Socioeconomic feasibility study of an integrated waste tyre pyrolysis and electricity generation system in the Gauteng region of South Africa

by

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Executive Summary

This study assesses the socioeconomic feasibility of an integrated waste tyre pyrolysis and electricity generation system in the Gauteng region of South Africa. The primary aim of the research is to address two of South Africa's challenges, waste tyre management and electricity generation shortages, by integrating waste tyre pyrolysis with a gas turbine. This research is in direct response to the call for further research into the applicability of pyrolysis from the South African government. Gauteng is a highly populated and economically significant province, which provides a crucial case study for this system due to its substantial waste tyre stockpiles, built-up infrastructure, dense population, and high electricity demand.

The designed system involves the pyrolysis of waste tyres to produce char and oils, which are then used to generate electricity through an external gas turbine. This integrated approach highlights the applicability of using pyrolysis outputs for electricity generation, bypassing the need for uncertain secondary markets for pyrolysis products. The system design relies on the availability of waste tyres, regulatory considerations, and market demands for electricity, sizing the system first for the desired electricity generation capacity and fitting the pyrolysis size to meet the demands for electricity generation.

The economic analysis shows that the combined system is a highly feasible solution, with a Net Present Value (NPV) of approximately R4.85 billion and a payback time of 5.4 years, building a solid investment case. The Levelised Cost of Electricity (LCOE) is calculated at 0.12 R/kWh, making the system more cost-effective than current electricity generation methods in South Africa under the national generation company. The economic model's outlook and results are supported by sensitivity analyses, which indicate the system remains feasible under changing waste tyre and electricity prices, even without government subsidies, a critical condition to eligibility for the support schemes.

The Social Cost-Benefit Analysis (SCBA) reveals a range of significant societal benefits that the integrated system provides. These include job creation, improved power quality, and increased national economic output through reduced load shedding. The system's Social Net Present Value (SNPV) is strongly positive at R8.56 billion, with significant social benefits across various different sectors. Further, the results highlight the benefits of pyrolysis for waste tyre management over the direct use of tyres in coal power plants, making a clear case to the government regarding the processing method to pursue. Significantly, these benefits outweigh the additional carbon emissions from the increased electricity generation capacity and the increased tax burden of the subsidies to the processing system. Not all of the societal benefits are evident in the SCBA; the system also plays a role in public health improvements and a reduction in road accidents by addressing the waste tyre stockpile issue. These benefits further highlight the potentially significant gains for society following implementation.

The study concludes that the proposed system is a socio-economically feasible solution for Gauteng's waste tyre and electricity challenges. And a potential driving force for South Africa's energy landscape transition, paving the way for renewable energy systems to connect to the grid en masse through the added grid stability. Its positive economic indicators and net societal benefits make it a promising candidate for addressing South Africa's energy transition and waste tyre management goals, meeting all of the government's objectives of the Industry Waste Management Plan and fitting into the Renewable Energy Independent Power Producer Role. The study paves the way for future research to focus on environmental impacts, changing system assumptions and long-term electricity grid impacts.

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1 Introduction

With the climate development targets of 2030 and 2050 ever approaching, countries are rapidly seeking new ways to decarbonise energy production, recycling and fuel, even as the economy and demands for these products continue to grow. South Africa, the world's 25th largest country by population, presents a significant challenge to meeting these targets due to the existing reliance on fossil fuels for electricity, the large road networks and the ongoing struggle against corruption (Department of Statistics South Africa, 2022). South Africa currently has a road network of over 750,000 km, the tenth largest globally (Department of Transport, 2020). This contributes to the primary mobility source for the country, the car, combined with a strong trucking industry that serves the country's major logistics systems. This has created a situation where waste tyres represent a major waste flow, being identified as one of the 38 key waste streams that need to be resolved under the 'Recycling and Economic Development Initiative of South Africa (REDISA)' (REDISA, 2023). The management of waste tyres has proven to be a challenge since the implementation of the National Environmental. Management: Waste Act, 2008 (Act No. 59 of 2008), with multiple plans and programmes being discussed and established between the 2000s and 2017 (REDISA, 2023). The years after 2017 saw the establishment of the Waste Management Bureau (WMB). Leading to significant declines in the collection, storage, and disposal of waste tyres due to limitations imposed by regulations and a lack of a cohesive plan. The present-day status quo has become an ongoing back and forth where, in 2018, the government called for industry participants to submit plans for waste tyre management due to the failings of the WMB, which has yet to provide a suitable answer to tackling the waste stream. This was compounded further in 2018 with new restrictions on whole and half tyre disposal via landfills, with plans to extend these restrictions to shredded tyres, creating an urgent requirement for an alternative disposal system (Department Of Forestry and Environment, 2022).

Reassessing the status quo, it is clear that South Africa is experiencing a breakdown of its tyre recycling business. There are an estimated 30 million tyres, approximately 250,000 tonnes of tyres, entering the waste stream annually (Jenkin, 2022; Godfrey and Oelofse, 2017). Where around 25% of the waste tyres generated are repurposed, 23% are used for construction material, 18% are converted using pyrolysis, 16% are incinerated, and roughly 18% are sent to landfill (Godfrey and Oelofse, 2017). However, this does not account for the significant stockpiles of tyres, reaching an estimated 900,000 tonnes of waste tyres kept at depots that are rapidly reaching capacity. Of these depot sites, as of 2022, 24 out of the 26 across the country are at 90% capacity, leading to depot site operators illegally dumping or burning tyres (Department Of Forestry and Environment, 2022). This is causing many tyres to end up back in circulation on the roads or be burnt for heat generation in the rural parts of the country, creating safety hazards through the increased risks of road accidents, pollution of noxious gases and further carbon-emitting sources (Schenck et al., 2023; Department of Environmental Affairs, 2012). For a country reliant on its road transport infrastructure, the challenge of tyre waste management will be significant for the foreseeable future.

Following the changing regulations and the system's current failings, it is clear a new approach is required to tackle the flow of waste tyres within South Africa if the country wishes to create a circular and sustainable economy. Larger-scale pyrolysis systems have been identified by the government in their 'INDUSTRY WASTE TYRE MANAGEMENT PLAN' as a viable part of a new waste tyre processing industry to tackle the growing waste tyre stockpiles; however, within these reports, it is made clear that government support will be required in establishing this waste tyre processing industry (Department Of Forestry and Environment, 2022). These systems can be the key to solving this challenge in South Africa as they offer a more environmentally friendly solution to the disposal of waste tyres while providing useful outputs that can be recycled back into the economy, further supporting development (EPA, 1997). Recent technological advancements in the recycling of tyres through the use of pyrolysis techniques have shown systems capable of producing syngas, fuel oil and rubber char at efficiencies of up to 75% with limited external emissions at large scale upwards of 10 tonnes of tyres per hour (Patel et al., 2020). Studies looking into the use of pyrolysis within South Africa have been conducted across a range of regions with different system parameters; however, there has yet to be a large-scale system that can prove feasible. These failings are largely due to the volatility of the output materials prices and continuing subsidies on fossil fuels, creating a situation where the technology is available. Still, the economic and social feasibility is lacking (Department Of Forestry and Environment, 2022). In particular, a recent study focused on waste tyre pyrolysis determined that the variability in demand and value of the output materials was the most significant contribution to the economic infeasibility and concluded that a more established secondary market, with clear use cases for each of the outputs (Nkosi et al., 2020). One such example of a secondary market is energy recovery for electricity or heat from the output products of the waste tyre pyrolysis.

South Africa's electricity system has been plagued by a lack of investment, corruption and crime, causing the current system to be underdeveloped for the growing energy demand of the population (Bloom, 2023). Within the current system, an electrical generation and demand imbalance of roughly 6000 MW per day exists, leading to a permanent cycle of severe load shedding that has been ongoing since 2003 with no end in sight as the sole electrical provider is teetering on the edge of bankruptcy (IEA, 2022; Rathi, 2022). With the lack of a stable electricity grid, the quality of life within South Africa has declined as many households cannot utilise basic electrical appliances daily. Much less focusing on integrating electric vehicles and storage systems to electrify the system further, thereby starting to reduce carbon emissions from other daily activities. This severe generation deficit has been exacerbated recently as only two new baseload power production plants have been built since 1996 following severe delays and sunken costs (Rathi, 2022). The influence of ESKOM, the national electrical provider, has proven to be a continuing detriment to the improvement and decarbonisation of the South African electrical system. The Renewable Energy Independent Power Producer Procurement Programme was stopped from 2015 to 2019 when pressure from ESKOM and government officials sought to delay the integration of independent power producers into the electrical market before being further delayed by COVID-19 (Evans and Ngcuka, 2023). These delays and political pressures have severely delayed the introduction of renewable and alternative energy sources to South Africa, contributing to the ongoing energy crisis. With the delays, interruptions and lack of development, South Africa's electricity system relies primarily upon coal plants, over 85% of capacity, with large domestic stores keeping the technology economically competitive (IEA, 2022). Many of these coal power plants are past their proposed lifetimes and are rapidly falling into disrepair with dropping efficiencies and rising carbon emissions. As these plants reach the point of no return, the current energy crisis is only set to increase unless solutions can be found elsewhere.

South African policymakers have been well aware of the looming power shortages in the country for quite some time. As early as 1998, a discussion on energy policy issued a warning, predicting that power shortages would manifest by 2007; in reality, this came about much sooner than was predicted (Bloom, 2023). Due to the national electrical company, ESKOM's shortcomings, and the continuing low cost of coal, the transition to alternative fuels or renewable energies is progressing slowly. However, tackling this power imbalance has been made possible now as South Africa moves to follow Europe in the liberalisation of its electricity market, opening the way for independent power producers and alternative systems to provide electricity in a brand new market ((NERSA), 2021).

Clearly, these two major sectors within South Africa are facing many different challenges, and there is no current clear solution that solves each one independently. However, with recent technological advancements, there may be a possible solution through the coupling of the waste tyre processing and the electrical generation sectors together. Through the use of large-scale waste tyre pyrolysis that is designed and coupled to an electrical turbine, South Africa can take steps to solve these challenges. Within an integrated system, waste tyres would be broken down, and the outputs would be sorted and processed before being used to provide electricity through the electrical turbine. One of the main challenges pyrolysis systems face is the lack of a suitable secondary market for the output products, which will cease to be a challenge should the outputs be used directly for electricity generation, which is an already established market. Similarly, the electricity sector has faced regulatory and political pressure with the implementation of pure independent power producers, for which a combined solution system would have the advantage of being supported by the waste processing industry. By coupling these two sectors, the integrated system would receive support from both the waste tyre processing sector as well as the electricity sector, significantly improving the outcomes and potential feasibility of such a system.

Through a large-scale pyrolysis system, South Africa can begin to solve its excessive waste tyre problem, turning this significant challenge into a positive driving force for the transition to a more climate-friendly and circular economy. However, for this to become a reality, further studies into the feasibility of such a system are required. As such, this paper seeks to determine the feasibility of a larger-scale waste tyre pyrolysis plant tailored for electricity production through the combustion of the carbon char and oils produced during the pyrolysis process using the Gauteng region of South Africa as a case study example. Gauteng, despite being the smallest of the nine provinces, represents more than a quarter of the country's population and is the business and economic centre of South Africa. Gauteng is the most interesting region to focus on, as any potential system will have the greatest overall impact. Further, Gauteng also hosts 8 out of the 26 waste tyre depot sites with an average fill rate of 97.5%, along with having the highest level of concentrated electrical demand.

Figure 1.1: Location of the Gauteng region in South Africa

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Conceptual Definitions and History

2.1. Introduction

Waste is an inevitable by-product of human activity and development, particularly associated with the industrialisation and modernisation of a country's economy. Waste streams have continued to escalate in both quantity and complexity due to economic development and improved living standards globally. This surge in waste encompasses two primary classes: general and hazardous waste. Among general waste, waste tyres are identified as one of the 25 most significant waste streams within South Africa; these tyres contribute to issues such as landfill complications, health concerns, and environmental hazards across the country (Department of Environmental Affairs, 2010).

Developing countries, including South Africa, must grapple with substantial hurdles in waste tyre disposal as many of these countries have built their logistics and transport infrastructure around roads and automobiles (Department of Transport, 2020). Within South Africa, these challenges range from tyre stockpiles becoming breeding grounds for disease-carrying mosquitoes to the potential for uncontrollable fires and air pollution from the large stockpiles. The existing focus, which emphasises reuse and retreading before disposal, has slowed the flow; however, it struggles to accommodate the diminishing capacity of storage depot sites and escalates the dumping of tyres. As landfill space becomes scarcer and regulations evolve, tyre disposal costs continue to rise, increasing incentives to find an alternative waste management plan.

Tyres, classified as non-biodegradable solid waste, present complexities due to their diverse composition of rubbers, carbon black, steel wire, and other challenging components. Traditional landfilling is no longer an option due to changing regulations and environmental agreements.

An alternative and promising approach is recycling through the pyrolysis process (Department Of Forestry and Environment, 2022). This method thermally decomposes waste tyres at high temperatures within an inert atmosphere, yielding oil, gas, and carbon char along with the reclamation of the steel wires. Despite the obvious benefits, pyrolysis can pose environmental challenges with respect to the expelled gases. This requires strict adherence to atmospheric protection standards that continue to tighten and is essential to mitigate these concerns. Additionally, the output products from the waste tyre pyrolysis need to meet set standards and have a sufficient market to be economically and socially feasible.

Pyrolysis products can be refined to create a viable product for electrical generation, making use of either the oils and flue gases or carbon bricks from the char. Depending on the choice of material for electrical production, the remaining output materials can be used in alternate ways, ranging from synthetic fuels to base materials for further tyre production (Ibrahim, 2020). Focusing on the production of electricity from the output products of waste tyre pyrolysis is particularly interesting for South Africa, given the severity of waste tyres combined with the excessive electrical demand and generation imbalance. Establishing a waste tyre pyrolysis system that is optimised to produce oil and char, that can be integrated with an electrical generation plant, can provide a system capable of processing South African waste tyres while providing electricity in a more net-environmentally friendly approach to the current coal dominated system.

2.2. Waste Definition and Hierarchy

2.2.1. Waste Definition

According to the South African Government Gazette of 24 August 1990, waste is defined as undesirable or superfluous by-product, emission, residue, or remainder of any process or activity, any matter, gaseous, liquid, solid, or any combination thereof. This covers all materials discarded, stored with the intention of later disposal or stored with the purpose of reuse, recycling or processing for useable materials (Department Of Agriculture and Environment, 2007).

South Africa generated around 59 million tonnes of general waste annually as of 2011, with an estimated growth rate of 3.5%, with Gauteng accounting for approximately 45% of this waste (Pam Yako and Forestry, 2007). This puts South Africa on par with developed countries for average waste generated per day per person of 0.9 kg, which is comparable to countries like the UK rather than fellow developing economies (Department of Environmental Affairs, 2012). The predominant waste management approach has been landfilling, accounting for over 90% of the waste. As of 2011, waste tyres made up around 1% of this total waste; however, this has increased as the country has continued to develop and living standards have improved (Department of Environmental Affairs, 2012; Department of Environmental Affairs, 2010).

2.2.2. General Waste Classification

Waste tyres are defined under the Waste Act (Act No. 59, 2008) as general waste (Department of Environmental Affairs, 2013). These classifications are based on the risk posed by the waste and are organised into two categories: general and hazardous. It is accepted within the South African government classifications that no waste will truly be non-hazardous; however, in the case of general waste, there are no precautionary measures that must be followed during disposal, and general waste can be disposed of at any authorised facility. In the case of waste tyres, this often occurs at the original tyre dealers, who will then move the tyres to one of the 26 depot sites located around the country (Department Of Forestry and Environment, 2022). In the case of general waste, the risks only account for the environmental and public health risks upon original disposal and fail to account for longer-term effects due to degradation, combustion or illegal reuse. This is being rectified as the *"government's objective is to move away from fragmented and uncoordinated waste management to integrated waste management (IWM). Such a holistic and integrated approach extends over the entire waste cycle, from the cradle to the grave, covering the avoidance, reduction, generation, collection, transport, recovery, recycling, reuse, treatment and final disposal of waste, with an emphasis on waste avoidance and minimisation"* (Department Of Agriculture and Environment, 2007).

General Waste
Domestic waste
Business waste not containing hazardous waste or hazardous chemicals
Non-infectious animal carcasses
Garden waste
Waste packaging
Waste tyres
Building and demolition waste not containing hazardous waste or hazardous chemicals
Excavated earth material not containing hazardous waste or hazardous chemicals

Table 2.1: Non-Exhaustive list of general waste that does not require further classification from the South African government (Department of Environmental Affairs, 2013)

2.2.3. Waste Hierarchy

The waste management strategy in South Africa is anchored in the waste hierarchy, introduced through the White Paper on Integrated Pollution and Waste Management. This hierarchy was a key feature of the 1999 National Waste Management Strategy (NWMS); this was then amended in 2010; the updated version is shown in Fig. 2.8 (Department of Environmental Affairs, 2010). The fundamental concept involves organising waste management measures across the entire system value chain. The foundational step and the primary choice in waste management is waste avoidance and reduction. If waste generation cannot be avoided, the next steps involve recovery, reuse, recycling, and treatment. Waste disposal should only be considered as a last resort in the waste management process.

Figure 2.1: Waste Hierarchy outlined in the NWMS of 2010 (Department of Environmental Affairs, 2010)

Waste Avoidance & Reduction
Waste avoidance & reduction form the basis of the waste hierarchy and is the preferred waste management technique. With the goal of prioritising the reduction of waste generation, South Africa is following in the steps of developed economies. However, the growing population, human development index and quality of life have continued to contribute to a growing level of waste within South Africa. The reduction of waste is particularly important for waste streams that are challenging to recycle or reuse, such as waste tyres, given the growing prevalence of automobiles.

Recovery, Reuse & Recycling
The 3 R's make up the second step of the waste hierarchy pyramid to reclaim as much material from the waste stream as possible. Thereby reducing the scale of waste that reaches the next steps. The goal of large-scale waste tyre pyrolysis is to provide a system that can act within this step of the waste hierarchy, moving waste tyres further down the pyramid and improving overall waste management.

Disposal
Disposal is the last step in the waste hierarchy for non-hazardous waste and represents the least ideal situation in waste management. Currently, the vast majority of waste tyres in South Africa are managed this way through landfilling and storage in depot sites. Under the Department of Environmental Affairs, alternative developments such as pyrolysis are being supported to tackle the waste stream.

2.3. Integrated Waste Tyre Management Plans

South Africa, acknowledged for its rapid economic growth, has achieved this through extensive industrial production to fulfil the socio-economic needs of its growing population. Nevertheless, the rising economic growth, quality of life and population have created a significant challenge in the generation of over 300,000 tonnes annually. The Department of Environmental Affairs, entrusted with safeguarding the environment and public health, operates under the Waste Management Act, which outlines objectives focused on protecting human health, well-being, and the environment (Department of Environmental Affairs, 2010). Recognising the necessity of a comprehensive national approach to address such issues, the Department formulated Waste Tyre regulations that became effective from June 30, 2009, in response to the National Environmental. Management: Waste Act, 2008 (REDISA, 2023).

Since then, only three national plans have successfully passed the initial screening stages. These are The South African Tyre Recycling Programme (SATRP), which submitted its first draft in June 2009, The Retail Motor Industry Association (RMIA) on December 21, 2011, and The Recycling and Economic Development Initiative of South Africa (REDISA plan) on April 19, 2010, with only the REDISA plan gaining approval and being implemented on November 30, 2012 (REDISA, 2023).

2.3.1. REDISA Plan

The REDISA plan was a tyre waste management and disposal plan that organised fees to be collected from tyre producers under a private body, REDISA NPC, a nonprofit organisation representing the tyre industry. The funds were collected to manage the collection and disposal of waste tyres through depot sites. This plan saw significant success in tackling the waste stream. However, it was brought to an end within three years of its establishment, with the parliament introducing additional legislation to inhibit the programme's effectiveness and the directors being threatened with criminal proceedings. Attacks on the programme continued for two years, with audits being brought against the organisation, an interim director attempting to seize full control and further limitations against the programme being forced through the parliament. This culminated in the cancellation of the REDISA plan in 2017,

2.3.2. Current Plans

Following the end of the REDISA plan in 2017, South Africa was again left with no centralised plan for waste tyre management, sparking calls in the government for immediate action to curb the growing flow of tyres. This central plan was established shortly after the end of REDISA under the Waste Management Bureau (WMB), which failed to successfully provide any meaningful way to deal with waste tyres, leading to a further call from the government for industry participants to step in and submit plans for waste tyre management (REDISA, 2023). This is the current status of tyre recycling and management in South Africa, with no established plan or system in place to manage the continually growing waste stream.

The situation has continued to escalate, with the government, in the latest calls for an Industry Waste Tyre Management Plan (IndWTMP), now pushing to finance waste tyre processes with a subsidy to provide the tyres from depot sites to the gate free of charge along with paying the processors a processing fee of R0.31/kg of waste tyres (Department Of Forestry and Environment, 2022). This is combined with the government funding tyre depot sites to specialise in the pre-processing of tyres based on the requirements of contracted processing sites, creating a situation where waste tyre processors can skip the initial setup of logistics and pre-processing and can instead focus on the processing of the waste tyres. In addition, the government has identified four main technologies for waste tyre processing: Energy recovery (TDF), Pyrolysis, Material recycling (crumbling) and Product recycling (reuse).

An outline of the objectives of the IndWTMP is shown below (Department Of Forestry and Environment, 2022):

Objective 1: Establishment of a viable waste tyre processing sector

1. Increase surety of supply contracts to waste tyre processors to support investment in the sector
2. Support investment in pollution abatement technologies and equipment through incentives on a cost-sharing basis
3. Supply pre-processed waste tyres to waste tyre processors, including the cement and brick industry
4. Payment of incentives in the form of a processing fee on a case-by-case basis to waste tyre processors, including the cement and brick industry
5. Support for development of markets for processed waste tyre products

Objective 2: Expand the waste tyre processing capacity of South Africa

1. Incentives developed by the Department and disbursed by the WMB including, but are not limited to:
   (a) Subsidies for plant establishment, equipment upgrades, and
   (b) Grants on a cost-sharing basis.
2. Establishing a forum to support accessing international investment opportunities
3. Providing binding supply contracts (7-10 years) between the Implementer(s) and waste tyre processors to support investment in the sector;
4. Creating pre-processing capacity at waste tyre storage site or depot
5. Subsidised delivery of waste tyres or pre-processed waste tyre materials to processors
6. Payment of a processing fee to all waste tyre processors, including the cement and brick industry
7. Capacity building, mentoring and training programmes aimed at new business development in waste tyre processing targeting SMMEs and designated groups
8. Investment in research, development and innovation in waste tyre management

2.4. Waste Tyre Pyrolysis

Pyrolysis is a heat-driven process that triggers the thermal breakdown of feed materials without introducing reactive gases like air or oxygen; this is typically done utilising nitrogen. The thermal efficiency of this method can reach 75% with limited external emissions; additionally, through using the gases produced during pyrolisation as fuel, it has been shown to rise to 90% (Islam et al., 2010). By substituting whole tyres with tyre chips, the efficiency of the process can be increased further. Pyrolysis is a promising technology in the field of waste tyre processing, however, there are some challenges associated with the process, including the high plant costs and treatment of the outputs. Typically occurring at temperatures between 400 and 700°C, pyrolysis results in varying product distributions, with lower temperatures tending to generate more liquid and solid products, while higher temperatures favour gas production (Department Of Forestry and Environment, 2022). Figure 2.2 depicts the flows and the general steps involved in the pyrolysis of tyres.

Additionally, the rate of the reaction can have a significant influence on the output products of the process with slow pyrolysis, particularly favouring a higher ratio of solid char production through carbonisation (Gao et al., 2022). Research into additives, such as steam to the pyrolytic chamber, can allow for the process to happen at lower temperatures. This is particularly useful as it promotes the removal of Sulphur from the char and can lead to greater concentrations of hydrogen in the produced gases (Gao et al., 2022). In the paper by Gao et al., 2022, an in-depth analysis of pyrolysis systems design, temperature, feed size, catalyst presence, resting times and additives is undertaken. The results determine that the most significant factors affecting the output materials are the temperature and potential catalysts/additives, with the other system parameters affecting the ratio of gas, oil and char in varying ways. Thus, temperature is the most significant parameter to focus on; figure 2.3 shows how the output ratios can vary depending on the system temperature.

2.4.1. Oil

The oil obtained in the pyrolysis process is a complex structure with similar properties to bunker oil. It has a boiling point of around 176 to 600°C and a calorific value of around 43.8 MJ/kg (Islam et al., 2010). Waste tyre pyrolysis can be designed to yield 40-60% oil with lower temperatures, giving more oil than gas(Doğan-Sağlamtimur et al., 2019). Pyrolytic oils can be used as liquid fuels for industrial furnaces and power plants or as a chemical feedstock. Pyrolytic oils can be converted to electricity in diesel engines, steam turbines and generators. However, in most applications, the oil requires further treatment, through hydro refining, the oil can have properties similar to diesel that can be refined further into higher-quality fuels, or it can be utilised as a precursor feedstock for industry due to the high

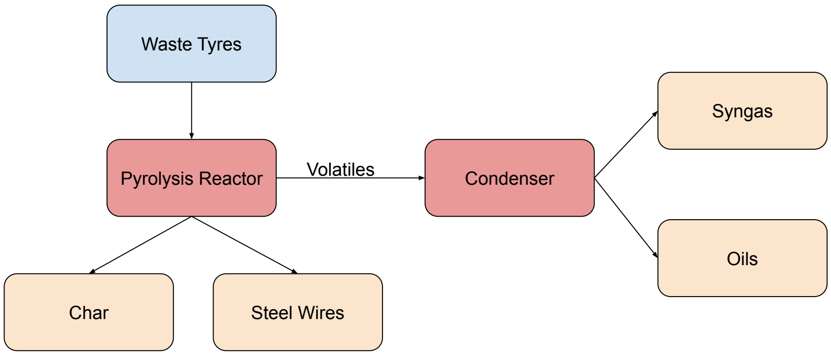

Figure 2.2: Waste tyre pyrolysis process diagram

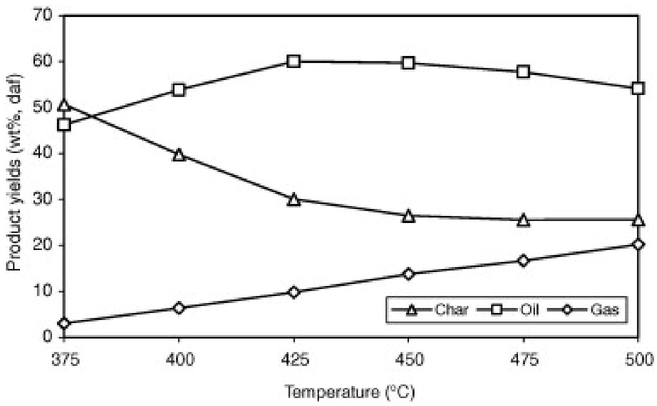

Figure 2.3: Graph depicting the changing yields from waste tyre pyrolysis with increasing temperature (Kar, 2011)

concentration of limenone (Nhlanhla and Edison, 2014). In the case of power production, the oil can be used directly; however, treatment is first required to remove impurities, predominantly sulphur.

Currently, within South Africa, there is one pyrolysis plant for waste tyres based in Pretoria, Gauteng, that is optimised in the production of pyrolytic oils. The plant processes 10 tonnes of waste tyres at a batch operation of 11 hours per day. It produces 40% pyrolysis oil, 30-35% carbon black, 15% steel cords and 10% gas. The oil is sold as crude for industrial applications. The plant mainly produces pyrolysis oil for industrial applications, furnace oil, or agriculture. The gases are flared and used in the pyrolytic chamber, reducing the release of harmful gases, and the main use for the carbon black is in manufacturing charcoal briquettes (SLATER, 2015).

2.4.2. Gas

The pyrolysis gas obtained from the process contains high concentrations of methane and ethane, closely resembling natural gas. The process can be designed to yield anywhere from 4-30% gas (Gao et al., 2022). Typically, this gas is a valuable fuel source in most pyrolytic processes. However, blending it with natural gas poses challenges due to elevated carbon monoxide and carbon dioxide levels, which also hinders its direct use for power production without further treatment. A notable advantage of waste tyre pyrolysis is the ability to use the produced gas to power the process, thereby improving its total efficiency. The operation can be sustained with just 10-15% of the generated gas; however, for larger systems, the gas requirement can increase to 90%, regardless of the quantity the application of the gas for the heating, substantially reduces total operating costs (Islam et al., 2010; Abdallah et al., 2020).

2.4.3. Steel Wire

Tyres are often reinforced with steel wires to give the rubber greater structural support. These wires are able to be reclaimed during the pyrolysis of waste tyres as they are unaffected by the pyrolysis process. The ease at which the steel wires can be reclaimed varies depending on the type of pyrolysis process. However, in all cases, the wires will have to be thermally processed to remove excess rubber and sulphur. Typically, the steel wires make up 10-16% of the tyre's total weight. As such, 10-16% of the pyrolysis process output will be steel wires (Nhlanhla and Edison, 2014). With regard to the economic value of the steel wires, cleaned and processed steel is easily sold as a base component of many industrial processes. In addition, the wire can be sold back to tyre manufacturers for use in new tyres. In any case, the steel wire will need to be baled to increase its market value.

2.4.4. Char

The carbon char obtained from the pyrolytic process is a fine powder-like substance composed primarily of carbon around 85%. This char has a calorific value of around 30 MJ/kg, putting it above the primary fossil fuel used in South Africa for electricity production, Lignite coal, which has a calorific value of 16.7 MJ/kg (Doğan-Sağlamtimur et al., 2019; Nhlanhla and Edison, 2014). This char can be upgraded through water and heat purification into a higher grade of activated carbon, which has numerous uses, from purifying water stores, filtering heavy metals, and ink production to being a fuel source for energy production. The purification step's benefit is removing sulphur and other impurities while improving the porosity of the char (Gao et al., 2022). Currently, no market in South Africa for carbon black is established, representing one of the greatest limitations to the feasibility of commercial-scale waste tyre pyrolysis.

The higher energy density of the pyrolytic char can provide an alternative to coal as a fuel source for electricity production, requiring less char to produce the same amount of power. This directly affects the CO2 emissions with a paper by Isla-Cabaraban and Cabaraban, 2016 mixing spent activated carbon into a bituminous coal power plant. The activated carbon used had a calorific value of 28 MJ/kg compared to the bituminous coal, which had a calorific value of around 27 MJ/kg, significantly greater than that of the lignite coal used in South Africa. This mixing rate took place at 10% and, in a life cycle analysis, concluded that it would reduce the CO2 emissions by around 13% and decrease other polluting gases in varying degrees. This is significant for South Africa as the difference between the pyrolytic carbon produced and the lignite coal is closer to double the energy density, leading to a greater reduction in emissions. This makes the char a prime fuel source for power production in South Africa, utilising the experience already in place for thermal based systems, tackling the tyre waste stream and creating a stable output market for the pyrolysis outputs creating a more reliable route to feasibility.

2.5. Waste Tyre Disposal Alternatives

The South African government has identified three alternative technologies to pyrolysis for the management of waste tyres other than landfilling, all of which have their own costs and benefits.

2.5.1. Energy Recovery (TDF)

Fuels derived from either partially or fully shredded tyres are denoted as TDF (Tyre Derived Fuel). With a general calorific value of 32 MJ/kg, tyres prove to be a competitive fuel option, particularly in comparison to alternatives like lignite coal (Department Of Forestry and Environment, 2022). Harnessing the energy from waste tyres as a fuel source emerges as a practical solution for waste tyre processing in South Africa, especially given the nation's heavy dependence on coal. However, this has limitations, given the impurities present in tyres requiring improvements to current coal-powered systems already in place. Further, tyres can only be mixed at low ratios into coal systems rather than replacing coal as a whole, limiting the quantities that can be processed. Waste tyres can be used in furnaces in industrial applications as a fuel source through incineration. However, these systems usually only achieve efficiencies of around 40% and usually require specially designed systems again due to the impurities (Fortuna et al., 1997).

2.5.2. Material Recycling (Crumbing)

Recycling materials, including processes like crumbing, has become a widely adopted approach for effectively managing used tyres. This involves mechanical grinding and devulcanisation, yielding various valuable products. While the separation of rubber, steel belts, and textile overlays from tyres involves expenses, the isolated materials can be repurposed (Department Of Forestry and Environment, 2022). Given the large array of useful applications for the recovered material, this is an appealing, environmentally friendly approach.

2.5.3. Product Recycling (Reuse)

Product recycling entails using tyres, either in full or part, in their original state for different purposes without undergoing any physical or chemical treatment, making this the easiest and cheapest option outside of landfilling. The unique characteristics of tyres, such as their shape, size, high elasticity, and effective damping properties, make them valuable in a wide range of applications. These include construction, protective barriers along roads and waterfronts, artificial reefs, road filler, and insulation. Tyres are also utilised in playgrounds and park settings as construction material (Department Of Forestry and Environment, 2022). It's important to note that product recycling or reuse represents a relatively small portion of the waste tyre processing industry, given its difficulty to scale (REDISA, 2023).

2.5.4. Landfilling

Landfilling has been the backbone of the waste tyre management plan in South Africa, accounting for the vast majority of all tyres. Landfilling of waste tyres in South Africa involves depositing the tyres with one of the 26 depot sites across the country, where they are stored with no further processing (Department Of Forestry and Environment, 2022). Given the changing regulations banning the landfilling of waste tyres and the limited available capacity left in the depot sites, this is no longer a suitable option. Further landfilling of tyres can create health, environmental and fire hazards.

2.6. South African Electricity Market

South Africa has historically had a nationalised electrical system under ESKOM. ESKOM acts as the power generator, transmission service operator and distribution system operator. This has opened up the South African system to corruption, directly contributing to the ongoing problems in the country. Following the continued failures of ESKOM, the decision to move the South African system towards a more European-style liberalised market has been made, allowing independent large power producers to enter the market and participate competitively. This market transition has been a slow process, with political pressure from ESKOM on top of coming at a time when the globe was facing COVID-19. As of 2022, this new policy shift was entered into force with an abolishment of the 100MW minimum generation capacity requirements for market participation, paving the way for a wave of new Independent Power Producers (IPP) actively promoting South Africa's transition away from ESKOM (de Villechenon and Smith, 2024).

Figure 2.4 shows how this new market will be integrated with ESKOM. As part of the electrical system, South Africa has two different designations of power producer plants: base load plants and peak plants. These classifications are split up based on the capacity factors and power generation availability.

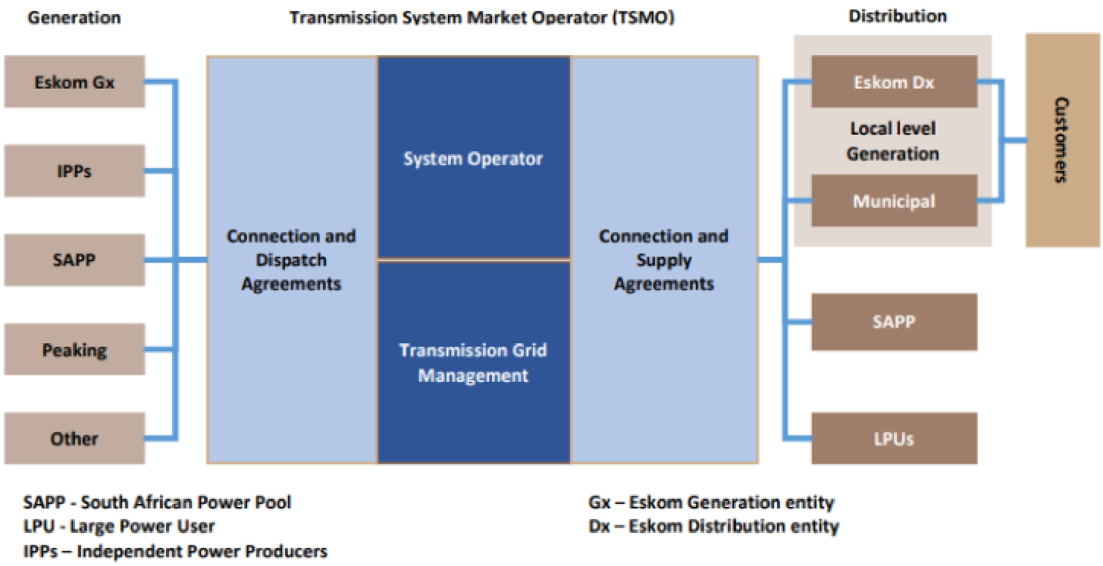

Figure 2.4: Proposed electricity market outline with separate entities for generation, transmission and distribution ((NERSA), 2021).

2.6.1. Base Load Plant

Base load plants in South Africa consist of a combination of coal-fired and nuclear power plants. They are intended to cover the largest proportion of the electrical demand on a daily basis, operating almost permanently. The base load plants collectively make up over 90% of the country's generation capacity, with coal alone making up 85% of the total electricity generation (IEA, 2022).

2.6.2. Peaking Plant

In South Africa, the term peaking power refers to the ability of the generation sources to respond quickly to changes in the system. Hence, the peaking plants are able to supplement the generation of base-load stations. South Africa's peak power stations are hydroelectric, hydro pumped storage and gas turbine stations. Due to the variable generation profiles, non-dispatchable generation sources like Solar and Wind are also classified as peaking plants. These peaking generation plants consist of stations that operate during peak periods or when the system is constrained. In the current period of generation and demand imbalance, many of the peaking plants are being run at capacity factors much higher than initially intended, raising the average operational cost of electricity production. The combined unmet demand and the higher operational capacity factors have contributed to the rapid increase in electricity prices, with an increase of 405% since 2010, an average of 15% per year (Codera Analytics, 2024).

3
Literature Review

3.1. Waste Tyre Pyrolysis System Studies

The developments and use cases of pyrolysis for tyre waste management have been well documented, with multiple studies covering the technical, economic, and sustainability challenges facing any technology seeking to break into a broader market (Khan et al., 2023; Martínez et al., 2014; Gao et al., 2022;). In research conducted by Singh et al., 2018 and Martínez et al., 2014, waste tyre pyrolysis's technical process and product yields are investigated using a thermogravimetric analyser and a batch reactor with combinations of tyres and biomass and only tyres. Their research determined that there are four main yields: black char from the rubber, steel wire that is utilised in tyre production and pyrolysis oils and flue gases of varying qualities. In addition, the most important factors in the yields were found to be the reactor temperature and the tyre composition. The paper by Gao et al., 2022 goes into detail on the effects of different pyrolysis techniques and how these changes will affect the obtained outputs. By looking into the types of reactors used, the temperature, catalysts and additives and feedstock size, Gao et al. create a comprehensive database of expected yields for waste tyre pyrolysis and how the system can be optimised to maximise a single output. The paper then continues to focus on carbon char and its uses as a global product in different applications. However, they neglect to discuss its capabilities as a fuel replacement in coal power plants.

A more economic-focused study from Nkosi et al., 2020 assessed the feasibility of a standalone 7-tonne-per-day waste tyre recycling plant that utilises batch vacuum pyrolysis for the region of Gauteng, South Africa. This research used literature analysis to assess the regional situation, after which the proposed system's economic output and indicators were modelled. It was found that a standalone system, while technically possible, requires further treatment of the output products, in particular hydro-refining of the pyrolysis oils, to be economically viable. The study also concluded that a well-regulated and stable market within South Africa would be required to ensure economic viability. While the conclusions are positive in some aspects, the authors didn't provide any insight into what sort of market would need to be sufficiently established for a standalone pyrolysis system to be economically viable. Further, the study was conducted during the middle of South Africa's changing regulations regarding waste tyre management; this meant the authors didn't take into account the current availability of subsidies and support from the government. In addition, the study doesn't look into the social impacts of standalone pyrolysis systems or whether this could make the system feasible from a societal perspective as a waste tyre management tool.

In this study by Goksal, 2022, the economic benefits of waste tyre pyrolysis based in Turkey have been analysed using economic analysis techniques and basic models to understand the inputs and outputs of these systems focused from an investors' point of view. Within their research Goksal, 2022 determined that a pyrolysis plant treating waste tyres is able to attain profitability, proving the economic viability of such plants. To add to these findings, a discussion around key influences and policies for the success of these systems was included to highlight how the economic benefit can change over time. While a broader discussion around the influences on the feasibility was included, the research failed to include influences outside of the economic factors, leaving out the societal benefits of a policy or how these benefits can influence the feasibility. By taking the point of view of an investor, the findings became increasingly narrow, once again ignoring benefits outside of the financial incentives.

In 2019, a study by Doğan-Sağlamtimur et al., 2019, a two-step decomposition and condensation pyrolysis process was developed and tested for waste tyres. This process is optimised in the production of pyrolytic oils and char and provides a much simpler system than traditional comparable systems at the time. By showing how a 10 tonnes per day system can achieve high levels of efficiency and profitability in Turkey, Doğan-Sağlamtimur et al., 2019 shows how waste tyre pyrolysis can be feasible on a commercial scale. In addition, the condensation process limits the amount of gas produced by the system while improving the quality of the pyrolytic oils, making them suitable for energy production. This paper has all the benefits of outlining an efficient and scalable pyrolysis process to produce higher-quality oil products with limited gas emissions and provides an overview of the economic benefits of a commercially sized system. However, there is no comparison or discussion on the societal impacts or comparison to other types of waste tyre recycling systems.

Outside of the world of published research, discussions are taking place regarding the feasibility of pyrolysis-based systems for future development towards a circular economy (Leeds, 2022; Riedewald and Sousa-Gallagher, 2016). Similar to the study performed by Nkosi et al., 2020, Leeds, 2022 has shown how it is not the technical capabilities of pyrolysis that are the limiting factor to the technology's usefulness but rather the economic and societal feasibility of the technology. Leeds, 2022 discusses the feasibility of a circular economy based on pyrolysis through literature analysis, thought experiment discussions and basic macroeconomic assessment. The book mostly focuses on when an economy based on pyrolysis would become feasible, the requirements for success and how it can help create a circular economy, particularly in developing economies. The main takeaway is that economic gain is not always the primary driver for feasibility, as technological gain and societal gain can play just as important a role in the adoption of technology. There are issues with this research, though, namely in the fact that it is not supported by data and takes a more surface-level discussion on when feasibility can be achieved.

3.2. Waste-to-Energy Systems

Combining a waste tyre pyrolysis system with a steam turbine power plant would create an integrated waste-to-energy system that can simultaneously tackle two of South Africa's major challenges. Research into the integration of these systems has been limited thus far, with studies focused on smaller scale systems as in Odejobi et al., 2020 or making use of biomass in co-pyrolysis systems (Khan et al., 2023). In their research Khan et al., 2023 created three simulations covering the input-output flows and the calculations of key economic indicators to analyse pyrolysis and co-pyrolysis plants of various scales, processing rice straw and scrap rubber tyres to produce oil and power in different regions of Punjab, Pakistan. The results determined that co-pyrolysis using rice straw and waste tyres and pyrolysis using waste tyres achieved profitability with positive indicators. These results were then recalculated through multiple scenarios in a sensitivity analysis to determine the most significant factors and influences on the economic feasibility before finally discussing the societal influences that can affect the economic feasibility. This research provides a detailed analysis of the economic and technical feasibility of the integrated waste tyre pyrolysis power plant, which includes an assessment of the economies of scale that will be present and how this can affect economic feasibility. However, Khan et al., 2023 failed to compare this system to alternative tyre recycling methods or more traditional power production systems, leaving a limited analysis of the societal impacts of a pyrolysis power plant.

While there have been limited studies on the feasibility of pyrolysis systems used to generate electricity, there have been countless studies analysing the feasibility of waste-to-energy systems as well as more traditional turbines for power production (Kwon and kyun Im, 2022; Weerd et al., 2022; Santos-Alamillos et al., 2017). Kwon and kyun Im, 2022 performed a feasibility study on waste-to-energy power plants utilising flow modelling to represent an incineration plant and thermal and non-thermal plasma gasification plants. The study focused on the technical feasibility of waste-to-energy systems and the designs that had to be implemented to maximise efficiency and thus create feasibility. The paper by Santos-Alamillos et al., 2017 looked at the economic feasibility of gradual decarbonisation of large-scale electric systems using levelised cost of energy (LCOE) as an indicator across three scenarios. It was determined that decarbonisation would be required to be completed in steps with a shift from Coal plants to new natural gas turbines in every scenario. This study also determined that the cost of fuel and the discount rate play the most significant roles in the feasibility of power systems, as these impact the LCOE the most. While Santos-Alamillos et al., 2017 formulated a strong economic comparison of three energy mixes based on a varying mix of renewables and gas turbines, it neglected to include any social impacts of the different energy sources and how this would affect the overall assessment of the different energy mixes.

In the paper by Gökalp et al., 2019, the feasibility of a 5 MWe gasification plant that utilises tyre granules was assessed. This study looked into an alternative energy recovery process for tyres, gasification. The study shows how a plant of this scale can be designed, operated and scaled to provide a self-sufficient energy generation system. The most significant takeaway from this study is that it highlights how waste tyre-powered systems can achieve net positive energy outputs. However, this heavily depends on the cost of the fuel source, regulation, and value of the output product. This study provides a good indication of the necessary information required to construct an economic model for a waste-to-energy system, however, it also doesn't look into any societal benefits provided by the implementation of the described system.

3.3. Social-Cost Benefit Analysis Frameworks

While there are a limited number of societal effects studied in relation to pyrolysis systems, especially in South Africa. There are multiple studies that make use of social cost-benefit analysis (SCBA) frameworks to incorporate the social aspects of waste-to-energy systems or grid-scale electricity systems. One such study by Jamasb and Nepal, 2010 uses SCBA to analyse multiple different forms of waste-to-energy management systems in the UK against Coal power and landfills. This study concludes that waste-to-energy management options can play an essential part in waste management strategy and renewable energy policy. Within their study Jamasb and Nepal, 2010 outline a framework with which the costs and benefits of the different management options are compared to one another on a per tonne of waste basis before analysing multiple future scenarios. An advantage of the framework used is that it compares different waste-to-energy systems, accounting for a mix of economic aspects and providing a very clear outline of the carbon emissions of each option. However, societal aspects outside of carbon emissions and the provision of electricity and heating are not included within the SCBA framework, neglecting other aspects like labour provision or more quantitative factors when determining the social feasibility of waste-to-energy systems.

The Social Cost Benefit Analysis technique has also been used in a study by Sidhu et al., 2018 analysing grid-scale electrical energy storage systems. Within their study, Sidhu et al., 2018 use a framework for incorporating the Social Welfare effects into the net present value of the storage systems as a measure of the societal feasibility, making for easy comparison between their proposed system and other systems. From their results, it was determined that there should be further regulatory change to encourage investment in grid-scale energy storage systems, citing a net positive result for society from such actions, especially as the technologies used continue to improve. This final fact was highlighted with the shift from a negative result to a positive outcome as the start date was moved from 2013 to 2017 and beyond. While Sidhu et al., 2018 has a very clear and concise framework for performing social cost-benefit analysis, the study focused almost entirely on the quantitative societal factors, leaving out some of the more qualitative factors that may lead to a varied result for the net outcome.

3.4. Knowledge Gap

Beyond the research by Khan et al., 2023, there are no further studies into the economic feasibility of a pyrolysis system that uses solely waste tyres for commercial-scale power production. There have been many studies into the output materials from waste tyre pyrolysis, with many concluding that char and oil can be used for power production. However, they did not discuss this further as the studies focused on the pyrolysis process instead (Gao et al., 2022; Doğan-Sağlamtimur et al., 2019). A reason for the limit on studies looking at using char or oil for power production may be due to a large capacity of research coming from developed economies where the use of coal and oil for electricity generation is on the decline in favour of renewable sources and gas turbines. Gasification of waste tyres has also been identified as a similar system for energy production in Gökalp et al., 2019. However, the South African government has specifically identified pyrolysis as a preferred energy recovery method (Department Of Forestry and Environment, 2022). As such, South Africa is a unique case where a waste tyre pyrolysis system integrated with a power generation plant can help to solve two major challenges while simultaneously helping to reduce the reliance on coal, thereby reducing South Africa's carbon emissions. Based on this unique case, the following research question has been formulated.

What is the socioeconomic feasibility of an integrated waste tyre pyrolysis and electricity generation system in the Gauteng region of South Africa?

3.4.1. Research Aim

Within this study, the primary focus will be on the socio-economic aspects of the feasibility of an integrated waste tyre pyrolysis power plant; these are the aspects previously identified as lacking in determining large-scale feasibility. The study will be broken into four steps, each building upon one another to formulate a comprehensive analysis of the feasibility of a large-scale integrated waste tyre pyrolysis and electricity generation system and the impacts and implications such a system would have on Gauteng and, further on, South Africa. The first section assesses the current situation within Gauteng, South Africa, by looking into the regulations, the demand for the system and the current status quo for waste tyre management and electricity production. The second section focuses on what an integrated system could look like and how the system can be designed to couple the two sectors together to meet the demands of waste tyre processing and electricity generation. Within this, the system's design, boundaries, scale, parameters, and expected flows are outlined. Following sections 1 and 2, section 3 looks into the economic aspect of the feasibility. In this Chapter, an economic model is created utilising the system design outlined previously, highlighting the expected economic feasibility of the integrated system and the calculation of select indicators with which the system can be evaluated. Section 4 focuses on the societal aspects of the feasibility through a Social Cost Benefit Analysis (SCBA) framework using the previous section's economic model. Within this framework, the use of pyrolysis for energy recovery is compared to the direct use of waste tyres in energy recovery across multiple parameters, such as carbon emissions, job creation and electrical market stabilisation and integration. This section will highlight and assess the potential positive or negative societal impacts of using pyrolysis for waste tyre management, determining the technology's societal feasibility and sector coupling. Finally, a sensitivity analysis will be conducted with a range of varying potential future scenarios highlighting the most significant risks and impacts across a range of future situations following the introduction of the integrated system.

3.5. Scope

This study focuses primarily on tackling two of South Africa's major identified challenges through the coupling of these sectors, assessing how pyrolysis technology integrated with a thermal power plant can provide a feasible solution that successfully solves these two challenges. These technologies are already being used globally in independent systems; however, they have yet to be integrated. The system's predefined border is from the point of entry for the pre-processed tyres to the exit of the electricity and other output yields. As such, this study does not include the costs, organisation, and emissions involved in pre-processing, logistical transport, and electrical distribution. The geographical scope of the study is the province of Gauteng in South Africa, with an implementation time of 2022.

4

Research Questions and Methodology

4.1. Research Questions

A feasibility study can pose a complex question as it is not immediately clear what makes a system feasible: is it purely the economic benefits, can the societal impacts have an effect, or is there a technical limitation that prevents feasibility? From the literature, it is clear that there are no technical limitations to the use of pyrolysis for waste tyre processing, nor is there a limitation on the use of the outputs for power production. The oils, and especially the char, can be used directly for power production in steam turbines following purification (Doğan-Sağlamtimur et al., 2019; Gao et al., 2022). With no technical restrictions, a greater focus can be placed on the economic and societal impacts of the system to determine its feasibility. This research into the societal and economic impacts will be broken down into four steps, each analysing different parts of the problem.

Initially, a greater understanding of the regional situation in which the proposed system would be located is required to evaluate the major actors involved, the current setup, and how these will be impacted. Following an assessment of the current status quo for Gauteng, the system design will need to be established. Here, the outline of the system will be created, describing the basic steps and determining the input and output flows. Throughout the literature, it is clear that economic analysis plays a fundamental role in determining the feasibility of a system, as the economic potential can, in some cases, solely determine the feasibility of a system. Therefore, a significant focus must be placed on the potential economic benefits that the implementation of this system can provide. The other significant contributing step to the feasibility will be the societal impacts; in particular, a comparison between this integrated system and the direct use of waste tyres for energy recovery, as these are both methods highlighted by the South African government to deal with waste tyres that yield the same result.

1. *What is the current situation of tyre recycling and power production in the Gauteng region?*

2. *What could an integrated waste tyre pyrolysis and electricity generation system look like for the Gauteng region?*

3. *What is the economic feasibility of the integrated waste tyre pyrolysis electricity generation system?*

4. *What are the social costs and benefits of waste tyre pyrolysis for electricity generation compared to direct-use energy recovery?*

4.2. Methodology

This Chapter provides insight into the methods and approaches that were undertaken to answer the sub-questions, which in turn have been used to answer the main research goal. By answering each subquestion, the overall socio-economic feasibility of a waste tyre pyrolysis plant can be determined along with the potential risks of such a plant to the region and the potential impacts. Figure 4.1 below shows the flow diagram of the steps performed to answer the previously outlined research questions. The diagram shows the various steps involved in each subquestion building to answer the main research question. Each step is further expanded upon and explained subsequently throughout this Chapter.

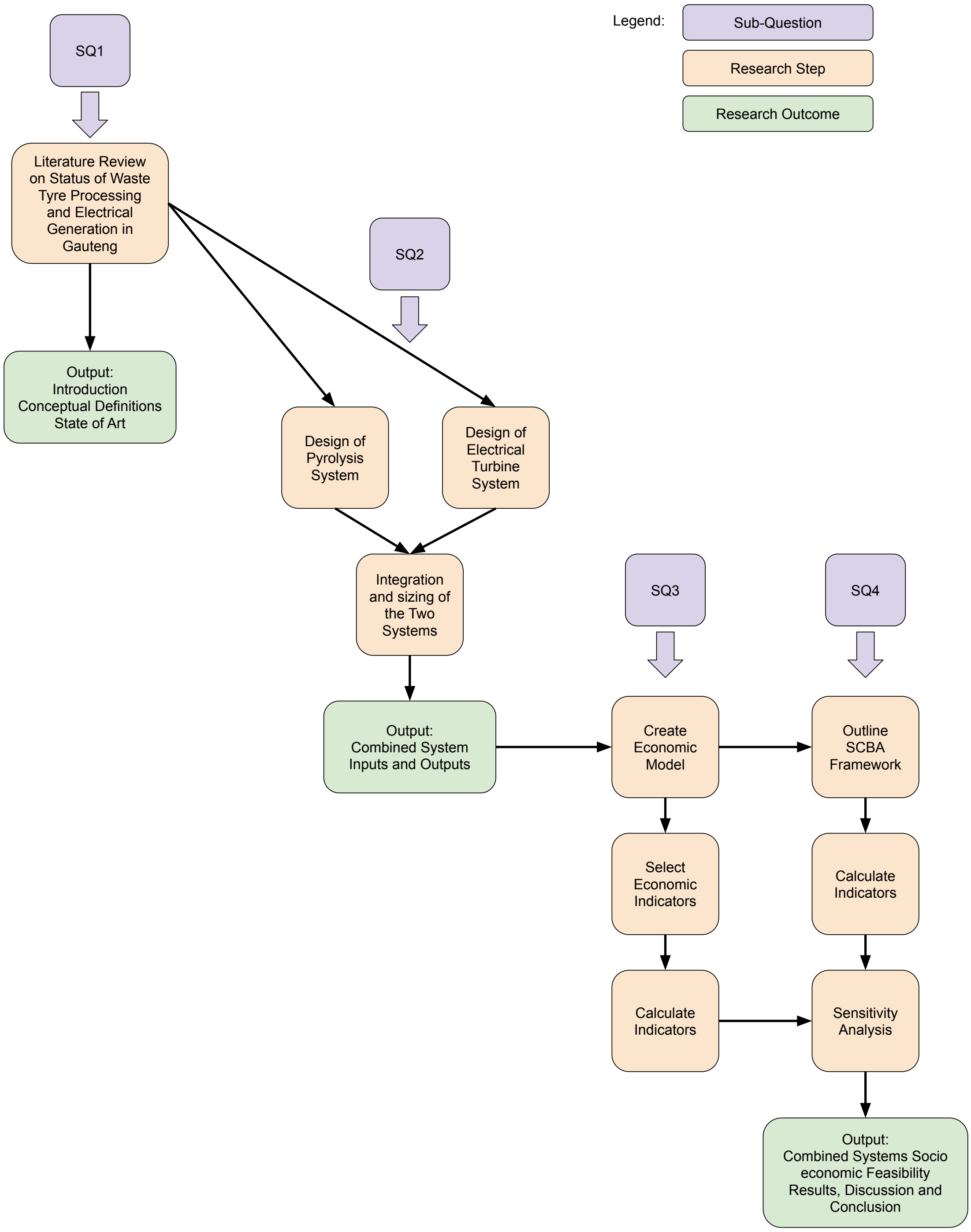

Figure 4.1: Methodology flow diagram of the steps taken in answering this study's research questions

4.2.1. Sub-Question 1

The first subquestion provides a clearer understanding of the current situation within Gauteng, South Africa, regarding the challenges of waste tyres and electrical imbalance. It outlines the scale of the problems, how South Africa has dealt with these challenges so far, and what solutions can be provided from current research.

Literature Review

The first step in answering the research question involved conducting literature review research on the current status quo and history of waste tyre processing and electrical generation within South Africa, followed by outlining the current and new research on waste tyre pyrolysis and waste-to-energy systems. The first part of this literature research focused on the collection of relevant historical data, updated government reports and numbers, relevant laws, regulations, and subsidies related to either waste tyre processors or independent electricity producers. This was conducted using keywords related to waste tyre recycling and pyrolysis in South Africa. An example of keywords used is Waste tyres recycling, South Africa pyrolysis, waste tyre management and a range of searches covering the electricity market in South Africa, specifically involving Electricity classification, Electricity market and South Africa Energy report. The second step covered the technological developments of waste tyre processing methods, in particular pyrolysis, waste-to-energy system studies and social cost-benefit analysis frameworks for large-scale energy systems. This step involved making use of the previous keyword searches in a more general sense and focusing on studies globally after 2010 where possible. From this keyword search, the snowball method was employed, using the citations of the studies found through keywords to expand the literature review covering a much broader geographical, technical, and time range.

The first part of this research step provided a broader understanding of the two sectors in South Africa, highlighting the scale of the challenges and the potential for these two sectors to be coupled through the implementation of this proposed solution. The second part of this research step created an understanding of the capabilities of the technology, the requirements for operation and the methods by which the system can be assessed for feasibility. This research then facilitated the remaining sections of the study, creating a basis for the scope and scale of the system, highlighting the most significant technological considerations and establishing a clear framework for the assessment.

4.2.2. Sub-Question 2

Sub-question 2 answers what an integrated system of waste tyre pyrolysis and power generation looks like, creating an overview of the processing steps involved, the inputs and outputs of each step, and the overall flows of the system. As part of this step, the system's size was determined based on regional factors such as supply, demand, and regulations, leading to further analysis steps.

Design of Pyrolysis System

The first step in the design process was the selection of the pyrolysis reactor, where an outline of the system's basic requirements was created before assessing the suitable options found throughout literature research that can meet these requirements for the system. Following this step, the working assumptions around the input materials and operational features, including heating methods and exhaust gas conditioning, were determined. A process flow diagram was created incorporating the design features representing the general scheme of the pyrolysis process while highlighting the inputs, outputs and exhausts.

The second step in the design of the pyrolysis system was the determination of the reactor's operating parameters, which in turn provided the assumed output yields for the system. Using a range of literature found previously, the most important operating parameters were determined before being selected based on the available feedstock and the intended end purpose of the system, leading to the assumed output yield levels used in the study. These assumed values were then compared to other waste tyre pyrolysis systems, ensuring that the values align with research and are reasonably attainable.

The final step in the pyrolysis system design was a validity check of the output products against the regulations for electricity production in South Africa. The expected qualities of the output products found throughout the literature for the chosen operating conditions were compared against the classifications of fuel sources in South Africa, outlining if there is a need for further processing steps to be included in the total system.

Design of Electrical Turbine System
Using the pyrolysis system's design, the electrical system's classification was chosen, accounting for the sector coupling limitations and the pyrolysis system's limitations. Once this classification had been determined, an analysis of South Africa's operational power plants was conducted, and the technology for the power plant was determined again, accounting for the pyrolysis system's limitations. A process flow diagram of the chosen technology was created again, including the input, output and exhaust streams. This process flow diagram, in combination with the pyrolysis systems diagram, was used to integrate the two systems.

Integration of the two systems
Following the design of the two independent systems, the systems had to be integrated, joining the two process flow diagrams into a single integrated process flow diagram. Within this, the combined processes were covered, including how each of the outputs would be linked between the pyrolysis system and the electrical system and how they would represent the total inputs and outputs. Following this linking, the sizing of the system had to be determined, utilising the power plant classification and the regulations in South Africa to determine the quantity of electrical output. These decisions, in turn, were used to calculate the size of the pyrolysis system, ensuring enough fuel would be processed to meet the demand for the power output.

Finally, the input and output flow for the masses and energies could be calculated for each independent system based on the assumptions about the pyrolysis yields, the fuel requirements of the electricity and the various utilities required for the process operations. The input and output flows were then further integrated together into a single system representation of mass balance. The information on mass and energy flows was then used in the subsequent sections for the economic and social cost-benefit analysis modelling.

4.2.3. Sub-Question 3

The third sub-question involved the quantification of the integrated system and, through the use of a range of indicators, outlined the economic benefits and feasibility of the integrated system.

Economic Model
Following the determination of the integrated systems input and output flows, these values were implemented into a representative model. The first step in the design of the model was to determine and designate the starting parameters, including the starting operational year, lifetime, operational time, inflation rates, tax rates and value of each of the required inputs and outputs.

With the outline of the model's parameters, the total operational expenditure could be calculated for each year through the required inputs and was then adjusted with inflation throughout the plant's lifetime; these costs include labour costs, material costs and carbon tax. The same step was then performed for the calculation of the revenues using the calculated outputs of the system, including the value of the sold electricity, waste tyre processing tariff and the sale of any internally unused outputs.

The final step in the design of the economic model was the calculation of the capital expenditure of the system. Initially, a list of each of the required major components for the full operation was created, and literature research was used to ensure a complete list. These components were then priced through further research of vendor sites and verified through the use of an equipment costing database from 2018, all of which were adjusted to the chosen starting year.

Selection of Economic Indicators

As the study focuses on South Africa as a case study, the economic indicators used to analyse the system had to be chosen based on standard practice within South Africa. As such, this step started with a further portion of literature research focused on best accounting and standard practices for financial analysis within South Africa, following which the chosen indicators were chosen and outlined, and the specific calculation methods were explained. The chosen indicators are *Payback Time*, *Net-Present Value* and *Levelised Cost of Electricity*. The equations used for each indicator are shown below.

$$PaybackTime = YearBeforePositiveCashFlow + \frac{RemainingInvestment}{FirstPositiveYear} \tag{4.1}$$

The payback time of the system is calculated through the summation of the system's cumulative cash flows against the total system cost. Following this summation, the exact point at which it breaks even is calculated from the ratio between the remaining investment and that specific year's cash flow.

$$NPV = \sum_{t=1}^{n} \frac{NCF}{(1+r)^t} - TotalFixedCost \tag{4.2}$$

The NPV is calculated by summing the total cash flows across the lifetime before adjusting this value with the time value of money; from this result, the total fixed cost is subtracted, resulting in the system's Net Present Value. In the equation, NCF represents the net cash flow for each respective year, *r* is the discount rate for the value of money, and t is the time of cash flow, in this case, the year the cash flow occurs and the total fixed costs are the total investment required to build the system at this given point in time.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX+OPEX}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{4.3}$$

LCOE represents the ratio of the NPV of the total costs of the system, including capital costs, operating costs, and any other relevant costs, and the NPV of the total system's lifetime generated electricity. The NPV of the system costs is calculated by summing the capital expenditure (CAPEX) and the operational expenditure (OPEX) to determine the total costs and adjusting these costs with the time value of money, while the NPV of the electricity is calculated by summing up the quantity of electricity produced (E_t) over the system's lifetime and adjusting this with the time value of money.

Calculation of the Economic Indicators

Following the selection of the relevant economic indicators, the data collected during the design of the model was input into the outlined equations. Which in turn yielded the economic model results that highlight the economic feasibility of the integration of these two systems.

4.2.4. Sub-Question 4

Sub-question 4 tackles the other aspect of the feasibility that is still to be determined: the societal feasibility. Within this section, the Social Cost Benefit Analysis framework that will be used to analyse the societal feasibility of the integrated system will be laid out. This will then be used to determine the net results on society across a range of factors and will compare this against the direct use of waste tyres for energy recovery.

Outline of SCBA Framework

The initial step in determining the societal feasibility was to create the framework with which to assess the system and, in comparison, the use of waste tyres directly as fuel. This framework was created using the standard cost-benefit analysis framework, which is then adjusted to be representative of a social cost-benefit analysis framework utilising the research obtained throughout the literature review.

This transition from a more traditional cost-benefit analysis framework to the SCBA framework was done through the incorporation of Social Welfare (ΔSW) into the Net Present Value equation used in the economic analysis. This change can be seen below in equation 4.4. For the case of differentiation between the economic and social analysis, the results from the SCBA will be labelled as the Social Net Present Value (SNPV).

$$SNPV = \sum \frac{1}{(1+r)^t} * \Delta SW \tag{4.4}$$

Here, the social welfare is calculated according to equation 4.5 below. Where V_t is the annual added value to Society and C_t is the annual cost to society.

$$\Delta SW = \sum V_t - \sum C_t \tag{4.5}$$

This method was adopted from Sidhu et al., 2018, where all transfer payments between agents in society are excluded as they are listed as having no net value generated. This method includes the time value of money within the calculation, allowing for the incorporation of system life cycle analysis along with the SCBA and accounting for the variable of inflation through the project.

The SCBA framework was then improved by incorporating parts from the study by Jamasb and Nepal, 2010 where the costs and benefits are distributed across private and external for each of the technologies against a base of coal. The main addition to the framework was through the differentiation of the agents. This distribution between private and external parties was adopted as it provided a positive outline in the case of this study, where the private costs and benefits have already been quantified and analysed throughout the economic model and economic feasibility section.

Making use of the aforementioned studies, the SCBA was conducted through a selection of the following factors. Each factor is labelled with a V_t or a C_t to represent if it is a benefit or a cost to society:

1. Electrical Grid Services (V_t)
2. Value of Lost Load of Electricity (V_t)
3. Greenhouse Gas Emissions (V_t and C_t)
4. Labour Creation (V_t)
5. Waste tyre Depots and Landfill Impacts (V_t)
6. Health Implications (V_t)
7. End of Life Decommissioning Costs (C_t)
8. Waste Tyre Processing Subsidies (C_t)

The explanations and relevance for each factor, including the monetisation of each, are discussed within the relevant Chapter. These factors were then organised in a table outlining how each waste tyre processing method affects society: cost or benefit or inapplicable.

Calculate Indicators
As with the economic calculations, following the SCBA framework's outline, the framework's indicators and results were calculated by inputting the data gathered during the literature review step and from the input and output flows of the designed system. These results were calculated for both the integrated system and the direct use of tyres as fuel before being input into equation 4.4, resulting in the net values to society. A further benefit to this framework is it includes the counterfactual opportunity cost of a project, such that the calculated SNPV can be used to guide decision-making and project investment.

4.2.5. Sensitivity Analysis

The final part of the determination of the socio-economic feasibility was conducted through a sensitivity analysis of the results. This analysis was done with varying scenarios that affect different aspects of the models, such as a variation in the cost of waste tyres or a variation in the value of electricity. These scenarios were done with a range of small changes based on potential system changes that may be brought about through the implementation of the sector coupling through the integrated system. These scenarios are further outlined later in the Chapter. This sensitivity analysis covered both the economic model and the SCBA framework and provided a level of insight into and identification of the inherent risks and critical factors that will influence the future outlook of the integrated system.

4.2.6. Socio-economic Feasibility Discussion and Conclusions

The results of the economic and societal analysis' determined through the design and balance of the integrated system have then been discussed and compared against using waste tyres directly as fuel, along with a section on alternative electricity generation systems. The potential implications of the integrated system and the benefits of coupling these sectors were also discussed within the context of the Gauteng region of South Africa. The limitations of this study, in particular with the design and analysis tools, have been highlighted, indicating areas for improvement. From the discussion of the results and the limitations of this study, areas for further research and studies were recommended, aiming to provide a basis for this further research. Finally, based on the completed research throughout this study, the four sub-questions have been independently answered, after which the main research question was addressed and answered in the conclusion. As a part of the conclusions, a list of recommendations was made to address the South African government and the Gauteng Provincial government on the socio-economic feasibility of the sector-coupled pyrolysis and power generation plant for tackling the waste tyre and electricity challenges.

5

Design and Integration of a Pyrolysis Powered Power Plant

Before any analysis of the economic or societal feasibility of the integrated system can be performed, the design of the individual systems and the integration needs to be outlined. This Chapter outlines the design of the waste tyre pyrolysis system, including the type of reactor, the overall process flow, the reaction temperature, and the process input and output flows. The same will be done for the electrical turbine system before the two independent systems are integrated, determining the final input and outputs that can be expected, allowing for the system to be economically modelled and for the social costs and benefits to be analysed.

5.1. System Boundaries

As established in Chapter 2, certain general assumptions can be made based on the chosen region of Gauteng that will affect the design of the system. These assumptions are:

- tyres will be delivered to the site pre-processed and at no extra cost outside of the cost of tyre;
- the government will assist in establishing and approving the use of outputs to produce electricity as an output market; and
- there will be a steady supply of waste tyres available throughout the system's lifetime.

The South African government has highlighted waste tyres as a significant challenge, with landfills being banned, depot sites at capacity and a growing waste stream. The government has issued objectives and created plans under the IndWTMP to tackle this challenge.

The first assumption that can be made in the design of the system comes from one of the most significant plans put in place to ”supply pre-processed waste tyres to waste tyre processors”. The government is actively working with depot sites to pre-process waste tyres through shredding or baling through either government-owned and operated equipment or by providing support to the depot sites to equip themselves. These pre-processed tyres are then made available to processors at no extra cost outside of the cost of the tyres themselves and, in some cases, provided for free (Department Of Forestry and Environment, 2022). With government activity, the assumption can be made that waste tyres will be provided to the gate of the system, which is already pre-processed and shredded to the 1-4mm size required for pyrolysis. This removes the necessity for an on-site pre-processing system, saving costs and eliminating the need for large storage space.

The second assumption comes from the government's objective of ”support for the development of markets for processed waste tyre products”. Due to this objective, it can be assumed that the approval of an integrated system, provided it meets the regulation standards, should face no barriers (Department Of Forestry and Environment, 2022). The approval of the integrated system that directly uses the pyrolysis outputs helps to solve the challenge of no suitable secondary market faced by commercial-scale pyrolysis systems that have been attempted in the past.

As part of the IndWTMP, the difficulties of supply are highlighted as a key requirement for any commercial system. Following this, the government has stated it wishes to ”increase surety of supply contracts to waste tyre processors to support investment in the sector”. This objective is already being achieved with the government working to provision binding supply contracts to waste tyre processors for 7-10 year periods (Department Of Forestry and Environment, 2022). Under this plan, the government guarantees the supply of waste tyres to the system, reducing the risk and uncertainty behind fluctuating prices, pre-processed quality and lack of availability.

5.2. Design of Pyrolysis System

Given the goal of generating electricity through the combustion of pyrolytic char and oil, a significant amount of fuel will be required to ensure that the electrical system can operate at maximum capacity. As such, to maximise fuel production and ensure a sufficient daily fuel supply for the thermal power system, the pyrolysis system will need to operate continuously. Two types of pyrolysis reactors have been shown to work continuously at large scale: the rotary kiln reactor and the conical spouted bed reactor (Lopez et al., 2017; Khan et al., 2023). There is a third reactor option, the auger reactor; however, this reactor has not been proven successful in large-scale operations (Gao et al., 2022).

The rotary kiln reactor serves as the best option for large-scale waste tyre pyrolysis due to the broader adaptability of the system to feedstock sizes from 0.3-4cm, which reduces the quality control requirements for shredded tyres delivered from depot sites (Gao et al., 2022). Additionally, the rotary kiln reactor facilitates continuous removal of the char, oil and gas without the need for constant system startup and shutdown procedures, meaning the temperature can be kept more stable inside the reactor, reducing the variation in the quality of the output products. One of the main disadvantages of using this reactor is the potential for heat differentials across the reactor due to the rotating shape and angle. This disadvantage can be remedied by applying heat indirectly through the walls of the reactor, ensuring a stable heat range inside the reactor (Abdallah et al., 2020).

The system does not require a pre-processing setup as it is assumed all waste tyres will be delivered shredded and ready for processing. Following delivery of the waste tyres, they will be added to a hopper system that facilitates the input of waste tyres into the pyrolysis reactor. As shown in Figure 5.1, the output products can be removed from the other end of the reactor. From there, the char and steel wires are filtered out, where they can be separated and stored for cooling. The other outputs consist of volatiles and flue gases sent through a water scrubbing unit where the oil and gas fractions are separated. The gases from the condenser are then recycled via a boiler, producing the heat necessary for the reaction. Approximately 90% of the pyrolysis gas is required to maintain the temperature around 550°C as shown in Abdallah et al., 2020. The reactor is housed in an insulating cover where the heat from the boiler is funnelled into the space between the reactor and the cover, creating even heating across the entire reactor. The oil is pulled out of the water scrubber and subsequently stored in a storage tank. The exhaust gases from the boiler are passed through a desulfurization and dust removal unit before being cooled in a cooling tower to 560°C maximum temperature before being exhausted into the atmosphere. A depiction of the process flows and layout can be seen below in Figure 5.2.

The general characteristics of the system are outlined as a continuous rotary kiln reactor that uses shredded waste tyres 0.3-4cm in size as feedstock and an external heating chamber, with heat provided from the combustion of the pyrolysis gas produced in the reaction. Therefore from this point on the feedstock will be assumed to be within this range, the yields will follow from the chosen reactor and the heating of the system will be maintained with the optimal range, this range will be determined later.

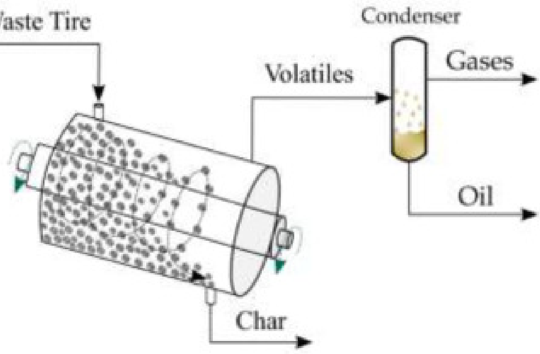

Figure 5.1: Diagram showing the setup of a rotary kiln pyrolysis reactor. Image retrieved from Gao et al., 2022

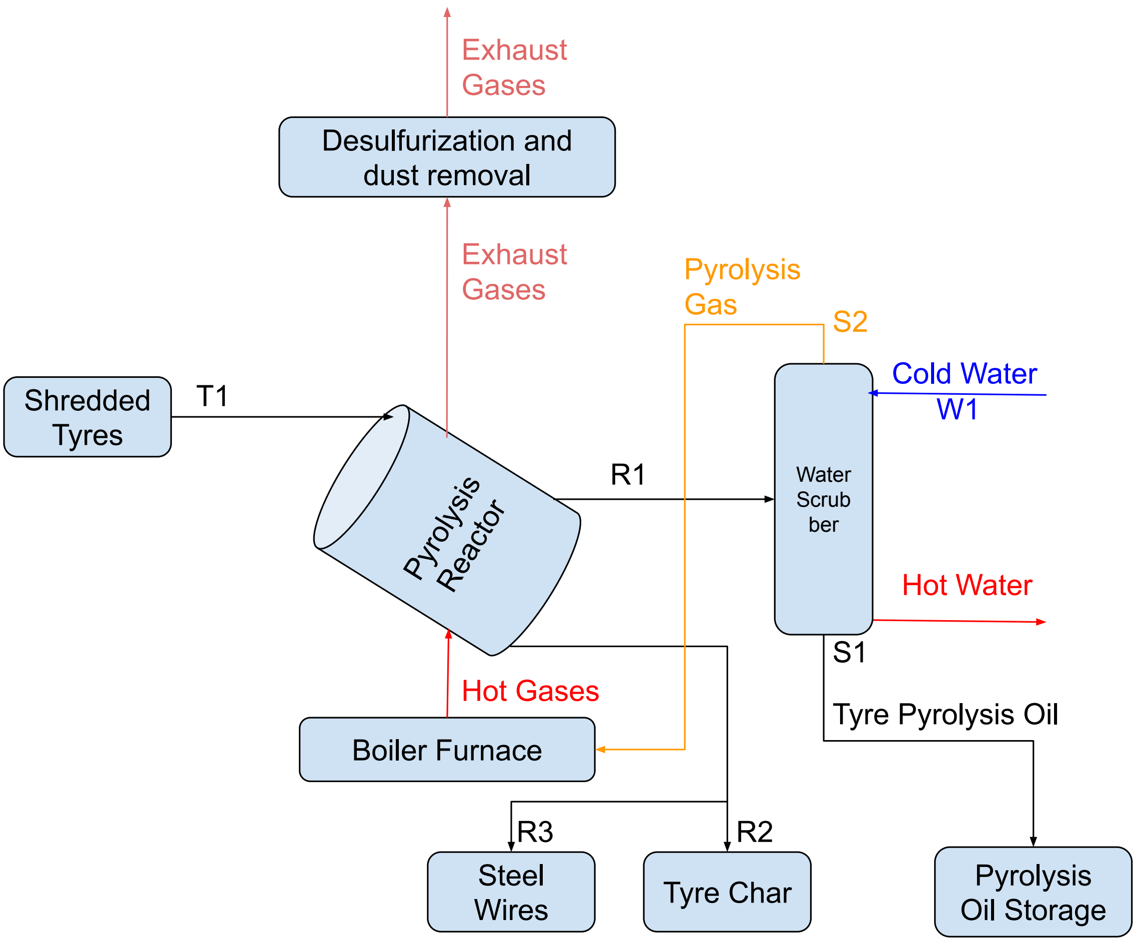

Figure 5.2: Process flow diagram for the Pyrolysis system

5.2.1. Operating Parameters and Yields

As shown in the literature review, the pyrolysis reaction temperature has the greatest impact on the output quantities, with lower temperatures favouring higher yields of char and oil. Mui et al., 2010 and Gao et al., 2022 have shown that an operating temperature of 400-500°C at ambient pressure inside a nitrogen atmosphere can yield char up to 50%, oils up to 50% and gases up to 10% with fluctuations in these values based on the residence time, waste tyre composition and heating rate. In addition, Abdallah et al., 2020 have shown how a rotary system running at 500°C yields 10% gas, sufficient for self-heating of the system, around 10% steel dependent on the tyre qualities, 45% oil, and 35% char. Additionally, these outputs are in line with the operational Pretoria plant, with slight variations due to the chosen use of continuous rotary kiln over batch processing (SLATER, 2015). Further studies by Williams et al., 1993, Kar, 2011, Doğan-Sağlamtimur et al., 2019 and Nhlanhla and Edison, 2014 all support that these outputs are viable at these operating conditions and are scalable over increasing system sizes.

The studies used to design and determine the operating parameters of the pyrolysis system have been chosen based on their similarity and relevance to the total system goal, showing how it is possible to tailor the system using temperature, reactor type and other parameters to yield the exact ratios and output product qualities suited for their intended purpose. In particular, the study by Gao et al., 2022 has been used as it highlights the variations in the outputs of not only the pyrolysis char but the oils as well across every type of reactor, a range of operating temperatures, the use of catalysts, feedstock sizes and multiple other parameters collecting data and information summarising from a large range of studies around waste tyre pyrolysis. In addition, the studies by Khan et al., 2023, Abdallah et al., 2020 and Nkosi et al., 2020 have been used because they show a much larger scale continuous waste tyre pyrolysis system that also includes electrical production, a waste tyre pyrolysis system of the same scale in similar operating conditions and waste tyre pyrolysis specifically for tyres from South Africa in similar operating conditions respectively.

As supported by the aforementioned research, it will be assumed that the process outputs will be averaged at:

- 45% Pyrolytic Oil
- 35% Pyrolytic Char
- 10% Gases
- 10% Steel Wire

All yields are with respect to the input weight of waste tyres.

5.2.2. Output Product Qualities

Pyrolysis Char

One of the main challenges with waste tyre pyrolysis is the quality of the output products, which often require further treatment to be commercially viable. With the intention of utilising the oil and char for power production, these products must meet the standards for ash, volatile matter and pollutants outlined by the South African government. ESKOM operates over 15 coal-fired thermal plants across the country and has strict regulations regarding the quality and type of fuel each system requires. In general, ESKOM follows a set of standards for grading the coal they use for electricity production. As such, the coal quality rejection rates are compared to the quality of the char obtained during pyrolysis to determine if further treatment of the char is required before it can be used for power production. Figure 5.3 shows ESKOM's standard, while Table 5.1 shows the typical quality of the pyrolytic char that can be expected from waste tyres in South Africa. These figures are all within the ranges specified for a rotary kiln reactor, as shown in Gao et al., 2022.

Parameter	Units	Pyrolytic Char
Calorific Value	MJ/kg	31
Moisture Content	Maximum %	1.3
Ash	Maximum %	14.5
Volatile Matter	Minimum %	24.3
Sulphur	Maximum %	2.61

Table 5.1: Pyrolytic Char qualities from the operational plant in Pretoria, Gauteng, based upon standard waste tyres across South Africa. Data is obtained from Nkosi et al., 2020

Table VI

Domestic coal specifications

Parameter	Units	A grade	B grade	C grade	D grade
Calorific value	MJ /kg ad	>27.5	>26.5	>25.5	>24.5
Total moisture	Maximum % (AR)	12.0	12.0	8.0	8.0
Ash	Maximum % (AR)	15.0	16.0	18.0	21.0
Volatile matter	Minimum % (AR)	24.0	23.0	23.0	23.0
Sulphur	Maximum % (AR)	1.0	1.0	1.0	1.5

Figure 5.3: ESKOM's coal specification and rejection ranges for use in thermal power stations. Image is taken from Steyn and Minnitt†, 2010

The pyrolytic char obtained from waste tyres is of excellent quality for the desired domestic specifications in all aspects except for the sulphur content, which is above the desired level of 1% and over the absolute rejection level of 2%. The elevated sulphur level requires the char to undergo steam activation to reduce the sulphur levels to below the rejection level as shown in López et al., 2009 where pyrolytic char from waste tyres had the sulphur level reduced below 1.26% well within the rejection range after treatment at 850°C. Alternatively, when combusting the char, the exhaust gases will need to pass through a desulfurization unit, bringing the emissions within regulations. An added benefit to the quality of the char is that it is significantly above the most common type of coal found in South Africa, lignite coal, and this includes the sulphur level, incentivising the use of the char as a coal replacement. The lignite coal across South Africa has to be mixed with other coal qualities to achieve the standards highlighted in Figure 5.3 (Falcont and Ham, 1988).

Pyrolysis Oil

The pyrolytic oil obtained during the pyrolysis of waste tyres falls into the category of heavy fuel oils or bunker oils Martínez et al., 2013. These oils can be burnt in thermal power stations along with coal to generate the necessary heat for steam generation Williams et al., 1998. Across South Africa, ESKOM often uses fuel oils as a backup fuel for baseload power plants and, for some peaking plants, uses diesel, kerosene and natural gas as fuel directly ("The Many Uses of HFO", 2019; ESKOM, 2021b). The characteristics of the pyrolytic oils from waste tyres can be seen in Table 5.2 below.

Parameter	Units	Pyrolytic Oil
Calorific Value	MJ/kg	42.46
Moisture Content	Maximum %	0.66
Ash	Maximum %	0.13
Volatile Matter	Minimum %	24.3
Sulphur	Maximum %	1.1
Flash Point	°C %	31.5

Table 5.2: Pyrolytic Oil qualities from waste tyres taken from Abdallah et al., 2020 and cross-referenced with Gao et al., 2022 and Martínez et al., 2013

Pyrolytic oil falls into the category of high-sulphur fuel oils under South African regulations. However, the pyrolytic oil is significantly below the cut-off of 3% and closer to the grade of low sulphur fuel oil at 0.5%, making it an attractive middle-ground fuel oil acceptable for combustion to produce electricity. One of the main challenges with tyre pyrolysis oil is the lower flash point around 32°C, which makes it more challenging to store for longer periods. The flash point can be increased through the addition of water by hydro-refining the oil, bringing the flash point up to the standard 66°C and bringing the viscosity in line with Diesel (SA OIL, n.d.).

Pyrolysis Gas
The pyrolysis gas resembles natural gas with a high calorific value and primary composition of Hydrogen and Methane. The full list of constituents for the pyrolysis gas obtained from a 450°C reaction can be seen below in Table 5.3. This gas is ideal for self-heating the pyrolysis reaction due to its very high calorific value of around 47.5 MJ/m^3 as shown in Abdallah et al., 2020 where 90% of the gas is sufficient for self-heating at 550°C.

The remaining 10% of the gas will be stored for use in the electrical system startup procedures and the pyrolysis reaction startup procedures.

Compound	% Volume
Methane	24
Ethane+Ethylene	26
Propylene	9
Butadiene	2.7
Remaining C4	1.6
C5	2
C6	0.2
CO	1.1
CO_2	1.9
H_2	30

Table 5.3: Gas constituents for waste tyre pyrolysis performed at 450°C, data retrieved from Díez et al., 2004 and cross-referenced with Martínez et al., 2013 and Nkosi et al., 2020

5.2.3. Design Summary

The following table summarises the design parameter choices, including the chosen type of reactor, heating source and output material yields for the pyrolysis system.

Unit/Stream	Data	Reference
Pyrolysis Reactor	Rotary Kiln Reactor	Gao et al., 2022
T1	0.3-4cm Shredded Tyres	Gao et al., 2022
R1	Mixed Oil and Gases	Gao et al., 2022
R2	Pyrolysis Char **35%** of Input weight	Mui et al., 2010
R3	Steel Wire **10%** of Input Weight	Nkosi et al., 2020
S1	Pyrolysis Oil **45%** of Input Weight	Martínez et al., 2013
S2	Pyrolysis Gas **10%** of Input Weight	Abdallah et al., 2020
W1	Input of Water for Oil&Gas Scrubber	Nkosi et al., 2020

Table 5.4: Summary of the different design parameter choices for the pyrolysis system

5.3. Design of the Thermal Power Plant

As seen in the literature review, pyrolysis products have a wide range of different applications; however, their use in a thermal power plant presents a unique opportunity for South Africa to solve two of its major hurdles towards economic and societal development in the future. Thermal power plants make up the large majority of South Africa's electricity production, with coal being the primary fuel source of these systems. As such, there is a large base of expertise within the country and clear examples of the requirements for a fully operational thermal power plant. As with any thermal system, the fuel, in this case the carbon char and the tyre pyrolysis oil, are combusted in boilers, furnaces or combustion chambers to generate heat. This heat is then used to create high-pressure steam or superheat air, which is then passed through turbines, which in turn rotate generators that produce electricity.

Due to the limitations of total fuel production from the pyrolysis process and the intention to utilise liquid, gas and solid fuels, it makes sense to designate the thermal system as a peaking plant rather than a base load plant. This designation will help to keep the total scale of the system within reason. This decision is further supported by South Africa's operation of peaking plants that use diesel, kerosene and natural gas as primary fuel sources and can operate with solid fuel dust (ESKOM, 2021a). The 'Ankerlig And Gourkiwa Gas Turbine Power Stations' are open-cycle gas turbines (OCGT) with a combined power of 1138 MW, each turbine providing 148 MW capacity. The turbines and generators have an efficiency of approximately 34-36%. The plants are expected to run 5 hours per day during the peak periods; however, they are operationally capable of 8 hours per day at max capacity, utilising 40 tons of liquid fuel per hour per turbine (ESKOM, 2021b). Additionally, these systems utilise around 19kg of natural gas for the start-up procedure of each unit. Both of these turbine plants are remotely operated with an automated startup procedure, significantly reducing the operating costs of the system. The OCGTs used in the Ankerlig and Gourikwa stations are independently housed units, each 75m x 25m. These units comply with the minimum emission standards and are significantly more environmentally friendly than the operational coal plants (ESKOM, 2021b).

A disadvantage of these electrical plants is a self-consumption electricity requirement during full operation of 30%, mainly used for the compressor system, with part of the electricity requirement being used for auxiliary systems, reducing the gross electricity output of the system (ESKOM, 2021a).

One of the advantages of placing the system in the province of Gauteng is the built-up infrastructure and the high concentration of peak demand, which places it in the ideal location to operate as a grid-balancing plant. The built-up infrastructure removes the need for on-site high-voltage transformers to be built into the system and reduces transmission distance, thereby increasing total system efficiency. An example of an electricity generation plant built in the Gauteng province is shown by the older 'Rooiwal power station' located in Pretoria, Gauteng, which doesn't have a transformer substation, instead making use of nearby facilities and connects directly to the local distribution grid which has the further added benefit of reducing electrical transmission fees ("Rooiwal power station", 2024). Figure 5.4 shows the process flow diagram of an open cycle turbine based on the Ankerlig and Gourkiwa units.

A further benefit to using a turbine-based system is that the working fluid is compressed air, significantly reducing the total water requirements for the system in a water-starved area. The total water requirement for the electrical generation system for these 147MW units is 80-100 litres used for flushing the systems after use (ESKOM, 2021a).

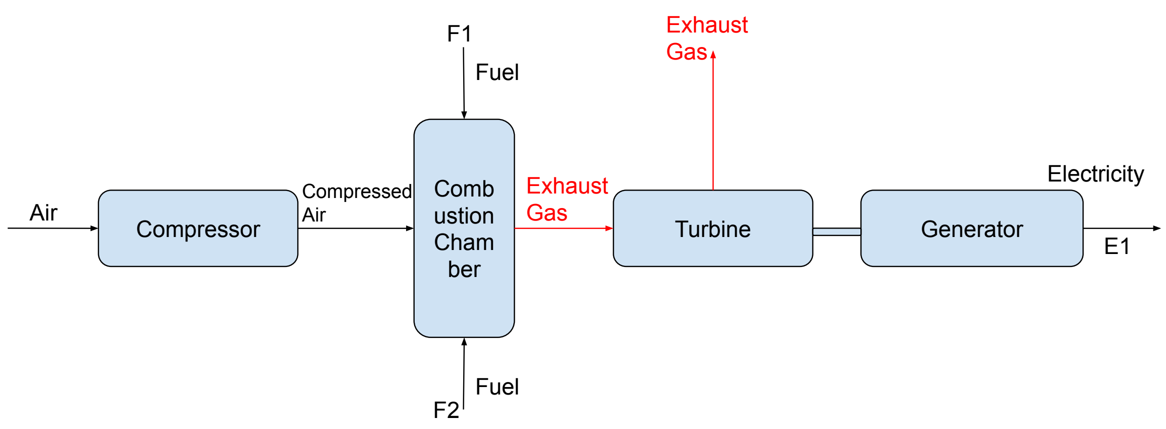

Figure 5.4: Process flow diagram of an open-cycle gas turbine

5.4. Final Integrated Design

The design of a theoretical integrated system is a relatively straightforward process as it only entails the coupling of already available systems through their inputs and outputs. In reality, this process would not be so straightforward for a multitude of reasons, namely temperature balances across the system, operating pressure differentials and mass balance matching. The temperature balances will need to be regulated from the outputs of the pyrolysis system before they can be stored safely; this will also apply to the exhausts of the integrated system, with both the hot gases from the pyrolysis heating step and the combustion in the turbine being routed through the same cooling tower. The integrated system will have multiple stages of processes and storage. As such, the connections between each step will need to be maintained, including the levels of pressure as the system moves from the hot reactor and combustion chambers to the storage tanks or cooling towers. Finally, while the fuel created from the pyrolysis system can be stored on-site and pumped or piped to the combustion chamber during peak electrical demand hours, there will be periods of maintenance or rapid startup procedures where sufficient storage of fuel will be required on-site at all times to ensure these can take place smoothly without the use of outside fuel sources.

As established in Chapter 5.2, the system will be designated as a peaking plant, given the limited capacity for fuel production from the pyrolysis reaction. This designation is further supported by the pyrolysis system yielding the largest quantity of tyre pyrolysis oil with similar properties to fuel used in other peaking plants across South Africa.

Due to the requirement to use oil, gas and carbon char as fuel, the combustion chamber will be moved to an external position using a heat exchanger to heat the compressed air that passes through the combustion chamber on the way to the turbine. This system can reach efficiencies of up to 31% using blast furnace oil and coal while significantly reducing the maintenance costs and risks of solid fuel use (Al-attab and Zainal, 2015). Despite the use of an external combustion chamber, the operating parameters, fuel flow rates, and system size are all in line with those of the Ankerlig and Gourikwa stations. The total integrated process flow diagram can be seen below in Figure 5.5.

The flue gases from the combustion of the pyro-gas for heating the pyrolysis reactor are passed through the combustion chamber to provide additional heating and create a single exit pathway from the system for the exhaust gases for cleaning.

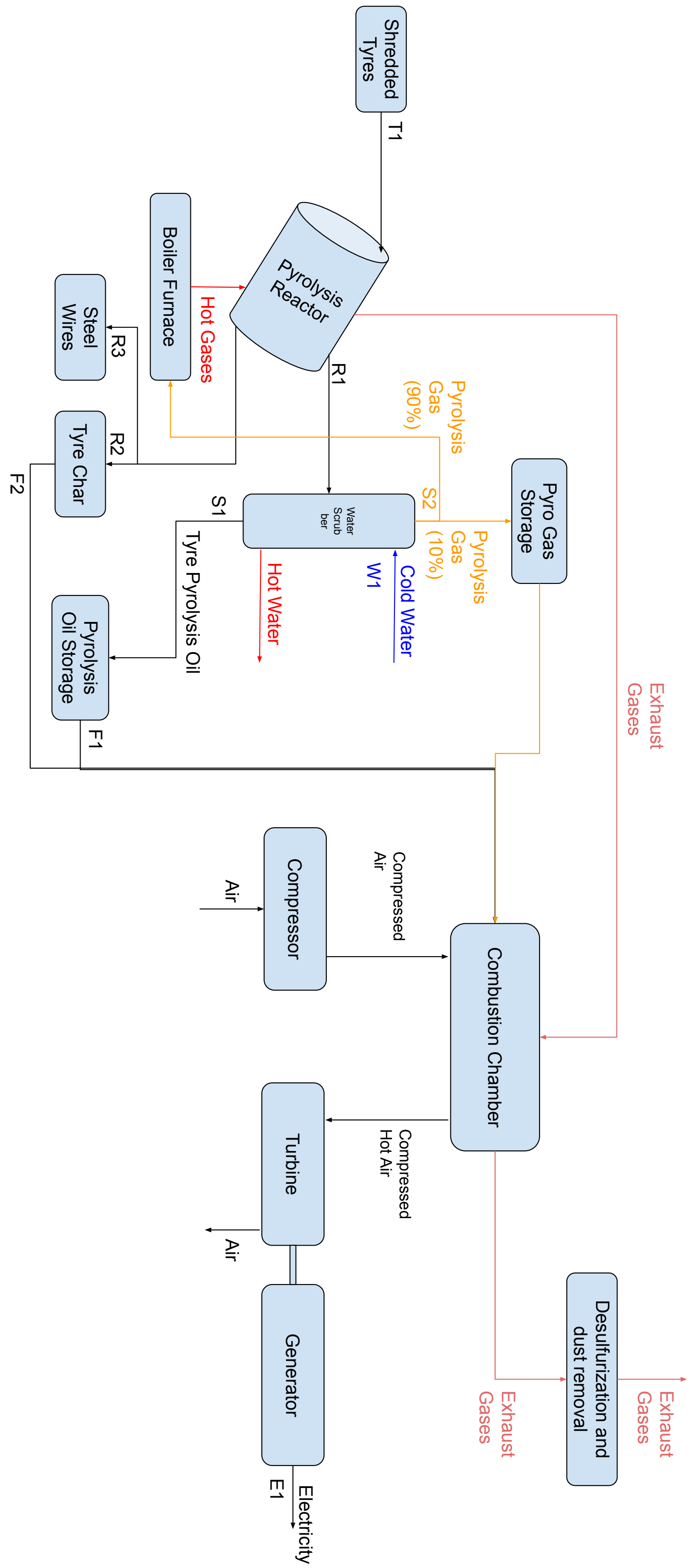

Figure 5.5: Process flow diagram of the integrated pyrolysis and turbine system

5.4.1. System Sizing

One of the main challenges with the design of the integrated system is system sizing and scale. Both the pyrolysis plant and the electrical plant can be scaled to nearly any size; however, they need to be matched together so that the fuel created during pyrolysis provides sufficient fuel for the 5-hour window of peaking power production. As such, the size of the electrical turbine has the greatest impact on the system size, and the pyrolysis system can be tailored to meet the required fuel demand. For this study, the electrical system will be scaled to 50 MWe as this is the smallest generator used in South Africa for peak power generation (ESKOM, n.d.). A further incentive to keep the system to this size is the application for the independent power producer role in South Africa's electricity system, where systems up to 100 MW are not required to obtain a license from the National Energy Regulator South Africa (NERSA) provided all generation and transmission requirements are met ("Independent Power Producers (IPP) and Generators", 2021). Saving the system from having to pay the registration fee each year, which is structured as a per kWh fee.

Following the designation and electrical output sizing, the system's other parameters can be sized using the Ankerlig and Gourikwa units. These units are 147 MW in capacity, consuming 40 tonnes per hour of diesel at base load capacity and fit in a closed system of 75m x 25m. Given that the turbine capacity will be 1/3 of these units, the fuel consumption, water consumption and start-up fuel will be reduced by 1-one-third as well. This scaling is further supported by the values aligning with the scale and fuel consumption of the 57 MW units in the Port Rex plant (ESKOM, n.d.). This gives a 50 MW system that consumes 13.3 tonnes of diesel per hour of operation, 27-33 litres of water per operational cycle for flushing, and 6 kg of gas for startup operation and takes up 49m x 12m of land area.

The plant is intended to run as a peaking system, fulfilling the peak electricity demand hours of 6:00 - 8:00 and 17:00 - 20:00. The system is assumed to operate at full capacity with an expected operating time of 5 hours daily, generating a total diesel demand of 66.67 tonnes. This fuel consumption is based on diesel, with an average calorific value of 45.5 MJ/kg. Therefore, the total energy requirement is 3,033,485 MJs for 5 hours of operation. The pyrolysis plant yields both pyrolytic char and pyrolysis oil that will be used for the energy source with a weighted average calorific value of 37.44625 MJ/kg based on the yield percentage of the oil and char from the pyrolysis process. Due to the lower average calorific value of the fuel, 81.1 tonnes of pyrolysis fuel will be required for 5 hours a day of operation; the gas has been excluded in this case for daily operation as 90% is used for self-sustaining the pyrolysis system while the remaining 10% is kept for start-up procedures of the system. With 81.1 tonnes of fuel required, the pyrolysis system must process 101.375 tonnes of waste tyres daily to provide sufficient fuel or around 37,002 tonnes for the year. With an estimated operational time per year of 8000 hours, taking into account industry standard times for maintenance, this equates to 4.625 tonnes of waste tyres per operational hour to be processed. This size of the pyrolysis system, while being larger than the currently operational Pretoria plant, is well within the feasible scale as shown by Khan et al., 2023, Riedewald and Sousa-Gallagher, 2016 and multiple other real-world examples such as BTG's Hengelo plant in the Netherlands.

A total land area of 5500m^2 has been designated for the integrated system, with the pyrolysis plant and electrical system making up 4628m^2. The remaining space is used for the storage of the outputs during the periods the electrical system is not running. The remaining land area is sufficient to house enough fuel to feed the turbine for 7 days while the pyrolysis plant undergoes maintenance.

5.4.2. Integrated System Inputs, Outputs and Mass balance

Waste tyre pyrolysis is an endothermic process that requires a constant source of heat. The system uses the yielded gas to provide this heat. Waste tyres have an enthalpy requirement of 1168 kJ/kg, which, when accounting for efficiencies of 90% for the burner and 80% for the heat exchange between the hot gases and the pyrolysis chamber for the proposed system, equates to 7495 MJ of total energy per hour of operation (Khan et al., 2023). The system yields around 462 kg of gas per hour of operation; 90% of this gas has a total energy value of 23,824 MJ at 1 atmosphere of pressure and 15°C showing that this gas is more than sufficient for the heating requirements of the pyrolysis reaction. The remaining 10% gas is used in the start-up procedure of the electrical turbine. Table 5.5 shows the energy balance of the system with the gas self-powering the pyrolysis process.

Energy Required for Pyrolysis of Waste Tyres	-7495 MJ	Khan et al., 2023
Energy Available from Pyro-Gas	23,824 MJ	Abdallah et al., 2020
Net Energy Balance	16,329 MJ	

Table 5.5: Energy balance showing the energy required for the pyrolysis of waste tyres and the energy provided from the pyrolytic gas.

Table 5.6 shows the pyrolysis system inputs and outputs, Table 5.7 shows the electrical system and Table 5.8 shows the integrated system. These values are calculated based on one year of operation.

Pyrolysis System Inputs	Quantity	Sources
Waste Tyres	37,002 tonnes	
Water	152,676 litres	Nkosi et al., 2020
Electricity	160 MWh	Khan et al., 2023
Nitrogen	68,965 litres	Gao et al., 2022
Pyrolysis System Outputs	Quantity	Sources
Pyrolysis Oil	16650.8 tonnes	
Pyrolysis Char	12950.7 tonnes	
Pyrolysis Gas	370 tonnes	
Steel Wires	3,700 tonnes	

Table 5.6: Pyrolysis system inputs and outputs based on a 4.625 tonne per hour system

Electrical System Inputs	Quantity	Sources
Oil	16,650.8 tonnes	
Char	12,950.7 tonnes	
Gas	4.380 tonnes	
Electricity	27,375 MWh	ESKOM, 2021a
Water	21,900 litres	ESKOM, 2021a
Electrical System Outputs	Quantity	Sources
Electricity	91,250 MWh	ESKOM, 2021b
Gross Electricity	63,875 MWh	ESKOM, 2021b

Table 5.7: Electrical system inputs and outputs based on a 50 MW system

Integrated System Inputs	Quantity	Sources
Waste Tyres	37,002 tonnes	
Nitrogen	68,965 litres	Gao et al., 2022
Water	174,576 litres	Nkosi et al., 2020;ESKOM, 2021b
Integrated System Outputs	Quantity	Sources
Gross Electricity	63,715 MWh	ESKOM, 2021a
Pyrolysis Gas	369.582 tonnes	
Steel Wire	3,702 tonnes	
Carbon Dioxide	123,145 tonnes	ESKOM, 2021b

Table 5.8: Integrated system inputs and outputs

It is estimated that the pyrolysis system consumes around 20kw of electricity per hour of operation for the pumping, piping and rotation of the kiln; this equates to 160 MWh per year Khan et al., 2023. While the electrical turbine has a self-consumption of roughly 30%, equating to 27,375 MW per year of electricity (ESKOM, 2021a). Accounting for the self-consumption and operational consumption, the integrated system is estimated to yield a gross electricity production of 63,715 MW per year, assuming the system runs for 5 hours per day during the peak demand periods.

The water consumption of the system is predominantly used for the water scrubbing of the flue gases from the pyrolysis, flushing of the electrical turbine systems, and cooling of the systems. The total water demand amounts to 174,576 litres of water per year based on comparable-size pyrolysis plants and the water usage of comparable gas turbines (Nkosi et al., 2020; ESKOM, 2021a). Gauteng is a water-stressed area with a high usage of water per capita due to the dense concentration of industry; as such, the system needs to operate within the regulated water consumption limits. For Industry in Gauteng, the average water consumption per year is 547,500 litres per year based on 1500 litres per day; therefore, this proposed integrated system is significantly below the industry average, providing a solution to waste tyre management without further increasing the water stress of the region (Zyl et al., 2010).

As the system is combusting a large quantity of carbon-based fuels to produce electricity, a carbon tax will be levied by the government each year to offset the emissions from the electrical generation. The carbon dioxide emission for the system is calculated from the carbon intensity of the Ankerlig power plant, where the yearly carbon emissions are converted to a per MWh basis before being adjusted to the scale of this system. To make the carbon dioxide emissions more accurate the total emissions are adjusted by the ratio of the HHV from Diesel to the Pyrolysis oil and char giving an expected yearly carbon dioxide emissions of 123,145 tonnes.

5.5. Assumptions about system design

Table 5.8 shows the major assumptions taken into account in the design, sizing, and mass balances of the integrated pyrolysis power plant system. For each of these major assumptions, the assumption and the potential effects are presented and discussed. Not all of the assumptions made in the design and integration of the integrated system are included in the table, as many of them are unlikely to have significant effects on the final outcomes. Whereas the assumptions presented below would require additional systems to be included in the final design and representative theoretical model.

Table 5.9: Table of all assumptions made in the design of the integrated system

Assumption	**Assumption Effect**
Tyres will be delivered to the site pre-processed and at no extra cost outside of the cost of the tyre.	Pre-processing facilities and capacity are not required, simplifying the overall system.
Assistance from the government is needed to establish and approve the use of outputs to produce electricity as an output market.	No direct effect on the design of the system, but creates the opening in regulation to create an integrated system.
A steady supply of waste tyres is available throughout the system's lifetime.	No direct effect on the design of the system, but it allows for the system scale to be freely adjusted based on other parameters without concerns for feedstock supply.
All power generated will be consumed throughout the system's lifetime.	Reduce the storage capacity requirements as the electrical generation system will run at full capacity each day to meet the electrical demand.
90% of the generated gas is sufficient for heating the pyrolysis reaction.	Significantly reduces the operating costs of the pyrolysis system as it becomes self-sufficient, keeping the continuous reaction going.
The reactor operating temperature remains in the ideal range chosen temperature range	The most significant factor affecting the output yields of the pyrolysis step is the reaction temperature. With a stable temperature, the yields are fixed to a set ratio for the system.
Fuel qualities are suitable for electrical generation.	The output products from the pyrolysis reactor require minimal refining or further processing to be used in the combustion chamber for electrical generation.
The operating hours of the pyrolysis system are 8000 hours over a year. The electrical system can operate 365 days a year at full capacity due to long periods between operations for system maintenance.	Used to determine the amount of fuel required for the year for electrical generation and, in turn, used for the sizing of the pyrolysis system to meet this fuel requirement based on the operating hours.
Exhaust systems from the example turbine systems meet all the regulations for emissions.	Removes the need to model the exhaust systems for the integrated system, as the system is expected to be within the allowed ranges.

6

Economic Model and Analysis

Following the design of the integrated system and the determination of the total flows that can be expected, the system can be financially modelled. This Chapter outlines the steps taken to create the financial model, the assumptions for each step, and the overall results of the financial model. The results are analysed to determine the economic feasibility of the integrated system and what the financial benefits of this system will be.

6.1. Design of the Economic Model

6.1.1. Project Scope

The financial model is based on a set of key parameters, which can be seen in Table 6.1. The plant's proposed lifetime is 20 years, starting in 2022. The starting year of 2022 has been chosen as it is the year that the Renewable Energy Independent Power Producer Procurement Programme was restarted at total capacity. Following the programme being stopped from 2015-2019 by ESKOM and Government officials looking to delay the integration of new power producers, the world entered COVID-19 caused the programme to be delayed further (Evans and Ngcuka, 2023). With the programme back at full capacity, new generators are being supported and allowed to register to enter the electricity market, bringing new generation capacity to the country. The plant has been sized in the previous Chapter with an annual capacity of 37,002 tonnes of waste tyres and a 50MW generator with a total yearly electricity production capacity of 63875 MWh after self-consumption; these are based on 8000 and 1825 hours of operation, respectively.

The inflation rates are chosen based on the South African government's tracked, expected, and targeted inflation rates over 2022-2024. While the national consumer price index has been used for the inflation rate, a differentiation is needed with the electricity inflation rate. This is due to the large disparity between the two values. The inflation rate of electricity in South Africa has totalled 367% after the standard inflation rate since 2007, averaging between 9-20% per year; the chosen inflation rate for electricity is on the lower end of this average at 12.72% which is the average electricity inflation rate from 2022 to 2024. This inflation rate has been used each year after 2024 as the rate is expected to remain elevated or further increase into the foreseeable future, evidenced by the 2024 rate being over 18%. By using a lower level of electricity inflation, the system's results will not be dominated by the increasing value of the electricity. The values of each input product have been determined for the year 2022, verified with 2023 and 2024 before being adjusted with the inflation rate for each year after 2024.

A separate table, Table 6.2, is shown for the pricing of the electricity system components, as the South African electricity market has multiple components and pricing structures depending on the user's role and status within the market. The proposed integrated system will fall under the Megaflex-GEN position within the South African market, with the tariffs depending on the highest total tariff for the generation side or the load side. In this case, the system is a net exporter of power by a large margin. This margin

Parameters	Value	Reference
Starting Year	2022	Evans and Ngcuka, 2023
Plant Size (Pyrolysis) (ton/hr)	4.625	
Plant Size (Electricity) (MW)	50	ESKOM, n.d.
Plant Life (yrs)	20	
Pyrolysis Operating Hours	8000	
Power Plant Operating Hours	1825	ESKOM, 2021b
Number of Operators	49	Turton, 2012
Monthly Salary of Operators in 2022 (ZAR)	49,052.50	Department of Statistics, South Africa, 2023
Electricity Price Inflation	12.72%	Codera Analytics, 2024
Electricity Tariffs Inflation	12.74%	Codera Analytics, 2024
Electricity Affordability Subsidy Inflation	25.24%	Codera Analytics, 2024
General Inflation	4%	Department of Statistics South Africa, 2024
Labour Cost Inflation	6%	Department of Statistics South Africa, 2024
Tax Rate	27%	South African Revenue Service, 2024
Exchange Rate (ZAR/Euro)	0.049	
Tyre Processing Fee (ZAR/kg)	0.31	Department Of Forestry and Environment, 2022
Value of Water (ZAR/litre) incl. VAT	0.066	Zyl et al., 2010
Water Demand Management Levy (ZAR)	3598.56	Zyl et al., 2010
Value of Nitrogen (ZAR/litre)	99	Nkosi et al., 2020
Value of Steel Wires (ZAR/kg)	0.99	Nkosi et al., 2020
Total Land Area (m^2)	5500	ESKOM, 2021b;Khan et al., 2023
Carbon Tax (ZAR/tonne)	134	Rentel, 2024

Table 6.1: Financial Model Parameters

means the generation tariffs will always be higher than the load tariffs; therefore, the electricity costs are calculated using the generation tariffs. A full breakdown of the tariff structure can be seen in Appendix A. The system is designated as a peaking plant operating during the five peak hours daily. As such, the revenue received for the electricity will be dependent on the peak period tariff shown in bold.

Table 6.2: South African Electricity Market Tariff and Pricing Structure

Year	2022	2023	2024
Average Value of Electricity (ZAR/kWh) incl. VAT	1.639	1.944	2.192
Yearly Average Peak Electricity Value (ZAR/kWh)	**3.03635**	**3.60265**	**4.0616**
Service Charge for the year (ZAR) incl. VAT	2,240,567.10	2,913,908.15	3,285,138.70
Administration Charge for the year (ZAR) incl. VAT	67,904.60	93,060.40	104,911.95
Ancillary Service Charge (ZAR/kWh) incl. VAT	0.0069	0.0082	0.0092
Distribution Losses Charge (ZAR/kWh) incl. VAT	0.213	0.253	0.285
Distribution Network Capacity Charge (ZAR/kW/m) incl. VAT	24.18	28.69	32.35
Electrification and rural subsidy on loads (ZAR/kWh) incl. VAT	0.1337	0.1587	0.1789
Affordability Charge for load (ZAR/kWh) incl. VAT	0.0654	0.0884	0.161

The value of electricity for 2022, 2023 and 2024 was used in the model for the first 3 years of operation to represent the expected revenues during these years more accurately. After these years, the value of electricity was adjusted with the inflation rate outlined in the economic model parameters, Table 6.1.

6.1.2. System Operational Costs and Revenues

The system will have three main revenue streams: electricity generation, the sale of scrap steel wires, and the waste tyre processing fee received from the government. The electricity generated is provided to the electrical grid during the peak demand period, collecting a fee of 3.03 Rand per kWh. This value is predetermined by the South African energy regulator NERSA each year. As such, it is a stable source of revenue each year that adjusts to inflation. The steel wires are sold at 0.99 Rand per kg, the going rate for scrap steel in South Africa. Finally, a processing fee of 0.31 Rand per kg of waste tyres processed by the system is collected from the government.

The operational expenditure (OPEX) of the integrated system is determined from the inputs calculated for yearly operation given in Table 5.8 adjusted with the values for each input outlined in Table 6.1 and 6.2. The only variable cost calculated differently is the Labour cost, which has been determined using the method outlined on page 247 in Turton, 2012. From this, it is calculated that the integrated system will need 49 operators to ensure the system can operate at the intended 8000 hours per year. The total labour costs are then calculated using the average salary of operators in the electricity industry in South Africa for 2022, 2023 and 2024 before being adjusted for inflation for the years after 2024. Due to the integrated nature of the system, it could be classified under either the manufacturing or the electricity industry. This classification has a significant impact on the labour costs of the system, as the average monthly salary in 2022 for an operator in the manufacturing industry was R21,705.25 compared to the electricity industry, R49,052.50 (Department of Statistics, South Africa, 2023). As the main product of the integrated system is electricity, the salary for operators in the electricity industry has been used for the economic analysis. This choice will also help to draw a closer comparison of the proposed integrated system to competitors in the electricity industry, as the labour costs will not impact the comparisons.

The same steps are performed for the integrated system's outputs, yielding the three revenue streams: electricity sale, steel sale, and tyre processing fee, as well as an additional system cost: the carbon dioxide tax. Figure 6.1 shows the integrated systems' variable costs and revenues from 2022 to 2027; the costs and revenues over the complete lifetime of the system can be seen in Appendix A.

Year	2022	2023	2024	2025	2026	2027
Variable Costs (OPEX) (ThousandZAR)						
Water	15.16	15.77	16.40	17.06	17.74	18.45
Electricity Usage and Capacity Charges	17,551.25	21,095.36	23,792.79	26,830.72	30,257.39	34,122.76
Nitrogen	6,827.54	7,100.64	7,384.66	7,680.05	7,987.25	8,306.74
Labour Costs	28,842.87	30,573.44	32,407.85	34,352.32	36,413.46	38,598.27
Maintenance Costs	61,828.19	64,301.31	66,873.37	69,548.30	72,330.23	75,223.44
Carbon Tax	16,501.43	17,161.49	17,847.95	18,561.86	19,304.34	20,076.51
Total Costs:	124,829.20	133,241.29	141,036.03	149,411.85	158,428.81	168,149.30
System Output Revenue (ThousandZAR)						
Electricity	193,946.86	230,119.27	259,434.70	292,434.79	329,632.50	371,561.75
Steel Wire	3,663.20	3,809.73	3,962.11	4,120.60	4,285.42	4,456.84
Tyre Processing Fee	11,470.62	11,929.44	12,406.62	12,902.89	13,419.00	13,955.76
	0.00	0.00	0.00	0.00	0.00	0.00
Total Revenue:	209,080.67	245,858.44	275,803.44	309,458.28	347,336.93	389,974.36

Figure 6.1: System Variable Costs and Revenues in 1000 Rand from 2022 to 2027

6.2. Systems Capital Costs

The total capital expenditure (CAPEX) of the system is estimated at R562,063,080.43. The breakdown of this cost can be seen in Figure 6.3. The land area cost is based on available industrial-use land areas already permitted for sale that contain onsite warehouses and buildings ready for use ("5500 m² Industrial space in Alberton", 2024). The CAPEX of the electrical system is based on the Ankerlig system by calculating the per-MW price before scaling this to the 50-MW proposed system ("Ankerlig power station", 2023). This value includes all construction, permitting, and engineering costs necessary to construct the turbine in South Africa. Additionally, the cost for the electrical system includes the addition of a desulfurization and dust removal unit to be compliant with governmental regulations.

The CAPEX of the pyrolysis system is based on the listed components' prices, with additions for engineering and construction. To determine the required components studies from Khan et al., 2023, Abdallah et al., 2020, Nkosi et al., 2020 and Lopez et al., 2017 were used. The list of components was also compared to plants created by the Beston group ("Continous Waste Tyre Pyrolysis Plant", n.d.) and BTG's Hengelo plant. The engineering and construction costs are based on similar-scale waste management plants in South Africa.

Component	CAPEX (ZAR)
Land Cost: (Based on comparable sites)	21,500,000.00
Pyrolysis Plant:	
Reactor	958,639.92
Boiler	2,189,158.58
Oil Storage	423,901.57
Char Storage	171,116.30
Pumps	2,338,185.58
Connection Pipes and Conveyors	12,805,612.88
Screw Conveyor for Char and Steel	904,193.78
Condensor	1,918,620.00
Distillation Column	1,147,410.00
Gas Scrubber	1,003,234.58
Engineering and Construction Costs	117,225,610.69
Electrical Turbine:	
Total Cost Electrical System: (ZAR)	386,289,639.01
Electricity Connection Cost	115,600.00
Total System Fixed Cost:	562,063,080.43

Table 6.3: Estimated fixed costs of the integrated system

6.3. Results of the Model

Following the economic model's setup, the selected economic indicators, the payback time, net present value, and the levelised cost of electricity can be calculated for the integrated system. The economic feasibility of the conceptual integrated system can then be determined through these three indicators. It is important to note that for each of the indicators, it is assumed that 100% of the net cash flow is being used to repay the fixed cost of the system. This assumption of the directed cash flow results in the PBT being shorter, the NPV being greater, and the LCOE being lower than if the cash flow is diverted to repaying interest on loans or providing a payout to investors. Three indicators are used in the economic analysis, representing the standard for capital budgeting practices within South Africa, where firms use between 2 and 3 indicators to rank capital projects (Correia, 2012).

6.3.1. Payback Time

Payback time represents the amount of time required for the cash flows of a proposed investment to net a positive return on the initial cost of the investment. The point at which this turns positive is the break-even point and signals a shift towards profitability for an initial investment. A shorter payback time indicates a more attractive and economically feasible investment or solution. Within South Africa, PBT is one of the preferred financial indicators firms use for budgeting and economic analysis of investment projects, often in support of the NPV (Correia, 2012).

The payback time of the system is calculated through the summation of the system's cumulative cash flows against the total system cost. This is then calculated until the summation turns positive in the case of the integrated system. We can see in Table 6.4 that this point occurs between years 4 and 5. The exact point between years 4 and 5 where the positive point occurs can be interpolated by determining the ratio between the remaining investment and that specific year's cash flow using equation 6.1. This is then added to the initial years that have passed. Using this method, the payback time for the integrated system is determined to be 5.4 years. Figure 6.2 shows how the cumulative cash flows change over the first 11 years of the project and the point at which the system breaks even.

System Fixed Cost		
Year	Yearly Cash Flow (ZAR)	Cumulative Cash Flow (ZAR)
Year 1	61,503,575.98	-489,405,966.90
Year 2	82,210,518.48	-407,195,448.42
Year 3	98,380,207.52	-308,815,240.90
Year 4	116,833,897.27	-191,981,343.63
Year 5	137,902,927.28	-54,078,416.35
Year 6	161,932,293.32	107,853,876.97

Table 6.4: Cumulative cash flows of the integrated system over the first five years.

$$PaybackTime = Year5 + \frac{RemainingInvestment}{CashFlowinYear6} \tag{6.1}$$

This is a highly favourable result as it shows the system will generate a profitable investment during its lifetime of 20 years, making it an economically attractive and feasible solution to both develop South Africa's waste tyre processing capabilities and help to improve the country's electricity generation capabilities.

A positive supporting point for this result is that the payback time is within the typical 2-7 years for

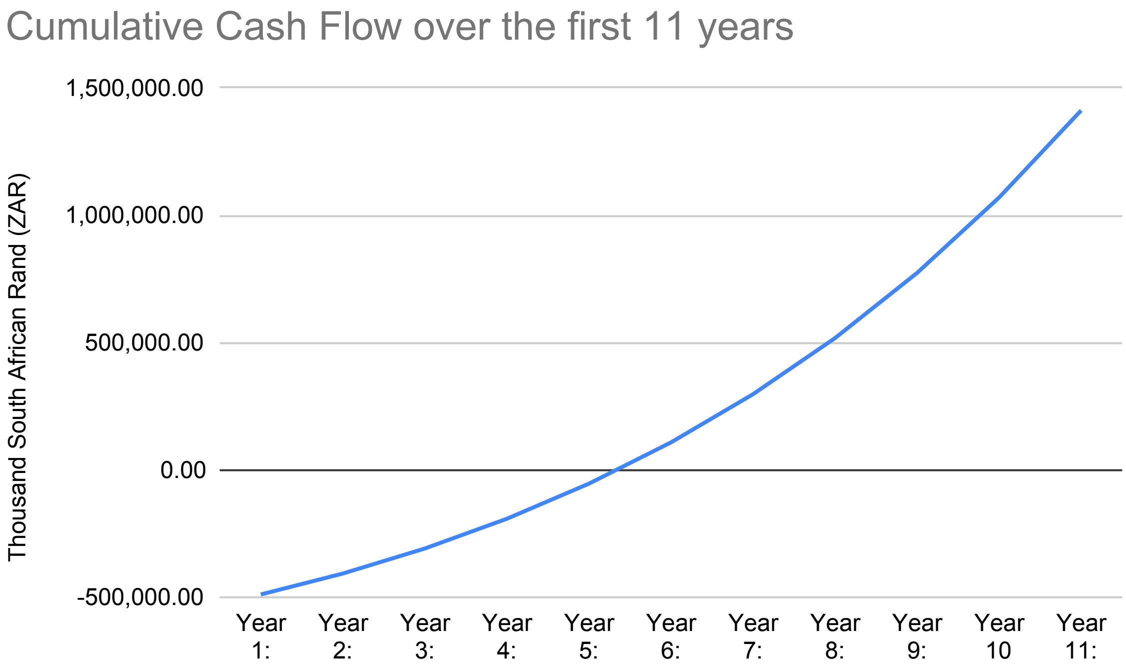

Figure 6.2: Cumulative Cash Flow of the integrated system over the first 11 years of operation given in Thousand Rand.

biomass processing plants (Edou and Onwudili, 2022). Further, this result is also in line with the system shown by Nkosi et al., 2020, which has a payback time of just under five years, as well as the system shown in Khan et al., 2023 with a payback time of 9.39 years, helping to validate this outcome.

6.3.2. Net-Present Value

Net present value is the difference between the present value of cash inflows and the present value of cash outflows over the lifetime of a project. These cash flows are adjusted using a discount factor to reflect the present-day value of money and provide a good indication of the total value of a proposed project. In general, projects that have a positive NPV are considered worth undertaking. Within South Africa, NPV is the preferred indicator when performing economic analysis on capital projects that exceed R50 million in value (Correia, 2012). This makes NPV a key metric with which the proposed system can be analysed and kept in line with standard practice in South Africa.

The proposed integrated systems NPV is calculated in steps. First, the integrated system's present value is calculated using Equation 4.2. The yearly cash flows are adjusted with the discount rate, r, using the standard rate in South Africa of 4% and the time period before being summed, yielding the present value of the total cash flow expected over the integrated system's lifetime. The system's total fixed cost is then subtracted from the calculated PV to determine its net present value and whether the integrated system will yield a positive or negative total cash flow over its lifetime.

The integrated system's NPV is R4,854,981,059.72, which shows a strongly positive value, with lifetime cash flows exceeding the system's cost by a large margin. This further indicates that the integrated system represents an economically feasible solution to tackling South Africa's waste tyres and electrical generation challenges. With how strongly positive the NPV is for the integrated system, it can be concluded that the economic outlook is robust to external factors and will be able to accommodate a wide range of financing options that cover the initial fixed costs. Further supporting the economic feasibility of implementing an integrated pyrolysis and electrical turbine system within Gauteng, South Africa.

6.3.3. Levelised Cost of Electricity

The levelised cost of electricity (LCOE) is an economic measure used to compare the lifetime costs of generating electricity for a generation system. This measure takes into account capital expenditure, operating expenditure, disposition costs and generation capacity, yielding a value that represents the cost per kWh of electricity for the system. Typically, the largest proportion of the LCOE comprises the fuel costs involved with the generation process. In South Africa, the LCOE measure is used by ESKOM each year to request increases in electricity tariff prices, and the liberalisation of the markets will form the basis for future electricity prices, as seen in Europe. Due to ESKOMs significant debts, ageing generation systems, and corruption scandals, the average LCOE of the generation capacity has steadily been driven up, contributing to significant prices associated with electricity in South Africa. By using the LCOE, we have a direct comparison point for the proposed system against the already existing generation systems in South Africa, as well as a further measure to determine the economic feasibility of the system.

The LCOE is calculated using Equation 4.3. LCOE represents the ratio of the NPV of the total costs of the system, including capital costs, operating costs, and any other relevant costs, and the NPV of the total system lifetime produced electricity. As such, the value shows the average cost of producing 1 kWh of electricity. The resulting LCOE from this calculation is 0.12 R/kWh.

This LCOE is below the current fixed price of electricity in South Africa, indicating that the system would be profitable to operate during only peak hours. Furthermore, this value is far below the LCOE of ESKOMS electrical generation systems of 0.45 R/kWh, excluding capital costs in this calculation (Musso, 2019). This comparison between ESKOMS LCOE and the price of electricity in South Africa is shown in Figure **??**. In fact, the calculated LCOE puts the integrated system on par with renewable energy generation sources in South Africa without even accounting for any additional services that the system could provide in the future. This comparison between the average costs of ESKOMs systems, the vast majority of electricity generation in South Africa, indicates that the integrated system would be economically feasible in the current electricity market of South Africa, quickly recouping the investment costs and operating at a profitable level per kWh of electricity produced.

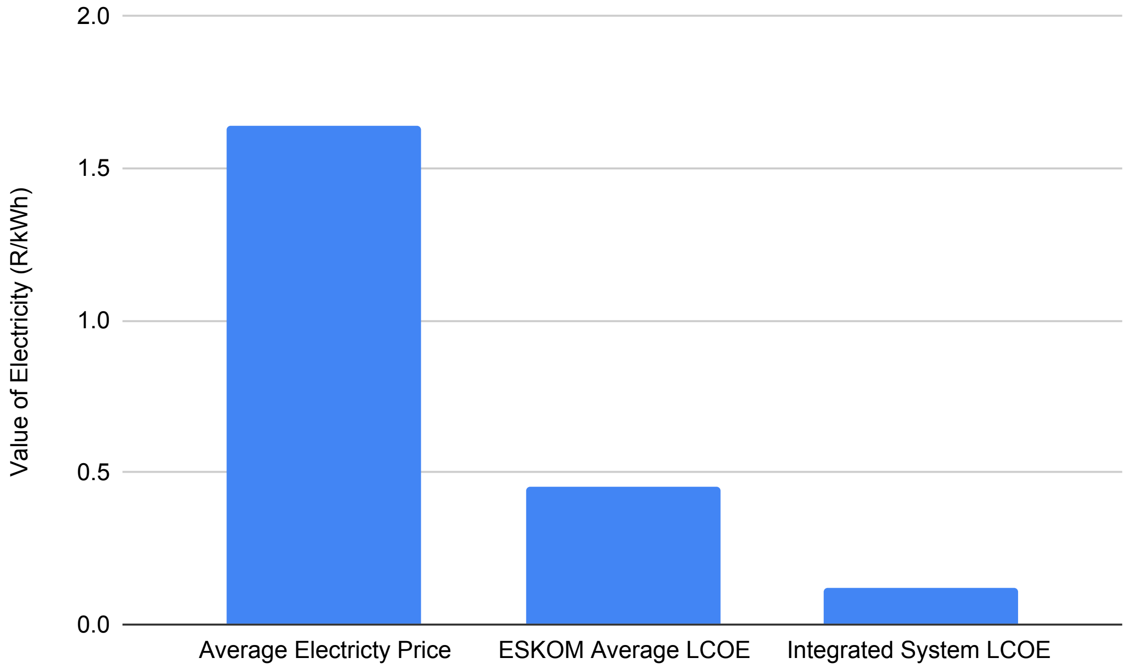

Figure 6.3: Comparison between the current price of electricity in South Africa, ESKOM's average LCOE and the calculated LCOE for the integrated system

6.3.4. Economic Indicator Summary

Table 6.5 shows a summary of the three calculated economic indicators for the integrated pyrolysis power plant system.

Calculated Indicator	Value
Payback Time (Years)	5.4
Net-Present Value (ZAR)	4,854,981,059.72
Levelised Cost of Electricity (ZAR/kWh)	0.12

Table 6.5: Overview of the Calculated Economic Indicators for the integrated system

7 Social Cost Benefit Analysis

Societal feasibility, while often overlooked in favour of economic or technical feasibility, is an increasingly important consideration for new technology and systems. Creating additional indicators with which new developments can be assessed and helping to create a more comprehensive understanding of the feasibility of systems from the perspective of society and the environment as a whole. Measuring Societal feasibility is challenging, with no single method providing a complete overview that includes every factor in large part due to the challenge of measuring specific factors. Within this study, Social cost-benefit analysis is used to assess the integrated system, building upon the economic indicators calculated in the previous Chapter while attempting to monetise some of the Social and Environmental costs and benefits. Not all of the social and environmental factors will be monetisable; as such, this Chapter also includes a section outlining these factors in a more qualitative way while still incorporating them into the final results. Utilising this framework, the proposed integrated system is then compared to the direct use of waste tyres for fuel for coal power plant co-firing in South Africa, creating a basis to provide the government with recommendations for the waste tyre processing sector. These two waste tyre processing methods will both be assessed based on the processing scale of the previously determined integrated system, 37,002 tonnes per year.

7.1. SCBA Framework Factors

The social cost benefit analysis framework is an effective tool for evaluating projects based on their expected impacts towards society. In this case, it makes an effective tool in determining the societal feasibility of the proposed system, helping to strengthen the case for coupling waste tyre processing to electricity generation within South Africa as a solution to two problems. As outlined in Boardman et al., 2018 and in Galal, 1994, the method of cost-benefit analysis relies heavily on the identification of the main agents involved not only directly with the project but also the agents that will be affected by the project. The integrated system would provide different results depending on the key identified agents. For example, a power producer would only look at the resulting value inflow following their investment, whereas the government would be concerned with the increased availability of electricity, reduced tyre stockpile and flow of taxes. The SCBA method aims to take a broader, higher-level approach by looking at multiple agents under the umbrella of society and looking at the net results across the entire value chain surrounding a project rather than only the project itself (Sidhu et al., 2018).
Further, there are many factors discussed within the framework that are non-quantifiable, making a good basis for the framework to be used in this study.

As mentioned in the methodology, the Social Cost Benefit Analysis framework that will be used to assess the societal feasibility of the integrated pyrolysis and electricity generation system will use a variety of features from Sidhu et al., 2018 and Jamasb and Nepal, 2010. Within this framework, the private costs will be excluded, as these are accounted for in the previous Chapter. Therefore, the external costs and benefits, or in this case, the costs and benefits gained by society from the implementation of the system, will be the agent and area of focus. A list of factors that affect society has been chosen previously, and the relevance of each will be outlined below. Some of the chosen factors are not easily monetisable. These will be incorporated into the results and considerations through a qualitative discussion instead. Finally, making use of equation 4.4, the Social Net Present Value will be calculated for the system across its lifetime, giving a further indication of the societal feasibility. These steps will all be completed for both the integrated system and the use of waste tyres as fuel in the co-firing of coal plants.

7.1.1. Electrical Grid Services

Controllable electrical generation assets, particularly systems like electrical turbines, can provide a multitude of grid services, such as frequency response and power quality support. These services are necessary for the stability of the electricity system, and many of them are a primary concern with large-scale implementation of renewable energy sources as these sources often are unable to provide certain services. The security of supply and generation curtailments will be discussed in separate sections as these have further implications outside of just the grid services.

Frequency Response

The electricity grid in South Africa operates at 50 Hz at an equilibrium point; should the grid frequency drop outside of this equilibrium, it means there is an imbalance in supply and demand. As such, new generation systems, usually systems that are capable of powering up rapidly, are required to restore this balance and thereby restore the frequency. Currently, in South Africa, there is no frequency response system as there is a permanent demand and supply imbalance; this equilibrium is controlled instead through load shedding. While there are no current frequency response systems in place in South Africa, there are plans to incorporate applicable IPPs into this role by 2032 (ESKOM, 2023). This service often cannot be performed by renewable energy systems as their generation capacity cannot be controlled; therefore, the electricity grid will always require systems like gas turbines to provide this service, indicating a potential future benefit to society through a grid-forming system. A final indication of a positive benefit is the requirement for these grid-forming systems to be localised, as the frequency imbalance is most often a localised incident that must be dealt with before it affects the entire grid. Gauteng, as of 2021, ranked lowest on the IPP installed capacity list, shown below in Figure 7.1, indicating there is an opening for systems that can provide these services in the coming years. In the case of this study, it will be assumed that once the applicability for IPPs to provide this service, the tariff payments will be in line with the current ancillary services charge levied by ESKOM, which, as of the latest prices (2024), is 0.8 c/kWh for distribution connected systems ((NERSA), 2021). With the uncertainty of the potential grid plans, this factor will be monetised based on the power output availability during the peak hour periods at the given rate provided by ESKOM; however, it will not increase over time, with inflation, thereby reducing the overall impact this factor has on the results.

Power Quality Support

Power quality support refers to reactive power support, voltage control, power quality, and distribution loss reduction that the system can provide to the grid. Within South Africa, reactive power and voltage control are all being controlled through ESKOM; however, it is possible to partner with ESKOM and provide your systems capabilities as an asset for these services. As the proposed integrated system is a net exporter of power, an increase in the reactive power capacity of the grid will be required to counteract the increased generation. With the voltage control, the integrated system will be able to provide this function through automatic voltage control mechanisms, much like with the frequency response, to help maintain the grid's equilibrium voltage levels. These two services fall under the same ancillary services charge as the frequency response service. As for the power quality and distribution loss reduction, these factors refer to the effect of distance on the quality and efficiency of the transported electricity, with increasing distances negatively impacting each factor. These loss factors are listed according to the grid balancing structure based on distance from the urban centre of Johannesburg, Gauteng, with a loss factor of 1.1111 for all loads and generators connected to the distribution system in Gauteng ((NERSA), 2021). Additionally, the distribution-connected generation capacity within

IPP capacities by type and location at 30 June 2021

Province, MW	RE-IPP Programme					Diesel	Total
	CSP	Solar PV	Hydro	Wind	Landfill		
Eastern Cape		70		1 253		335	**1 659**
Free State		196	8				**204**
Gauteng					8		**8**
KwaZulu-Natal						670	**670**
Limpopo		118					**118**
Mpumalanga							**–**
Northern Cape	500	1 419	10	801			**2 730**
North West		275					**275**
Western Cape		133		458			**591**
Total	**500**	**2 211**	**18**	**2 512**	**8**	**1 005**	**6 254**

1. Capacities (MW) indicate the contracted maximum or operational capacity, if lower.

Figure 7.1: List of installed IPP capacity by province and type as of June 2021 (ESKOM, 2021c)

Gauteng is 16.68 MW; as such, the 50 MW capacity provided by the integrated system located within the province itself would help to further reduce the requirement for electricity from further away being used (ESKOM, 2023). This distance reduction would reduce the 1.1111 factor as the total electricity efficiency within Gauteng would increase for the distribution system, thereby reducing the total costs for all users. It is not possible to further quantify without information about how this factor is determined, which is currently not publicly accessible information.

7.1.2. Value of Lost Load of Electricity

The value of the lost load of electricity (VoLL) is used as a measure of the willingness to pay for guaranteed supply. In South Africa, under the fixed tariff scheme for electricity, NERSA, the national regulator, measures this value as a direct cost of load-shedding under its Cost of Load Shedding (CoLS) and Cost of Unserved Energy (CoUE). The CoLS measures the cost of planned blackouts while CoUE measures the costs of unplanned power disruptions; these measures are determined per sector basis in R/kWh. In the case of this framework, the national values of each will be used as the electricity is being exported directly to the grid; this gives a value of 9.53 R/kWh as of 2020 for CoLS and 40.08 R/kWh as of 2022 for CoUS (Minnaar et al., 2023). The total gain to society from this factor is difficult to estimate as the capacity under which load shedding will continue in South Africa is uncertain going forward, and this is more challenging with unplanned blackout events. However, looking historically, this can be estimated by looking at the average unmet demand during scheduled load-shedding and unplanned blackouts. We can then reduce this unmet demand by the electricity provided by the integrated system before recalculating the total lost income and determining the difference. Alternatively, this can be done by calculating the product of the electricity generated and the CoLS/CoUE provided there is an average unmet demand greater than the generation provided by the integrated system. In the first half of 2021, South Africa experienced load-shedding outages of over 963 GWh and unplanned disruptions of 15,300 MW; as the planned generation capacity does not exceed the current daily imbalance when accounting for decommissioning plants, it can be assumed that these unmet demands will continue at a sufficient capacity (Minnaar et al., 2023). As such, the second method will be used to calculate the benefits to society, where the addition of the system will actively reduce the unmet demand during this load-shedding. It is important to note only the CoLS will be accounted for in the Social Cost-Benefit analysis as the CoUS occurs at random points and in varying capacities, so there is no accurate measure of how much of an impact the implementation of the new capacity will have on these periods. This addition of electricity capacity will actively improve the economic output of the country based on the calculated values from ESKOM and NERSA (Minnaar et al., 2023).

7.1.3. Greenhouse Gas Emissions

As there is a significant amount of electricity demand remaining to be filled in South Africa, introducing new generation systems will not reduce other generation forms, such as coal (IEA, 2022). As such, South Africa is not currently in a position to begin abating its greenhouse gas emissions from its more polluting systems with alternative electricity generation. This results in the increased emissions produced through the use of waste tyres in any form for energy production, which will be a net cost to society in the foreseeable future. This cost can be accounted for based on the carbon tax as this represents the ascribed cost of carbon to society under the South African regulations. The cost of carbon has risen over time from 134 R/tonne in 2022 to 190 R/tonne in 2024 (Rentel, 2024). Therefore, the effect of inflation will be included in this factor to represent this change. The direct use of waste tyres for energy generation in South Africa is a different story, where the most common use of this approach to processing waste tyres is co-firing in coal plants. Waste tyres, on average, have a higher calorific value than coal, reducing the amount of fuel required to produce the same power level, thereby actively reducing the total CO2 emissions from these plants, acting as a form of abatement. The emissions value of replacing coal with waste tyres is calculated to be 42,554 tonnes of CO2 saved per year, assuming 37,002 tonnes of waste tyres are used in place of coal. This quantification will then work in reverse with the carbon tax providing a benefit to society worth the amount of CO2 saved times the current value of the carbon tax. This reduction in CO2 emissions was calculated from Dzene et al., 2010 making use of the low calorific value of South African lignite coal.

7.1.4. Labour Creation

With the creation of new systems or a scaling up of original systems, there will be an increased demand for labour. In the framework outlined by Jamasb and Nepal, 2010, this would be excluded from the calculations as it would be outlined as a transfer payment between the private business system and society. However, in this case, only the external costs and benefits are being assessed from society's viewpoint; therefore, the labour costs experienced by the private system will be considered a net benefit to society. In the economic analysis Chapter, the number of operators required for the operation of the system has been determined along with the average wage for the electricity industry in South Africa. These values will then be used to determine the benefit to society in the form of new wages created through the implementation of the integrated system. Regarding the direct use of waste tyres, there will be no increase in labour from the co-firing of waste tyres in coal plants as a transition from one fuel source to an alternative fuel source is not expected to lead to a change in the number of operators required by a coal power plant.

7.1.5. Waste Tyre Depots and Landfills

Across South Africa, the 26 available waste tyre depot sites are rapidly approaching full capacity. This is exacerbated by the tightening of regulations around the dumping of tyres and limitations on whole and partially shredded tyres no longer being allowed in landfill sites. Therefore, a solution to solve these filling depot sites is to turn them into preprocessing locations capable of shredding tyres, which can then be used in systems such as the one outlined in this study or in the co-firing of coal power plants, amongst other uses. With the implementation of processing systems for waste tyres, a pre-processing industry will be created naturally to meet the demands of these processing systems. This will have a knock-on effect on job creation, further diversion of waste tyres from landfills and a reduction in the illegal resale of waste tyres. This factor has not been quantified, as there is no foreseeable accurate method to determine this knock-on effect of job creation. With no way to accurately measure the number of jobs created in this secondary industry, any quantified number will not be representative of the end benefits to society. As such, this factor represents a net benefit to society through the creation of a supporting pre-processing industry for waste tyre processing systems and approaches.

7.1.6. Health Implications

Stockpiled, dumped or illegally resold waste tyres all pose different health risks to society, such as fire hazards, breeding sites for mosquitoes, or sudden failure during use. These effects are all a direct consequence of the insufficient waste tyre processing industry in South Africa. Following the implementation of a large-scale processing facility, each of these hazards will begin to decrease directly. South Africa has 26 depot sites spread throughout the provinces, some of which are open-air air and pose a significant area for insect breeding grounds, in particular mosquitoes, which are responsible for the spread of malaria in South Africa, with an estimated 10% of the population at risk of the disease (Department of Health Republic of South Africa, 2018). This is not a direct risk for the region of Gauteng; however, the provinces bordering Gauteng are the most at risk in the country. Therefore, the overall reduction of the waste tyre stockpiles in the Gauteng province would have a knock-on effect by reducing the stockpiles in the at-risk areas, helping to reduce the impact of these breeding grounds indirectly. Malaria accounted for 38 deaths in 2020 and around 8200 contracted cases. While measures have significantly reduced these numbers down to the 2020 levels, the cost of malaria is still significant for the country, ranging from R4.88 billion to R6.34 billion as of 2020 (Njau et al., 2021).

A further risk in South Africa regarding waste tyres is the ongoing illegal resale of used tyres past their safe use lifetime. Each year in South Africa, there are more than 14,000 deaths due to road-related accidents, with 41% of these accidents being attributed directly to the mechanics of the car, which includes the tyres (SATMC, 2020). This is coupled with a report from the South African Tyre Manufacturers conference chairperson listing burst tyres as being responsible for 73.5% of mechanics failure accidents. According to these statistics, tyre failures are responsible for around 4000 deaths each year, directly posing a significant cost to society brought about in large due to the failure to manage the waste tyre stream successfully. Approximately 1.5 to 2 million, around 10,600 to 14,200 tonnes, of second-hand tyres are sold yearly in South Africa, with 60% of these being deemed illegal and unsafe. As such, either through the implementation of the integrated system or through the co-firing of tyres, this flow could be single-handedly reversed or, in large part, reduced, contributing to a reduction in tyre failure-related deaths.

While it is clear there are gains to society in South Africa through the creation of waste tyre processing systems or methods, how to measure these gains is unclear. There would need to be a significant study into the breeding levels of mosquitoes being directly impacted through a reduction of waste tyre storage sites, which in turn would then need to show a clear impact in a reduction of malaria cases through this reduction in breeding to attribute any quantifiable gain to society. However, this still has a more qualitative scope as waste tyre depot sites are linked to increasing mosquito numbers in the area. With respect to the illegal reuse and sale of tyres, there is a more quantifiable approach as end-of-life tyres directly account for a significant number of deaths each year, of which the scale of waste tyre processing would have a meaningful impact in regards to reducing the number of end of life tyre but also starting to build up a formal economy around the waste tyres. However, as this would require quantifying the accounting and valuation of human life, the author has instead chosen to analyse this factor qualitatively due to uncertainty and ethical issues around valuing human life.

7.1.7. End of Life Decommissioning Costs

Decommissioning is an essential step for an industrial system as it reaches its end-of-life period, requiring careful management to ensure the system can be broken down, cleaned and disposed of safely and environmentally friendly. This cost is expected to be borne by the private parties involved in the system; however, in the case of South Africa, this is often not the case where the provisions outlined in the investment documents are often inaccurate and are instead attributed as future debt obligations in the accounting (Yelland, 2021). This is evidenced by ESKOM passing along the costs to the taxpayers for many of the plants set to or undergoing decommissioning (Sguazzin, 2024). The implementation of the integrated system would ideally involve suitable accounting measures for the decommissioning costs. This factor is still a consideration for the external agent of society and must be accounted for as a cost based on previous practices in South Africa. There is no clear-cut way to determine the cost to society for the decommissioning and dismantling of the proposed integrated system. However, ESKOM has determined an attributed value for the cost of decommissioning coal power plants. This value of R 877,273 per MW will be used to measure the cost borne to society for the decommissioning of the electrical turbine part of the integrated system once it has reached its end of life (Bhushan, 2023). This value has been chosen as it comes directly from South Africa and is calculated for electrical systems across the country, of which more than 50% of the initial capital expenditure of the integrated system is made up of the electrical turbine. The pyrolysis part of the plant decommissioning cost will be assumed to be 10% of the capital costs of the system (Nuclear Energy Agency, 2016). This assumption has been made from the standard practice of nuclear site decommissioning, as no current studies or figures could be determined for chemical or industrial sites. Furthermore, this figure can be considered plausible given the complexity of nuclear plant decommissioning, in which case this would be an overestimate; however, with regards to the cost to society, it is better to overestimate rather than underestimate. Both of these values will be adjusted with inflation to be representative of the costs after the previously chosen end-of-life year of 2042.

7.1.8. Waste Tyre Processing Subsidies

Under the current South African government's plans for the waste tyre processing industry is the inclusion of the waste tyre processing disposal levy paid to the processors per tonne of the tyres processed (Department Of Forestry and Environment, 2022). This payment to waste tyre processors is funded through taxes, representing a direct cost to society in the form of an increased cost on the government budget. Again, if the private party were to be incorporated in this SCBA, this cost would be excluded under the guise of transfer payment. Following this, the cost to society for this tax can be accounted for directly based on the payment made to the waste tyre processors, which is outlined as revenue in the economic analysis Chapter as 0.31 R/kg of waste tyres processed (Department of Environmental Affairs, 2010). This would be a cost attributed to the integrated system discussed in this study and a cost in the case of direct fuel use, as this method is also eligible for payment under the current waste management plans.

7.1.9. Factor Summary

The following table summarises the different factors listed above for both the integrated system described in this study and the application of waste tyres as direct fuel for coal power plants. Each factor is highlighted, including whether it represents a positive or a negative for society and how the factor is quantified if applicable.

Table 7.1: SCBA Factors Summary for pyrolysis power plant system and co-firing of waste tyres in coal plants

Factor	Integrated Pyrolysis Power Plant	Co-firing of Waste Tyres	Valuation Method	Ref
Electrical Grid Services	Benefit to Society	Not Applicable	Valued based on current services - 0.8 c/kWh	(NERSA), 2021
VoLL of Electricity	Benefit to Society	Unclear if there is any impact	9.53 R/kWh for CoLS and 40.08 R/kWh for CoUS	Minnaar et al., 2023
Greenhouse Gas Emissions	Cost to Society	Benefit to Society	CO2 - 134 R/tonne (2022)	Rentel, 2024
Labour Creation	Benefit to Society	Not Applicable	Average wage per job in electricity industry - R49,052.50 monthly	Department of Statistics, South Africa, 2023
Waste Tyre Depots and Landfills	Benefit to Society	Benefit to Society	Non-quantifiable	
Health Implications	Benefit to Society	Benefit to Society	Non-quantifiable	

End of Life Decommissioning Costs	Cost to Society	Not Applicable	10% of capital costs of pyrolysis system and R877,273 per MW for the turbine	Nuclear Energy Agency, 2016; Bhushan, 2023
Waste Tyre Processing Subsidies	Cost to Society	Cost to Society	0.31 R/kg of tyres processed	Department Of Forestry and Environment, 2022

7.2. SCBA Results

The Social Costs and Benefits have been calculated according to the distribution outlined in Table 7.1, along with the previously determined outputs for CO2, Electricity, Number of Jobs created, Capital Costs, Volume of tyres processed and the different parameters such as the starting year, lifetime and inflation rates. A list of each of these parameters can be seen below.

1. Waste Tyre processing subsidy 0.31 R/kg
2. Cost of Power Plant Decommissioning 877,273 R/MW
3. Capital Cost of Pyrolysis System R143,004,303.87
4. Electricity Tariffs Inflation 12.74%
5. General Inflation 4%
6. Labour Cost Inflation 6%
7. Carbon Dioxide Emitted 123,145 tonnes/year
8. Carbon Dioxide Abated 42,554 tonnes/year
9. Electricity Produced 63875 MWh/year
10. Processed Tyres 37,002 tonnes
11. Electrical Grid Services 0.8 c/kWh
12. CoLS 9.53 R/kWh
13. Carbon Tax 134 R/tonne
14. Labour Creation 49,052.50 (R/month)/person
15. Number of Operators 49

These factors were then used to calculate the benefits and costs for both the integrated pyrolysis power plant system and the co-firing of waste tyres in coal plants. The results are shown below in Tables 7.2 and 7.3 for the year 2022 for all aspects except the decommissioning costs of the integrated system, which is only accounted for in the year 2042. In these Tables, the net results for 2022 are also shown for each processing method; these net results are also known as the change in social welfare outlined in Equation 4.5. We see a significant benefit to society each year following the implementation of the integrated system, in large part due to the estimated gain in economic output by even a small reduction in the unmet demand during load-shedding periods. However, while this gain appears significant, it is a small benefit in relation to the experienced cost of load shedding due to lost economic output each year, estimated to be a loss of 1.8% of the GDP yearly, around 7.3 billion USD in 2022 (Minnaar et al., 2023). In comparison, co-firing waste tyres in coal power plants is shown as a cost or a decrease in social welfare. This waste tyre processing method results in a reduction in carbon emissions; however, under the current structure, there would be a greater cost to public taxes to facilitate the waste tyre processing subsidy. The values shown in Tables 7.2 and **??** were extended for 20 years, the system lifetime with the values for inflation outlined in the above list. The results of this can be seen in Appendix B.

Table 7.2: Costs and Benefits to Society of the Integrated Pyrolysis and Electricity Generation system for the year 2022

Benefits:	
Electrical Grid Services CoLS Labour Creation	R511,000.00 R608,728,750.00 R28,842,870.00
Total Benefits	R638,082,620.00
Costs:	
Carbon Dioxide Emissions Decommissioning Costs (Value in 2042) Waste Tyre Processing Subsidy	R16,501,430.00 R127,444,662.63 R11,470,620.00
Total Cost in 2022	R27,972,050.00
Net Result for 2022	R610,110,570.00

Table 7.3: Costs and Benefits to Society of co-firing of waste tyres in coal power plants for the year 2022

Benefits:	
Carbon Abatement	R5,702,236.00
Costs:	
Waste Tyre Processing Subsidy	R11,470,620.00
Net Result	R-5,768,384.00

7.2.1. Social Net Present Value

Following the extension of the cost-benefit tables with inflation, the Social Net Present Value was calculated using Equation 4.4 with a general discount rate of 4%. This calculation yields the following results for the integrated system and for co-firing, respectively:

1. **Integrated System SNPV: R 8,560,759,752.44**
2. **Cofiring of Waste Tyres SNPV: R -84,084,882.72**

Again, as shown in the cost and benefits table, Table 7.2, for the integrated system, the result is significantly positive owing to the extreme valuation of the creation of the electrical generation capacity for the grid. Following the counterfactual opportunity cost present within the NPV methodology, a positive result indicates a worthwhile investment as the measured benefits outweigh the costs. As a sanity check, the SNPV for the integrated system has also been calculated, while ignoring the estimated benefit from the addition of generation capacity to the grid. This resulted in a SNPV of R 20,806,754.30. A much smaller positive value, however, is still a positive outcome owing to the increased grid stability, power quality and jobs created through the system. These results prove that investing in pyrolysis systems optimised for electricity production is a worthwhile endeavour to tackle both South Africa's waste tyre challenge and electricity generation imbalance.

The calculated SNPV for the co-firing of waste tyres in coal power plants has been determined to be negative, with the waste tyre processing method not being a worthwhile method of tackling the waste tyre stream under the current subsidy scheme for society. Again, following the counterfactual opportunity cost, this would indicate this processing method is not worthwhile for society to undertake and should only be undertaken in the most extreme circumstances if no other processing options would be available.

7.2.2. Qualitative Factors

Waste Tyre Depots

As previously outlined, it is expected that the implementation of waste tyre processing methods will have a knock-on effect on the depot sites and landfills. This knock-on effect is expected to come in the form of stimulus to these agents within the value chain as a demand for pre-processing would be created along with an inherent value to the waste tyres, transitioning these agents from a passive collection and storage role to a collection, pre-processor and supplier to facilitate the processing systems/industry. This transition is expected to create jobs and grow these small businesses, directly contributing to an increasing benefit to society as these industries grow in tandem. As such, this factor will have a direct positive influence on the social feasibility of the integrated system as well as on the co-firing of waste tyres. Furthermore, this knock-on effect is desirable for the government, as outlined in the Industry Waste Tyre Management Plan (IndWTMP), where the goal of facilitating a value-add-on business model to these depot sites would be required to fully tackle the waste tyre stream in the future (Department Of Forestry and Environment, 2022).

Health Implications

With a fixed number of deaths each year being directly attributed to the sudden failure of second-hand tyres, with a large portion of these being through illegal resale, the implementation of both the integrated system and the use of waste tyres for fuel is beneficial for helping to reduce this number. By processing the waste tyres, there will be an expected reduction in the number of tyres available, which will not only directly reduce the number of accidents but contribute to the development of a waste tyre processing industry, further reducing the number of end-of-life tyres reentering the road infrastructure. This development would directly work to provide an economic value for these end-of-life tyres, thereby discouraging illegal resale in favour of a safer and more guaranteed income. All in all, the institution of waste tyre processing is essential in South Africa and can be seen as a significant benefit to society through a direct reduction in the number of sudden road accidents each year, not only reducing the damages of these accidents but also saving lives in the process.

As for the risk of disease, it is well attributed that waste tyre landfill sites or dumping sites provide ample breeding grounds for mosquitoes, contributing to increased population exposure to malaria. This, in turn, will have an effect on the number of cases each year requiring medical assistance, driving up the cost of the disease to society. Therefore, the implementation of waste tyre processing methods and systems will begin to reduce the number of waste tyres ending up in these storage sites, with the goal being to reduce the number of stockpiled tyres, directly reducing the number of mosquitoes each year, having a knock-on effect on the cost of malaria each year. The effect on the mosquito breeding sites and direct reduction in road accidents makes it clear that the investment in waste tyre processing is of utmost importance to society in South Africa, with there being significant benefits and gains just in the improvement in human life across the country.

8

Sensitivity Analysis

The final part of the results of the socio-economic feasibility of the integrated pyrolysis and turbine system involves a sensitivity analysis across a selection of scenarios. Through these scenarios, the feasibility of the system will be tested under changing parameters, highlighting if there are more dominant factors that affect the feasibility; these potential factors will, in turn, indicate the key areas of risk to the implementation of the integrated system. These scenarios are outlined below, and the justification for each change is included.

8.1. Scenarios - Waste Tyre Price

The first set of scenarios analysed concerns a fluctuation in the price of the waste tyres acquired by the system. In the base scenario, this is 0, and it is subsidised further through a disposal processing fee. However, as the industry is built up, this subsidy is expected to disappear, along with the increased demand for end-of-life waste tyres, contributing to the creation of an inherent level of value for waste tyres in South Africa. Therefore, a range of values for the waste tyres used by the integrated system has been attributed an increasing value with each step, starting with the removal of the waste tyre processing subsidy followed by increasing costs up to R1800 per tonne of shredded tyres ("Shredded tyre scrap", 2024). This max value has been selected based on quote prices across South Africa for pre-shredded tyres to be used in construction and would be representative of the feasibility of the system without the aid of government subsidies in the current market. The different scenarios and how they affect the 4 indicators used throughout this study, PBT, NPV, LCOE and SNPV, are laid out below in the following Figures.

Figure 8.1 shows how the integrated systems payback time scales with the increasing cost of waste tyres in South Africa compared to the base scenario where the tyres are free and the subsidy is paid. The Payback time was calculated as outlined in Chapter 6 Equation 6.1, with the changing scenarios being added in by adding an additional system cost in the form of the waste tyres and removing the revenue from the waste tyre processing subsidy. These results are then scaled with the base scenario so that the base scenario represents 0, and the alternative scenarios show the deviation from this. The payback time increases for each scenario as an increased cost of waste tyres directly contributes to a decrease in revenue experienced by the system, requiring longer and longer periods to recoup the initial capital costs. This increase is nonlinear, as evidenced by the PBT for R500 per ton being 7.07 years versus the PBT for R1000 per ton being 7.27 years. This indicates that the value of the waste tyres while being important for the payback time, is not a significant influencing factor compared to the overall results of the system. In addition, the fact that the payback time of the system remains below the lifetime of the system despite significant price increases of tyres further supports the economic feasibility of the integrated system and shows that it remains an attractive investment opportunity.

Figure 8.2 shows how the integrated systems' net present value changes over time as the cost of waste

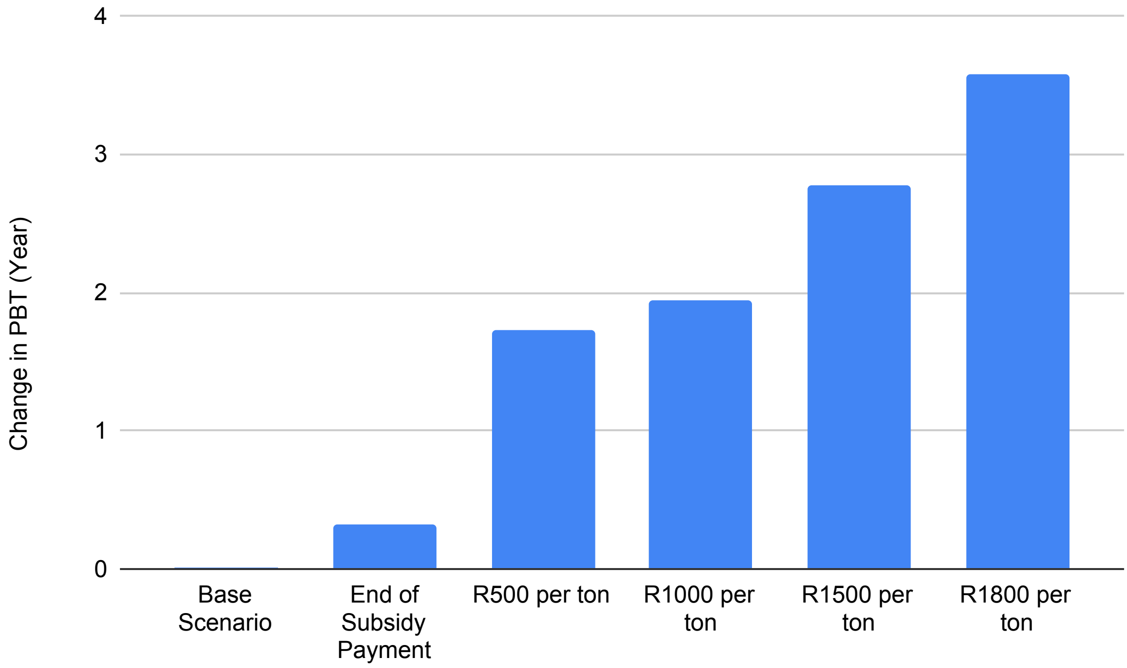

Figure 8.1: Variation of Integrated Systems Payback Time with changing cost of waste tyres

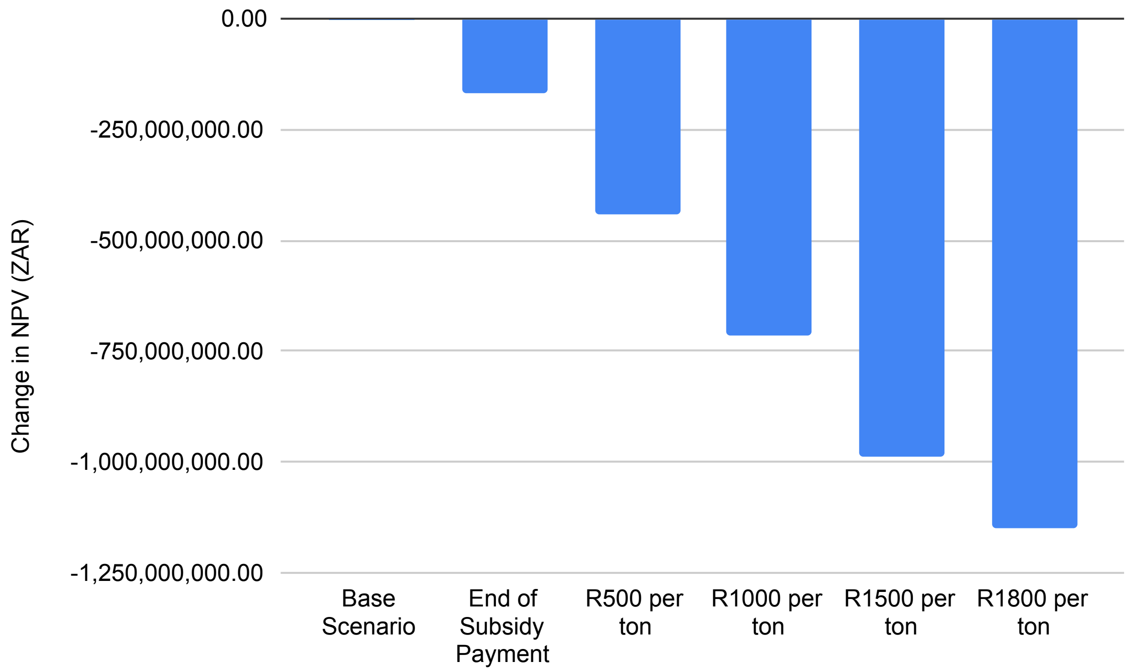

Figure 8.2: Variation of Integrated Systems Net Present Value with changing cost of waste tyres

tyres increases for the year 2022. The results were calculated using Equation 4.2 before once again being scaled with the base scenario to show how each scenario changes with respect to the base scenario. Opposite to the Payback time, the Net present value decreases as the price for tyres increases; this is directly due to the decrease in profit experienced from the increasing costs. As such, the total earnings that can be expected from the system throughout its lifetime decreases. However, much like with the payback time, the fact that the NPV is positive in each scenario regardless of the waste tyre price supports the economic feasibility of the system.

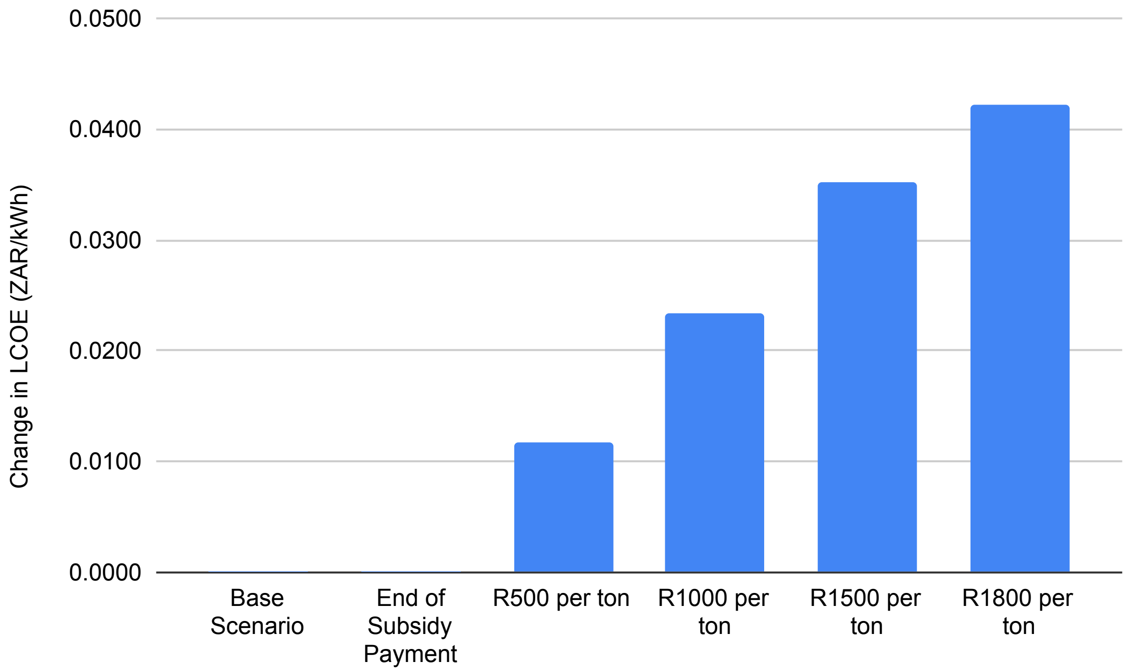

Figure 8.3: Variation of Integrated Systems LCOE with changing cost of waste tyres

Figure 8.3 shows the fluctuation in the LCOE as the cost of waste tyres increases. The LCOE for each scenario was calculated using Equation 4.3 before again being scaled to the base scenario level. As the price increases, so does the LCOE. This is a direct relation that is a significant part of the calculation of the LCOE, which consists of the total costs of the system, including fuel costs. However, while there is an increase in the LCOE, it still remains below the electricity tariffs in South Africa and below the LCOE of ESKOM's systems. As such, despite an increase in the cost of waste tyres, the integrated system is still economically feasible as a source of electricity.

Figure 8.4 incorporates the change in the social net present value for the integrated system. The different scenarios were calculated using Equation 4.4, calculating the social welfare change with Equation 4.5 for each scenario before determining the SNPV. The SNPV shows a slight increase in the transition from the base scenario to the end of the subsidy payment scenario. This increase comes from the removal of the cost to society in the form of the taxes used to pay for this subsidy. As such, it is clear that as the waste tyres increase in value and the subsidy ends, the potential gap in society is set only to increase further, indicating that the implementation of the integrated system is socially feasible.

With regard to the qualitative factors, an increase in the value of waste tyres would likely lead to an increase in the profitability of the pre-processing and storage industry, creating a need for further jobs. Additionally, with waste tyres having an increasing value, it would reach a point where illegal resale of the waste tyres would no longer be profitable, directly helping to reduce the number of road accidents from mechanical failures of the tyres, benefiting society further.

An interesting point of comparison for social feasibility is how, with the removal of the waste tyre subsidy fee, the co-firing of waste tyres would also be a net gain to society, potentially opening the way for

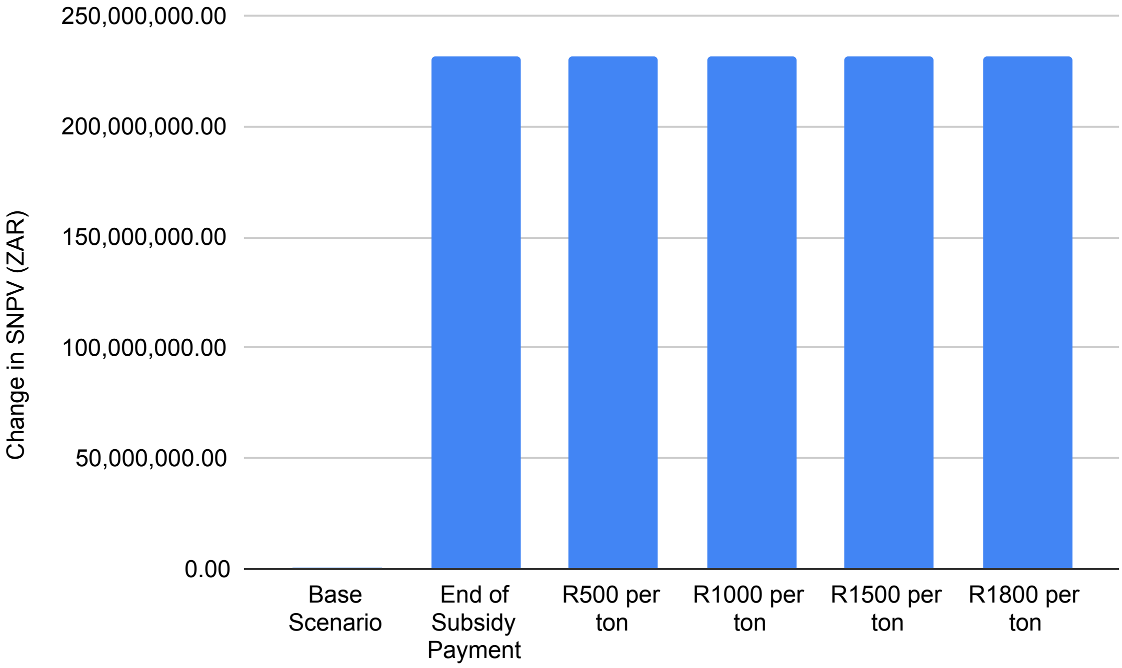

Figure 8.4: Variation of Integrated Systems SNPV with changing cost of waste tyres

further waste tyre processing methods to be implemented.

8.2. Scenarios - Electricity Price

The second set of scenarios analysed concerns changing electricity tariffs. Currently, the price of electricity in South Africa is excessively high due to the severity of the situation, and these high prices are only expected to increase further. This represents a favourable outlook for any system that can provide additional electricity generation for the country. However, as the independent power producer plans are brought back to full capacity and the electricity market continues to shift towards liberalisation, there is no guarantee that these electricity prices will remain high forever. In particular, an increase in renewable energy integration or greater levels of competition in an open market would cause the value of electricity to drop. Increasing electricity prices would have a clear, increasingly positive impact on the integrated system, evidenced by the NPV being positive with a high level of inflation incorporated from the electricity prices already. As such, the scenarios will highlight the system's feasibility under decreasing electricity prices. Following this, the scenarios that have been chosen are the base scenario with increasing prices, stagnant prices, and deflating prices ranging from -1% up to -3%. Again, the different scenarios and their effects on the indicators are shown in the following figures.

Figure 8.5 shows how the integrated systems' payback time changes as the value of electricity changes. The Payback time was calculated by adjusting the inflation of electricity in the economic model's parameters shown in Chapter 6.1 before making use of Equation 6.1 to calculate the values for each scenario. These values were then scaled with the base scenario by subtracting the base value from each scenario value to show the change in the PBT as the value of electricity changes. Currently, the revenue generated from electricity generation is the most significant portion of the system's income; as such, small changes in the value of the electricity are expected to show significant increases in the required payback time. It is clear that as the electricity price decreases, the payback time increases; however, again, the required time is below the system's lifetime, indicating net profitability can be achieved, and thus, the system remains economically feasible. Interestingly, should the electricity price continue to deflate or deflate at a much faster rate than chosen for the scenarios, it is expected that the system

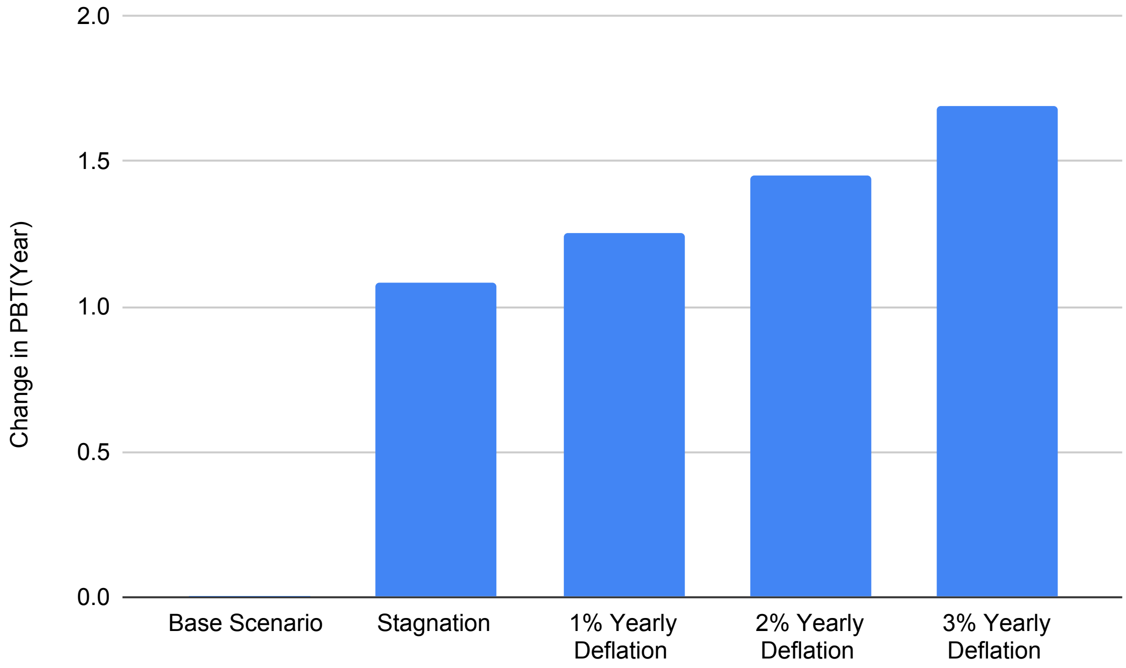

Figure 8.5: Variation of Integrated Systems Payback Time with changing values of electricity

would never reach its payback period as the revenue from the electricity would decrease beyond a sustainable level.

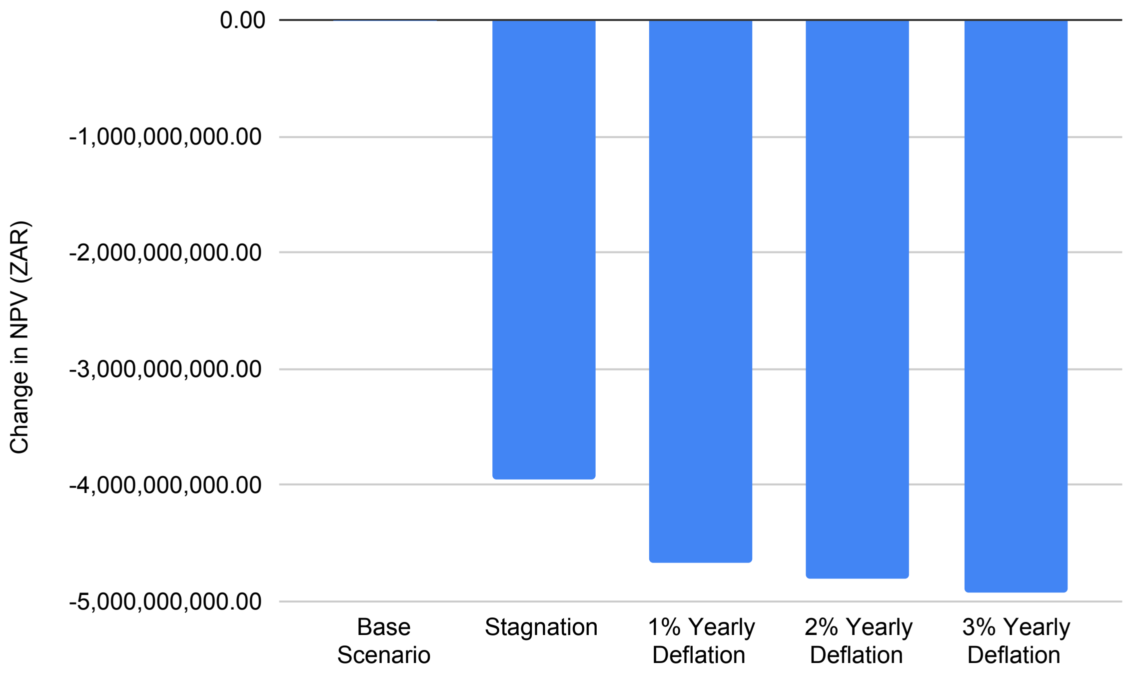

Figure 8.6: Variation of Integrated Systems Net Present Value with changing values of electricity

Figure 8.6 shows how the NPV of the integrated system varies as the value of electricity changes. Like with the NPV in the changing tyre prices scenarios, the NPV here was calculated using the economic model by changing the inflation rate for electricity before calculating the results using Equation 4.2. These values were scaled by subtracting the base scenario value from each to determine how the scenarios change relative to the base scenario. As mentioned previously, the revenue generated from electricity makes up the most significant portion of the earnings of the system; in particular, the high level of inflation that South Africa is both experiencing and expected to continue to experience contributes significantly to the future outlook of the system. This is strongly evidenced by the difference between the base scenario and the stagnation of the electricity prices, where the NPV drops to nearly a quarter of the base scenario. An interesting takeaway from the stagnation case is the costs of the system and the value of the other revenue sources continue to increase with general inflation, representing a scenario where the remaining goods of the country catch up to the excessive electricity inflation level of the past 20 years. The 3 scenarios where the value of electricity is actively reducing show decreasing results for the NPV, with the 3% yearly deflation showing a negative result. These negative results show the system is unable to recoup the initial investment cost over the 20-year lifetime, which would indicate that the system would no longer be economically feasible as an investment should the electricity prices in South Africa drop significantly in the future. However, in the 3% deflation scenario, there is a point where the net revenue flips negative; this occurs after 2035. Upon recalculating the NPV a positive result of R56,432,832.86 is obtained. This highlights that a climate of decreasing electricity prices would result in a much shorter lifetime for the integrated system; however, it is still a worthwhile investment, even over this shorter time frame. With the significant changes to the NPV and the changing values of electricity, it is clear that the value of electricity is one of the most important factors in the determination of economic feasibility.

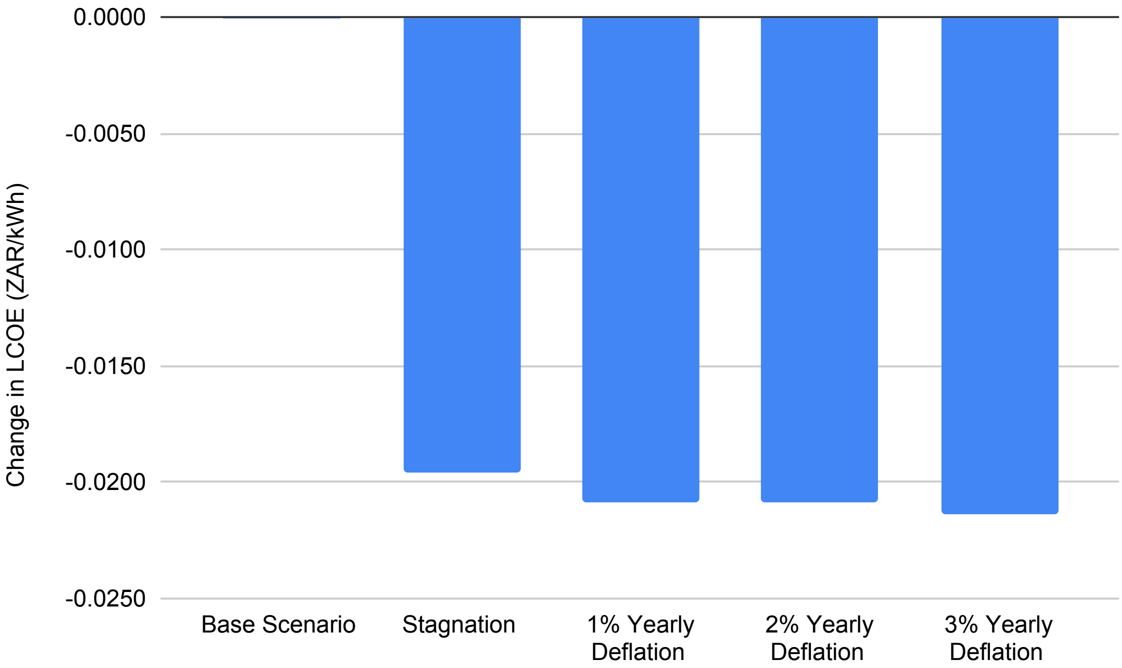

Figure 8.7: Variation of Integrated Systems LCOE with changing values of electricity

Figure 8.7 shows how the LCOE changes for the integrated system across the varying electricity prices. The LCOE was calculated by adjusting the inflation rate in the economic model before using Equation 4.3. These calculated values were then scaled with the base scenario again to show how the LCOE changes with respect to the base value for each scenario. The transition from the the base scenario to the stagnation scenario shows a decrease in the LCOE, which is expected as the LCOE is calculated from the systems costs and would have a decrease in costs initially as the cost of the electricity to run the pyrolysis system would decrease resulting a lower operating cost which in turn lowers the LCOE. The remaining three scenarios show no change in the LCOE. This relation is because the remaining costs are increasing while the electricity cost is decreasing; as such, they are balancing each other out, resulting in a steady LCOE across the three scenarios. The LCOE in each scenario is still below the average LCOE of ESKOM, and even in the worst-case scenario represented here, the average value of electricity is still greater than the LCOE, indicating the system can be economically feasible as an electrical generation source.

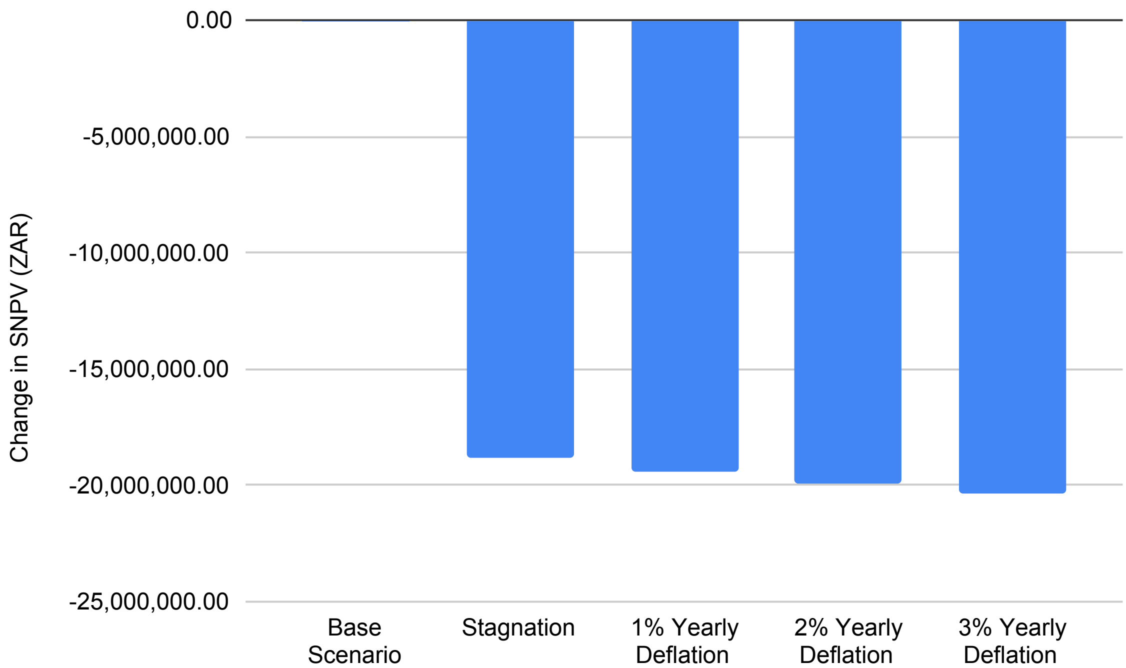

Figure 8.8: Variation of Integrated Systems SNPV with changing values of electricity

Figure 8.8 shows the results of the SNPV over the changing scenarios. These values were calculated by adjusting the inflation rate in the SCBA framework outlined in Chapter 7 before using Equation 4.4 to calculate the SNPV for each scenario. The SNPV of each scenario was then scaled down with the base scenario, showing how the results change as the electricity value changes with respect to the baseline value. very slight decrease in the benefit to society can be observed across all of the scenarios; this is attributed to a decrease in the value of the electrical grid services provided by the integrated system. While there is a slight decrease, each scenario still shows a significantly positive outcome for society. This is due to the high valuation placed upon the addition of new generations to the grid, which is not affected by the electricity price as it is a measure of missed-out economic output across the country. As such, the implementation of the integrated system can still be considered to be socially feasible solely down to the increased electricity.

As for the other factors of the SCBA, it is unlikely there will be any change in the outcomes as the price of electricity decreases; if anything, the decreasing price of electricity would represent an increase in the quality of life across the country due to decreased utility expenditure for the population.

9
Discussion

This Chapter discusses the design, economic, and societal feasibility of a 37,002-tonne-per-year integrated pyrolysis and electricity generation system. The discussion covers the steps involved in this research. It focuses on how each one contributes to answering the main research question on the socio-economic feasibility of implementing an integrated waste tyre pyrolysis and electricity generation system in the Gauteng region of South Africa. This research question focuses on the economic and social aspects of the study. It addresses the significant challenges of waste tyre management and electricity imbalances in South Africa, with a solution from readily available technologies coupling the two challenges together to create a favourable investment opportunity that heavily benefits society with various effects. Within the discussion Chapter, the key findings, implications, limitations, and areas of future research will be highlighted and elaborated on.

9.1. System Design

A theoretical design of the system was created to assess the feasibility of pyrolysis-based power generation. By linking the pyrolysis process of waste tyres to the electrical generation process of an external gas turbine, a single integrated system that effectively processes waste tyres into electricity was created. The sizing of the system is based on the availability of tyres in the surrounding regions, the regulations of industrial plants, and the electrical market demands. Through the design process, it became clear that these technologies are compatible and ready to be integrated on a large scale, tackling two of South Africa's major challenges.

Historically, one of the most significant challenges with the economic viability of the pyrolysis process was the use case for the output materials. South Africa is no exception to this difficulty. Following this theme, the main limitation faced by the South African government and others in their research on large-scale pyrolysis systems was a suitable market for the outputs. However, instead of being a limitation, the compatibility of the two independent systems created one of the primary drivers for the economic feasibility of the integrated system. Using oil and char directly in the power generation process circumvented the need to rely on volatile and fluctuating markets. By avoiding the markets for the goods themselves and instead relying on the more highly regulated electricity market, the main challenge faced by pyrolysis in the past was effectively removed. This removal has benefits to the system, a reduction in the inherent economic risks of the wholesale markets due to natural supply and demand fluctuations and increased income projection due to the fixed electricity market pricing structure of South Africa.

9.2. Economic Feasibility

The results from the economic analysis indicate that an integrated pyrolysis and power generation system is an economically feasible solution to South Africa's waste tyre problem and its electricity generation imbalance. The economic analysis highlighted that the system's Net Present Value (NPV) is strongly positive, with lifetime cash flows exceeding the system's cost by a large margin. This result shows that coupling the waste tyre management and electricity sectors through an integrated system will be an economically feasible solution for the Gauteng region. The resulting high NPV is attributed to the elevated level of electricity prices that have been apparent in South Africa since the 2000s, providing equally elevated earnings per year. However, without these elevated electricity prices, it is unclear how economically feasible the integrated system would be due to the high initial capital cost of the electrical turbine system. When looking at the research by Khan et al., 2023 and Nkosi et al., 2020 both had positive NPV's for the pyrolysis-based systems. In particular, the study by Khan et al., 2023 is the closest representation of a waste tyre pyrolysis plant being used to generate electricity on a larger scale than the system in this study, with Pakistan being the case study. In their study, the resulting NPV was only slightly positive due to the waste tyres' procurement cost, significantly reducing the net revenue generated. Should the assumption around the availability of tyres made in the economic model cease to exist, the results of the NPV are expected to exhibit a much closer result to that of Khan et al., 2023, highlighted in the sensitivity analysis with the changing values of tyres scenarios. When comparing, this makes the case of Gauteng, South Africa, a much more economically feasible option for the integrated system, largely due to the government's ongoing subsidy schemes making tyres available and paying to have them processed.

Beyond the NPV, the payback time, calculated to be 5.4 years, aligns well with the typical values expected for biomass processing plants and is comparable to alternative pyrolysis systems found throughout research. With this expected PBT falling well within the system's lifetime range, it is economically feasible due to the ability to pay itself off by recouping the initial capital costs and more. When looking at the comparative research of the study by Khan et al., 2023, we see a payback time of around nine years for the waste tyre system, owing again to the procurement costs of the waste tyres. And the study by Nkosi et al., 2020 shows a payback time of 5 years. This result is also comparable to other waste-to-energy systems that use different technology, like gasification, with Gökalp et al., 2019 showing a payback time of 3.2 years in Turkey when designed for electricity generation. The payback time was expected to be higher given the large capital costs of the system and the need to pay off both the pyrolysis system and the electricity system. However, the sensitivity analysis gives insight into why the result is lower than the expectations with both the increasing waste tyre costs and decreased electricity value, bringing the payback time closer to that of Khan et al., 2023 and in line with the initial expectations.

The Levelized Cost of Electricity (LCOE) was another critical indicator evaluated, giving a metric with which the cost of electricity could be directly compared against other generation systems. The LCOE of 0.12 R/kWh for the integrated system was significantly below the competition of ESKOM and the current fixed price for electricity in South Africa. This result indicates that the integrated system is a cost-effective means of electricity production for the region of Gauteng. This level of LCOE suggests the integrated system can be competitive with renewable energy sources in South Africa; however, it relies on the current status quo of subsidies and negligible costs of end-of-life waste tyres. Nevertheless, from a purely electricity generation perspective, the system can provide a cost-effective alternative to the current ageing conventional energy system of South Africa.

Throughout the range of scenarios studied in the sensitivity analysis, electricity's value plays the most significant role in economic feasibility with regard to the NPV and the PBT despite a slightly lower inflation rate than the current one used for electricity. When looking at the results from the scenarios of adjustment to the electricity value, decreasing electricity values all showed significant drops in the net gain of the system and increasing payback times. These variations are all consistent with expectations, as the central area of revenue is the provision of electricity. Furthermore, the system's lifetime would reduce dramatically with decreasing electricity values as the system would reach a point where it operates at a yearly net loss. Unlike the NPV and the PBT, the value of the electricity had the opposite effect on the LCOE, reducing the operating costs and, thereby, the LCOE. In the scenarios of increasing cost of waste tyres, all three economic metrics showed worsening outlooks, with the NPV reducing, indicating a lower overall return, the PBT time increasing due to lower net cash flows and the LCOE increasing proportionally with the increased fuel costs. An interesting comparison is how the NPV and the PBT approached closer to the values shown in Khan et al., 2023 as the procurement costs increased for the waste tyres, highlighting the significant impacts on the final results, the availability of free tyres and how, as this change the economic feasibility will change with it.

A significant point of the results from the sensitivity analysis is that it proves the integrated system is economically feasible without government subsidies, as shown by the changing waste tyre values. This result is a key requirement the government highlighted in its Industry Waste Tyre Management Plan: that all processors must be self-sustainable without subsidies (Department of Environmental Affairs, 2010). Meeting this requirement further strengthens the economic feasibility of the system as it provides an additional revenue source, resulting in a shorter time to recoup the investment costs.

The results of the sensitivity analysis highlight that there are risks to the economic feasibility of the integrated system with the changing situations in Gauteng, South Africa. With the ongoing liberalisation of the electricity market and integration of renewable energy sources, the value of electricity in South Africa may experience periods of deflation as the level of competition increases and the average cost of generation decreases. Additionally, as the waste tyre stream and stockpiles begin to reduce through the implementation of the integrated system or alternative systems, the government may choose to cancel the ongoing subsidy schemes and financial support to induce a competitive market in its place. These changes would potentially cause the integrated system to be pushed out of economic feasibility as a waste tyre processing solution and an electricity generation option in the future.

9.3. Social Feasibility

The social cost-benefit analysis and the resulting social net-present value show that integrated pyrolysis and electricity generation are highly feasible for society. The benefits to the South African population far outweigh the carbon emissions cost from adding generation sources to the grid. In particular, when compared to the alternative waste tyre processing method of energy recovery as direct fuel, which is being actively pursued by the South African government (Department Of Forestry and Environment, 2022).

With the eight factors assessed, the integrated system benefits society significantly across various areas. The country's projected economic output will be improved by reducing the electricity imbalance and helping to ease the current period of load shedding. Electrical grid services are provided with the addition of an inertial power system regulating the local frequency. The localised location improves power quality and efficiency, reducing strain on distribution systems and costs borne by consumers due to higher efficiency.

The potential for the integrated system to act as a grid stabilisation solution in the future period of renewable energy integration South Africa is expected to go through makes the system an attractive addition to the region of Gauteng. Allowing for a higher level of renewable energy sources without worrying about the power quality and stability will act favourably for South Africa in its future decarbonisation plans. This action alone would be worth considering the system socially feasible, as it would pave the way for the energy transition while simultaneously providing a solution to the waste tyre stream.

Significant job creation is expected not only directly from the system itself but also from the development of the adjacent industries, such as the waste tyre pre-processing and storage industry, along with boosting the logistics industry in the surrounding area. This increase in job creation is proven to be a significant advantage to society; with national average unemployment in South Africa reaching 32.9%, the creation of a waste tyre processing system and surrounding industry represents a massive gain to society and the labour force.

Potential health improvements through reducing the waste tyre stream and stockpiles are expected to improve public health directly. Outside of the effects a reduction in the stockpiles has on insect breeding grounds, the reduction in illegal end-of-life tyres reentering the infrastructure represents a net benefit to the safety of the roads. This safety increase would directly contribute to a reduction in road accidents each year, with most fatal accidents attributed to burst tyres. A further potential benefit that is still being studied may be realised through the reduction of tyre stockpiles, which is a reduction in microplastics leaking into the environment. Tyres are a primary source of these microplastics, and by reducing the stockpiles through the process of pyrolysis, these particulates can be broken down and prevented from entering the environment (**plastics**). From just the potential lives saved by tackling the waste tyre stream, the integrated system is a feasible solution for society, not accounting for future benefits.

However, not all of the eight factors benefitted society, with an expected increase in carbon emissions further delaying South Africa from meeting its climate agreements. A drain on the government budgets through increased spending to fund the subsidy scheme for the waste tyre processor. And, an unfortunate cost of end-of-life dismantling and decommissioning once the system reaches the end of life, the costs of which are footed by the government and society in more cases than not within South Africa.

Nevertheless, the net result is a positive outcome for society and the economic development of the country, indicating that the integrated system is a socially feeble solution to pursue in the effort to tackle the waste tyre and electricity generation challenges. This positive outcome was further proven to be the case through the range of scenarios assessed in the sensitivity analysis, showing slight increases or decreases in the SNPV for each scenario. However, these results were all still a positive benefit to society, mostly due to the increased availability of electricity.

The use of eight independent factors builds upon the frameworks from both Sidhu et al., 2018 and Jamasb and Nepal, 2010 and highlights the social benefits of pyrolysis for waste tyre management compared to the studies analysed in the literature review. Furthermore, this goes a step further than the studies from Khan et al., 2023, Nkosi et al., 2020, Goksal, 2022, Gao et al., 2022 and Gökalp et al., 2019 where the societal benefits were written off under the sustainable processing of waste tyres and an area for future research. As for the results of the social feasibility, they are within expectations with the ongoing severity of load shedding, the growing stockpiles of waste tyres and the number of deaths from road accidents each year. The net result was expected to benefit society.

9.4. Socio-Economic Feasiblity

The two most important results for determining the socio-economic feasibility are the Net Present Value and the Social Net Present Value. These two results are strongly positive and account for different agents within Gauteng. In the case of the NPV, this result highlights the private case as the owner of the integrated system, showing that there is currently a strong investment case when accounting for the time variability. While the SNPV outlines the social case, with society being the intended agent of the result, it shows a strong incentive for society to encourage and pursue implementing the integrated system. Following the results of these two key indicators, the system can be deemed socio-economically feasible and answers the government's request for industry-led solutions.

9.5. Governmental IndWTMP Objectives

The South African government has struggled to develop and incentivise a viable waste tyre processing sector and industry following the cancellation of the REDISA plan (REDISA, 2023). This results in significant stockpiles and waste build-up of waste tyres each year. As they seek to remedy this through the Industry Waste Tyre Management Plan, the government has created a list of objectives and areas of focus for this plan and sector (Department Of Forestry and Environment, 2022).

One of the main focuses has been on the research into available technologies for waste tyre processing, with four methods being highlighted for focus in South Africa. Pyrolysis is one of these methods, with the government concluding the same result as past literature studies that the output product market poses the most significant risk to the technology. From this, a request for further research into the feasibility of the pyrolysis process and a viable solution to the main challenge faced by pyrolysis needed to be conducted (Department Of Forestry and Environment, 2022). This study has sought to provide a solution to the issue faced by the government, showing through sector coupling, pyrolysis of waste tyres is a feasible processing method that has further reaching benefits to the electricity sector, another central area in need of development in South Africa.

In its plans to develop a feasible waste tyre processing sector, a list of objectives was outlined for any potential systems or candidates to meet to prove feasibility from the government's perspective. This list contains five criteria that participants in the plan must work towards.

An important note from the government's plans is that, first and foremost, for a system to be eligible for government subsidies, it must be proven to be financially independent. It does not rely on the offered subsidies for waste tyre processing to ensure the system's economic feasibility. This primary concern has been met in the integrated system assessed in this study, fulfilling the first pre-requisite of the government's criteria.

The first objective specifies what areas of technology are shortlisted in South Africa. Pyrolysis is included on this list, with the focus of this objective being on the output products of each processing method. In the case of this study, a new off-take market, that of electricity, has been explored and shown to be socio-economically feasible. This decision directly meets the government's plans for the industry by creating a new market direction through sector coupling. Furthermore, the areas of intervention the government have outlined as part of its strategy in meeting this objective are the following, "Government intervention through policy changes to stimulate demand for tyres as an alternative fuel source where appropriate", further contributing to the incentive to couple these sectors.

The second objective focuses on increasing the processing capacity to meet the demand in both the processing and off-take markets. With the coupling of the waste tyre processing sector and the electricity sector, there is sufficient room for growth, and the capacity will be limited based on the number of available tyres in the long run rather than the demand of the product's market. Specifically for the system studied in this report, 37,002 tonnes of waste tyres would be processed yearly, equating to 21.7% of the annual flow of 170,266 tonnes of waste tyres each year. The addition of this system would double the current processing capabilities of South Africa, currently around 24% of the stream, helping to meet the demand for processing capacity.

Objective three is related to the adjacent industries to the waste tyre processing sector and, as such, is not directly met by the studied system in this paper. However, an increase in demand for these industries would indirectly work to benefit these industries, promoting optimisation and efficiency to meet the pre-processed waste tyre demand.

The fourth objective relates to the creation of jobs and small and medium enterprises (SMME) in the different sectors around waste tyre processing. Specifically, from the integrated system, an estimated 49 additional jobs would be created minimum for the full-time operation of the system, not accounting for the surrounding development of the adjacent industry. Furthermore, as proven by the economic feasibility of this system, it would contribute to the financial sustainability of SMMEs due to its resilience across varying scenarios and conditions.

Finally, the fifth objective seeks to equally distribute the gains across the industry. With the social cost-benefit analysis, it is clear that the gains are not limited to the waste tyre processing industry exclusively, but rather, they will impact each and every industry when coupled with the electricity sector. The integrated system analysed in this study meets the fifth objective just through the country's increased economic output by reducing load shedding.

9.6. Change in Goals

Within this study, the main goal of electricity generation was set during the designing and assessment of the system, sizing the system based on the requirements and limitations of the electricity grid. As the South African electricity system is in a transition period and has faced ongoing and past hurdles from the influence of ESKOM, the system was limited to 50 MW. Purposefully falling under the limit to generation capacity that would require registration and approval from the national energy regulator, NERSA. Furthermore, the decision to designate the integrated system as a peaking plant was made with the limitations of the NERSA, the influence of ESKOM and the period of greatest load shedding for the region of Gauteng in mind. These regulations, decisions and goals all, in turn, limited the number of waste tyres the system could process.

If the main goal had been to maximise the number of waste tyres that could be processed through this sector coupling approach, the size of the system would have been determined based on the availability of tyres in the region instead, with the sizing of the electricity system then being derived from the amount of fuel being produced each year. Given the large stockpile and inflow of waste tyres in the region, this would have resulted in a larger electricity generation capacity. This alternative design would most likely have yielded positive results as well, both economically and socially. Again, this is due to the positive results being dominated by the high value of electricity in South Africa. However, when it comes to practical implementation, a large electricity system may be more challenging with more pushback from the electricity system agents, potentially limiting the connection to the grid in fear of increasing competition to ESKOM. However, it is important to note that for this study, it was assumed that if the system was kept below the chosen size and given its specific designation, there would be no limitations placed on the connection and power provision to the grid. In reality, this may not be the actual outcome. In this case, the difference between the changing goals is uncertain, and which choice would benefit society more.

9.7. Assumption Limitations and Implications

Despite the promising findings, this study has several limitations, many arising from the assumptions made throughout. One of the primary limitations is the assumption that the continuous supply of waste tyres will be free of charge and that the stability of government policies and subsidies will ensure this supply. As shown in the sensitivity analysis, if the subsidies around waste tyre processing were to end, the economic outlook of the system, while still positive, would no longer be as attractive of an option. Additionally, the study assumed that the waste tyres would be delivered pre-processed to the door of the system. If this assumption were not to be the case, pre-processing capabilities would be required to be added to the system. As this is not accounted for in this study, it is expected to increase the system's CAPEX and OPEX further, potentially resulting in a change in the socio-economic feasibility.

Further limitations also arise from major assumptions about the integrated system's design and operation. Following the government's IndWTMP, the logistics solutions to provide waste tyres are expected to be covered as part of the incentive to waste tyre processors. As such, should this assumption be false due to changing policies or issues surrounding the supply chain, the integrated system is expected to incur additional operational costs in the form of the delivery fee for the waste tyres. This change would impact the system's economic feasibility and require further consideration to fully understand the possibility's risks.

From an environmental perspective, the pyrolysis products have been assumed to comply with South Africa's regulations, allowing for direct use in electricity generation. With the variability of tyres available in South Africa, a certain level of impurities is expected to make their way into the pyrolysis products. Resulting in the need for further purification or refining of the products before they are allowed to be used in the electricity generation process. Again, this would further increase both the CAPEX and the OPEX, tweaking the case for economic feasibility. However, it may increase the case for social feasibility.

9.8. General Limitations

A limitation outside of the assumptions made within this study is the specific location focus on Gauteng. This study is based on data and conditions specific to the Gauteng region, which may not be generalisable to other regions with different socio-economic and environmental contexts. Even within South Africa, the model is expected to change from region to region substantially due to the variations in electricity prices for each province, the connection availability to the grid and the supply of waste tyres. Therefore, the results and determined socio-economic feasibility are only applicable for the select case of Gauteng, South Africa, until further research is done to modify the setup to match the regional specifics.

While the study outlines a theoretically sound model, the practical implementation may encounter unforeseen technical issues that could impact efficiency and effectiveness. Integrating pyrolysis and power generation technologies requires careful planning and coordination to ensure seamless operation. Potential challenges would include managing pyrolysis by-products, maintaining high-temperature reactors, and optimising the power generation process. Another area that is a limitation to the model and the design is the use case of the excess pyrolysis gas; in this study, the gas has only been used to heat the reactor, and a small part was used in the startup of the electrical turbine. However, the remaining pyrolysis gas has not been considered further. Considering the excess gas, the outcomes would potentially change through an increased capacity availability for the electricity turbine or by reducing the size of the pyrolysis reactor.

South Africa has a varied and complex political climate, where, unfortunately, corruption has swayed many government actions in the past. The level of corruption in South Africa has not been accounted for with the socio-economic feasibility. In particular, the assumption that the system would be implemented smoothly, connected to the infrastructure of the electricity grid smoothly, and allowed to operate smoothly has been followed. This connection may not be the case with ESKOM, the electricity provider potentially proving to be the greatest hurdle in the intended sector coupling, as shown by their efforts to delay further and discriminate favour in integrating independent power producers (Creamer, 2024). This potential corruption is an inherent risk to operation with South Africa and cannot be accounted for sufficiently; it can only be minimised; this has been done with a focus on sector coupling and accounting for the societal benefits. This focus will make it more challenging for the project to be impeded by ESKOM with a clear outline of the gains society stands to make, along with the backing of the IndWTMP.

Finally, the extent of the environmental analysis covers the carbon emissions released from the combustion of the different products, ignoring any potential waste materials that need to be disposed of. Therefore, the long-term environmental impacts of the pyrolysis process, particularly related to air emissions and waste management, need to be further investigated. Due to tightening environmental standards, this limitation will become significantly more impactful in the coming years. Should the system be tested and implemented, continuous monitoring and improvements in emissions control technologies are essential to minimise the project's environmental footprint.

9.9. Practical Implications

One significant implication is that by integrating different industries, a system that uses pyrolysis to convert waste tyres into electricity can offer a viable solution to address South Africa's increasing waste tyre problem. By meeting the government's specified criteria and supporting the call for further investigation into pyrolysis as a workable solution, this research demonstrates how the primary obstacle to the long-term success of pyrolysis—a stable market for the end products—can be overcome by integrating two systems into one and directly demonstrating a practical application for the pyrolysis by-products, in this example, electricity generation.

A key practical implication of this study is the focus on sector coupling. Which involved reconsidering technologies that may currently have limited applications or play a niche role in single sectors and exploring how they could be utilised across multiple sectors. This approach may highlight alternative use cases for niche technologies within South Africa to tackle not only the waste tyre stream and electricity imbalance but also other challenges.

The creation of a social cost-benefit analysis (SCBA) framework that considers a wide range of factors is crucial for assessing future systems, especially in the context of the ongoing energy transition in South Africa. It is necessary to evaluate systems beyond their purely economic or technical benefits, particularly as non-monetisable factors such as quality of life and health play an increasingly significant role in the solutions to current challenges. The development of a comprehensive SCBA framework is required in order to effectively measure these wider considerations. From this study the framework can serve as a first step for future studies, ensuring that societal factors are accounted for in planning and implementation of future systems.

9.10. Future Research

The study is limited in scope and is based on several key assumptions made during the research. However, it has paved the way for exploring new research areas related to the potential of pyrolysis in addressing South Africa's waste tyre problem. The study's limitations have also identified areas for future research in finding ways to incorporate these limitations in future studies.

The next step following this study involves creating a simulation model of the system using a programme such as Aspen. This model will provide valuable insights into the operational flows of the system, including mass and energy balances, ultimately helping to optimise and efficiently integrate the pyrolysis and electricity systems together.

The study predominantly centres on the Gauteng province in South Africa, making use of its various advantages as an ideal location for implementing the integrated system. To fully understand the system's feasibility beyond this specific area, future research focused on alternative regions within South Africa or other countries is required.

The study's primary focus was on the design of an integrated system that maximised self-sustainable electricity generation in South Africa during peak demand periods while adhering to regulations for independent power producers. It would be interesting to research the design of a system with a different main purpose, such as maximising waste tyre processing capacity, and compare the size, expected results, and limitations with the original system. Additionally, expanding the turbine to provide heat as well as electricity could enhance efficiency and improve the economic and social feasibility of the system. Additionally, there are currently opportunities for further optimisation in the design an example is the use case of the pyrolysis gas beyond providing the reaction heat.

The study utilised three key indicators to conduct an economic analysis, which were then subjected to sensitivity analysis across various scenarios. Further research is needed to expand upon this economic analysis by improving the model to provide a more accurate projection of the economic feasibility of the integrated system. Additionally, further research on a wider range of scenarios in the sensitivity analysis, such as policy changes, economic climate changes, and failures of assumptions would create further insight into the future outlook of the system. This expanded research would offer more detailed insights into the economic feasibility of utilising pyrolysis for waste tyre processing and electricity generation, while also considering the system's resilience within the context of South Africa's ongoing energy transition.

Further research focusing on the environmental impacts of large-scale pyrolysis systems is required. This includes assessing the emissions from the integrated system, potential waste creation, and the wider impacts on the surrounding region. This study only considers carbon dioxide emissions, but a focus on alternative emissions is needed for the longer-term effects. Additionally, the assumption that the process has minimal waste by-products may not hold true; as such, this would need to be assessed further. It would also be interesting to compare these outcomes to alternative waste tyre processing and electricity generation systems to aid with the decision-making in the choice of solutions to these challenges. By combining economic, social, and environmental analyses, a multi-criterion analysis weighing the costs and benefits can be created, determining trade-offs and focuses for the future to reduce the costs.

Further research into the impacts on the surrounding industry, job creation, and health impacts would provide a greater level of detail into the social feasibility of the integrated system. This research would provide guidance on how the integrated system can be used to create a sustainable waste tyre processing sector within South Africa.

Finally, further research can be conducted on the ability of the integrated system and alternative powered turbine systems to provide grid stability and support services in South Africa, focusing on the changing electricity market and the role these independent systems will have within. This would simultaneously give further insight into the longer-term socio-economic feasibility while providing a clear option for South Africa to support the energy transition from a grid-secured perspective.

10

Governmental Recommendations

Based on the findings and limitations of this study, there are several recommendations that can be made to the South African government and the province of Gauteng. The first recommendation involves ensuring a stable and sufficient supply of waste tyres to the pyrolysis plant and waste tyre processors in general. To facilitate this, direct partnerships should be formed between the depots, transporters and the waste tyre processors, facilitated through the government. This would establish clear supply contracts and guarantees, ensuring mutual benefits for the parties involved in the future. As the waste tyre processing industry grows, so do the collectors, depots, and transporters in partnership. This approach would also help in achieving one of the five objectives outlined in the IndWTMP.

The history of waste tyre management and processing in South Africa has been impacted by changing policies and corruption, leading to unsuccessful attempts in the past. Shifting waste tyre management to an industry-based approach can reduce the corruption risk, especially when considering economic feasibility beyond subsidies. However, in order to attract industry interest in investing in these solutions, the government must ensure that subsidies and support for waste tyre processing remain in place. This will reduce industry risk and encourage the development of this sector. Establishing binding agreements between the Waste Management Bureau funded by the tyre levy can provide a guarantee that these contracts will be upheld, as the funding for the future has already been secured.

The integration of Independent Power Producers (IPP) into the grid has been limited by the management of the national electricity grid through ESKOM. This hindrance has slowed down the energy transition, particularly in the case of this study impacting the size of the integrated system. As the market moves towards liberalisation and the restructuring of ESKOM, policies for grid participation need to be revised to allow for larger independent systems to connect to the South African market.

The government's IndWTMP outlines that waste tyre processors will have access to funding and investment support. However, the plan is currently underdeveloped with no clear structure regarding the available support and the conditions to receive support. Tackling the waste tyre stream is vital for South Africa's continued economic development, but many of the solutions come with high initial costs. For South Africa to fully open the way for the industry to join the waste tyre processing sector, clear outlines regarding the available support, the conditions to receive it, and the key objectives that need to be met are necessary.

The government is strongly recommended to consider implementing pyrolysis systems as a feasible solution to address South Africa's waste tyre stream. This approach, to be pursued through sector coupling as outlined in the study, offers an economically feasible solution to overcome the significant hurdles faced by pyrolysis. The systems show net benefits for society, including alleviating load shedding, creating job opportunities, and establishing financially competitive electricity generation solutions to help regulate and stabilise the grid. Furthermore, this could pave the way for the swift introduction of renewable energy sources, reducing the impact of outdated coal plants.

11 Conclusion

This study assessed the socio-economic feasibility of implementing a combined waste tyre pyrolysis and power generation system in the Gauteng region of South Africa. The research addresses two significant challenges faced by the region and the country alike: waste tyre management and electricity generation imbalance. By integrating and coupling these two sectors, the proposed system provides a socio-economically feasible solution to simultaneously tackling these challenges.

The theoretical design of the combined system, joining waste tyre pyrolysis with electrical generation based on multiple real-world and literature examples, highlights the compatibility for integration. The economic analysis proves that the system is highly feasible, with a strongly positive Net Present Value (NPV) that benefits from the ongoing government plans and a payback time comparable to other waste-to-energy technologies. The Levelised Cost of Electricity (LCOE) calculated for the system indicates that it is a cost-effective means of electricity production that is competitive with current electricity generation sources in South Africa and will work to reduce excessive prices in the country.

The social feasibility, assessed through a detailed Social Cost-Benefit Analysis (SCBA), further supports the implementation of the combined system. The SCBA highlighted significant societal benefits, including job creation, improved power quality and efficiency, and contributions to reducing the electricity imbalance in the region, resulting in increased national economic output. Beyond these, the system is expected to contribute to the increasing level of public health and a reduction of road accidents as it works to reduce the stockpiles of end-of-life tyres. However, the combined system would add to the country's carbon emissions as it works to provide a higher electricity generation capacity. Nevertheless, the overall positive impact on society and the economy is clear.

The study has a number of limitations, primarily due to assumptions made throughout the design process. One of the most significant is the availability of a continuous supply of waste tyres at no cost to the system, which contributes to positive results when compared to past studies. Future studies should explore the feasibility of similar systems with varying assumptions, simulation modelling and further research into the impacts on the regional industry. Additionally, the environmental consequences or gains of large-scale pyrolysis used to power electric turbines require further study to determine the long-term effects.

In conclusion, this study demonstrates that a combined waste tyre pyrolysis and power generation system is a feasible and socially beneficial solution for Gauteng, South Africa. It addresses the critical issues of waste management and electricity generation through a sector coupling and integrated approach. The system is shown to be economically feasible, with a positive NPV, an expected PBT shorter than the lifetime and an LCOE that is well below the competition. Additionally, the system stands to provide a benefit to society, creating jobs, reducing the excessive ongoing load shedding and providing a support system for future grid stability. The research provides a strong foundation for future studies and practical implementation, highlighting the potential of sector-coupled solutions to drive the energy transition and tackle multiple challenges simultaneously.

A
Economic Model Additions

Megaflex Gen - Non-local authority

Transmission zone	Voltage	Active energy charge for loads [c/kWh] – High demand season [Jun - Aug] – Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Low demand season [Sep - May] – Peak	VAT incl	Standard	VAT incl	Off Peak	VAT incl	Transmission network charges [R/kVA/m]	VAT incl
≤ 300km	< 500V	457.47	526.09	139.18	160.06	76.00	87.40	149.80	172.27	103.36	118.86	65.90	75.79	R 13.09	R 15.05
	≥ 500V & < 66kV	450.29	517.83	136.41	156.87	74.09	85.20	146.87	168.90	101.10	116.27	64.14	73.76	R 11.96	R 13.75
	≥ 66kV & ≤ 132kV	436.03	501.43	132.08	151.89	71.74	82.50	142.25	163.59	97.88	112.56	62.13	71.45	R 11.64	R 13.39
	> 132kV*	410.94	472.58	124.47	143.14	67.61	77.75	134.09	154.20	92.26	106.10	58.54	67.32	R 14.72	R 16.93
> 300km and ≤ 600km	< 500V	461.20	530.38	139.74	160.70	75.87	87.25	150.46	173.03	103.59	119.13	65.72	75.58	R 13.18	R 15.16
	≥ 500V & < 66kV	454.78	523.00	137.76	158.42	74.81	86.03	148.38	170.64	102.10	117.42	64.77	74.49	R 12.07	R 13.88
	≥ 66kV & ≤ 132kV	440.31	506.36	133.37	153.38	72.41	83.27	143.62	165.16	98.85	113.68	62.72	72.13	R 11.73	R 13.49
	> 132kV*	415.06	477.32	125.76	144.62	68.24	78.48	135.38	155.69	93.16	107.13	59.09	67.95	R 14.85	R 17.08
> 600km and ≤ 900km	< 500V	465.79	535.66	141.10	162.27	76.60	88.09	151.94	174.73	104.59	120.28	66.33	76.28	R 13.33	R 15.33
	≥ 500V & < 66kV	459.35	528.25	139.17	160.05	75.57	86.91	149.84	172.32	103.14	118.61	65.43	75.24	R 12.18	R 14.01
	≥ 66kV & ≤ 132kV	444.81	511.53	134.75	154.96	73.16	84.13	145.09	166.85	99.88	114.86	63.37	72.88	R 11.80	R 13.57
	> 132kV*	419.24	482.13	126.98	146.03	69.00	79.35	136.75	157.26	94.11	108.23	59.72	68.68	R 15.07	R 17.33
> 900km	< 500V	470.48	541.05	142.58	163.97	77.38	88.99	153.49	176.51	105.62	121.46	67.03	77.08	R 13.42	R 15.43
	≥ 500V & < 66kV	463.92	533.51	140.52	161.60	76.28	87.72	151.31	174.01	104.12	119.74	66.07	75.98	R 12.32	R 14.17
	≥ 66kV & ≤ 132kV	449.27	516.66	136.08	156.49	73.89	84.97	146.54	168.52	100.86	115.99	63.99	73.59	R 11.91	R 13.70
	> 132kV*	423.32	486.82	128.29	147.53	69.70	80.16	138.17	158.90	95.14	109.41	60.38	69.44	R 15.18	R 17.46
WEPS energy rate excluding losses		406.59	467.58	123.15	141.63	66.89	76.93	132.67	152.57	91.28	104.98	57.92	66.61		

* 132 kV or Transmission connected

Distribution network charges for loads – Voltage	Network capacity charge [R/kVA/m]	VAT incl	Network demand charge [R/kVA/m]	VAT incl	Urban low voltage subsidy charge [R/kVA/m]	VAT incl
< 500V	R 26.01	R 29.91	R 49.31	R 56.71	R 0.00	R 0.00
≥ 500V & < 66kV	R 23.85	R 27.43	R 45.24	R 52.03	R 0.00	R 0.00
≥ 66kV & ≤ 132kV	R 8.52	R 9.80	R 15.77	R 18.14	R 21.01	R 24.16
> 132kV / Transmission connected	R 0.00	R 0.00	R 0.00	R 0.00	R 21.01	R 24.16

Transmission network charges for generators – TUoS [> 132kV]	Network charge [R/kW]	VAT incl
Cape	R 0.00	R 0.00
Karoo	R 0.00	R 0.00
Kwazulu-Natal	R 3.09	R 3.55
Vaal	R 10.29	R 11.83
Waterberg	R 13.18	R 15.16
Mpumalanga	R 12.23	R 14.06

Distribution network charges for generators* – Voltage	Network capacity charge [R/kW/m]	VAT incl
< 500V		
≥ 500V & < 66kV		
≥ 66kV & ≤ 132kV	R 21.03	R 24.18

* The Distribution network charge will be rebated by the Losses charge, but not beyond extintion

Customer categories [kVA or MVA = loads] [kW or MW = generators]	Service charge [R/account/day]	VAT incl	Administration charge [R/POD/day]	VAT incl
≤ 100 KVA/ kW	R 21.25	R 24.44	R 4.67	R 5.37
> 100 kVA/ kW & ≤ 500 kVA/ kW	R 97.04	R 111.60	R 27.22	R 31.30
> 500 kVA/ kW & ≤ 1 MVA/MW	R 298.57	R 343.36	R 54.04	R 62.15
> 1 MVA/MW	R 298.57	R 343.36	R 134.56	R 154.74
Key customers or Transmission connected generators	R 5 850.83	R 6 728.45	R 186.85	R 214.88

Ancillary service charge for loads and generators – Voltage	Ancillary service charge [c/kWh]	VAT incl
< 500V	0.60	0.69
≥ 500V & < 66kV	0.59	0.68
≥ 66kV & ≤ 132kV	0.57	0.66
> 132kV	0.53	0.61

* 132 kV or Transmission connected

Applicable to loads: Electrification and rural network subsidy charge [c/kWh]	VAT incl	Affordability subsidy charge [c/kWh] Only payable by non-local authority tariffs	VAT incl
11.63	13.37	5.69	6.54

Reactive energy charge [c/kVArh] (loads) – High season	VAT incl	Low season	VAT incl
21.03	24.18	0.00	0.00

Losses charge for generators

Distribution connected generators – Formula	Transmission connected generators – Formula
Distribution = - ((Energy produced x WEPS rate excluding losses) x (Distribution loss factor x Transmission loss factor-1)) in each TOU period	Transmission = (Energy produced x WEPS rate excluding losses) x (Transmission loss factor-1/Transmission loss factor) in each TOU period

Transmission loss factors for Distribution connected – Distance from Johannesburg		Distribution loss factors – Voltage		Generator loss factor	
≤ 300km	1.0107	< 500V	1.1111	Cape	0.9710
> 300km & ≤ 600km	1.0208	≥ 500V & <	1.0957	Kwazulu-Natal	1.0040
> 600km & ≤ 900km	1.0310	≥ 66kV & ≤	1.0611	Vaal	1.0200
> 900km	1.0413	> 132kV*	1.0000	Waterberg	1.0230
				Mpumalanga	1.0210
				Karoo	0.9950

* 132 kV or Transmission connected

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Figure A.1: Megaflex Gen pricing structure for independent parties in the South African Electricity market in 2022 (ESKOM, 2022)

Year	2022	2023	2024	2025	2026	2027
Variable Costs (OPEX) (ZAR)						
Water	15,164.48	15,771.06	16,401.90	17,057.98	17,740.30	18,449.91
Electricity Usage and Capacity Charges	17,551,246.53	21,095,361.55	23,792,794.65	26,830,724.55	30,257,393.61	34,122,759.13
Nitrogen	6,827,535.00	7,100,636.40	7,384,661.86	7,680,048.33	7,987,250.26	8,306,740.27
Labour Costs	28,842,870.00	30,573,442.20	32,407,848.73	34,352,319.66	36,413,458.84	38,598,266.37
Maintenance Costs	61,828,187.25	64,301,314.73	66,873,367.32	69,548,302.02	72,330,234.10	75,223,443.46
Carbon Tax	16,501,430.00	17,161,487.20	17,847,946.69	18,561,864.56	19,304,339.14	20,076,512.70
Total Costs:	124,829,200.30	133,241,290.87	141,036,029.99	149,411,846.27	158,428,806.59	168,149,297.82
System Output Revenue (ZAR)						
Electricity	193,946,856.25	230,119,268.75	259,434,700.00	292,434,793.84	329,632,499.62	371,561,753.57
Steel Wire	3,663,198.00	3,809,725.92	3,962,114.96	4,120,599.56	4,285,423.54	4,456,840.48
Tyre Processing Fee	11,470,620.00	11,929,444.80	12,406,622.59	12,902,887.50	13,419,003.00	13,955,763.12
Total Revenue:	209,080,674.25	245,858,439.47	275,803,437.55	309,458,280.89	347,336,926.15	389,974,357.16

Figure A.2: System Variable Costs and Revenues in Rand from 2022 to 2027

2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
19,187.91	19,955.42	20,753.64	21,583.79	22,447.14	23,345.02	24,278.82	25,249.98	26,259.98	27,310.38	28,402.79	29,538.90	30,720.46	31,949.28	33,227.25
38,483,252.16	43,402,629.75	48,952,942.92	55,215,636.47	62,282,799.95	70,258,591.67	79,260,861.20	89,423,000.10	100,896,055.19	113,851,144.86	128,482,225.19	145,009,261.40	163,681,869.30	184,783,503.60	208,636,283.34
8,639,009.88	8,984,570.28	9,343,953.09	9,717,711.22	10,106,419.66	10,510,676.45	10,931,103.51	11,368,347.65	11,823,081.55	12,296,004.82	12,787,845.01	13,299,358.81	13,831,333.16	14,384,586.49	14,959,969.95
40,914,162.35	43,369,012.09	45,971,152.81	48,729,421.98	51,653,187.30	54,752,378.54	58,037,521.25	61,519,772.53	65,210,958.88	69,123,616.41	73,271,033.40	77,667,295.40	82,327,333.12	87,266,973.11	92,502,991.50
71,118,910.53	73,963,666.95	76,922,213.62	79,999,102.17	83,199,066.26	86,527,028.91	89,988,110.06	93,587,634.47	97,331,139.84	101,224,385.44	105,273,360.86	109,484,295.29	113,863,667.10	118,418,213.79	123,154,942.34
20,879,573.21	21,714,756.14	22,583,346.39	23,486,680.24	24,426,147.45	25,403,193.35	26,419,321.08	27,476,093.93	28,575,137.68	29,718,143.19	30,906,868.92	32,143,143.67	33,428,869.42	34,766,024.20	36,156,665.17
178,642,817.71	189,986,861.18	202,267,923.85	215,582,639.69	230,039,071.74	245,758,178.07	262,875,478.64	281,542,952.65	301,931,201.30	324,231,915.99	348,660,699.50	375,460,295.34	404,904,290.51	437,301,368.32	473,000,202.11
418,824,408.62	472,098,873.40	532,149,850.09	599,839,311.03	676,138,871.39	762,143,735.83	859,088,419.03	968,364,465.93	1,091,540,425.99	1,230,384,368.18	1,386,889,259.81	1,563,301,573.66	1,762,153,533.83	1,986,299,463.33	2,238,956,755.07
4,635,114.10	4,820,518.66	5,013,339.41	5,213,872.98	5,422,427.90	5,639,325.02	5,864,898.02	6,099,493.94	6,343,473.70	6,597,212.65	6,861,101.15	7,135,545.20	7,420,967.01	7,717,805.69	8,026,517.92
14,513,993.64	15,094,553.39	15,698,335.52	16,326,268.94	16,979,319.70	17,658,492.49	18,364,832.19	19,099,425.47	19,863,402.49	20,657,938.59	21,484,256.14	22,343,626.38	23,237,371.44	24,166,866.30	25,133,540.95
437,973,516.36	492,013,945.45	552,861,525.02	621,379,452.95	698,540,618.99	785,441,553.34	883,318,149.24	993,563,385.34	1,117,747,302.19	1,257,639,519.42	1,415,234,617.10	1,592,780,745.24	1,792,811,872.27	2,018,184,135.32	2,272,116,813.93

Figure A.3: System Variable Costs and Revenues in Rand from 2028 to 2042

B

SCBA Additions

Benefits:	2022	2023	2024	2025	2026	2027	2028	2029	2030
Electrical Grid Services (ZAR)	511,000.00	495,670.00	480,799.90	466,375.90	452,384.63	438,813.09	425,648.69	412,879.23	400,492.86
CoLS (ZAR)	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00
Labour Creation (ZAR)	28,842,870.00	30,573,442.20	32,407,848.73	34,352,319.66	36,413,458.84	38,598,266.37	40,914,162.35	43,369,012.09	45,971,152.81
Total Benefits (ZAR)	638,082,620.00	639,797,862.20	641,617,398.63	643,547,445.56	645,594,593.46	647,765,829.45	650,068,561.04	652,510,641.32	655,100,395.67
Costs:									
Carbon Dioxide Emissions (ZAR)	16,501,430.00	17,161,487.20	23,397,550.00	24,333,452.00	25,306,790.08	26,319,061.68	27,371,824.15	28,466,697.12	29,605,365.00
Decomissioning Costs (ZAR)									
Wate Tyre Processing Susbsidy (ZAR)	11,470,620.00	11,929,444.80	12,406,622.59	12,902,887.50	13,419,003.00	13,955,763.12	14,513,993.64	15,094,553.39	15,698,335.52
Total Cost (ZAR)	27,972,050.00	29,090,932.00	35,804,172.59	37,236,339.50	38,725,793.08	40,274,824.80	41,885,817.79	43,561,250.50	45,303,700.52

Figure B.1: System Costs and Benefits in Rand from 2022 to 2030

Benefits:	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Electrical Grid Services (ZAR)	388,478.07	376,823.73	365,519.02	354,553.45	343,916.84	333,599.34	323,591.36	313,883.62	304,467.11	295,333.10	286,473.10	277,878.91
CoLS (ZAR)	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00	608,728,750.00
Labour Creation (ZAR)	48,729,421.98	51,653,187.30	54,752,378.54	58,037,521.25	61,519,772.53	65,210,958.88	69,123,616.41	73,271,033.40	77,667,295.40	82,327,333.12	87,266,973.11	92,502,991.50
Total Benefits (ZAR)	657,846,650.05	660,758,761.03	663,846,647.56	667,120,824.70	670,592,439.37	674,273,308.22	678,175,957.77	682,313,667.01	686,700,512.51	691,351,416.22	696,282,196.21	701,509,620.41
Costs:												
Carbon Dioxide Emissions (ZAR)	30,789,579.60	32,021,162.79	33,302,009.30	34,634,089.67	36,019,453.26	37,460,231.39	38,958,640.64	40,516,986.27	42,137,665.72	43,823,172.35	45,576,099.24	47,399,143.21
Decomissioning Costs (ZAR)												127,444,662.63
Wate Tyre Processing Susbsidy (ZAR)	16,326,268.94	16,979,319.70	17,658,492.49	18,364,832.19	19,099,425.47	19,863,402.49	20,657,938.59	21,484,256.14	22,343,626.38	23,237,371.44	24,166,866.30	25,133,540.95
Total Cost (ZAR)	47,115,848.54	49,000,482.48	50,960,501.78	52,998,921.86	55,118,878.73	57,323,633.88	59,616,579.23	62,001,242.40	64,481,292.10	67,060,543.78	69,742,965.53	199,977,346.79

Figure B.2: System Costs and Benefits in Rand from 2031 to 2042

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