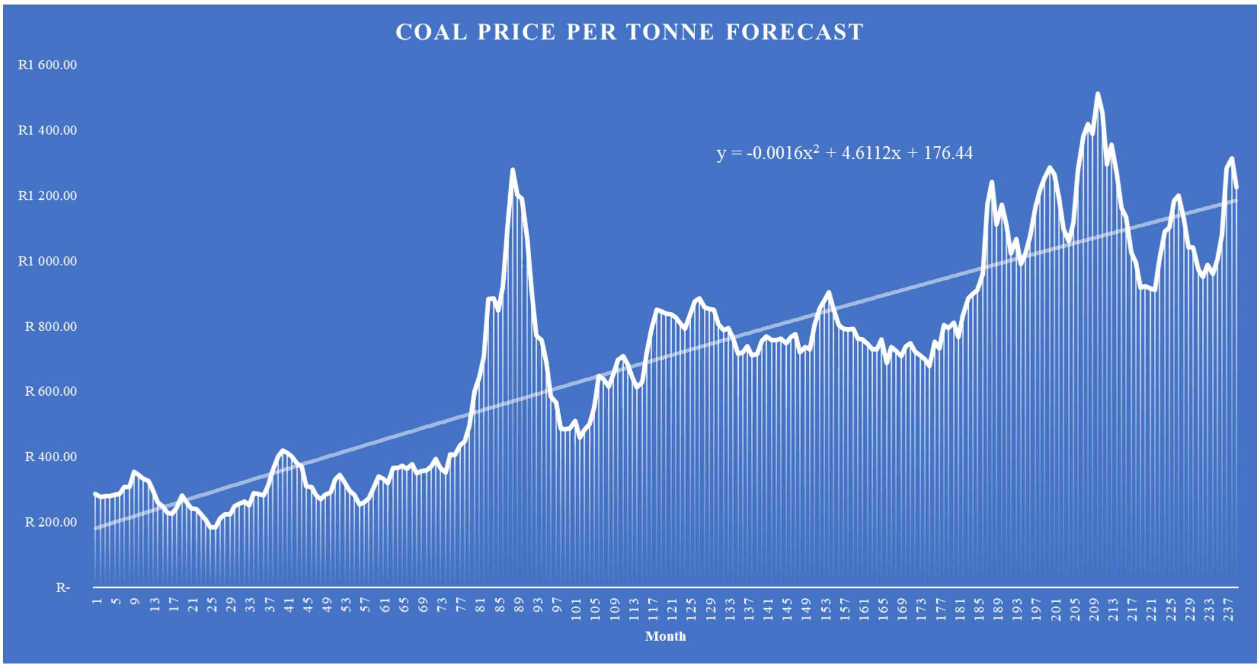
Projected Coal Price Calculation (L_2)

Forecasting price to years after 2020

Polynomial Equation constants	A	B	C
(IndexMundi, 2020)	-0.0016	4.6112	176.44

30-Years	**Years**	**Months**	**Price per ton**		**Price increase**	**Coal price per MWh**
2020	20	240	R	1 190.97	0	101.7857143
2021	21	252	R	1 236.86	1.039	105.7075181
2022	22	264	R	1 282.28	1.037	109.5899398
2023	23	276	R	1 327.25	1.035	113.4329794
2024	24	288	R	1 371.76	1.034	117.2366368
2025	25	300	R	1 415.80	1.032	121.0009121
2026	26	312	R	1 459.38	1.031	124.7258053
2027	27	324	R	1 502.51	1.030	128.4113163
2028	28	336	R	1 545.17	1.028	132.0574452
2029	29	348	R	1 587.37	1.027	135.664192
2030	30	360	R	1 629.11	1.026	139.2315567
2031	31	372	R	1 670.39	1.025	142.7595392
2032	32	384	R	1 711.21	1.024	146.2481396
2033	33	396	R	1 751.57	1.024	149.6973578
2034	34	408	R	1 791.47	1.023	153.107194
2035	35	420	R	1 830.90	1.022	156.477648
2036	36	432	R	1 869.88	1.021	159.8087198
2037	37	444	R	1 908.40	1.021	163.1004096
2038	38	456	R	1 946.45	1.020	166.3527172
2039	39	468	R	1 984.04	1.019	169.5656426
2040	40	480	R	2 021.18	1.019	172.739186
2041	41	492	R	2 057.85	1.018	175.8733472
2042	42	504	R	2 094.06	1.018	178.9681263
2043	43	516	R	2 129.81	1.017	182.0235232
2044	44	528	R	2 165.10	1.017	185.0395381

2045	45	540	R	2 199.93	1.016	188.0161708
2046	46	552	R	2 234.30	1.016	190.9534213
2047	47	564	R	2 268.20	1.015	193.8512898
2048	48	576	R	2 301.65	1.015	196.7097761
2049	49	588	R	2 334.64	1.014	199.5288802



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Coal Fuel Cost (L_3)

(Eskom, 2020)		**Arnot**	**Duvha**	**Hedrina**	**Kendal**
Downtime percentage	%	**8%**	**10%**	**NO Data**	**No Data**
Installed capacity	*MW*	2100	3600	2000	4116
Turbine efficiency rate		35.60%	37.60%	34.20%	35.30%
Average production over last 3 yrs	*MWh*	9 675 000	22 798 000	NO Data	No Data
Average production over 1 year	*MWh*	3 225 000	7 599 333		
Max actual capacity	*MWh*	6 548 976	11 857 536	5 991 840	12 727 824
1 Year Capacity Factor		49%	64%	60%	60%
Gj of energy	*Gj*	23 576 314	42 687 130	21 570 624	45 820 168
Fuel Cost for year 1 production		R 666 592 200.00	R 1 206 927 771.43	R609 883 714.29	R 1 295 510 706.00

(Eskom, 2020)		**Kriel**	**Lethabo**	**Majuba**	**Matimba**
Downtime percentage	%	**23%**	**No Data**	**No Data**	**6%**
Installed capacity	*MW*	3000	3708	4110	3990
Turbine efficiency rate		34.99%	34.20%	34.20%	35.60%
Average production over last 3 yrs	*MWh*	17 880 000	No Data	No Data	23 789 000
Average production over 1 year	*MWh*	5 960 000			7 929 667
Max actual capacity	*MWh*	9 195 372	11 108 871	12 313 231	12 443 054
1 Year Capacity Factor		65%	60%	60%	64%
Gj of energy	*Gj*	33 103 339	39 991 937	44 327 632	44 794 996
Fuel Cost for year 1 production		R 935 957 507.14	R 1 130 724 406.29	R 1 253 311 032.86	R 1 266 525 180.00

(Eskom, 2020)		**Matia**	**Tutuka**	**Medupi**	**Kusile**
Downtime percentage	%	**6%**	**21%**	**No Data**	**No Data**
Installed capacity	*MW*	3600	3654	4788	4800
Turbine efficiency rate		37.60%	38.00%	34.20%	34.20%
Average production over last 3 yrs	*MWh*	25 199 000	19 764 000	No Data	No Data
Average production over 1 year	*MWh*	8 399 667	6 588 000		
Max actual capacity	*MWh*	11 857 536	12 163 435	14 344 465	14 380 416
1 Year Capacity Factor		71%	54%	60%	60%
Gj of energy	*Gj*	42 687 130	43 788 367	51 640 074	51 769 498
Fuel Cost for year 1 production		R 1 206 927 771.43	R 1 238 063 940.00	R 1 460 061 612.00	R 1 463 720 914.29

(Eskom, 2020)		**Camden**	**Grootvlei**	**Komati**
Downtime percentage	%	**No Data**	**No Data**	**No Data**
Installed capacity	*MW*	1510	1200	940
Turbine efficiency rate		34.20%	34.20%	34.20%
Average production over last 3 yrs	*MWh*	No Data	No Data	No Data
Average production over 1 year	*MWh*			
Max actual capacity	*MWh*	4 523 839	3 595 104	2 816 165
1 Year Capacity Factor		60%	60%	60%
Gj of energy	*Gj*	16 285 821	12 942 374	10 138 193
Fuel Cost for year 1 production		R 460 462 204.29	R 365 930 228.57	R 286 645 345.71

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Coal OPEX Cost(L_4)

		Arnot	**Duvha**	**Hedrina**	**Kendal**
Water usage	*l/MWh*	**2220**	**3806**	**2610**	**4351**
Water tarrif (2017)	R/kl	**7.6493**	**7.6493**	**7.6493**	**7.6493**
Fixed O&M(used fill installed capacity) (2017)		R 1 339 800 000.00	R 2 296 800 000.00	R 1 276 000 000.00	R 2 626 008 000.00
Variable O&M (2017)		R 392 938 560.00	R 711 452 160.00	R 359 510 400.00	R 763 669 468.80
water (2017)		R 111 211 082.30	R 345 185 326.76	R 119 625 126.27	R 423 628 253.65
Total O&M		**R 1 843 949 642.30**	**R 3 353 437 486.76**	**R 1 755 135 526.27**	**R 3 813 305 722.45**

		Kriel	**Lethabo**	**Majuba**	**Matimba**
Water usage	*l/MWh*	**3171**	**3920**	**4345**	**4218**
Water tarrif (2017)	R/kl	**7.6493**	**7.6493**	**7.6493**	**7.6493**
Fixed O&M(used fill installed capacity) (2017)		R 1 914 000 000.00	R 2 365 704 000.00	R 2 622 180 000.00	R 2 545 620 000.00
Variable O&M (2017)		R 551 722 320.00	R 666 532 281.60	R 738 793 872.00	R 746 583 264.00
water (2017)		R 223 072 447.24	R 333 092 640.16	R 409 231 664.10	R 401 472 007.10
Total O&M		**R 2 688 794 767.24**	**R 3 365 328 921.76**	**R 3 770 205 536.10**	**R 3 693 675 271.10**

			Matla		Tutuka		Medupi		Kusile
Water usage	l/MWh		3806		3863		120		120
Water tarrif (2017)	R/kl		7.6493		7.6493		19.27		19.27
Fixed O&M(used fill installed capacity) (2017)		R	2 296 800 000.00	R	2 331 252 000.00	R	4 591 692 000.00	R	4 603 200 000.00
Variable O&M (2017)		R	711 452 160.00	R	729 806 112.00	R	1 147 557 196.80	R	1 150 433 280.00
water (2017)		R	345 185 326.76	R	359 401 729.36	R	33 170 140.77	R	33 253 273.96
Total O&M		**R**	**3 353 437 486.76**	**R**	**3 420 459 841.36**		**R 5 772 419 337.57**		**R 5 786 886 553.96**

			Camden		Grootvlei		Komati
Water usage	l/MWh		2310		1710		2490
Water tarrif (2017)	R/kl		7.4886		3.5077		7.6493
Fixed O&M(used fill installed capacity) (2017)		R	1 035 860 000.00	R	823 200 000.00	R	644 840 000.00
Variable O&M (2017)		R	271 430 352.00	R	215 706 240.00	R	168 969 888.00
water (2017)		R	78 256 383.36	R	21 564 034.17	R	53 638 806.62
Total O&M			**R 1 385 546 735.36**		**R 1 060 470 274.17**		**R 867 448 694.62**

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Low Income Power Schemes(L_5)

Convention low-income scheme

	Annual government contribution (units)	year Rand cost per kwh	for 300kwh annual over and above consumption	government pays	TVM Gov Pay	User pays	TVM User Pay
2020	600	1.65	R 5 945.96	R 990.99	R 990.99	R 4 954.96	R 4 954.96
2021	600	1.81	R 6 507.87	R 1 084.64	R 1 023.25	R 5 423.22	R 5 097.83
2022	600	1.98	R 7 122.88	R 1 187.15	R 1 056.56	R 5 935.73	R 5 244.81
2023	600	2.17	R 7 796.01	R 1 299.33	R 1 090.95	R 6 496.67	R 5 396.03
2024	600	2.37	R 8 532.75	R 1 422.12	R 1 126.46	R 7 110.62	R 5 551.61
2025	600	2.59	R 9 339.12	R 1 556.52	R 1 163.12	R 7 782.60	R 5 711.68
2026	600	2.84	R 10 221.69	R 1 703.61	R 1 200.98	R 8 518.07	R 5 876.36
2027	600	3.11	R 11 187.66	R 1 864.61	R 1 240.07	R 9 323.05	R 6 045.79
2028	600	3.40	R 12 244.92	R 2 040.82	R 1 280.44	R 10 204.10	R 6 220.10
2029	600	3.72	R 13 402.10	R 2 233.68	R 1 322.11	R 11 168.42	R 6 399.45
2030	600	4.07	R 14 668.63	R 2 444.77	R 1 365.15	R 12 223.86	R 6 583.96
2031	600	4.46	R 16 054.86	R 2 675.81	R 1 409.58	R 13 379.05	R 6 773.79
2032	600	4.88	R 17 572.08	R 2 928.68	R 1 455.46	R 14 643.40	R 6 969.09
2033	600	5.34	R 19 232.69	R 3 205.45	R 1 502.84	R 16 027.24	R 7 170.03
2034	600	5.85	R 21 050.23	R 3 508.37	R 1 551.76	R 17 541.86	R 7 376.76
2035	600	6.40	R 23 039.53	R 3 839.92	R 1 602.27	R 19 199.61	R 7 589.45
2036	600	7.00	R 25 216.83	R 4 202.80	R 1 654.42	R 21 014.02	R 7 808.27
2037	600	7.67	R 27 599.88	R 4 599.98	R 1 708.27	R 22 999.90	R 8 033.40
2038	600	8.39	R 30 208.14	R 5 034.69	R 1 763.87	R 25 173.45	R 8 265.02
2039	600	9.18	R 33 062.89	R 5 510.48	R 1 821.29	R 27 552.41	R 8 503.33
2040	600	10.05	R 36 187.42	R 6 031.24	R 1 880.57	R 30 156.18	R 8 748.50
2041	600	11.00	R 39 607.22	R 6 601.20	R 1 941.78	R 33 006.02	R 9 000.74
2042	600	12.04	R 43 350.21	R 7 225.03	R 2 004.98	R 36 125.17	R 9 260.25
2043	600	13.18	R 47 446.91	R 7 907.82	R 2 070.25	R 39 539.10	R 9 527.25
2044	600	14.43	R 51 930.77	R 8 655.13	R 2 137.63	R 43 275.64	R 9 801.94
2045	600	15.79	R 56 838.36	R 9 473.06	R 2 207.21	R 47 365.30	R 10 084.55
					TVM adjusted		
			Total cost for g	**R 99 227.93**	**R 39 572.25**		**TVM adjusted**
				Owner pays		**R496 139.67**	**R 187 994.94**

New low-income scheme							
		50%	50%				
solar AW cost	Sun energy equivalent value generated	owner solar units use 50%	government solar units receive 50%	owner night buy	TVM adjusted	Gov return	TVM adjusted
-6871.96	R 6 121.96	R 3 060.98	R 3 060.98	R 2 884.98	R 2 884.98	-R 3 810.98	-R 3 810.98
-6871.96	R 6 700.50	R 3 350.25	R 3 350.25	R 3 157.62	R 2 978.88	-R 3 521.71	-R 3 322.37
-6871.96	R 7 333.71	R 3 666.86	R 3 666.86	R 3 456.02	R 3 075.84	-R 3 205.11	-R 2 852.53
-6871.96	R 8 026.77	R 4 013.38	R 4 013.38	R 3 782.62	R 3 175.96	-R 2 858.58	-R 2 400.12
-6871.96	R 8 785.32	R 4 392.66	R 4 392.66	R 4 140.09	R 3 279.34	-R 2 479.30	-R 1 963.84
-6871.96	R 9 615.55	R 4 807.78	R 4 807.78	R 4 531.34	R 3 386.08	-R 2 064.19	-R 1 542.48
-6871.96	R 10 524.25	R 5 262.12	R 5 262.12	R 4 959.56	R 3 496.30	-R 1 609.84	-R 1 134.87
-6871.96	R 11 518.82	R 5 759.41	R 5 759.41	R 5 428.25	R 3 610.10	-R 1 112.56	-R 739.91
-6871.96	R 12 607.37	R 6 303.69	R 6 303.69	R 5 941.24	R 3 727.61	-R 568.28	-R 356.54
-6871.96	R 13 798.80	R 6 899.40	R 6 899.40	R 6 502.70	R 3 848.94	R 27.44	R 16.24
-6871.96	R 15 102.83	R 7 551.41	R 7 551.41	R 7 117.22	R 3 974.22	R 679.45	R 379.40
-6871.96	R 16 530.08	R 8 265.04	R 8 265.04	R 7 789.82	R 4 103.58	R 1 393.08	R 733.86
-6871.96	R 18 092.22	R 9 046.11	R 9 046.11	R 8 525.98	R 4 237.15	R 2 174.15	R 1 080.48
-6871.96	R 19 801.98	R 9 900.99	R 9 900.99	R 9 331.70	R 4 375.07	R 3 029.03	R 1 420.13
-6871.96	R 21 673.32	R 10 836.66	R 10 836.66	R 10 213.57	R 4 517.47	R 3 964.70	R 1 753.59
-6871.96	R 23 721.50	R 11 860.75	R 11 860.75	R 11 178.78	R 4 664.51	R 4 988.79	R 2 081.65
-6871.96	R 25 963.24	R 12 981.62	R 12 981.62	R 12 235.20	R 4 816.34	R 6 109.66	R 2 405.04
-6871.96	R 28 416.84	R 14 208.42	R 14 208.42	R 13 391.46	R 4 973.11	R 7 336.46	R 2 724.50
-6871.96	R 31 102.30	R 15 551.15	R 15 551.15	R 14 656.99	R 5 134.99	R 8 679.19	R 3 040.70
-6871.96	R 34 041.55	R 17 020.78	R 17 020.78	R 16 042.11	R 5 302.13	R 10 148.81	R 3 354.31
	R 37 258.57	R 18 629.28	R 18 629.28	R 17 558.14	R 5 474.71	R 18 629.28	R 5 808.70
	R 40 779.60	R 20 389.80	R 20 389.80	R 19 217.42	R 5 652.91	R 20 389.80	R 5 997.77
	R 44 633.37	R 22 316.69	R 22 316.69	R 21 033.52	R 5 836.91	R 22 316.69	R 6 192.99
	R 48 851.34	R 24 425.67	R 24 425.67	R 23 021.24	R 6 026.90	R 24 425.67	R 6 394.57
	R 53 467.92	R 26 733.96	R 26 733.96	R 25 196.81	R 6 223.07	R 26 733.96	R 6 602.71
	R 58 520.78	R 29 260.39	R 29 260.39	R 27 577.97	R 6 425.63	R 29 260.39	R 6 817.63
-R137 439.27		R 306 495.24	R306 495.24	R 288 872.36	R 115 202.72	R 169 055.97	R 38 680.62

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BIPV case studies Calcs (L_6)

Source (Onyx Solar, 2020) 35-Year Usefull Life in Cape Town		Double Skin Spandrel (Not Transparent)		Curtain Wall (Medium Transparency)		PV Canopy (Not Transparent)		PV Skylight (Low Transparency)	
		Amorphous Silicone	Crystalline Silicon	Amorphous Silicone	Crystalline Silicon	Amorphous Silicone	Crystalline Silicon	Amorphous Silicone	Crystalline Silicon
Net investment required	*ZAR/m2*	**R 3 258.00**	**R 3 896.40**	**R 4 529.60**	**R 5 251.10**	**R 3 258.00**	**R 3 896.40**	**R 4 574.40**	**R 5 306.90**
Glass Cost	*ZAR/m2*	R2 710.80		R3 951.60		R2 710.80		R3 894.40	
Electric Installation Cost	*ZAR/Wp*	R 9.50	R 7.60	R 17.00	R 11.30	R 9.50	R 7.60	R 17.00	R 11.30
Peak Power	*Wp per m2*	57.6	156	34	115	57.6	156	40	125
Environmental Benefits									
Electricty Generated	*Kwh per m2*	1662	4457	981	3286	2532	6718	1984	6055
CO2 avoided	*Kg per m2*	1444	3873	853	2855	2200	5838	1724	5262
EV kms supplied	*Km per m2*	9557	25629	5642	18893	14557	38627	11410	34817
Light Points Fed	*per m2 daily*	3.3	8.8	2	6.5	5	13.2	4	12
Economic Benefits									
Value of electricty Generated	*ZAR per m2*	R 8 002.00	R 21 458.00	R 4 724.00	R 15 819.00	R 12 188.00	R 32 341.00	R 9 553.00	R 29 152.00
Benefit obtained	*ZAR per m2*	R 9 123.00	R 25 031.00	R 5 115.00	R 17 616.00	R 14 007.00	R 38 061.00	R 10 951.00	R 34 280.00
Times the investment is recovered	*times*	6.4	13.7	3.2	6.2	8.5	20.3	6	15.4
IRR		28.20%	48.90%	16.20%	23.90%	33.90%	67%	28.40%	57.20%
Payback Time	*Years*	2.4	1.3	4.6	3.4	2	1	2.1	1
Increase of Building value	*ZAR per m2*	R 2 746.00	R 7 365.00	R 1 621.00	R 5 429.00	R 4 183.00	R 11 100.00	R 3 279.00	R 10 005.00

Source (Onyx Solar, 2020) 35-Year Usefull Life in Cape Town		PV Balustrade (High Transparency)		PV Brise (No Transparency)		PV Fins (No Transparency)		Average Value
		Amorphous Silicone	Crystalline Silicon	Amorphous Silicone	Crystalline Silicon	Amorphous Silicone	Crystalline Silicon	
Net investment required	*ZAR/m2*	**R 4 523.00**	**R 5 199.60**	**R 3 258.00**	**R 3 896.40**	**R 3 258.00**	**R 3 896.40**	R 4 143.01
Glass Cost	*ZAR/m2*	R4 047.00		R2 710.80		R2 710.80		
Electric Installation Cost	*ZAR/Wp*	R 17.00	R 11.30	R 9.50	R 7.60	R 9.50	R 7.60	R 10.95
Peak Power	*Wp per m2*	28	102	57.6	156	57.6	156	R 92.74
Environmental Benefits								
Electricty Generated	*Kwh per m2*	808	2914	2857	7557	1662	4457	R 3 423.57
CO2 avoided	*Kg per m2*	702	2533	2483	6567	1444	3873	R 2 975.07
EV kms supplied	*Km per m2*	4646	16757	16430	43452	9557	25629	R 19 685.93
Light Points Fed	*per m2 daily*	1.6	5.7	5.6	15	3.3	8.8	R 6.77
Economic Benefits								
Value of electricty Generated	*ZAR per m2*	R 3 890.00	R 14 031.00	R 13 757.00	R 36 381.00	R 8 002.00	R 21 458.00	R 16 482.57
Benefit obtained	*ZAR per m2*	R 4 187.00	R 15 731.00	R 15 742.00	R 42 898.00	R 9 123.00	R 25 031.00	R 19 064.00
Times the investment is recovered	*times*	3	6	8.6	22.7	6.4	13.7	R 10.01
IRR		15.10%	24.80%	33%	73.40%	28.20%	48.90%	37.65%
Payback Time	*Years*	4.9	3.1	2.2	1	2.4	1.3	2.34
Increase of Building value	*ZAR per m2*	R 1 335.00	R 4 815.00	R 4 721.00	R 12 486.00	R 2 746.00	R 7 365.00	R 5 656.86

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Hyperloop for Freight (L_7)

Mode 1	**For Freight**	**R1 543.22 billion**				
COST	0	1	2	3	19	20
CAPEX	-R111 660 303 043.89					-R5 583 015 152.19
OPEX		-R7 463 326 070.17	-R8 306 868 499.25	-R8 763 746 266.70	-R20 640 924 688.20	-R21 776 175 546.05
TOTAL COST	**-R111 660 303 043.89**	**-R7 463 326 070.17**	**-R8 306 868 499.25**	**-R8 763 746 266.70**	**-R20 640 924 688.20**	**-R27 359 190 698.24**
Discount factor		4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	-R111 660 303 043.89	-R7 141 938 823.12	-R7 606 848 285.75	-R7 679 641 092.31	-R8 943 749 581.01	-R11 344 293 069.77
Cumalative Present Value	-R111 660 303 043.89	-R118 802 241 867.01	-R126 409 090 152.76	-R134 088 731 245.07	-R278 412 189 219.19	-R289 756 482 288.96
BENEFITS						
Tangible		R 88 498 258 715.45	R 96 642 310 973.74	R 100 991 214 967.56	R 204 241 618 868.66	R 213 432 491 717.75
Intangible		R 14 527 934 943.36	R 15 864 868 156.53	R 16 578 787 223.57	R 33 528 444 454.39	R 35 037 224 454.83
Phased adoption		20%	30%	50%	100%	100%
TOTAL BENFITS	**R -**	**R 20 605 238 731.76**	**R 33 752 153 739.08**	**R 58 785 001 095.57**	**R 237 770 063 323.05**	**R 248 469 716 172.59**
Discount factor		4.50%	4.50%	4.50%	4.50%	4.50%
Present Value		R19 717 931 800.73	R30 907 858 097.65	R51 513 096 829.41	R103 026 193 658.82	R103 026 193 658.82
Cumalative Present Value		R19 717 931 800.73	R50 625 789 898.38	R102 138 886 727.79	R1 729 952 746 537.10	R1 832 978 940 195.92
C/B NPV	-R111 660 303 043.89	R12 575 992 977.61	R23 301 009 811.90	R43 833 455 737.10	R94 082 444 077.80	R91 681 900 589.04
Cumalative C/B NPV	-R111 660 303 043.89	-R99 084 310 066.28	-R75 783 300 254.39	-R31 949 844 517.29	R1 451 540 557 317.91	R1 543 222 457 906.96

Hyperloop for passengers

Mode 2 **For Passengers**	**Year**					
COST	0	1	2	3	19	20
CAPEX	-R111 660 303 043.89	R0.00	R0.00	R0.00	R0.00	-R5 583 015 152.19
OPEX	R0.00	-R7 463 326 070.17	-R8 306 868 499.25	-R8 763 746 266.70	-R20 640 924 688.20	-R21 776 175 546.05
TOTAL COST	**-R111 660 303 043.89**	**-R7 463 326 070.17**	**-R8 306 868 499.25**	**-R8 763 746 266.70**	**-R20 640 924 688.20**	**-R27 359 190 698.24**
Discount factor	0.0%	4.5%	4.5%	4.5%	4.5%	4.5%
Present Value	-R111 660 303 043.89	-R7 141 938 823.12	-R7 606 848 285.75	-R7 679 641 092.31	-R8 943 749 581.01	-R11 344 293 069.77
Cumalative Present Value	-R111 660 303 043.89	-R118 802 241 867.01	-R126 409 090 152.76	-R134 088 731 245.07	-R278 412 189 219.19	-R289 756 482 288.96
BENEFITS						
Tangible		R 1 065 720 443.88	1 163 793 367.73	1 216 164 069.27	2 459 533 914.89	2 570 212 941.06
Intangible		R 490 763 117.40	535 925 593.28	560 042 244.98	1 132 612 720.68	1 183 580 293.12
Phased adoption		20%	30%	50%	100%	100%
TOTAL BENFITS		**R 311 296 712.26**	**R 509 915 688.30**	**R 888 103 157.13**	**R 3 592 146 635.57**	**R 3 753 793 234.17**
Discount factor		4.50%	4.50%	4.50%	4.50%	4.50%
Present Value		R 297 891 590.68	R 466 945 068.38	R 778 241 780.64	R 1 556 483 561.28	R 1 556 483 561.28
Cumalative Present Value		R 297 891 590.68	R 764 836 659.06	R 1 543 078 439.70	R 26 135 518 707.95	R 27 692 002 269.23
C/B NPV	-R111 660 303 043.89	-R6 844 047 232.45	-R7 139 903 217.37	-R6 901 399 311.67	-R7 387 266 019.73	-R9 787 809 508.49
Cumalative C/B NPV	-R111 660 303 043.89	-R118 504 350 276.34	-R125 644 253 493.70	-R132 545 652 805.37	-R252 276 670 511.24	-R262 064 480 019.74

Hyperloop for freight and passenger

VS 50% freight & 50% Rail	Year					
COST	0	1	2	3	19	20
CAPEX	-R111 660 303 043.89	R0.00	R0.00	R0.00	R0.00	-R5 583 015 152.19
OPEX	R0.00	-R7 463 326 070.17	-R8 306 868 499.25	-R8 763 746 266.70	-R20 640 924 688.20	-R21 776 175 546.05
TOTAL COST	**-R111 660 303 043.89**	**-R7 463 326 070.17**	**-R8 306 868 499.25**	**-R8 763 746 266.70**	**-R20 640 924 688.20**	**-R27 359 190 698.24**
Discount factor	0.0%	4.5%	4.5%	4.5%	4.5%	4.5%
Present Value	-R111 660 303 043.89	-R7 141 938 823.12	-R7 606 848 285.75	-R7 679 641 092.31	-R8 943 749 581.01	-R11 344 293 069.77
Cumalative Present Value	-R111 660 303 043.89	-R118 802 241 867.01	-R126 409 090 152.76	-R134 088 731 245.07	-R278 412 189 219.19	-R289 756 482 288.96
BENEFITS						
Tangible	R	44 781 989 579.67	48 903 052 170.73	51 103 689 518.42	103 350 576 391.77	108 001 352 329.40
Intangible	R	7 509 349 030.38	8 200 396 874.90	8 569 414 734.28	17 330 528 587.54	18 110 402 373.98
Phased adoption		20%	30%	50%	100%	100%
TOTAL BENFITS	**R**	**10 458 267 722.01**	**R 17 131 034 713.69**	**R 29 836 552 126.35**	**R 120 681 104 979.31**	**R 126 111 754 703.38**
Discount factor		4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	R	10 007 911 695.70	R 15 687 401 583.01	R 26 145 669 305.02	R 52 291 338 610.05	R 52 291 338 610.05
Cumalative Present Value	R	10 007 911 695.70	R 25 695 313 278.72	R 51 840 982 583.74	R 878 044 132 622.53	R 930 335 471 232.58
C/B NPV	-R111 660 303 043.89	R2 865 972 872.58	R8 080 553 297.26	R18 466 028 212.71	R43 347 589 029.04	R40 947 045 540.28
Cumalative C/B NPV	-R111 660 303 043.89	-R108 794 330 171.31	-R100 713 776 874.04	-R82 247 748 661.33	R599 631 943 403.34	R640 578 988 943.61

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Transport Tunnel (L_8)

Project: Tunneling

Inflation at 4.50%

BCR 2.13

COST	0	1	2	3	59	60
CAPEX	-R318 517 654 810.47					-R31 851 765 481.05
OPEX		-R17 357 295 100.27	-R19 319 103 378.97	-R20 381 654 064.82	-R408 674 147 714.12	-R431 151 225 838.40
TOTAL COST	**-R318 517 654 810.47**	**-R17 357 295 100.27**	**-R19 319 103 378.97**	**-R20 381 654 064.82**	**-R408 674 147 714.12**	**-R463 002 991 319.45**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	-R318 517 654 810.47	-R17 357 295 100.27	-R17 691 081 595.18	-R17 860 374 242.02	-R30 445 003 562.04	-R33 007 024 082.18
Cumalative Present Value	-R318 517 654 810.47	-R335 874 949 910.74	-R353 566 031 505.92	-R371 426 405 747.94	-R1 850 487 243 762.59	-R1 883 494 267 844.76
BENEFITS						
Tangible		R 11 344 590 718.13	R 12 388 576 678.96	R 12 946 062 629.52	R 152 282 489 750.71	R 159 135 201 789.49
Intangible		R 68 413 442 600.42	R 74 709 189 655.72	R 78 071 103 190.23	R 918 338 054 713.73	R 959 663 267 175.85
Phased adoption		10%	20%	30%	90%	90%
TOTAL BENFITS	**R0.00**	**R7 975 803 331.85**	**R17 419 553 266.94**	**R27 305 149 745.92**	**R963 558 490 018.00**	**R1 006 918 622 068.81**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	R0.00	R8 334 714 481.79	R15 951 606 663.71	R23 927 409 995.56	R71 782 229 986.69	R71 782 229 986.69
Cumalative Present Value	R0.00	R8 334 714 481.79	R24 286 321 145.50	R48 213 731 141.06	R3 948 381 560 418.12	R4 020 163 790 404.82
C/B NPV	-R318 517 654 810.47	-R9 022 580 618.48	-R1 739 474 931.47	R6 067 035 753.54	R41 337 226 424.65	R38 775 205 904.52
Cumalative C/B NPV	-R318 517 654 810.47	-R327 540 235 428.95	-R329 279 710 360.42	-R323 212 674 606.88	R2 097 894 316 655.54	R2 136 669 522 560.05

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NMT (L_9)

Mode	**NMT**	**R1 085.95 billion**		**BCR**	**13.92**	
COST	0	1	2	3	19	20
CAPEX	-R 7 165 433 573.40					-R716 543 357.34
OPEX		-R 3 403 386 992.94	-R3 788 054 807.81	-R3 996 397 822.24	-R9 412 566 722.34	-R9 930 257 892.07
TOTAL COST	**-R7 165 433 573.40**	**-R3 403 386 992.94**	**-R3 788 054 807.81**	**-R3 996 397 822.24**	**-R9 412 566 722.34**	**-R10 646 801 249.41**
Discount factor		4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	-R7 165 433 573.40	-R3 256 829 658.31	-R3 468 835 244.44	-R3 502 029 840.08	-R4 078 481 993.94	-R4 414 620 116.55
Cumalative Present Value	-R7 165 433 573.40	-R10 422 263 231.71	-R13 891 098 476.16	-R17 393 128 316.24	-R79 615 476 219.16	-R84 030 096 335.71
BENEFITS						
Tangible		R 54 005 260 582.19	R 58 975 094 687.26	R 61 628 973 948.19	R 124 636 597 474.69	R 130 245 244 361.06
Intangible		R 11 690 523 807.50	R 12 766 344 260.88	R 13 340 829 752.62	R 26 980 095 908.36	R 28 194 200 224.23
Phased adoption		20%	30%	50%	100%	100%
TOTAL BENFITS	**R -**	**R 13 139 156 877.94**	**R 21 522 431 684.44**	**R 37 484 901 850.40**	**R 151 616 693 383.05**	**R 158 439 444 585.29**
Discount factor		4.50%	4.50%	4.50%	4.50%	4.50%
Present Value		R13 730 418 937.44	R19 708 735 316.90	R32 847 892 194.84	R65 695 784 389.68	R65 695 784 389.68
Cumalative Present Value		R13 730 418 937.44	R33 439 154 254.35	R66 287 046 449.19	R1 104 280 439 806.15	R1 169 976 224 195.83
C/B NPV	-R7 165 433 573.40	R10 473 589 279.13	R16 239 900 072.46	R29 345 862 354.76	R61 617 302 395.74	R61 281 164 273.13
Cumalative C/B NPV	-R7 165 433 573.40	R3 308 155 705.73	R19 548 055 778.19	R48 893 918 132.95	R1 024 664 963 586.99	R1 085 946 127 860.13

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New Surface Road (L_10)

Project: New Surface Road

Inflation at **4.50%**

BCR **1.03**

COST	0	1	2	3	59	60
CAPEX	-R5 187 024 128.04					-R17 829 524 027.30
OPEX		-R40 137 932.10	-R44 674 521.87	-R47 131 620.57	-R945 039 828.81	-R6 646 701 587.71
Lost Benefits		-R10 964 352 880.24	-R11 973 347 454.04	-R12 512 148 089.48	-R147 178 421 557.34	-R153 801 450 527.42
TOTAL COST	**-R5 187 024 128.04**	**-R11 004 490 812.33**	**-R12 018 021 975.91**	**-R12 559 279 710.05**	**-R148 123 461 386.15**	**-R178 277 676 142.44**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	-R5 187 024 128.04	-R11 004 490 812.33	-R11 005 262 677.97	-R11 005 654 159.29	-R11 034 755 525.27	-R12 709 238 730.79
Cumalative Present Value	-R5 187 024 128.04	-R16 191 514 940.37	-R27 196 777 618.35	-R38 202 431 777.64	-R658 543 613 100.58	-R671 252 851 831.37
BENEFITS						
Tangible		R 214 475 891.69	R 234 213 035.63	R 244 752 622.23	R 2 878 986 434.14	R 3 008 540 823.68
Intangible		R 13 550 739 372.00	R 14 797 746 162.71	R 15 463 644 740.03	R 181 896 410 439.35	R 190 081 748 909.12
Phased adoption		10%	20%	30%	90%	90%
TOTAL BENFITS	**R0.00**	**R1 376 521 526.37**	**R3 006 391 839.67**	**R4 712 519 208.68**	**R166 297 857 186.15**	**R173 781 260 759.52**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	R0.00	R1 376 521 526.37	R2 753 043 052.74	R4 129 564 579.11	R12 388 693 737.32	R12 388 693 737.32
Cumalative Present Value	R0.00	R1 376 521 526.37	R4 129 564 579.11	R8 259 129 158.22	R681 378 155 552.77	R693 766 849 290.09
C/B NPV	-R5 187 024 128.04	-R9 627 969 285.97	-R8 252 219 625.23	-R6 876 089 580.18	R1 353 938 212.05	-R320 544 993.47
Cumalative C/B NPV	-R5 187 024 128.04	-R14 814 993 414.01	-R23 067 213 039.24	-R29 943 302 619.42	R22 834 542 452.19	R22 513 997 458.72

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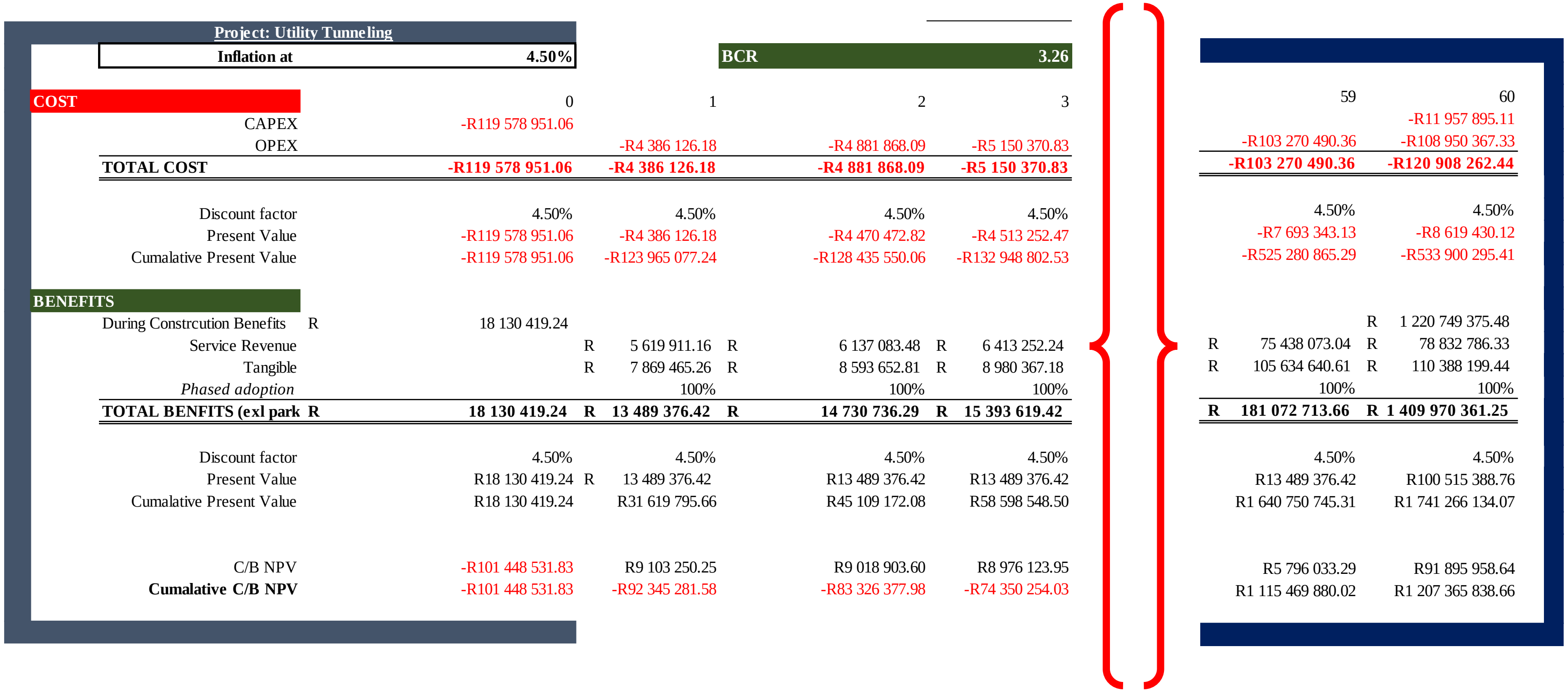
Utility Tunnel (L_11)



Project: Utility Tunneling

Inflation at 4.50%

BCR 3.26

	0	1	2	3	59	60
COST	0	1	2	3	59	60
CAPEX	-R119 578 951.06					-R11 957 895.11
OPEX		-R4 386 126.18	-R4 881 868.09	-R5 150 370.83	-R103 270 490.36	-R108 950 367.33
TOTAL COST	**-R119 578 951.06**	**-R4 386 126.18**	**-R4 881 868.09**	**-R5 150 370.83**	**-R103 270 490.36**	**-R120 908 262.44**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	-R119 578 951.06	-R4 386 126.18	-R4 470 472.82	-R4 513 252.47	-R7 693 343.13	-R8 619 430.12
Cumalative Present Value	-R119 578 951.06	-R123 965 077.24	-R128 435 550.06	-R132 948 802.53	-R525 280 865.29	-R533 900 295.41
BENEFITS						
During Constrcution Benefits	R 18 130 419.24					R 1 220 749 375.48
Service Revenue		R 5 619 911.16	R 6 137 083.48	R 6 413 252.24	R 75 438 073.04	R 78 832 786.33
Tangible		R 7 869 465.26	R 8 593 652.81	R 8 980 367.18	R 105 634 640.61	R 110 388 199.44
Phased adoption		100%	100%	100%	100%	100%
TOTAL BENFITS (exl park	**R 18 130 419.24**	**R 13 489 376.42**	**R 14 730 736.29**	**R 15 393 619.42**	**R 181 072 713.66**	**R 1 409 970 361.25**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	R18 130 419.24	R 13 489 376.42	R13 489 376.42	R13 489 376.42	R13 489 376.42	R100 515 388.76
Cumalative Present Value	R18 130 419.24	R31 619 795.66	R45 109 172.08	R58 598 548.50	R1 640 750 745.31	R1 741 266 134.07
C/B NPV	-R101 448 531.83	R9 103 250.25	R9 018 903.60	R8 976 123.95	R5 796 033.29	R91 895 958.64
Cumalative C/B NPV	-R101 448 531.83	-R92 345 281.58	-R83 326 377.98	-R74 350 254.03	R1 115 469 880.02	R1 207 365 838.66

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Green Design (L_12)

Project: Green Design

Inflation at **4.50%**

BCR **9.48**

COST	0	1	2	3	59	60
CAPEX	-R85 962 437 736.82					-R8 596 243 773.68
OPEX		-R7 499 247 944.31	-R7 499 247 944.31	-R7 499 247 944.31	-R7 499 247 944.31	-R7 499 247 944.31
TOTAL COST	**-R85 962 437 736.82**	**-R7 499 247 944.31**	**-R7 499 247 944.31**	**-R7 499 247 944.31**	**-R7 499 247 944.31**	**-R16 095 491 718.00**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	-R85 962 437 736.82	-R7 836 714 101.81	-R8 189 366 236.39	-R8 557 887 717.03	-R100 665 081 411.28	-R225 778 028 144.41
Cumalative Present Value	-R85 962 437 736.82	-R93 799 151 838.63	-R101 988 518 075.02	-R110 546 405 792.04	-R3 322 566 026 475.00	-R3 548 344 054 619.41
BENEFITS						
Service Revenue		R 154 075 753 930.99	R 154 075 753 930.99	R 154 075 753 930.99	R 154 075 753 930.99	R 154 075 753 930.99
Revenue confidence		0.40	0.50	0.60	0.75	0.75
Tangible		R9 853 599 808.80	R9 853 599 808.80	R9 853 599 808.80	R9 853 599 808.80	R9 853 599 808.80
Intangible		R123 150 935.13	R123 150 935.13	R123 150 935.13	R123 150 935.13	R123 150 935.13
Phased adoption		10%	20%	30%	90%	90%
TOTAL BENFITS	**R0.00**	**R 7 160 705 231.63**	**R 17 402 925 541.89**	**R 30 726 660 930.76**	**R 112 980 209 572.96**	**R 112 980 209 572.96**
Discount factor	4.50%	4.50%	4.50%	4.50%	4.50%	4.50%
Present Value	R0.00	R7 482 936 967.06	R19 004 429 764.88	R35 064 224 588.54	R1 516 573 672 317.21	R1 584 819 487 571.48
Cumalative Present Value	R0.00	R7 482 936 967.06	R26 487 366 731.94	R61 551 591 320.48	R32 043 577 675 856.60	R33 628 397 163 428.10
C/B NPV	-R85 962 437 736.82	-R353 777 134.75	R10 815 063 528.49	R26 506 336 871.52	R1 415 908 590 905.93	R1 359 041 459 427.07
Cumalative C/B NPV	-R85 962 437 736.82	-R86 316 214 871.57	-R75 501 151 343.08	-R48 994 814 471.56	R28 721 011 649 381.60	R30 080 053 108 808.60

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Various Conventional boring projects (L_13)

					USD/ZAR (2016)	*2021 inflation factor*	
Source (Membah, 2016)	**Similar geological conditions**		**Short length tunnels**		**R 14.56**	**1.25969897**	
	Excavation Method	**Depth**	**Length (m)**	**Diameter**	**2016 Cost ($ M) per km**	**2021 ZAR Cost (M) per km**	
Project 8	**Cut and Cover**		**1**	**5.8**	**62**	**R**	**1 136.99**
Project 6	**Cut and Cover**		**3**	**10.5**	**216**	**R**	**3 961.13**
Project 16	**Cut and Cover**	**9**	**1**	**17.2**	**48**	**R**	**880.25**
Project 20	**D&B**	**30**	**4.3**	**6.93**	**110**	**R**	**2 017.24**
Project 15	**NATM**	**0**	**2.5**	**7.83**	**314**	**R**	**5 758.31**
Project 4	**RBM**	**36**	**7.6**	**6.56**	**531**	**R**	**9 737.79**
Project 19	**Road Header**	**30**	**1.2**	**6.93**	**23**	**R**	**421.79**
Project 1	**TBM**		**29.1**	**5.38**	**139**	**R**	**2 549.06**
Project 17	**TBM**	**12**	**15.6**	**5.91**	**86**	**R**	**1 577.12**
Project 2	**TBM**	**15**	**4.6**	**6.3**	**372**	**R**	**6 821.95**
Project 5	**TBM**	**15**	**4.6**	**6.3**	**372**	**R**	**6 821.95**
Project 18	**TBM**	**26**	**1**	**6.4**	**34**	**R**	**623.51**
Project 3	**TBM**	**36**	**9.5**	**6.56**	**682**	**R**	**12 506.91**
Project 11	**TBM & Cut and Cover**		**5**	**4.2**	**246**	**R**	**4 511.29**
Project 12	**TBM & Cut and Cover**	**13**	**8**	**5.8**	**424**	**R**	**7 775.56**
Project 14	**TBM & Cut and Cover**	**16**	**6**	**6.27**	**252**	**R**	**4 621.32**
Project 7	**TBM & Cut and Cover**		**13.5**	**6.4**	**1072**	**R**	**19 658.96**
Project 13	**TBM & Cut and Cover**	**10**	**2.4**	**6.5**	**1475**	**R**	**27 049.41**
Project 10	**TBM & Cut and Cover**	**20**	**2.3**	**6.7**	**181**	**R**	**3 319.28**
Project 9	**TBM & Cut and Cover**	**20**	**5.6**	**6.86**	**209**	**R**	**3 832.76**

					USD/ZAR	*inflation factor*
Source (Arup North America Ltd, 2008)					R 7.81	2.05

Name	Length (km)	Dia.	Bores	Soils	2008 M $ cost per km	2021 ZAR cost per km
Single Bores						
A-86W	9.92	10.36	singe	limestone, sand, clay, marl, chalk	151.25	R 2 423.64
SMART Tunnels	2.976	13.20	single		53.125	R 851.28
Elbe Tunnel	2.56	14.17	single	sand, rock, marly til and mica, schist	189.375	R 3 034.56
Groene Hart	2.56	14.63	single	unknown	450	R 7 210.84
				Average	R 210.94	R 3 380.08
Twin Bores						
Beacon Hill	2.56	6.40	twin	unknown	280	R 4 486.74
Pannerdenschkanaal	3.2	9.75	twin	unknown	173	R 2 772.17
Port of Miami	2.4	10.97	twin	unknown	1000	R 16 024.08
Westerschelde	6.56	11.28	twin	soft, permeable ground	37.5	R 600.90
Wuhan	5.44	11.28	twin	unknown	288	R 4 614.93
Dublin	8.96	11.58	twin	unknown	530	R 8 492.76
Wesertunnel	1.6	11.67	twin	clay,sand,turf,til,silt	112.5	R 1 802.71
Airport Link Brisbane	10.4	12.50	twin	unknown	2206	R 35 349.12
Lefortovo	2.08	14.20	twin	fine to coarse sand, clay, limestone	274.375	R 4 396.61
Nanjing	5.92	14.93	twin	unknown	245	R 3 925.90
Madrid M-30	5.84	15.24	twin	marly clays, gypsum	81.875	R 1 311.97
Shanghai river	7.36	15.42	twin	sand,clay,rubble	16.875	R 270.41

				Average	R	437.09	R	7 004.03
Triple Bore								
I-710 (A3)	**19.84**	**15.24**	**triple**	**unknown**	**3585**		**R**	**57 446.33**
I-710 (C3)	**17.44**	**12.80**	**triple**	**unknown**	**3195**		**R**	**51 196.93**
				Average	**R**	**3 390.00**	**R**	**54 321.63**

Other tunnelling products (2012)

		Actual CAPEX 2012 [GBP M]			
Source (Naghashian, 2014)	**Channel Tunnel Rail Link**	**£**	**11 932.00**		
	Tunnel Length	**50.45**		**km**	
	Cost per km	**£**	**236.51**	**M**	
		R	**4 820.03**	**M**	
		2018 USD M Cost/km			
Source (Levy, 2018)	**San Francisco Subway**	**575**			
	Los Angeles Regional Connector	**575**			
	Los Angeles Purple Line	**500**			
	Seattle U-Link	**375**			
	Honolulu Area Rapid Transit	**312.5**			
	Boston Green Line Extension	**306.25**			
	Washington Metro Silver Line Phase 2	**150**			
	Caracas Line 3 (2012)	**98.4**			
	Santiago Line 5 extension (2012)	**71.8**			
	Average Total cost per km	**$**	**329.33**	**R**	**4 915.05**

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Tree Carbon Sequestration Factors (L_14)

INPUT no of trees	1 214 950.00						
Share of Hardwood	50%						
Share of Conifer	50%						
no of hardwood	607475						
no of Conifer	607475						
		Moderate Squestration Rate		**Moderate Squestration Rate**		**Carbon Sequestered per year**	
Source (Groth et al., 2008)		lbs/tree/year	lbs/tree/year	kg/tree/year	kg/tree/year	kg of C	kg of C
Tree age	**Survival Factor**	Hardwood	Conifer	Hardwood	Conifer	Hardwood	Conifer
1	0.873	1.9	1	0.86	0.45	456 969.97	240 510.51
2	0.798	2.7	1.5	1.22	0.68	593 589.86	329 772.14
3	0.736	3.5	2	1.59	0.91	709 685.08	405 534.33
4	0.678	5.2	3.1	2.36	1.41	971 298.80	579 043.52
5	0.658	6.1	3.7	2.77	1.68	1 105 797.35	670 729.54
6	0.639	7.1	4.4	3.22	2.00	1 249 910.81	774 592.61
7	0.621	8.1	5.1	3.67	2.31	1 385 786.85	872 532.46
8	0.603	9.1	5.8	4.13	2.63	1 511 744.93	963 529.73
9	0.589	10.2	6.6	4.63	2.99	1 655 142.09	1 070 974.29
10	0.576	11.2	7.4	5.08	3.36	1 777 298.29	1 174 286.37
11	0.564	12.3	8.2	5.58	3.72	1 911 190.73	1 274 127.16
12	0.551	13.5	8.1	6.12	3.67	2 049 298.32	1 229 578.99
13	0.539	14.6	9.9	6.62	4.49	2 168 010.78	1 470 089.50
14	0.551	13.5	9.1	6.12	4.13	2 049 298.32	1 381 378.87
15	0.516	16.9	11.8	7.66	5.35	2 402 460.31	1 677 457.50
16	0.504	18.1	12.7	8.21	5.76	2 513 210.86	1 763 413.14
17	0.493	19.4	13.7	8.80	6.21	2 634 926.26	1 860 746.89
18	0.483	20.6	14.7	9.34	6.67	2 741 158.62	1 956 069.50
19	0.472	21.9	15.7	9.93	7.12	2 847 776.68	2 041 556.80
20	0.462	23.2	16.7	10.52	7.57	2 952 907.05	2 125 583.95
21	0.452	24.4	17.8	11.07	8.07	3 038 421.90	2 216 553.68
22	0.442	25.8	18.9	11.70	8.57	3 141 678.87	2 301 462.43
23	0.433	27.1	20	12.29	9.07	3 232 786.35	2 385 820.18
24	0.424	28.4	21.1	12.88	9.57	3 317 447.15	2 464 723.06
25	0.415	29.8	22.2	13.51	10.07	3 407 094.48	2 538 171.05
26	0.406	31.2	23.4	14.15	10.61	3 489 799.24	2 617 349.43
27	0.398	32.5	24.6	14.74	11.16	3 563 577.83	2 697 354.30
28	0.381	33.9	25.8	15.37	11.70	3 558 315.81	2 708 098.76
29	0.373	35.3	27	16.01	12.24	3 627 466.02	2 774 549.08
30	0.365	36.5	28.2	16.55	12.79	3 670 333.65	2 835 709.83
31	0.365	35.2	29.5	15.96	13.38	3 539 609.43	2 966 434.04
32	0.358	36.7	30.7	16.64	13.92	3 619 669.40	3 027 897.84
33	0.35	41.1	32	18.64	14.51	3 963 051.19	3 085 587.30
34	0.343	42.6	33.3	19.32	15.10	4 025 534.33	3 146 720.50
35	0.336	44.1	34.7	20.00	15.74	4 082 232.00	3 212 096.38
36	0.329	45.6	36	20.68	16.33	4 133 144.19	3 263 008.57
37	0.322	47.1	37.3	21.36	16.92	4 178 270.90	3 308 906.68
38	0.15	48.6	38.7	22.04	17.55	2 008 386.73	1 599 270.92
39	0.308	50.2	40.1	22.77	18.19	4 259 653.27	3 402 631.40
40	0.302	51.7	41.5	23.45	18.82	4 301 474.00	3 452 827.29
41	0.296	53.3	42.9	24.17	19.46	4 346 490.51	3 498 394.80
42	0.289	54.8	44.3	24.85	20.09	4 363 130.64	3 527 129.33
43	0.283	56.4	45.8	25.58	20.77	4 397 292.50	3 570 851.00
44	0.277	58	47.2	26.30	21.41	4 426 164.78	3 601 982.38
45	0.269	59.6	48.7	27.03	22.09	4 416 908.02	3 609 117.80
46	0.261	61.2	50.2	27.76	22.77	4 400 598.49	3 609 641.24
47	0.254	62.8	51.7	28.48	23.45	4 394 537.51	3 617 796.01
48	0.247	64.5	53.2	29.25	24.13	4 389 110.19	3 620 165.30
49	0.239	66.1	54.8	29.98	24.85	4 352 303.54	3 608 263.75
50	0.232	67.8	56.3	30.75	25.53	4 333 486.97	3 598 455.99
51	0.226	69.4	57.9	31.47	26.26	4 321 034.42	3 605 012.86
52	0.219	71.1	59.4	32.24	26.94	4 289 765.30	3 583 854.55
53	0.213	72.8	61	33.02	27.66	4 271 995.62	3 579 556.77
54	0.207	74.5	62.6	33.79	28.39	4 248 605.77	3 569 969.41
55	0.201	76.2	64.2	34.56	29.12	4 219 595.73	3 555 092.47
56	0.195	77.9	65.9	35.33	29.89	4 184 965.53	3 540 298.18
57	0.189	79.6	67.5	36.10	30.61	4 144 715.14	3 514 676.79
58	0.184	81.3	69.2	36.87	31.38	4 121 242.64	3 507 871.96
59	0.178	83	70.8	37.64	32.11	4 070 220.25	3 471 946.91
					Total C sequestered over 59 Years	189 537 572.23	147 656 758.03
					Total C sequestered over 59 Years	**337 194 330.26**	**kg**

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8.6 Appendix J

Other Benefits Identified			
Transport Tunnels			
	Easier adoption and operation of autonomous vehicles		
	Better overall control of ingress and egress		
	Improved Aesthetics		
Utility Tunnels			
	Quicker and safer access to utilities		
	Reduced wear and tear of utilities from environmental factors		
	Reduced heft possibility due to determinable control points of entry		
	Flexible Infrastructure		
Green Design			
	Safter Walking Environments		
	Increased Security		
	Improved Business		
	Less drainage infrastructure		
	UV Protection		
	CO2 sequestering		
	Improve aesthetics		
	Improve overall citizen health		
	Reduce time and travel perception		
	Increased property values		
	Traffic calming		
	Heat flux reduction from EV adoption	78%	
	Heat flux reduction from Autonomous EV adoption	90%	
	Near Surface Green Roof Temp Reduction	3.5	℃
	Water retained	44800000	m3