Department of Chemical Engineering

Waste Tyre Recycling: Current Status, Economic Analysis and Process Development

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

The disposal of waste tyres has become an increasing problem in many countries worldwide. It is a costly issue for the whole tyre manufacturing and automobile industry, while the environmental costs over the years have reached significant levels. Current government's regulations which ban landfilling in some developed countries such as United Kingdom have sparked an increased interest in finding new ways to dispose of waste tyres in environmentally safe manner.

First part of this thesis explores the current status of the industry and identifies the most promising technologies which could provide a suitable solution for safe disposal of tyres. Once identified, the technology with the biggest potential is screened through a series of experiments which will form a basis for further process development. Finally, an in-depth economic analysis will evaluate the commercial feasibility of newly developed process and identify key recommendations for further work.

After careful consideration, the pyrolysis of waste tyres was chosen for further process development and experimental research. The main goal of this work was to develop a suitable process for safe disposal of tyres and develop a unique tool which will provide a guideline on the process conditions required in order to optimize the production of a specific product. This tool, known as POT (Product Optimization Table) will play major part in identifying key operating conditions required for optimizing the overall process economics.

Key findings in this report concentrate on identifying best possible process conditions required to make the process as economically favorable as possible at current market conditions. This is achieved by completing a case study together with a number of different economic models and looking at what makes the particular model economically viable. The result of this economic analysis points out a few major limitations of waste tyre pyrolysis process and dwells deeper into finding the key causes for this.

Key recommendations presented at the end of this report are aimed at tyre manufacturing industry as well as relevant government bodies. Federal governments of developed nations are to play a major role in promoting the commercialization of the waste tyre pyrolysis technology. It is clear that new technology such as pyrolysis which is characterized by high risk and minimal returns is going to struggle in today's market. Implementing the recommendations given in this report is crucial in order to encourage significant investments into technology such as pyrolysis and aid the further development and commercialization in the near future.

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Chapter 1 : Introduction

1.1 Introduction

In recent years, one of the biggest growing environmental problems in the world has been the management of scrap tyres. The difficulty in disposing them makes the scrap tyres an unwanted commodity. However there is a growing interest in developing technologies which will not only help with the management and disposal of scrap tyres, but will also make them a good source of income. This income constitutes of tyre collection fees, as well as marketing the value added products manufactured from processing waste tyres. Nevertheless, the costs associated with the already trialled technologies are high which prevents any significant profit from being generated. This lack of profitability makes the processing of tyres unappealing business prospect and this is why the development of new technologies has been moving at a slow pace over the years. However, the environmental authorities in many countries have adopted regulations which ban some of the current tyre disposal methods and have imposed heavy fines for breaching these. Currently this is the basic driver for the development of new solutions.

Tyres are a very difficult waste to process because of their complex structure. The tyre has been built in a way as to resist high wear and tear, and to be “unbreakable”. In order to achieve this, tyre manufacturers combine steel, textiles, a rubber matrix and various additives, including carbon black, aromatic extender oils and zinc oxide. Trying to process something that has been manufactured to be durable and tough is a difficult and energy intensive task. This is why many companies have opted for an easier solution of land filling the tyres, reusing them in some way or just stockpiling them and waiting for a better solution to come their way.

Despite all this, the latest analysis shows a significant decrease in percentage of tyres being disposed of to landfill. This is mainly due to new rules and regulations on scrap tyre management, imposed by the environmental authorities in many developed countries. However at 17 % it is still the third most significant tyre management option throughout the world after energy recovery and mechanical processing.

1.2 Objectives

The main objectives of this research are to review and appraise the current status of the scrap tyre recycling in the world, develop an in-depth economic analysis and expand on the current process development. The report is divided into three parts and it considers all of aspects mentioned above. The scope of the report is worldwide and it considers the problem as a global issue rather than local. Economic analysis and appraisal of the current situation will vary depending on the location and it can have significant effect on the final result. This is why even though the problem is global the report tries to focus on those countries where there is a greater interest in finding an alternative solution to landfill disposal of waste tyres.

In addition, the report will evaluate the existing technologies and compare them in a technical, commercial and economic terms before reaching the conclusion on which of these have a greater potential to be adopted commercially in the near future. Another part of the report will focus on the discussion of results obtained from a series of experiments conducted on pyrolysis of scrap tyres. The experiments were done in order to further understand and develop this particular thermal treatment, as well as to provide the possible solutions to current limitations of this technology. Current problems of pyrolysis have been both technical and economic [1]. A detailed study of these limitations is essential not only to understand the reasons why this technology has not been successfully commercialized to date, but also to further develop the technical aspects of it and to test it under new and improved conditions.

1.3 Thesis outline

This thesis is structured into 6 chapters as briefly outlined and described below.

Chapter 1 introduces the topic of waste tyres and it covers the scope of the thesis, as well as the objectives and a brief outline of the report.

Chapter 2 provides an in-depth look into scrap tyre industry and its current status. It identifies some key drivers responsible for further technology development as well as an overview of current rules and regulations worldwide regarding the safe disposal of waste tyres.

Chapter 3 examines the current management options for waste tyres and provides a brief evaluation of each. It also provides an insight on which technologies provide the best potential for future development.

Chapter 4 covers the process development which includes an in-depth analysis of a simple waste tyre pyrolysis system. The results obtained from lab scale experimental runs are presented and discussed in order to examine the effect of different process parameters have on the quality and ratio of final products. Further developments will be identified and presented in this chapter, together with any recommendations for further study.

Chapter 5 analyses the feasibility of commercial pyrolysis process by developing a number of different economic models and evaluating them. This economic analysis utilizes the key findings from experimental studies which are presented in Chapter 4 and searches for the “perfect” financial model.

Chapter 6 concludes the thesis and provides recommendation for any future work to follow.

Chapter 2 : Literature Review 1 - (Industry status)

2.1 The problem of scrap tyres

The problem of scrap tyres is not recognised within the society as a major concern but many professionals will agree otherwise [2]. In recent past most of the environmental concern has been raised around the emissions of greenhouse gases, with solid wastes being in the shadow for much of the time. However, this is slowly changing and the main reason for this are increasing stockpiles of waste tyres worldwide. More and more are scrapped every day mainly due to increasing use of vehicles and stricter rules on what is acceptable as a road-worthy tyre. Another reason for such a high volume being stockpiled is due to a lack of markets for scrap tyres as well as more rigorous government regulations prohibiting many of the old disposal methods such as land filling.

Apart from being breeding grounds for disease spreading mosquitoes, the tyre dumps are considered a major fire hazard. They are extremely hard to control and once alight the solid waste problem becomes a greenhouse gas problem with millions of tonnes of toxic gases being released to atmosphere [2]. Therefore, even though it is not considered a major environmental problem at the moment by many, waste tyres can easily become one if this accumulating trend continues.

2.1.1 How big is the problem?

The latest survey completed in 2008 indicates that over a billion tyres are scrapped each year worldwide [3]. This is more than 13 million tonnes of waste which needs to be dealt with and disposed. This figure is based on the growth in production of new vehicles, the lifetime of a tyre as well as the mileage travelled each year. It is important to keep in mind that the above estimate is based only on the number of new scrap tyres arising each year, not including the existing stockpiles and landfills. Add these two categories as well and scrap tyres become the single biggest waste problem in the world [2]. Additional bad news is that this trend is not going to slow down anytime soon. Increase in world population as well as the dependency and availability of more affordable vehicles will require high level of production of new tyres, resulting in further scrap tyre arising. Some predictions propose the scrap tyre arising will reach staggering 17 million tonnes per annum by year 2012, which is equivalent to 1.4 billion tyres [4]. However, one limiting factor in the long term future will be the shortage and pricing of fuel, which should decrease the vehicle use across the world. Regardless of what the future trend is going to be, the current situation requires development of alternative management options for scrap tyres. The map below represents the worldwide percentage of tyres being scrapped each year, by regions of the world and countries.

Source: WBCSD Managing End of Life Tire Report (2008) [ref. 67]

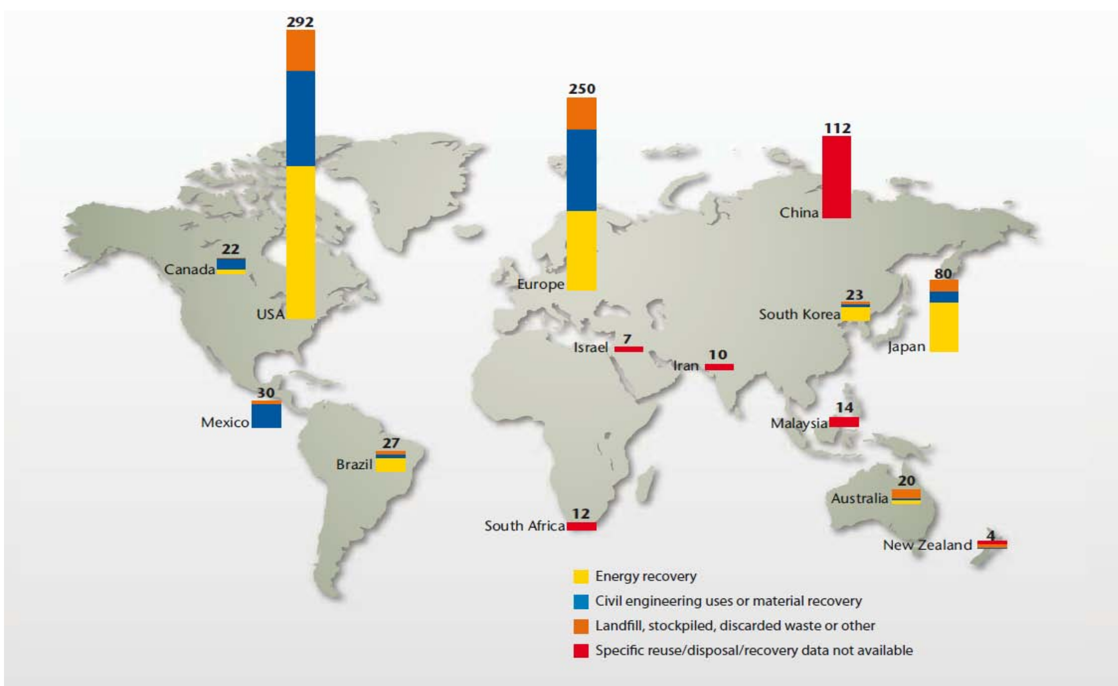


Figure 2-1: Worldwide annual scrap tyre arisings by region.

2.1.2 Source reduction and tyre reuse

Over the past forty years there have been great strides to try and extend the life of tyres which would reduce the rate at which tyres are being scrapped. New technologies developed by the tyre manufacturers have improved the average lifetime of tyre from 40,000 to 60,000 miles, with some tyres designed to sustain up to 80,000 miles [2]. However this is not the only factor influencing the life of the tyre. Other important factors include the speed and style of driving, road conditions as well as the local climate.

One of the recycling alternatives is different reuse of tyres. Very often when one or two tyres of a set are worn out, the whole set is replaced, leaving some useful tread on the remaining ones. These tyres are frequently resold as second hand tyres, or exported to other countries with higher legal limits on thread depth and reused there [5].

On the other hand some of the worn tyres undergo retreading. This process involves application of a new tread to scrap tyres that still have a good casing. Even though retreading has the advantage of reducing the quantity of oil, rubber and steel required for making new tyres, this form of scrap tyre management is on the decrease. Market for retreated passenger tyres is declining as a result of increase in the competition from suppliers of cheap new tyres, mainly from Eastern Europe and Asia, and common public misperception that retreads are unsafe [5]. Another contributing factor in this decline trend is the production of "buffings", which is unwanted tread rubber that is "buffed" away before the new tread is applied to the tyre casing [5]. This creates additional problem of managing residue stream and adds additional cost to tyre retreading process. Noticing the continuous downfall of tyre retreading, governments in some countries have tried to encourage the use of retreaded tyres. In 1988, US Environmental Protection Agency has introduced "*Guideline for Federal Procurement of Retread Tires"* 40 CFR Part 253, requiring that all federal, state and local government agencies must purchase retread tyres to a maximum degree [7]. This guideline also applies to contractors in receipt of federally funded contracts. Even with an increased number of governments introducing similar rules and regulations, the number of passenger tyre retreads is reaching record lows. This continuous decline will considerably increase the number of scrap tyres that require alternative management option and will put added pressure on already troubled industry.

As the retreading of passenger tyres is becoming less common, truck tyre retreading business is increasing. Analysis completed by Juniper Consulting suggests up to 50% of truck scrap tyres are being retreaded at the moment [4]. This is a significant amount considering the truck tyre is nearly three times the size of the passenger tyre. However, all of the above recycling solutions only slow down the rate at which tyres are scrapped but do not solve the problem on the long term basis, so further process development is required.

2.1.3 Processing scrap tyres

The tyre structure is very complex and includes materials such as steel, textiles, rubber matrix (carbon-sulphur cross links) and various additives such as carbon back, aromatic extender oils and zinc oxide [8]. This makes them very difficult to process and requires a significant amount of energy in order to produce new raw materials. As a result, many pilot plants and smaller commercial projects all over the world have failed. These tyres are made to last, to be “unbreakable”, so it is no wonder that the biggest challenge will be developing technology which will successfully process the scrap tyres. A more in-depth analysis of possible management options is discussed later in the report.

2.1.4 Tyre landfills

Due to the high cost and difficulty in processing such a waste, many tyre disposal companies have opted for a cheaper option of sending their waste to landfill. However, tyres are very difficult to landfill because they do not compact well and they tend to work their way up to the surface [2]. In addition fear of soil and groundwater pollution has caused further support for ban on landfill and in some countries environmental agencies have imposed rules and regulations in order to control disposal of scrap tyres [9].

Disposal of tyres is becoming more expensive and this trend will continue in the future as less and less space becomes available for landfill. One of the key reasons for increasing tipping fees at landfills is due to past incidents involving scrap tyres. A number of large underground fires caused by scrap tyres in the landfill being set alight, has caused a great damage to the local environment by polluting the air, soil and groundwater. The best known incident happened at landfill site in Powys, Wales, where scrap tyres fire burned underground for 9 years, before extinguishing itself [4]. The main problem with such fires is the difficulty in controlling them and also in putting them out. It is dangerous to try and extinguish the fire with water because the runoff which contains the different hydrocarbons can potentially contaminate nearby soil and groundwater [10]. The only solution remaining is to let the fire extinguish itself eventually. However, air pollution generated from such a long lasting fire can cause more than enough damage to surrounding environment [10].

It is very important to avoid mixing tyres and other types of waste in landfill. The methane gas produced by the decomposition of organic waste is trapped in void between tyre membranes and is possible ignition source resulting in fire or even explosion. However, the more common occurrence is the instability of landfill site resulting from the methane gas carrying the scrap tyres up to the surface [5].

Finally the biggest environmental concern caused by scrap tyres being deposited in landfills is the possible contamination of surrounding groundwater and soil [11]. There has been a great debate over the years between environmentalists and other experts concerning this issue. In the late 1980’s a number of studies reported no threat to ground or surface water when in contact with scrap tyres. However one particular study conducted by the Minnesota Pollution Control Agency showed that the leachate from scrap tyre samples in acidic conditions contains traces of heavy metals exceeding the legal limits in drinking water [4]. Subsequent studies on the same issue found no evidence to support these claims. Even though there is a lack of proof that disposal of tyres to landfill causes soil and groundwater pollution, there is a general concern among the public about the possibility of such a contamination occurring in the surrounding environment.

If landfilling is a chosen option then it is preferable to landfill shredded tyres since they take much less space than the whole tyres and this also eliminates the buoyancy problem whole tyres have. Shredding can reduce the volume of tyre by up to 75 %, eliminating the void created by a whole tyre [2]. Even the tipping fee for the shredded tyre is much lower than the fee for a whole tyre, reflecting the space required to landfill both. Additional savings can be also made by reducing the transportation as fewer trips are required to landfill site and back. This saving is significant and it can be as much as 60% of transportation costs [4]. However, it is important to remember that shredding of tyres requires an extra processing step which will add considerable cost. This cost is variable and depends on the product size as well as the throughput required. In addition a large capital investment of few hundred thousand dollars is required when purchasing and setting up a shredder. This is a main limiting factor for some of the smaller companies as such a large investment is not an option for them. As a result they are either forced to pay high fees to other shredding companies to do the job or they decide on sending whole tyres to landfill. Either way the company will incur additional costs.

Higher disposal costs, together with new legislations put in place have forced many companies to rethink their strategy and possibly look at alternative management options for scrap tyres.

2.1.5 Tyre stockpiles

Restrictions on tyre landfill have resulted in increased number of tyre stockpiles in some countries. Close estimates by some of the leading industry experts point to more than 10 billion waste tyres currently being stockpiled worldwide and more are added to this figure each day [4]. The stockpiles of tyres can be a source of major health problems. The structure of these tyre piles together with doughnut shape of tyres is ideal for rainwater collection. This rainwater stagnates and becomes an elegant breeding house for vermin. Rats, birds and insects use this type of structure to hide and protect themselves from their predators [5]. However, the most significant health issue comes from mosquitoes using tyre dumps as breeding grounds. This appears to be a worldwide problem which is spread by the movement of tyres from one continent to another. For example, scrap tyre casings imported from Asia to U.S. contained mosquito larvae which matured and have spread a more violent strain of diseases [12]. Cases of deadly diseases such as malaria, dengue fever and encephalitis have been traced back to specific colonies in stockpiles of tyres.

Most of the countries in the world have not been active in avoiding further health risks due to lack of financial resources. Developed countries have been publicly criticized for exporting large numbers of scrap tyres to developing nations for “recycling”. These tyres will eventually become waste and the lack of resources in these third world nations will prevent the correct disposal, which will cause further health and environmental problems [4]. In these countries disposal of scrap tyres is not effectively controlled and illegal practises such as dumping tyres in open countryside as well as deliberate burning for heating purposes is very common. Pollution caused by this illegal burning for heat and fuel, as well as recovery of steel just adds to the global problem and it affects everyone, not only the nearby environment. This is why governments worldwide need to take a specific action not only in their home country, but also in other, less developed nations as well. Passing the problem to others is only a temporary solution and in due course it will have to be dealt with globally.

Even though tyres are not easily ignited and do not spontaneously combust, the stockpiles present an enormous fire hazard. Once afire they burn vigorously and they burn for days [13]. This is due to the easy access and exposure to air caused by their low bulk density. If the pile of tyres begins to burn, it does so with a hot, sooty and very malodorous flame. As a result an entire range of hazardous chemicals and even some carcinogens are emitted into the air [13]. The damage this can do to the nearby environment and people is frightening. And this is not all. The tyre pile can act like an enormous pyrolysis reactor due to the already burning tyres supplying an indirect heating to adjacent tyres. This results in a formation of petroleum oil, creating a runoff problem. This is where contamination of nearby groundwater and soil is more than likely if the runoff is not contained in time [5].

There has been a number of incidents in the past involving large scrap tyre fires. One of largest occurred in Ontario, Canada, where a large stockpile of over 14 million tyres set on fire in 1990 and it took 17 days for fire to be controlled and finally extinguished [14]. In order to do this, fire fighting services had to physically separate and remove unburned tyres before they set alight as well. This was the first case where samples of smoke and effluent gases were taken and tests performed on these samples documented the range of chemical compounds present [4]. Toxic metals such as cadmium as well as over half a million litres of oil resulted from the fire. Over CAN$12 million was spent on controlling the fire as well as immediate cleanup efforts [15]. But this is not all. Further CAN$5 million has been spent on a small water treatment plant in order to deal with contaminated water, as well as moving the contaminated soil and burned waste to a landfill [4]. Also the properties and farms adjacent to site were purchased by the government in fear of contamination.

As seen from the above sample, the total costs of dealing with a tyre stockpile fire can reach well into millions of dollars. The continuing problems with stockpiles and landfills are a main driver in search for new and more sustainable waste management practices, including the search for new technologies which will recover resources from tyres.

2.2 Technical and commercial challenges in processing scrap tyres

Tyres are one of the most difficult and challenging waste products to process. This is due to a large number of technical and commercial challenges the industry is facing. Indentifying and understanding these issues is the first step in developing the most appropriate option for scrap tyre management.

2.2.1 Technical challenges

The manufacturing process of tyres and its constituents is a key reason why recycling of scrap tyres faces many different technical challenges. As a result, the processing of the scrap tyres is much more difficult than many other waste products. To better understand the limitations of scrap tyre processing it is essential to investigate the production process and identify materials used in manufacturing the tyre.

The main issue with the structure of tyres is that not all tyres are the same. Depending on their intended use as well as the manufacturer, the makeup of tyres can vary significantly. This in turn effects the processing of scrap tyres down the track. A typical modern tyre consists of synthetic and natural rubber; textiles; steel; carbon black as well as a number of chemical additives [8]. The exact proportions of these materials vary according to manufacturer, usage and specific characteristics of the tyre itself. As an example passenger tyre has a much lower proportion of natural rubber then truck tyre [2].

Manufacturers of tyres specify the processing conditions and additives required in order to obtain the best performance and unique properties which will distinguish their product in an extremely competitive market. Different additives and different proportions of the same result in different levels of physical properties such as strength, skid properties, wear resistance and adhesion.

2.2.1.1 The basic components and structure of the tyre

The complex structure of a tyre is a major constraint in scrap tyre processing. In order to understand the scope of technical challenges scrap tyre industry faces today, we need to start at the beginning and look at the constituents of a tyre itself. Both natural and synthetic rubbers, such as cis-polyisoprene (CPI) and styrene-butadiene rubber (SBR), are used as constituents in the main tread, side wall and carcass of the tyre [16]. However these are not the only materials used as they alone do not provide tyre with the necessary strength. Addition of materials such as carbon black fillers and sulphur by the way of vulcanization solves this problem [5]. Vulcanisation process is further discussed in the section to follow.

Additional strength and rigidity of the tyre is attributed to steel reinforcement. The steel beads which anchor the tyre to the wheel rim are made up of high tensile bronze coated steel wire (98% Cu and 2% Sn) [4]. Breaker belts in tyres as well as the casing ply in truck tyres ensure that the tyre keeps its shape and helps resist punctures. Most of the manufacturers use high tensile brass coated steel cord (66-70% Cu and 30-34% Zn) in the construction of these [4].

Source: ref [15]

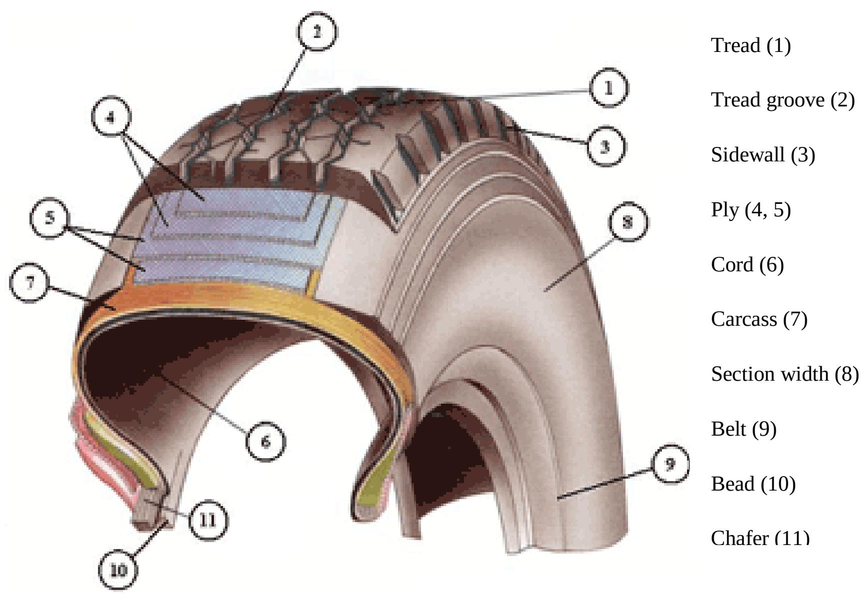


Figure 2-2: The structure of the tyre.

Other major components of a tyre which help improve its strength and structure are textiles. These are used as reinforcing cord in tyres. Different manufacturers use different types and quantity of textiles however the most common materials found in a modern tyres are fibreglass, nylon, aramid, polyester and rayon [5].

The table on the next page presents the most common additives and tyre constituents.

Table 2-1: Typical composition of tyres.

Component	Weight %
Rubber & Elastomers	46 – 62.1
Carbon black	21 – 31.0
Metal	17
Textile	6
Extender Oil	1.9
Zinc Oxide	1 – 1.9
Stearic acid	1.2
Sulphur	1.1
Accelerator	0.7

Source: Juniper Report [4]

Heavy organic compounds found in extender oils assist in processing rubber at the time of tyre manufacturing and together with other additives significantly alter the final properties and handling of final product. One compound present in tyre in small amounts (only about 1-2%) but a very significant obstacle in reuse of tyre-derived products is zinc oxide. The reason for its use in tyre manufacturing is to protect against UV degradation, enhance bleeding and control vulcanization [5].

It is important to note that the ratios of tyre components vary according to the type of tyre, classes of tyre as well as the manufacturers. This varying composition of a tyre has an effect on the composition and proportions of tyre derived materials. It is a very important factor to consider when evaluating different management options and different technologies.

2.2.1.2 Vulcanisation and de-vulcanisation of tyres

In 1839 the founder of vulcanisation, Charles Goodyear, perfected the process one way without considering the need for possible reversal in the future. This has left us with the dilemma of how to best separate the “Goodyear’s” idea of hydrocarbon chains in rubber cross linking through sulphur bonds [17]. Vulcanization creates an elastic three dimensional structure of these bonds and together with textile lining and steel reinforcement ensures the best possible performance of a tyre [17]. However it also creates difficulty in separating these components and makes it very costly to obtain clean and distinct tyre derived products.

The reversal process which includes removal of the sulphur cross links in order to retrieve the rubber from the tyre is called de-vulcanisation. It has only been recently that we have had the ability to successfully trial this process, however hours and hours of in-depth research have shown that de-vulcanisation is very impractical mainly due to the costly processing [18]. In spite of this, a combination of thermal, mechanical and chemical techniques has been used in India on a commercial basis [4]. The main reason for this is the wide spread use of natural instead of synthetic rubber in the manufacture of tyres in India, which enables it to be more easily de-vulcanised.

2.2.2 Commercial challenges

Apart from the difficult technical issues, scrap tyre recycling is facing a number of commercial challenges. These problems range from the transport and collection of scrap tyres, poor past track record, illegal practices as well as developing a market for the recycled and value added products from scrap tyres [5].

2.2.2.1 Challenges in collection and transport of scrap tyres

The shape and high volume to weight ratio of tyres makes them very difficult and costly to transport and dispose of. Because of such a low bulk density, transporting tyres is not very economic considering the fact that trucks and ships used never reach their load-carrying capacity. For example a 40 ft semitrailer has a maximum payload mass of about 25 tonnes but in some countries road restrictions restrict this capacity down to 22 tonnes. The same semi-trailer can hold approximately 1,000 to 1,200 25-lb tyres, depending on the way they are packed [4]. This in-turn creates a total load of about 12 to 14 tonnes, far less than its load-carrying capacity. It is important to realize that scrap tyres occupy almost as much space as they did when they were first manufactured [2]. This means that transport costs are the same, while the value of the product being transported is much lower. This is why scrap tyres tend to stay close to where they have been generated.

Due to the high transportation costs, tyre collection is usually regional or local business. This results in a number of small players, called ‘tyre jockeys”, who, for a fee, periodically pick up the tyre dealer’s scrap tyres and transport them to their place of business [19]. Some of these “tyre jockeys” have installed tyre shredders at collection points, which reduced the bulk and in turn reduced the transportation costs. It is rare to find a tyre collection business which operates on the national basis unless their business is restricted to smaller geographical areas and employs sub-contractors in order to improve the economies of scale [4].

2.2.2.2 Poor past track record

Looking at the past track record of the management of scrap tyres, it is easy to notice that apart from some mechanical processing and reuse of tyres, most of the developed commercial processing projects have failed. There have been numerous initiatives across North America, Asia and Europe and the reason for the disappointing results is attributed to many different factors. Some of these include [15]:

- Unreliable technologies, resulting in higher operating costs and lower production ;
- Underestimating the environmental compliance costs;
- Overestimating the value of tyre derived products and certainty of securing firm markets for these;
- False expectations about the ease of processing scrap tyres and optimistic assumptions about the revenues associated with such activity.

The above reasons will be further discussed in this report and a more detailed evaluation will be performed for a specific management option.

2.2.2.3 Illegal practises in scrap tyre collection and disposal

Increasing number of scrap tyres every year is only the part of the challenge posed. A more serious problem is the increase in illegal stockpiling and fly tipping of tyres. This trend has been on an increase worldwide, however the exact figures are not known. What is for certain is the fact that the environmental and health hazards from these illegal practices will be significant. Numerous incidents across the world, such as large tyre stockpile fires in United States, have increased the public's awareness about the difficulty and dangers of scrap tyre management. Fly tipping is a fairly easy business to enter due to the nature of scrap tyre collecting industry. Minimal initial investments and non standardised professional requirements make this industry very vulnerable to new smaller entrants. These smaller collectors operate on the low margin and high turnovers in order to keep their business running. In order to increase their profits and make their time worthwhile, some of them turn to illegal practices. It is these smaller "players" that contribute the most to current commercial challenge of safe disposal of scrap tyres.

2.2.2.4 Tyre derived products and their markets

Most of the research in scrap tyre management has revolved around the development of new processes which would yield value added products from scrap tyres. Finding the appropriate and viable markets for these products will ensure profits are generated, allowing alternative management options of scrap tyres to compete with the landfill disposal.

The main challenge in this sector is developing the technology which is going to be able to produce a viable product or ideally a process which is flexible enough to produce a wide range of products that can be a great source of profit. Ensuring the quality of the products is high, makes the second stage of finding the viable market much easier. This is why the primary focus of the project and business developers is on developing the best possible technology and then looking at securing the markets for the value added products.

Even thought the primary focus is on developing the technology, identifying the viable markets can be as much of a challenge. This is more than evident by looking at the most obvious market, the tyre industry itself. Even though it is expected for tyre industry to be the main user of tyre derived products, this is not the case. Use of scrap tyre rubber in production of new tyres is very rare and limited. This use accounts only about 5% of the total rubber content in new tyres [20]. This is mainly due to the poor quality of reclaimed rubber compared to virgin rubber, which in turn affects the lifespan of tyres, as well as the safety and performance in general. Another reason why tyre industry is so cautious in accepting reclaimed rubber is due to the large effort and resources already spent on plantations of natural rubber as well as developing technologies for the production of synthetic rubber. Using scrap tyre rubber would not only affect the quality of the new tyres but would also cost tyre industry millions of dollars by replacing the already developed virgin rubber production.

2.3 Key market drivers influencing the scrap tyre industry

Scrap tyre industry has dedicated decades and millions of dollars on intensive research for new and better scrap tyre management options and the trend is not likely to change in the near future. This is due to a number of key market drivers that also influence the growth of scrap tyre industry itself. The market drivers are sorted into three categories. They range from environmental, legislative to economic drivers. The following section reviews all of the above and examines the necessary efforts required by the tyre industry in order to meet the demand for new solutions.

It is very important to understand that not all of these drivers directly influence the tyre recycling industry. Some of them play an important part in automotive and tyre manufacturing industries, and indirectly affect the management of scrap tyres. As explained in the following examples, indirect drivers are as significant, and sometimes can even have more of an impact then the drivers which are directly associated with the scrap tyre industry.

2.3.1 Environmental Drivers

One of the most significant environmental impacts associated with improper tyre collection and disposal is definitely scrap tyre fires in landfills and stockpiles. As mentioned in previous section 2.1.4 and 2.1.5, these fires can burn for days resulting in high emissions of toxic gases as well as soil and groundwater pollution caused by the formation and runoff of hydrocarbons. Health impacts, such as the risks of disease and infection, resulting from large tyre stockpiles are also covered in section 2.1.5. The spread of malaria and encephalitis is directly linked to vermin and mosquito breeding in these stockpiles. This is a clear example of a direct market driver influencing the further development and growth of tyre recycling industry.

If we concentrate on the tyre manufacturing industry we can notice that there is a significant environmental concern relating the extensive use of natural and non-renewable resources. These resources are limited and continuous exploitation will cause an enormous damage to the environment in the long term. The main objective of developing a new solution for scrap tyre management is the conservation of these resources by either re-using tyres or recovering the main tyre's constituents. However as explained in section 2.2.1 this is not a straight forward task. De-vulcanizing the rubber is energy intensive and re-using tyres can account for only a small percentage of the total scrap tyre arisings. The other possible solution is the development of new technologies that target the production of higher value products such as carbon black and oil. This will recover the original value of used resources by reducing the use of virgin rubber and fossil fuels.

Improving the existing technologies in tyre manufacturing can help reduce the amount of energy needed in the production process. This directly attributes to the quantity of fossil fuels required and plays an important factor in reducing the CO_2 emissions. Some tyre manufacturers such as Dunlop claim that the fossil fuel consumption in their process today is approximately 40% lower than it was the case in 1985 [21]. On the grand scale this is a very significant amount. Improving the energy efficiency of their process, tyre manufacturers not only help conserve the global resources, but they also improve their operations financially. This is why leading tyre manufacturers continue to spend a lot of money on research and process development, and the trend is likely to continue in the future.

It is difficult to say from the environmental point of view if recycling and re-use of scrap tyres and its derived products is a preferable option to energy and resource recovery. Many experts argue that energy recovery is more sustainable and that it helps avoid the use of fossil fuels in processing with surplus being used for other production processes [15]. Also the energy recovery utilises all the constituents of tyres, especially the ones with high calorific value such as textiles, additives and rubber matrix. On the other hand the emissions created and unreliable technology raise a valid question about the true impact energy recovery from scrap tyres has on the environment. Material recycling is regarded as the preferred solution because it does not have a big impact on environment directly [2]. However, the indirect impact this option has on the environment is very significant. High energy requirements for processing suggest the high dependence on fossil fuels and additional CO_2 emissions. Difficulty in securing the markets for some of the lower end products could lead into this product having to be landfilled and indirectly having a negative impact on the surrounding environment. It is clear that no one solution is considered as the "better" option. This means that a possible integration of the two options together could possibly provide us with the solution necessary in order to meet the growing demand.

2.3.2 Legislative and regulatory market drivers

Legal market drivers consist of international rules and regulations as well as producer responsibility obligations, also known as PRO's. These PRO's can be both legally binding and voluntary initiatives, depending on the country as well as the nature of the industry in the particular region.

2.3.2.1 International rules and regulations

One of the main regulations that the governments all over the world have been trying to implement is the principle of the "Duty of Care". This principle simply ensures safe disposal of waste, including scrap tyres, by requiring some kind of proof from the last party handling the waste that it has been disposed of within the general waste rules and regulations [22]. This will help in ensuring that the scrap tyres are being disposed of in a safe and sustainable manner.

There has been a lot of talk about the shipment of scrap tyres to less developed countries and if this was considered to be within general waste rules and regulations. Basel Convention has ensured that the shipment of hazardous wastes to other countries is constrained. This prevents the developed countries passing their “problem” over to less developed countries that will struggle to keep up with the potential environmental issues created by disposal of hazardous waste [23]. However there is a one big loophole when it comes to scrap tyres. Scrap tyres itself are not considered as hazardous waste under Basel Convention, unless part of the scrapped vehicle [15]. Therefore, Basel Convention does not prohibit the export of scrap tyres to other countries, making this one of the most popular tyre disposal activities in the world. It is very beneficial and important to refine the Basel Convention in the future so it can include scrap tyres as well. If this does not occur, the cheap option of continually exporting tyres will slow down the development of alternative management solutions.

The most widespread ban within the developed world today is the ban on depositing tyres in landfill. The extent of the ban and the exact details of the regulations introduced depend on the country and the differences can be significant. For example, some countries like Japan have introduced jail sentence on top of the regular fines for not complying with the ban. On the other side of the world in the USA, 35 states have introduced a landfill ban on whole tyres, while only 9 states have banned the landfilling of both whole and shredded tyres [24]. Australian government opted for a more geographically based landfill bans. For example, in NSW scrap tyres have been banned from the metropolitan landfills only, while in the non residential country regions scrap tyres are allowed to be landfilled as long as they are shredded to a particular size [5]. Current laws specify this to be 250 mm per single piece of tyre [5]. It is a widespread belief that restrictions such as these are the single most important driver for new tyre recovery solutions today.

The biggest impact a single ban has made up to date is credited to European Directive 1999/31/EC, also known as the EU Landfill Directive. This landfill ban has been implemented by 25 member countries in 2006 and since then tyres in any shape or form are banned from landfills [24].

2.3.2.2 PRO's – Producer Responsibility Obligations

Producer Responsibility Obligations concept is based on the "Polluter Pays" principle and it ensures that producers are liable for the waste produced resulting from the use of their product [25]. The concept itself is very simple however the interpretation of it causes some confusion and complications between the involved parties. This is due to unclear definition of who is the producer in regard to tyre recycling. For example, is it a tyre or a car manufacturer that is considered to be a producer/polluter? If the tyre or a vehicle is imported is it an importer or a retailer who is responsible for the management of scrap tyres? The answer to questions such as these will vary according to the country as well as the regulations introduced by the governments in order to help with the identification of the responsible parties.

There is a popular view that the PRO's are not the best approach for encouraging the further development of waste tyre industry. Instead the emphasis should be put on developing a stable market for the recycling and value added products from waste tyres. Thus the financial revenue generated from marketing these products would be a key incentive for private sector investors to get involved in the industry. Additional incentives such as financial grants, taxation on non-recycled alternative products and removal of restrictive practices are only some of the examples which can be supported and introduced by governments all over the world.

2.3.3 Economic Market Drivers

One of the most influential market drivers influencing the development of scrap tyre management is the economic value of the waste itself. As long as the scrap tyres have a positive economic value and are viewed as a resource rather than a waste, then the demand for the scrap tyres will generate an income for the collection companies. The newly developed solution which is able to do this will attract more investment from the private sector because scrap tyres will be seen as a possible “gold mine”. This will ensure the tyre recycling industry grows even more and as a result better technologies will be developed. Unfortunately, this is not the case with the current situation. Today, scrap tyres are seen more as a waste rather than a resource resulting in a negative “economic value” [15]. However, this negativity is also a good market driver for the further development of the scrap tyre industry. High cost of waste disposal, such as high gate fees for scrap tyres, has forced many companies to look for alternative solutions. More resources are being spent on the research of new technologies such as pyrolysis and other tyre-to-energy options. Turning the disposal of this waste into a profitable industry is the main goal of every company involved. The negative “economic value” of tyres is a great market driver in today’s industry and has forced a continuous search for new and better options of managing scrap tyres.

To understand how this negativity has been turned into a positive and could lead to finding a better management solution it is important to look at the current status of disposal charges and levies on scrap tyres. The gate fees can vary significantly across the Europe. Additional to this are the costs of transportation as well as administrative costs. The collector has no direct income from selling scrap tyres and will have to pay to landfills or recycling facilities to dispose of them. To account for the high disposal and treatment costs of scrap tyres most of the collectors charge a set fee. This fee can be added on the price of a new tyre at the time of sale if the collector is the retailer, manufacturer or the importer. However this is cannot be the case for independent collection business. These companies will usually charge this fee directly to customers at the time of the collection.

In many countries, governments collect taxes or levies which help finance the general environmental programmes. Since it is the governments that collect these taxes, money generated as a result might not be used specifically for scrap tyre programmes but can be used for overall government spending and other general environmental schemes instead. However, more and more countries are introducing levies which are collected exclusively for collection, transportation and safe disposal of scrap tyres. Danish government has developed a system which has been proven to work and could be a great learning curve for countries worldwide. Denmark's whole tyre collection and disposal programme is financed through a tax imposed on tyre importers, manufacturers and distributors [27]. This tax is collected by the Danish Environmental Protection Agency (EPA) and the revenue generated is used to provide subsidies to registered collection services. This tax will cover the costs of collection and transportation of scrap tyres, temporarily solving the current environmental problem in managing this waste. However, the consumers (customers) of tyres will be the one who will have to pay a little extra out of their pockets to account for this tax. But if consumers are prepared to pay hundreds of dollars for new tyres then a small marginal increase due to tax will not have a big impact on their buying power. In all fairness customers are the main users of the tyres produced so if they are prepared to pay to use it, it is only fair for them to pay a small amount to ensure safe disposal. The same can be said for large global tyre manufacturing powerhouses such as Goodyear and Bridgestone who generate millions of dollars each year in sales of their new tyres. A small portion of that profit should be dedicated to safe disposal and collection of scrap tyres. Surely the amount needed for safe disposal is only a fraction of what the manufacturer's total profit is and it will certainly not bring any of them to a brink of bankruptcy. Their small losses will create enormous gains for the environment and people who are an essential part of it.

Tyre projects can have a positive impact on the development of local communities by providing additional employment opportunities and spurring further economic growth. However the capital investment required for the majority of such projects presents the biggest challenge for the tyre recycling industry. One possible solution mentioned above comes in a form of grants and government subsidies [5]. At present, most of the grants available are targeted at general environmental issues and not specifically at scrap tyre management industry. Luckily, scrap tyre projects are on the eligible list for these grants and successful applicants will be able to lower their capital investment. This will take enormous pressure of investors in private sector, encouraging them to continue their investment in such projects in the future.

Additional to grants and governmental subsidies, the key economic market driver for scrap tyre recovery is definitely carbon trading. We have seen such a huge increase in interest when it comes to renewable energy sector ever since the carbon trading has been introduced. Renewable energy incentives such as RECs and ROCs (Renewable Energy Certificates and Renewable Obligation Credits) have spurred rapid technological advancement in this industry and encouraged many investors to get involved in the projects worldwide. Introduction of such carbon credits could have an enormous impact on the economics of tyre recovery and could well develop a new source of sustainable energy. Take into consideration that the energy produced from scrap tyres is equivalent to energy derived from 100 million tonnes of coal or 470 million barrels of oil and it becomes clear how significant tyre-to-energy projects can be [6]. However, before we can look at establishing carbon credits for waste tyres, a key predicament has to be resolved and this is a question; are tyres considered renewable fuel? The following section will look at the reasons why tyres should/shouldn't be considered a renewable fuel.

2.3.3.1 Are tyres a renewable fuel?

As described in previous sections tyres are composed of two types of rubber, a natural rubber which is derived from biomass and synthetic rubber which is sourced from fossil fuels. As we already know fossil fuels are not classified as a renewable resources while the biomass is. This is due to the biomass completing the "closed loop" by using the carbon from the atmosphere by the photosynthesis process and releasing it back into the atmosphere when being used to generate energy [28]. So it is clear that the natural rubber in tyres can be classified as a renewable fuel and could possibly be eligible for carbon credits. While this is the case for natural rubber, the same cannot be argued for fossil fuel derived rubber.

So if the rubber manufactured from biomass is considered to be a renewable resource why don't waste tyres qualify for renewable incentives such as ROCs and RECs? In order to evaluate the carbon emission values it is important to determine the percentage of the biomass derived rubber in tyres. Based on these values it is possible to evaluate the eligibility of tyre recovery projects for renewable incentives. Looking at the typical tyre the rubber content varies between 45-60% and up to 50% of this value is biomass derived [2]. This works out to approximately 2.5 kg of biomass derived rubber per tyre. Multiplying this figure by the amount of scrap tyres generated annually worldwide and we arrive at the amazing figure of 2.5 million tonnes of biomass derived rubber generated every year [1]. That is a lot of carbon credits and it is a great new source of income for the potential investors.

However, determining the precise biomass concentrations of the tyres used in tyre recovery plants is not as easy as it seems. This is due to the high variety of tyres entering the plant and their inconsistency in composition. Some manufacturers will derive 40% of their rubber from the biomass while the other ones might opt for a much larger percentage. As a result it is not possible to calculate an accurate carbon reduction value of the tyre project. There are some suggestions that the use of project benchmarks, such as the ones used for assessing the biomass content of mixed household waste, could possibly provide an easier way of evaluating the carbon reduction value of the project. However, this has just been listed as a possible solution and it has not yet been implemented by the governments or carbon trading community. One reason might be that the project benchmarks evaluation of mixed household waste has been developed because this type of waste breaks down much faster than tyres and in doing so it releases methane rich gas into the atmosphere which is 21 times more dangerous as a greenhouse gas then carbon dioxide is [29]. On the other hand tyres do not break down quickly and can remain in the landfill anywhere between 70-100 years [2], sometimes even longer. So the mixed household waste is evaluated on the basis of total avoided landfill emissions, while tyres cannot be classified in the same category for the reasons mentioned above.

To make matters worse the above is not the only reason why it is so difficult for scrap tyres to be considered for carbon credits. Meeting essential project criteria is the first step that tyre projects need to overcome. Fundamental requirements include the proof that the project does not result in any secondary environmental impacts (such as any carbon derived from tyres), that it is in compliance with local laws and regulations, as well as showing that the project clearly benefits in reducing the carbon emission. Up to date it has been difficult and seemingly impossible for scrap tyre projects to meet these requirements and so far, in spite of great potential, the general consensus between governments and carbon trading community is that the tyres are not considered as a renewable fuel.

Chapter 3 : Literature Review 2 – (Current Management Options)

The following section examines the current management options for waste tyres and provides a brief evaluation of each. The four subsections of scrap tyre management options are the re-use of tyres, their de-vulcanisation, mechanical and thermal processing. They have been grouped on the basis of their application as well as their method of recovery.

3.1 Scrap tyre re-use

Scrap tyres can be used for a variety of applications such as road construction, embankments, marine reefs, sea defences as well as retreading [2]. Section 2.1.2 in Chapter 2 of this report examines the retreading of scrap tyres and looks at the current status and future challenges regarding this management option.

Most of the tyre re-use utilizes the whole or partly cut tyres. This is the case in most civil and marine engineering applications of tyres. This type of waste management option is very attractive due to the low level of processing and preparation of scrap tyres. Tyres are used in the same state as when collected, with exception of some tyres being baled and used as a single unit. Another reason for this management option being so popular is the desirable physical characteristics of tyres which makes them a perfect material for civil and marine engineering applications. Their durability, good insulation, excellent drainage, high load bearing capacity, energy dissipation ability, lightweight, compressive and tensile strength makes them an excellent and very affordable construction material [6].

3.2 Devulcanization

Devulcanization has been briefly discussed in Chapter 2, Section 2.2.1.2, but further evaluation of the technology and their current status is necessary. As mentioned previously devulcanization is the process which involves the breaking down of the sulphur cross-links within the rubber matrix. It is simply the reverse process to vulcanization of the tyre. The breaking of sulphur-carbon bonds will result in a loss of the physical, visco-elastic and dynamic properties those tyres posses [18]. This means that the rubber in tyres will become more plastic and it can be re-used in the manufacture of new tyres and other rubber products.

It is estimated that during WWII, devulcanized rubber accounted for 60% of the world's total rubber consumption in new tyres [2]. However, the further development and availability of the synthetic rubber have slashed the above figure to around 2% by the year 1990's [2]. Today more than 75% of the world's devulcanized rubber comes from the Asian countries, with India contributing a whopping 25% of the total global capacity [4]. In comparison to this, Europe accounts to a mere 12 % while the USA has less than 5% of the global share [4]. The remaining contribution is equally shared between other regions.

3.2.1 Process description

There is a wide range of devulcanization technologies available today but only a handful of these have been able to evolve into a commercially viable project. Methods such as mechanical, chemical, thermal, irradiative and biological have all been researched at some stage however the devulcanization still remains one of the least popular tyre management options today. This is due to the complex nature of the process, together with the high energy consumption and strong competition in price of synthetic virgin rubber [18]. Devulcanization process must be such as to successfully break the sulphur cross-links within the rubber matrix, while trying to avoid the breaking of the bonds in the rubber material itself which would result in depolymerisation [4].

The simplest and most common method of devulcanizing rubber is referred to as a traditional pan heating process. This type of technology is very widespread across developing countries such as India and a few eastern European nations. The rubber obtained through this process is referred to as reclaim rubber and has a wide range of applications. The front end of the so called pan process involves preparation of tyres where whole tyres are shredded to uniform particle size and steel is removed by magnetic screening. The following step is performed in the batch reactor where a mixture of chemicals, filler materials, oil and steam is added to already ground rubber particles [17]. The reactor is a pressurized vessel with temperature and pressure maintained at 200-300ºC and 180-360 psi respectively, depending on the type of material being processed [17]. The residence time varies from 4 to 7 hours depending on the desired application for the reclaim rubber [17]. Oil and water used in the process are recovered through condensation of vapours leaving the reactor, while the remaining gases are released into the atmosphere. Following the batch reaction, materials are transferred to a mechanical stage of the process better known as mastication stage. This process consists of a two roll mill which further assists the breaking down of sulphur cross-links and devulcanization of rubber. The final stage of the process involves a series of screening methods which ensure any remaining vulcanized rubber and oversized particles, inorganics and non-ferrous metals are removed from the final product. The refiner mills produce the finishing touch on reclaimed rubber by fabricating it into the sheet form ready for sale.

3.2.2 Process outlook

The devulcanization technology has been around for a very long time and it could be argued that the process has been proven on both pilot and commercial basis. However, the commercial attractiveness of such a project is limited due to a strong competition from synthetic rubber as well as high energy requirements. Tougher environmental requirements in developed countries have added extra pressure on project economics and have led to a rapid decline of such management options [4].

Another major issue is the scale at which such a process can be operated. The plants are very small and it is unclear if this is due to limited finances which prevents endorsement of larger projects or if the restriction is attributed to a lack of process development. In conclusion, this technology option is unlikely to play a major role in solving the problem of waste tyres on the global basis and additional management options must be explored.

3.3 Mechanical Processing

3.3.1 Process description

Mechanical processing was not always considered to be an independent waste tyre management option. It was regarded more as a feedstock preparation stage for other treatment processes such as thermal treatment. The main objective of mechanical processing at this stage was to aid in feed handling as well as to improve the heat transfer in the main process. Apart from the mentioned use, tyre shredding and granulation has been very popular in reducing the volume of the tyres intended for landfill [2]. However, the strong market opportunity for crumb rubber and aggregate in construction, sporting and manufacturing industries has resulted in mechanical processing providing significant revenues for many companies without the need for further processing. This meant lower capital costs and for many investors this is a very important aspect. Realizing this, many companies started to concentrate on recovering value from tyres using only mechanical methods.

The growth in the rubber industry has demanded for better quality of rubber to meet the requirements of the current applications. This also applies to rubber recovered from tyres using mechanical methods. In order to meet these new criteria new mechanical systems have been developed and the process itself has become more complex and in turn capital costs have increased significantly [6]. The economics of the process has greatly changed from the early years and now it is directly related to operating parameters such as the energy consumption and maintenance. However, number one factor influencing the economic viability of the process has remained the market value of the products.

There are two main types of mechanical processing used today and they differentiate by the type of tyre derived products they fabricate. The larger sized particles are obtained by tyre shredding while the granulation process produces much finer particle sizes [33].

3.3.2 Process outlook

Mechanical processing is extremely energy inefficient as 98% of the input energy to the machinery is lost as heat, noise, vibration and friction in the process itself [4]. There have been attempts to reduce this energy loss by improving the technology, varying the magnitude of the feed and the time over which the force is applied. Even after the mentioned improvements the energy requirement for tyre shredding is 10-50kW per tonne, while the granulation process is even more energy intensive [6].

After the energy use, the next biggest contributor to already high operational costs is the machinery wear and maintenance. Tens of thousands of dollars are spent each year in replacing the damaged knives and plates, with additional cost associated with equipment cleaning, servicing and day to day maintenance. High steel content in the tyres is the main culprit in machinery wear, with reinforcing fibres and strong vulcanized rubber elastomer adding the further damage. While the steel is the main concern regarding the level of machinery wear, the textile content affects the throughput in the process. This is due to the low bulk density of the textiles which can lead to a few problems regarding the flow in the equipment with smaller tolerances.

A well designed system must include a series of screens, filters, conveyor belts and magnetic separators between the shredding and granulation equipment. This is necessary in order to remove all the steel, textile and fines out of tyres shreds before they are further reduced in size [2]. If this is overlooked, the granulation equipment will be compromised due to its low tolerances.

The demand for tyre derived products will expand rapidly in the future especially in civil engineering applications and this will be a major contributor to mechanical processing becoming a very attractive business prospect for many investors. We can expect to see further developments in the areas of technology, process development as well as new and innovative uses for TDP's in the future, with major growth in civil engineering applications.

3.4 Thermal Technologies for Managing Waste Tyres

Thermal treatment of waste tyres offers a wide range of conversion technologies dedicated to the disposal of waste tyres by either recovering materials or energy. This management option is subdivided into incineration, co-combustion, gasification and pyrolysis. The last two are relatively new technologies and have been a subject of extensive research over the past few years. It is estimated that up to date over 50 different systems have been developed for the thermal treatment of waste tyres, with majority of those being based upon the gasification and pyrolysis technologies [4]. Nearly 70% of these thermal technologies have been sourced from USA, United Kingdom and Germany alone [4]. This shows the extent of the costs associated with the development of such technologies, as only the developed countries have made significant progress in this area as the investment and research sponsorship opportunities are far greater than in other regions. Another possibility for such a high level of development activity is the increasing need for these countries to provide renewable energy sources in order to reduce their carbon emissions and meet the tougher environmental requirements. The search for alternative sustainable energy sources to replace fossil fuels in the future also provides an additional incentive for such a high level of research. This following section will provide an extensive analysis of each of the four thermal technologies with one of these being identified as having the biggest potential for further process development. This management option for waste tyres will become the foundation of experimental work and product analysis completed as part of this thesis.

3.4.1 Incineration of Waste Tyres

Over the years incineration has been used as the disposal method for many solid wastes and when applied to tyre disposal some additional steps are required in order to account for a complex composition of tyres and their bulkiness. However, the fundamentals of the process remain the same regardless of what type of waste is processed.

The incineration is a combination of pyrolysis, gasification and combustion processes all in one, with varying presence of each depending on the process design and the process conditions. This multi-stage process takes place in a single furnace or a reactor, with key parameters being the residence time and the design of the reactor itself [39]. The quantity of air present in the reactor system will determine if the system will predominantly contain pyrolysis and gasification, or in fact the combustion will be the governing process. Many systems are designed in such a way to utilize all of the three processes by ensuring insufficient air supply at one end of the furnace while the combustion conditions dominate at the other.

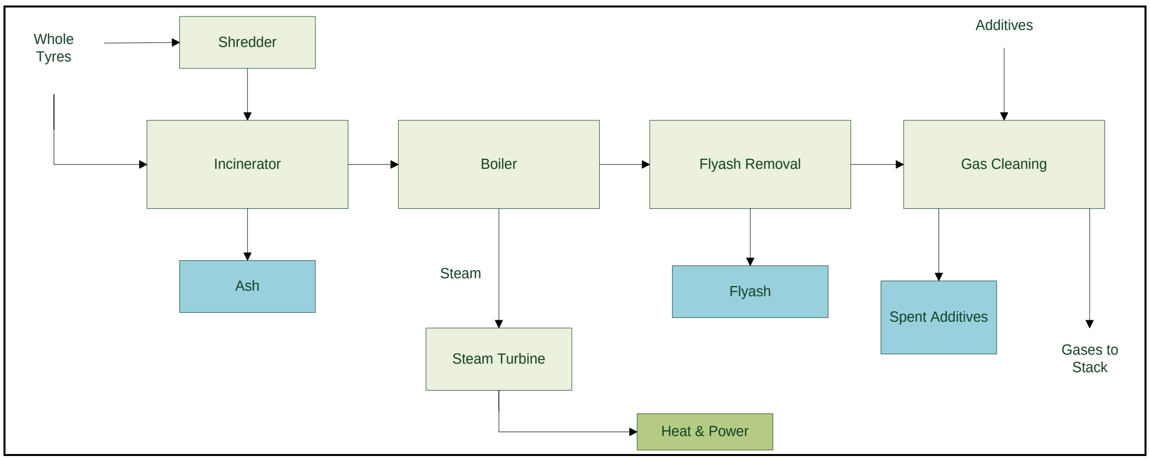


Figure 3-1: Process flow diagram (PFD) of the tyre incineration system.

The above PFD illustrates typical schematics for the tyre incinerator. After initial size reduction (2-6 inches), tyre shreds are fed into a boiler at approximately 1200°C [8]. In most cases the boilers are usually equipped with a hydraulic driven multiple step grate, however the design varies with each system. The process itself will produce residues such as ash and steel and the amount of each will depend very much on the grate design as well as the feed size, as explained above. This, together with the ineffective control of the gaseous emissions, has been blamed for the poor performance by many commercial projects, eventually resulting in their closure [2]. However further analysis has shown this not to be the case.

In order to reduce the NO_x formed during the combustion process, urea is directly introduced into the boilers [40]. At such extremely high temperatures urea is converted into CO_2 and ammonia. The later reacts with produced NO_x to form nitrogen and water. The further clean up of gases involves removal of particulates (ash) using electrostatic precipitator, followed by wet scrubber using the hydrated lime in order to reduce the concentrations of SO_2 and HCl present [40]. This type of setup ensured the recovery of ash without any contamination, enabling further processing to recover materials such as zinc and gypsum. Facilities such as Modesto and Exeter have used the above process arrangement or similar and it has been reported that the air emissions have met the permit requirements [2]. Therefore, poor control of gaseous emissions can be eliminated as the cause of closure for some of these projects.

At the back end of the process, electricity is generated through the steam turbine generator. From past experiences and large projects that have been a success it has been estimated that a feed of about 100,000 tonnes (based on 10 kg/tyre) per annum of mainly whole tyres can produce about 27 MW of electricity [2]. However this energy production comes at a cost. A facility that has such capabilities would cost hundreds of millions of dollars (similar Exeter plant cost about $US100 million, in 1991 [2]) and returns on such a large investment would have to be considerable. Such a high capital investment could also be a main reason for limited development and research in this area in recent years.

It is true that many well known facilities around the world have closed down and only a handful have operated satisfactorily. However, the reasons for such a poor performance are not limited to only technical difficulties. Many of the projects failed due to economic or other external factors. The perfect example is the Modesto plant in California, which operated with a capacity of 50,000 tonnes per annum for 12 years [4]. This was the first dedicated waste tyre to energy incinerator and it was closed down due to a fire in a nearby tyre stockpile. This did not affect the process itself however it has brought an increased public concern and opposition to the facility. Under extreme pressure from public as well as many government's environmental agencies the facility was closed down even though the technology was proven over the 12 year period. A vast amount of money was paid in settlements as a result of stockpile fire, leaving the facility in financial crisis. Even after the plant shut down the legal battles continued with final settlement of $9 million paid out to 10,000 residents as a result of health problems and property damage caused by the fire.

The main limitation of this management option is the requirement for high capital investment. This is due to the high level of cleanup methods in order to meet the air emission requirements. Strict regulatory control together with public opposition for projects like this only increases the pressure and threatens the success of the venture. Because of this increased risk a steady market for the product must be obtained in order to relieve some of the pressure. However even this is not easy with incineration projects. This is due to many plants being operational only from time to time without steady and consistent electricity production. As the majority of grid operators require a very reliable supply of power, negotiating long term agreements and obtaining steady market is very difficult. Additional problem is the limited market for other by-products. Steel recovered from tyres is likely to be carbonized which making it a low value product, while the ash, which is high in zinc and could potentially provide significant income, is found to contain traces of heavy metals such as cadmium and lead [6]. As a result any by-products that could not secure a steady market would need to be disposed of, which further increased the total cost of the project. It has been estimated that the cost of power generation from waste tyres is approximately four times higher than the conventional methods utilizing the coal [4]. This seems relatively close to costs of other alternative methods for power generation however waste tyres, so far, have not been eligible for any carbon credits as is the case with other renewable energy sources.

All of the limitations listed above have to be overcome before this management option has the ability to provide a long term sustainable solution to global waste tyre problems. Enabling projects like this to be eligible for financial subsidies based on the renewable energy basis would be an ideal start. It is essential to provide steady markets for by-products of the process. This can be done by completing further research and development, as well as improving the process (specifically the carbon burnout), which would in turn eliminate the potential for those by-products becoming contaminated and therefore unsuitable for sale. Unfortunately, due to the ‘arrival’ of new technologies which have hit the market recently (such as pyrolysis), there is less and less interest in further developing the incineration process. Instead the attention will be turned to more ‘environmentally friendly’ ways for a disposal of waste tyres.

3.4.2 Co-combustion of waste tyres

Waste tyres can be utilized as the replacement for many fossil fuels used in the existing processes. Based on the scale of the process and the technology specifications, this replacement can be total or in most cases partial. This means that only one portion of the total feed is replaced by the waste tyres while the remaining amount is the original feedstock. This type of management option is mainly found in applications such as paper or metallurgical boilers, electric utilities and the cement kilns [2]. However, the most widely used application today is in the cement industry, providing the replacement for fossil fuels used in the cement kilns in more than 17 countries worldwide. Since the majority of the co-combustion activity up to date has been in the cement industry, this section will analysis in depth the potential for further growth of this particular management option.

The cement making process is a perfect market for waste tyres due to such a huge energy requirement. Here it is finally, a process of such an enormous scale which could utilize a very large amount of waste tyres worldwide. In addition the capital costs are minimal due to the existing infrastructure and previous cement production systems already in place. To better understand the scope of cement making process and the potential for utilizing a large number of tyres as a result, it is crucial to understand the current situation of the cement industry and look at the process in more detail.

3.4.2.1 Benefits and limitations of using tyres in cement kilns

The first question that comes up when considering such a management option is why co-combust waste tyres in cement kilns. The answer comes simply down to the extremely high energy intensive nature of the cement making process and an increasing demand for fuel in order to support it. A rough calculations estimate that in order to manufacture one tone of cement, the process requires about 120 kg of fuel such as coal which equals to approximately 3.2 GJ of energy [41]. This includes all the necessary material preparation and handling as well as the energy necessary for the cement making process itself. Up to 40% of the total manufacturing cost is associated with the energy requirement [41]. This is a considerable percentage and any savings made in this area would greatly benefit the economics of the complete production process. This is why many companies have started to diversify their feedstock and one of the obvious replacements for traditional fossil fuels has been different types of waste. Additional benefits of reducing the emissions of greenhouse gases have been viewed very positively by government environmental agencies. This provided the assistance in meeting carbon targets of many countries around the globe.

The reason for choosing tyres over many other waste streams is their availability as well as the extremely high GCV (Gross Calorific Value) they possess. At 36 MJ/kg, tyres compare very satisfactorily with other traditionally used fuels for this type of process [42]. The Table 2-2 presents the comparison of GCV values from other commonly used fuels and waste tyres. Usually the fuel with similar GCV would have to be paid for, while the use of waste tyres in most cases provides a free source of feedstock, which is one of the key reasons for such a high demand by the cement industry. However, the use of new feedstock does require high level of control during the operation of the plant and the clear understanding on the behaviour of alternative fuel sources is instrumental in running the process safely.

Table 3-1: Energy content of common fuels.

Fuel	Calorific Value (MJ/kg)
Bituminous Coal	27.0 – 32.6
Petroleum coke	28.0
Heavy fuel oil	40.1
Natural gas	33.8
RDF	12.5 – 18.0
Scrap tyres (TDF)	28.5 – 36.0

The cement kilns operate at temperatures between 1500°C and 2000°C and therefore the need for such a high energy requirement [41]. At temperatures like these most of the tyre is combusted, while the remaining residue is utilized by being mixed in the cement clinker. This ensures the complete disposal of a tyre. With this, the additional costs required in order to landfill remaining ash and other particulates are eliminated, which is one of the key problems in the previously discussed incineration process. The further comparison with the incineration process reveals that another very expensive step might be eliminated if co-combustion is the preferred option. This refers to the gas cleanup system which is a large and expensive part of any process. The need for this stage in cement kilns is somewhat eliminated, although with newer and stricter regulations this might not be the case and the addition of gas cleanup equipment might still be required. However even if this is the case the system will be a lot simpler and cheaper. This is due to the presence of limestone in the cement making process itself, which acts as the absorbent for SO_2 and HCl solutions, similar to the way the lime solution acts in the incineration cleanup stage [40].

Germany is the world leader in developing an environmentally friendly operation of cement kilns that utilize the waste tyres as the replacement for the more traditional fossil fuels. Decades of intensive research have resulted in German monitoring agencies giving their tick of approval to practices such as the co-combustion of tyres in cement industry [43]. It is important to mention that the German rules and regulations are some of the most rigorous in the world and to be in compliance with them is a big achievement. This really gave a big boost to co-combustion as a management option which might finally provide a real solution to a problem of scrap tyres.

However, the arguments against co-combusting tyres in cement kilns continue coming from a variety of credible sources. Claims such as the high level of toxic elements in both air emissions and cement mixture have raised concern within the industry. This argument was made on the basis of the fact that when tyres are burned at such high temperatures the oils and polymeric compounds contained could produce some carcinogenic by products such as dioxins and furans, as part of the process gas emissions [5]. Also, it is suggested that heavy metals such as zinc, copper, lead and cadmium are present in the final cement mixture. This is mainly due to gas cleaning systems in co-combustion being very basic in comparison to the equipment used in incineration process.

At present the fuel replacement by waste tyres in cement kilns ranges between 5-10% depending on the process design and regional rules and regulation [5]. There is an increased pressure by the industry on environmental agencies in some countries to be allowed to increase this figure up to 25%. However this is unlikely to happen until further studies such as the ones described in previous section clarify the environmental impact of this management option. Also, care has to be taken when determining the amount of tyres used in replacing the original fuel as tyres require very high temperatures in order to combust entirely, and this is only possible if other fuel sources are present. Therefore, only a small portion of fuel can be replaced otherwise the combustion will not be complete.

3.4.3 Gasification and co-gasification of waste tyres

It is very difficult to differentiate between gasification and combustion processes. This is due to both being thermal processes generating gas as the end product. However, the two resulting gases are very different and possess unique properties enabling them to be converted into energy distinctively. As explained in the previous section the combustion permanently converts the chemical energy into heat, in the form of flue gas. On the other hand the gasification only changes the form of the fuel, from solid into the gaseous stage, retaining most of the chemical energy of the original fuel [42]. This gaseous fuel is known as the syngas and it is mainly a mixture of CO and H_2 gases. Since the syngas is a fuel itself it can be further used for combustion purposes or others, such as fuel cells or methanol production. There is a wider range of use for the final product and many see this as a big advantage of the gasification process over combustion.

In comparison to pyrolysis (see next section), gasification is performed in a controlled atmosphere, with limited amount of air, allowing for the partial combustion of fuel. This aids the breakdown of the heavy hydrocarbons in the tyre, which in turn optimizes the syngas production. If the gasification process utilizes more than one type of fuel, the term co-gasification is used instead [5]. This is the case with part of coal feed being replaced by tyres or other similar waste. So far the only commercially operated gasification facilities have been the ones which have utilized sewage sludge, agricultural waste as well as biomass together with the original coal fuel. Tyres do not belong to this group and no commercial projects utilizing waste tyres exist at the moment. The lack of tyre dedicated gasification facilities is attributed mainly to high level of difficulty in obtaining the clean syngas from heavy organic molecules found in tyres, especially considering the lack of air presence in the process [42].

The economics of waste tyre gasification suggest that there is a positive outlook for processes operated at conventional temperatures of 800-900 °C. However, such moderate temperatures would produce excessive amounts of tar due to the presence of heavy hydrocarbons in the waste tyres. This is why it is necessary to run the process at much higher temperatures. Although this is not a problem technically, the economics of the process will struggle to perform satisfactorily due to increased capital and operating costs.

The only operational dedicated gasification process was developed by the Krupp Polysius Technology, however it is only a small system incorporated into a cement making facility. The way this process is utilized is by providing syngas from the gasification of waste tyres to the cement kiln for combustion, while the ash residue is combined with the cement clinker. This system is an alternative to direct co-combustion of waste tyres into the cement kilns. At present the technology is operational on two locations, a facility in Switzerland utilizing approximately 24,000 tonnes per year of tyres, and another one in Germany which consumes about 40,000 tonnes per year [4].

Apart from the above examples, gasification is also often used in combination with pyrolysis to process waste tyres. Pilot plants in UK and Belgium are the result of proprietary processes developed by Compact Power and NESA respectively. Even though the initial results from the two projects look very promising, the technology is a long way from being implemented on a commercial basis. This is mainly due to high capital costs as well as adjusting the process for a large tyre feedstock associated with the commercial operations.

Major drawback of gasification technology over combustion is the lack of proven commercial operating facilities. This results in higher capital costs and increased uncertainty about the possible operational costs. The only way to account for this uncertainty is to secure long term power purchase contracts which should account for any discrepancy in cost estimation. Apart from this, further research is needed on a large scale basis in order to address the above constraints. However, obtaining financial investments for unproven projects is very difficult and it will continue to be the major hurdle in further development of this technology.

3.4.4 Plasma Technology

Plasma is very often described as the fourth state of matter. It is a positively charged gas resulting from collisions between the electrons of the high frequency induction discharge and the uncharged gas particles [46]. Plasma has very distinctive properties and is very different from gas under normal conditions. The table below summarizes some advantages and disadvantages of the plasma technology when used for waste treatment.

Table 3-2: Advantages and disadvantages of plasma processing.

Advantages	Disadvantages
Very high temperature waste degradation	Energy intensive
Destruction of organic compounds to simple molecules	NO_x formation
Fast processing times	Relatively new technology that is still being developed for waste applications
Faster start up and shutdown than conventional thermal processes	Few commercial plants in operation worldwide
Smaller off-gas treatment plant	Relatively small scale
Vitrified solid by-products that can be recycled	Extensive feed preparation might be required
High CO and H2 containing syngas suitable for fuel cells	Syngas cleaning is more complex
Modular equipment that can be scaled to suit application	Doubtful economics
	Source: Juniper Report [4]

There are a number of different plasma systems currently available in the industry and they differ by the temperature of the generated plasma gas. Thermal plasma, also known as hot plasma, is generated by high frequency induction discharge or electrical discharges, both AC and DC. The resulting plasma exhibits very high density and high temperature in the region between the two electrodes due to the heat released by electrons dropping to a lower excitation states [47]. If the carrier gas is introduced into the system it will create what is known as a plasma jet, extending the plasma beyond the initial region between the electrodes.

On the other hand non-thermal plasma systems contain plasma gas close to room temperature and it is formed under vacuum conditions by either using the direct current electricity, microwave or low power radio frequencies. Non-thermal plasma uses the energy from charged particles in order to alter the atoms and molecules that come into contact with the plasma arc [46]. This type of plasma is not suited for the purpose of tyre degradation but it is widely used in the sterilization, surface modification and the treatment of gaseous contaminants.

From the above analysis we recognized that the thermal plasma would a suitable choice for tyre degradation. However these plasma systems can further be divided into a transferred or non-transferred type. The main difference is that non-transferred plasma systems require the feed to be directly injected into the plasma jet because the electrodes, generating the discharge, do not participate in the degradation process and are solely used for generation purposes. In order for the degradation to be complete, particle size of the feed has to be relatively small due to a very short residence time inside the plasma jet [47]. In the context of tyre degradation this has a very big negative effect due to the increased costs in feed preparation and sizing of the particles.

In contrast to the above, the transferred plasma systems could incorporate the electrodes into the reactor itself, resulting in increased contact time and better degradation. This will eliminate the need for preparation of the feed, reducing the costs associated with this, as well as minimize electrode erosion and corrosion.

3.4.5 Microwave technology

Microwave energy is generated by electromagnetic radiation within the frequency range of 0.3-300 GHz. International Telecommunications Union has accepted four main frequencies as being appropriate for industrial microwaves and these are 0.915 GHz, 2.45 GHz, 5.8 GHz and 24.125 GHz [48]. At these frequencies the microwaves penetrate through solid objects. However, the degree of penetration depends on the frequency used as well as the properties of the receptive material. The depth of penetration is indirectly proportional to the microwave frequencies and if the listed frequencies above are used the penetration will usually vary between 1-32 cm. Once the material is penetrated, the electromagnetic field associated with the microwaves causes the polar molecules and free ions to vibrate. These vibrations result in a molecular friction, producing heat which in turn assists the degradation of tyres.

As shown above, it is clear that microwaves can be more energy efficient then other traditional methods of thermal tyre degradation mainly due to the fact that the temperature present in the reactor is a result of the molecular heating process itself rather than the required temperature gradient as is the case in the other systems. As a result heat loss is minimized and the process is more energy efficient.

The main limitation of this technology is the fact that different materials exhibit different reactions to microwave fields [48]. Because tyres contain a wide range of different materials, the degradation will vary across the process and is not clear-cut. Metal parts of a tyre tend to reflect microwaves while some non-polar compounds such as plastics are totally transparent to them. The materials suitable for microwave technology degradation will be the ones that contain any polar molecules, ionic or conductive compounds. Good examples are water and carbon black.

One of the main advantages of microwave technology is the fact that the whole tyres can be degraded without any major problems. This has been proven on a demonstration scale by Molectra Technology in Queensland, Australia. The results of other independent studies also showed microwaves penetrate solids better at smaller feedstock sizes, however the difference is not significant enough to justify the increase in energy requirements and cost required in feed preparation. This is why even though it results in smaller rate of degradation, using whole tyres as a feedstock remains the most efficient option in microwave systems.

The depth of microwave penetration into solid material is indirectly related to the microwave frequencies used in the process [48]. The lower the frequency of the microwaves the deeper the penetration and vice versa. However the better penetration comes at a cost of reduced heat generated by lower molecular friction. This will be a key factor in determining frequency of the microwaves in the system. Before deciding on frequency, it is important to check the available of the same for use in the location where the plant is built as well as the full economic analysis of the microwave generation at the specific frequency. All of these factors together will play crucial part in deciding which frequency is used in the process.

Table 3-3: Advantages and disadvantages of microwave processing.

Advantages	Disadvantages
No ancillary equipment needed for reactor heating	High cost of microwave generators
No external heat generating equipment required	Technology relatively unproven for waste treatment applications
Potential for very efficient heat transfer and hence relatively fast processing times	Relatively small scale
Low energy losses	Only a couple of reference plants in operation
Faster start up and shutdown than conventional thermal processes	Markets will have to be found for char, oil &steel when processing tyres for technology to be viable
Can treat whole tyres	Increasing metal and polymer content of tyres make processing difficult
Produces a variety of potential added-value products when treating scrap tyres	Challenging to engineer as a continuous process
Relatively better process control and therefore more control over the quality of products	Doubtful economics

Source: Juniper Report [4]

Every material has the ability to transform microwaves into heat at a specific frequency. However, some materials are better at it than others. This is why it is important to consider this when designing the system. Dissipation factor or tan δ is used to describe the materials ability to transfer this electromagnetic energy into heat required to degrade the tyre [49]. If the tan δ is low, than the material's ability to transfer electromagnetic energy into heat is very poor and vice versa. In order to improve the tan δ, it is necessary to constantly monitor and maximize the phase differences throughout the reactor. This can only be achieved with the use of complex built-in electronics in the system. However, this significantly increases the overall cost of the project.

3.4.5.1 Process Outlook

After careful analysis of this emerging technology it is clear that well designed process can improve some of the restricting factors in many previously evaluated systems. This is mainly true for its ability to treat the whole tyres, as well as providing a more efficient heat transfer and improved process control. However, the high cost of the microwave generators as well as the lack of existing commercial scale projects around the world are the main reasons for the lack of interest by many investors. This leaves the microwave process as the relatively new and developing technology which should be revisited in the future when financial benefits offered become a much better proposition for investors then the current one.

3.4.6 Pyrolysis

The last technology examined in this literature review is the use of pyrolysis for the degradation of tyres. Pyrolysis is performed under specific conditions which prevent combustion or gasification from taking place. Heat is applied to the process in the absence of oxygen or in very limited concentrations. When exposed to high temperatures under pyrolysis conditions, tyres degrade into three main products, char, oil and syngas [50]. The ratio of the product components depends on the operating conditions of the reactor, including the temperature, pressure, residence time, and the rate of heating as well as the type of mixing performed. Additional to this, the use of catalyst could be beneficial in improving the efficiency of the whole process. This will be further discussed later in the report.

Both combustion and gasification reactions are autothermic, meaning the process is both exothermic and endothermic. The heat which is generated by the exothermic reaction in the process is consumed within the reactor at the same time in order to support the endothermic reforming reaction. Pyrolysis of tyres is different since it requires the input of energy, making the process entirely endothermic. There are many variations in which heat can be applied to the process, with most common being indirect heating through the walls of the reactor or in some cases a partial oxidation two stage reactor design. Below is a typical block diagram for the tyre pyrolysis process.

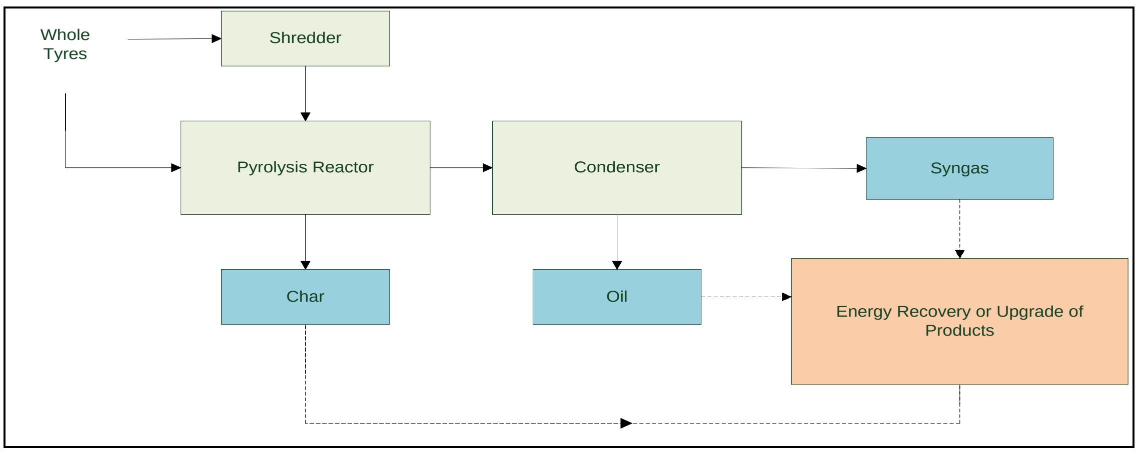


Figure 3-2: Process flow diagram (PFD) of the typical tyre pyrolysis system.

Pyrolysis of tyres involves a very complex network of reactions taking place simultaneously within the reactor. These range from thermal degradation, cracking, evaporation and re-polymerization of either reactants or products in the process [2]. Figure 3-2 illustrates one possible mechanism for tyre pyrolysis reactions. The extent of each reaction largely depends on temperature and heating rate of the process. This will also directly affect the ratio of products produced. The oil and char are considered to be added value products, with further revenue coming from selling the recovered steel. The remaining syngas can be used as a source of energy required to support the whole pyrolysis process. This way the system is considered to be self-sufficient. It is easily noticed that not much residue is formed during the pyrolysis and this is a very important factor in reducing the total operational costs since no disposal is required.

3.4.6.1 Commercial status of tyre pyrolysis processes

Over the years, tyre pyrolysis plants have been operating mainly on a pilot scale, with very few exceptions managing to develop a sustainable fully commercial scale project. However, even those projects operated with very limited success, resulting in their eventual closures mainly due to the financial difficulties.

At present, only a single tyre pyrolysis plant is operating on a semi-commercial scale in Europe, with 15,000 tpa capacity. This plant is operated by Anglo United Environmental Ltd (AUEL) and is located in the UK. The financial performance of the facility could not be obtained for the purpose of this study, therefore making it hard to further evaluate the pyrolysis system employed.

Number of plants have been operated on a commercial basis throughout the world, however they have all ceased trading after a number of years. Other projects which have been on the cards for some time now such as 25,000 tpa LIG pyrolysis plant in Miltzow, North East Germany and 60,000 tpa plant in Wolverhampton, UK, have all been scraped due to problems in obtaining necessary funds [4].

One of the forerunners in tyre pyrolysis processing, Titan Technologies, has operated three separate commercial facilities in recent past, one in Taiwan and the other two in South Korea. The location of these facilities is a major reason for operating longer than other similar projects, since the process economics for pyrolysis in Asian countries are noticeably different. This is due to more lenient environmental rules and regulations, including the emission levels as well as policies on residue and waste disposal [15]. However, even these facilities could not manage to operate on a long term basis, mainly due to technical unreliability. Considering this, it is clear further process development is required as well as the additional testing on processing conditions and their effect on properties of final products (char, oil, steel and syngas). This will be the basis for experimental work and economic analysis in subsequent chapters of the report.

3.5 Summary

After careful evaluation of all the existing waste tyre management options, it is evident one particular technology offers better potential then the rest and it is a suitable candidate for further process development. The pyrolysis of waste tyres seems to be heading in the right direction, however, the increasing number of technical and financial challenges needs to be overcome before a reliable process can be implemented into a full scale commercial plant.

Chapter 4 : Process Development

4.1 Process Development Overview

The process development will include an in-depth analysis of a simple waste tyre pyrolysis system. A number of lab scale experimental runs will be completed in order to examine the effect of different process parameter values on quality and ratio of final products. The products obtained in the trial runs will be analysed accordingly and any major change in the quality will be noted. Additionally, a short economic study will be performed using the results obtained in the experimental work. This will provide a significant insight on the process economics and value of such a process being implemented worldwide. Finally, conclusions will be drawn and suitable suggestions presented, using all of the information which was obtained as part of this research.

4.2 Process Technology

The design of the pyrolysis system, such as the type of heating and reactor design were mainly constricted by the budget of the research project. Apart from this, another very key factor was the complexity of the system and the level of process controls available. This was very important in order to provide other fellow students with the safe working environment and reduce the potential risks. For example, heating methods such as plasma and microwave have not been considered because of the reasons above.

In order to easily change process parameters and observe the effect they have on the products, it was important to have a fairly simple and flexible pyrolysis system. This had additional advantage of reducing the maintenance time as well as eliminating any significant downtime due to system shut downs. Keeping it simple also meant that any mechanical or control issue was easily resolved by the operator while the operational and maintenance costs were minimized.

In order to meet the budgetary constraints as well as targeted operational simplicity of the system, it was decided that the conventional pyrolysis with electric heat furnace will meet the requirements and needs of this specific project. The experimental setup is described in more detail in the following section.

It is important to note that the design of the pyrolysis system employed on the lab scale basis is not an optimal one, but rather a tool which is used to optimize the process itself and recognize the factors affecting the ratio and quality of the products. Once the optimum process parameters are identified and the process has been proven, further design of the system will target other factors which play an important part in improving the process economics. Some of these include energy utilization of the process, process control, handling of the feedstock and the control of emissions. Such a design of the pyrolysis system is not within the scope of this project and it will not be discussed. However, certain assumptions regarding these will be made in order to complete a brief economic analysis of the pyrolysis process.

4.2.1 Experimental rig setup

The pyrolysis experiments were conducted using a standard electric heat furnace. The heat required for the pyrolysis reactions was supplied indirectly by the induction furnace through the walls of a cylindrical batch reactor. The pyrolysis reactor inside the furnace was made out of heavy steel. A cylindrically shaped unit, 100 mm i.d. and 200 mm long, was positioned such as to provide the maximum heat transfer in the system. The tyre samples were loaded manually into the reactor while the nitrogen was used as an inert carrier gas at the rate of 2 L/min. Product gases leaving the reactor passed through the condenser system where the product oil was separated and collected while the remaining syngas was vented out.

The condenser system consisted of an ice bath, which provided the necessary cooling medium. A series of stainless steel coils, together with a tar trap were immersed into the ice bath, cooling the product gas until the oil condensed. In order to complete the condensing and recover all of the oil, it was important to maximize the retention time of product gas in the condenser system. This was achievable in two ways.

Firstly it was necessary to ensure the coils were long enough to provide sufficient retention time. This was done by running a few trial experiments with varying coil lengths and connecting a glass U tube extension, densely packed with glass wool, at the end of the condenser. This provided an indication if there was any remaining oil in the vented gas which did not condense inside the coils. As the U tube is densely packed with glass wool, it provided large residence time, enough for even the smallest droplets of oil to condense. Also, transparency of the tube enabled visual detection of any oil droplets forming. As the trial and error runs progressed, the longer the coil was, the lower the amount of oil condensed in the glass tube. As soon as there was no sign of oil formation on the glass wool, the minimum length of coil required for the experiments was reached. Since the amount of oil formed in the pyrolysis at different process conditions varies, it was imported to design the length of the coils to account for this. As a rough estimate the minimum length of the condenser coil was doubled, giving us a standard design length which was used in all of the experiments. As an extra precaution the U tube remained positioned at the end of the condenser in order to confirm if all of the oil present in the system has collected inside the condenser and none remained in the released syngas.

To further increase the efficiency of the condenser system, the tar trap was added and it was densely packed with Teflon chips, approximately 2 mm in length. This increased the amount of oil collected in the trap, making subsequent recovery and clean up of the condenser much easier. This modification came after initial trials showed that recovering oil from the coils presents a very long and time consuming process while this is not the case with the tar trap. In order to simplify the recovery and clean-up process, it was necessary to maximize the oil collection inside the trap. This was achieved by increasing the residence time inside the tar trap as well as increasing the surface area for oil droplet formation with the addition of unstructured packing (Teflon chips).

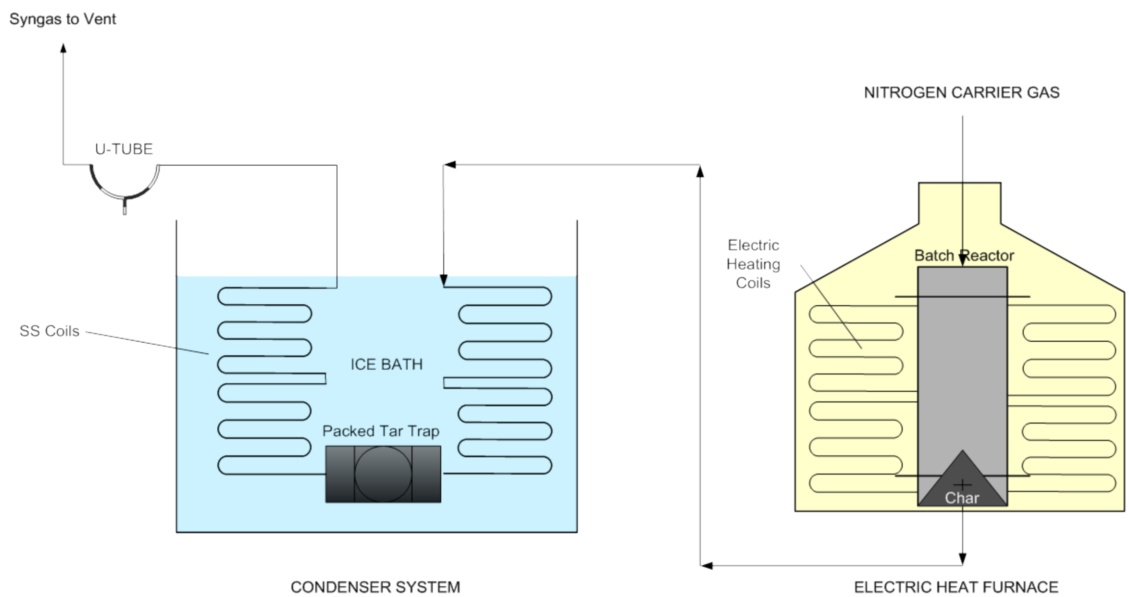


Figure 4-1: A schematic diagram of the experimental setup including the pyrolysis reactor and the condenser system.

4.2.2 Objectives of experimental work

The main objective of the experimental work is to assist further process development for the pyrolysis of waste tyres. The scope of this research includes the study of how the main process parameters affect the ratio and quality of products formed. The pyrolysis process will be tested under different conditions and the created ratio of products will be recorded and compared. A useful tool, called POT (Product Optimization Table) will be developed which summarizes the findings and provides a guideline on the process conditions required in order to optimize the production of a specific product. This will vary from vendor to vendor depending on marketability of products and their relative value to each other. The vendor will decide on optimizing the manufacture of a product that will generate biggest profit margin, therefore improving the total process economics.

Another advantage of this tool is that it could provide a quick and easy solution to possible changes in market value of products, depending on the global economic trend. For example a facility decides to optimize the production of oil due to current demand and price of oil being higher than that of char and syngas. However, in a few years time the price of oil falls or the price of other products increases due to a newly developed use in the industry and demand for this product rises. This means that the facility is not performing as well as it could if the production of other products was to be maximized. This is a situation where POT can be utilized. By referring to POT, the vendor performs minor changes to process conditions which shift the ratio of products to desired specifications.

Once the pyrolysis process is complete, the products are collected, weighted and stored. Following the completion of rig experiments, the products undergo detailed analysis in order to determine different properties and suggest possible uses in the industry. This will assist in the development of brief economic model of the process on a commercial scale.

4.2.3 Process conditions

Temperature is the single most important parameter in determining the ratio of products and their composition. That is why this research paper will examine the ratio of products as well as the composition, as a function of temperature between 350 °C and 600 °C. It has been reported in the literature that tyre decomposition is nearly complete at temperatures above 600 °C and further increase in temperature does not provide any significant increase in oil yields [50]. Instead the syngas production is increased at the expense of remaining products. In developing POT, three sets of experiments were completed at 300 °C, 350 °C, 400 °C, 450 °C, 500 °C and 600 °C each. The first set of experiments will be carried out using larger sized tyre samples (2-3 cm) and with the retention time at the specified temperature of 60 minutes. The second set will use the same retention time, however the sample size will be reduced to finely ground rubber crumbs (2-3 mm) in order to examine the effect different sized feedstock can have on the ratio as well as the quality of the products. Finally, the last set will be performed with retention time increased from 60 minutes to 180 minutes, in order to see if there is any significant change in the results obtained. The size of the tyre crumb samples used in this final set of experiments is approximately 2-3 cm. All of the experiments used a constant heating rate of 3000 °C/hr or 50 °C/min, with the nitrogen flow rate of 2.0 L/min.

The three sets of experiments, each carried out under six different pyrolysis temperatures will provide sufficient information in order to develop the POT tool. Every set of experiments has been repeated three times in order to ensure the results can be reproduced. A total of 54 experiments (3 sets x 6 experiments x 3 repeats) were performed plus the additional 8 experiments for which the results have not been recorded. The 8 initial experiments were used as a training ground for gaining familiarity with the pyrolysis system and in order to optimize the design of the condenser.

On the following page is a POT template which is completed after the experimental data is obtained and analysed. POT contains data from the three sets of the experiments, with variable temperature, sample feed size and retention time.

Table 4-1: POT – Product Optimization Table.

Set 1 (2-3 cm /60 min) Set 2 (2-3 mm/60 min) Set 3 (2-3 cm/180 min)	Char %	Oil %	Syngas %
300 °C			
350 °C			
400 °C			
450 °C			
500 °C			
600 °C			

4.2.4 Waste tyre samples

Tyre samples used in the experiments were provided by Reclaim Industries Ltd, located in Bibra Lake. Samples were obtained in 2 different sizes, ranging from small shreds to finer tyre crumbs. Only regular car passenger tyres were used for the purpose of this research. The samples contained only slight traces of steel with the majority being separated prior to their collection from the recycling facility. Synthetic fibres however, remained with the tyre and have been included in the pyrolysis feed.

Size of the feed required for the commercial pyrolysis facilities has a great impact on process economics. Smaller sized feedstock requires additional pre-treatment in a form of mechanical shredding or grinding, therefore increasing the total cost of the process. As a result, it was important to study the effects of feedstock size on the ratio and quality of products in the process. Separate set of experiments will be performed using the large (2-3 cm) and small (2-3 mm) waste tyre crumb as part of the feed. The aim of the experiments performed will be to examine if change in the feedstock size results in any major discrepancies in the final results. If this is the case then it will be worthwhile to consider spending additional funds for further reduction in feedstock size. However, if no major discrepancies are found then additional cost of pre-treatment can be reduced or perhaps even eliminated completely.

The weight of the samples used in a single experimental run was limited to 50 grams. Initial trials used 100 g as the feed basis due to straight weight to percentage conversion (30 g of product oil would equal 30% wt, etc.). However this produced significant volumes of oil which exceeded the capacity of the current condenser system. Therefore the amount of sample used had to be reduced. It was decided that 50 grams was a more suitable choice.

4.2.5 Methodology

Detailed step by step experimental process is described below.

Step 1: Preparation of samples

Samples are weighed in a clean glass beaker and checked for any foreign material present in order to prevent possible contamination of the system. The sample is then manually loaded into the batch reactor ready to be placed inside the furnace.

Step 2: Install and secure reactor inside the furnace

Once loaded with the sample, the reactor is placed in the middle of the furnace where it is firmly secured. The nitrogen gas supply line is connected to the lid of the reactor and provides the necessary entry point for the inert gas. All of the connections, including all of the nuts and bolts inside the furnace, are greased with LOCTITE® Silver Grade Anti-seize Lubricant in order to enable easy disassembly after exposure to high temperatures.

Step 3: Assemble the condenser system

The stainless steel tar trap is filled with unstructured Teflon packing and connected in-between the two stainless steel coils, each 2.2 m in length. At the end of the condenser line, a transparent glass U tube is installed and it is tightly packed with glass-wool. Finally a rubber hose is added to the end of glass U tube and is used to carry syngas through to ventilation system. Once the whole condenser system is assembled, it is weighted on a scale and immersed in the ice bath and connected to the reactor located inside the future.

Step 4: Cycle the nitrogen gas through the system and test for leaks

Nitrogen supply is released and cycled through the whole system in order to test for any leaks. Online flow-meter located upstream of the furnace ensures that the flowrate remains steady at 2L/min. Every fitting, valve and connection is tested by using the gas leak detection fluid. Small leaks will produce foaming while the large ones will produce bubbles which are easily noticeable. If this is the case, the system is shut down and the connection is refitted ensuring the leak is eliminated. On the other hand if there are no leaks present keep the nitrogen supply going and proceed with step 5.

<u>Note:</u> Additional testing for leaks can be performed using a portable flow-meter at the syngas outlet and comparing it to the inlet flowrate. Any gas leaks will cause major inconsistency in flow-rates measured.

Step 5: Program the experiment method and complete final safety checks

Ensure all the connections are in place and all the equipment is firmly secured. Check that the furnace door is securely shut and the flow-rate of nitrogen gas remains constant at 2 L/min. Specify process conditions including the temperature, heating rate and holding time and enter the values on the furnace control panel. Ensure that the ventilation system and all the fans are on and operational. Place the "DANGER! HOT SURFACE" sign and position the protection screen in front of the furnace.

Step 6: Start the experiment

Start the experiment by switching the furnace on.

Step 7: Monitor the process and keep the progress log of the experiment

Ensure the process is monitored constantly and respond promptly to any disturbances detected. Temperature change inside the reactor is to be recorded periodically every 5 minutes as part of the progress log. Thermocouple inside the reactor provides accurate temperature measurements and displays them on the furnace control panel. The location of the thermocouple has been changed from inside the furnace to inside of the reactor, due to our focus being the temperature of the pyrolysis site.

Note: Attention needs to be paid to the ice bath where the condenser is located so that the temperature of the water is kept at the level necessary for the efficient condensation of oil.

Step 8: After completion of the experiment cool down the furnace and the reactor

At the end of the experimental run the nitrogen supply is turned off and the furnace door is carefully opened. The furnace is left open until both the furnace and the reactor are cooled down to an acceptable level to be manually handled. Once the temperature of the reactor has reached 80 °C the lid is removed with the use of hand protection thermal gloves. The condenser system is disconnected from the reactor and it is taken out of the ice bath for recovery and clean-up. The reactor itself is removed from the furnace and the char product recovered, weighted and stored in a safe manner.

Step 9: Weigh the condenser

Once the condenser has been removed from the ice bath it is weighted. The difference in the weight before and after the experiment will give us the total weight of the oil recovered from our pyrolysis process. It is important to dry the surface walls of the condenser well before weighing to eliminate any water droplets present which could add to its total mass, therefore giving the wrong indication of the total oil produced.

Step 10: Recover the oil and clean the condenser system

The oil collected inside the condenser is recovered by using the solvent mixture of chloroform and methanol, having a volume ratio 20:80. The stainless steel coils and Teflon packed tar trap are injected with the solvent inside the fume cabinet. The recovered oil is placed inside the beaker and heated to 35 °C for 6 hours in order to evaporate the solvent, leaving the pure oil. This is also done inside the fume cabinet. “Lean” oil is then safely stored for further analysis.

The clean condenser is placed inside the drying furnace where any remaining liquid is evaporated, leaving the coils and the tar trap dry and ready for use in the next experiment.

Step 11: Ensure all of the product samples are carefully labelled and stored away safely.

4.2.6 Product Analysis

After the char and the oil have been collected and stored accordingly, an in-depth analysis of all of the samples was carried out. The analysis of the syngas is not within the scope of this project due to insufficient resources including the supply of necessary equipment in order to perform an online analysis and budgetary constrictions.

4.2.6.1 Char Analysis

The char samples from the pyrolysis experiments are required to be milled in order to obtain an analysis sample at a nominal top size of 0.5 mm. Four char samples from experiments with different process parameters were used for the analysis in order to examine if the quality of the product is dependent on process conditions. Minimum 10 grams of each sample was required in order to complete all analysis. The following samples obtained under specific process conditions have been used in the analysis.

Table 4-2: Samples used in char analysis.

Sample	Date	Temperature °C	Retention time	Feed size
1	19/05/2008	600	60 min	2-3 mm
2	28/04/2008	450	180 min	2-3 cm
3	12/05/2008	450	60 min	2-3 mm
4	05/05/2008	350	60 min	2-3 mm

The high cost of the char analysis performed limited the larger number of samples from being analysed. The four samples above are sufficient in order to meet the objectives set out at the start of the research. The effect of different temperature, retention time and size in the pyrolysis process on the quality of char produced will be examined.

The samples were sent to HRL Technology laboratory in Melbourne for a proximate, ultimate and calorific analysis. Gross dry calorific value and gross wet calorific value were determined on a Leco AC350 calorimeter, according to AS 1038.5. Also, moisture and ash content were determined using a Leco MAC Analyser according to HRL Method 1.6. Volatile matter and fixed carbon within the samples was determined according to AS 2434.2. Carbon, hydrogen and nitrogen were determined according to HRL Method 1.4, using a Leco CHN Analyser. Finally, the sulphur content was determined using a Leco SC32 Sulphur Determinator, according to HRL Test Method 1.14.

4.2.6.2 Oil Analysis

After recovery the oil samples were stored in a dark fridge at 4 °C. Five samples have been used for all analysis. Four of these samples are from the oil produced in the same experiments as the above char samples (please refer to Table 4-3), while one additional sample was required in order to investigate the moisture content. This sample was obtained at 450 °C, 60 min retention time and using 2-3mm tyre feed samples. The volume required for all analysis was minimum 8ml per sample, apart from the moisture analysis sample which was 50ml.

All of the samples were sent to HRL Technology laboratory in Melbourne, where the analysis was performed. The ash content of the samples was determined using 1.5g of sample at 600 °C. Carbon, hydrogen and nitrogen were determined according to HRL Method 1.4, using a Leco CHN Analyser. Gross dry calorific value was determined on a Leco AC350 calorimeter, according to AS 1038.5. Furthermore, washings were collected from the Leco AC350 calorimeter and sulphur content was determined via ICP analysis according to method USEPA 5050 and ASTMD 808-05. Moisture content was to be determined via the Dean & Stark method, ASTM D0095, however during the distillation analysis the sample was not viscous enough to be distilled and this method was deemed a failure. The sample was recovered and then analysed via the Karl-Fischer method, ASTM D6304.

The GC-MS analysis of pyrolysis oil was performed with the assistance of Geoff Chidlow, a Senior Technician from Applied Chemistry department at Curtin University of Technology in Perth. The oil samples were analysed using a Hewlett-Packard GC-MS with a HP-5MS capillary column (length 50 m, i.d. 0.2 mm and film thickness 0.33 μm). The initial temperature set was 40 °C, and it was increased to 280 °C with the heating rate of 8 °C/min. Both initial and final temperatures had retention times of 10 min each. The injector temperature was 280 °C and the carrier gas in the system was Helium of 99.999% purity. The MS detector was set to scan mode with mass range 50-550 amu. Due to time constraints and budgetary limitations of the project, only qualitative analysis of the oil was performed. The identification of compounds within the oil samples was attained by matching the retention times and mass spectrum measured against the standard in the NBS library.

Four oil samples were used for the GC-MS analysis. The summary of these is presented below.

Table 4-3: Samples used in GC-MS oil analysis.

Sample	Date	Temperature °C	Retention time	Feed size
1	19/05/2008	600	60 min	2-3 mm
2	02/08/2008	450	180 min	2-3 cm
3	12/05/2008	450	60 min	2-3 mm
4	24/04/2008	450	60 min	2-3 cm

The reason behind choosing these specific test samples is because sample 1 & 3 are obtained from experiments carried out under the same conditions apart from the temperature. The GC-MS results should shed some light on the changes in oil composition due to changes in process temperature. On the other hand samples 3 & 4 can be analysed in order to explore the composition change with changes in feedstock size and the variations in composition are not expected to be significant. Finally samples 2 & 4 will provide valuable details on the effect of retention time at 450 °C.

Sample 3 and 4 have been recovered with the chloroform/methanol solvent while the first two oil samples were pure. Even though the solvent has been removed from the two samples by evaporation at 35 °C, there is a possibility of contamination which might affect the results of GC-MS analysis. Another possibility that has to be anticipated is the likely loss of some light end hydrocarbons during the evaporation of solvent, and this should be evident when compared to GC-MS analysis of clean oil samples.

Choosing the right samples to use for both oil and char analysis was a very big challenge and very important one indeed. Because of time and budgetary constraints, it was not possible to test all of the samples. However, with the right choice of samples this number can be minimized. As seen above, only four samples were sufficient enough to complete the full analysis and obtain the necessary data for our comparison study.

4.3 Results and Discussion

4.3.1 Pyrolysis yields

The results of oil, char and syngas mass yields obtained from pyrolysis experiments carried out under different process conditions are presented in the tables and graphs below. Mass balance was used to calculate the yield percentage of solid, liquid and gas products. Liquid and solid fractions were quantified and subtracted from the total feed mass in order to calculate the percentage yield of syngas and complete the mass balance. The first set of results shown below presents the mean value and standard deviation calculated from 3 experiments carried under the same temperature. As the temperature of the pyrolysis was increased there was a considerable increase in oil yield and a decrease in char produced. However, an increase in synthetic gas produced is minimal as the process temperature rises. This change in product yields was expected as levels of cracking exhibited at different temperatures vary. The same trend was observed in previous works as well.

At 300 °C pyrolysis has only started and large fraction of char (86%) remains in a product. However, as the temperature increases to 400 °C we see a clear drop in the amount of char remaining, resulting in the considerable increase of oil yield. This is the most “active” period of the pyrolysis process. At 450 °C oil recovery is at its highest reaching up to 59%. This is a very significant amount and when compared to previous works it is one of the best results demonstrated on this scale. Some of the more impressive results such as the ones published by Araki et al and Gonzales et al demonstrate maximum oil recovery at 50% and 55% respectively[55,51]. It is also very interesting to note that many previous works have shown the maximum oil yield occurring at 500 °C and 600 °C rather than 450 °C. This could be due to reduced heat transfer efficiency as a result of experimental set up or type of heating used in the pyrolysis process. In any case, obtaining the maximum oil yield at 450 °C is a very promising result as the energy savings associated with 100 °C or 200 °C reduction in process temperature are very significant and could improve the process economics considerably.

Table 4-4: Experimental set 1 (wt % is mean value ± standard deviation of 3 repeat experiments).

Temperature (C)	Char	s.d.	Oil	s.d.	Syngas	s.d.
	% wt	±	% wt	±	% wt	±
300	86.14	4.30	9.61	2.71	4.25	1.67
350	58.92	3.24	36.84	2.68	4.24	0.56
400	39.25	2.44	54.92	1.78	5.83	0.67
450	36.00	0.58	58.69	0.84	5.30	1.41
500	34.99	0.18	57.70	1.09	7.31	0.91
600	35.23	0.36	57.84	0.22	6.93	0.25

It is interesting to note that beyond 450 °C there is no further increase in oil yield but rather a slight decrease trend. This however does not coincide with the continuing decrease in the amount of char recovered, since it is expected the lower oil yield is due to lower thermal degradation of tyres. One explanation for this unusual behaviour could be found in the slight increase of the syngas formed. This suggests a possible anomaly in the condenser performance for these particular set of experiments. Factors such as the inconsistent ice bath temperature and an increased concentration of pyrolysis gas inside the condenser resulting in shorter residence time are just some of the examples which could influence its performance. However, a more realistic explanation for the slight decrease in oil recovery is the presence of stronger thermal cracking at higher temperatures as described by Rodriguez et al [52]. As a result more liquid products are further cracked into gaseous products, affecting the final product ratio. This is more evident at temperatures higher than 600 °C which are not within the scope of this work and therefore cannot be confirmed.

In relation to standard deviation of data, it is evident that at lower temperatures they are higher while they decrease with an increase in temperature. This is due to thermal decomposition being incomplete at lower temperatures and uneven temperature distribution within the reactor. As a result more or less rubber material will be decomposed resulting in product yield variations. On the other hand, as the temperature increases this effect becomes less relevant due to tyre degradation nearing its completion.

Finally it can be concluded that within the scope of this study, 450 °C is the optimum pyrolysis process temperature regarding the product yields, producing the maximum oil yields at lowest energy requirements.

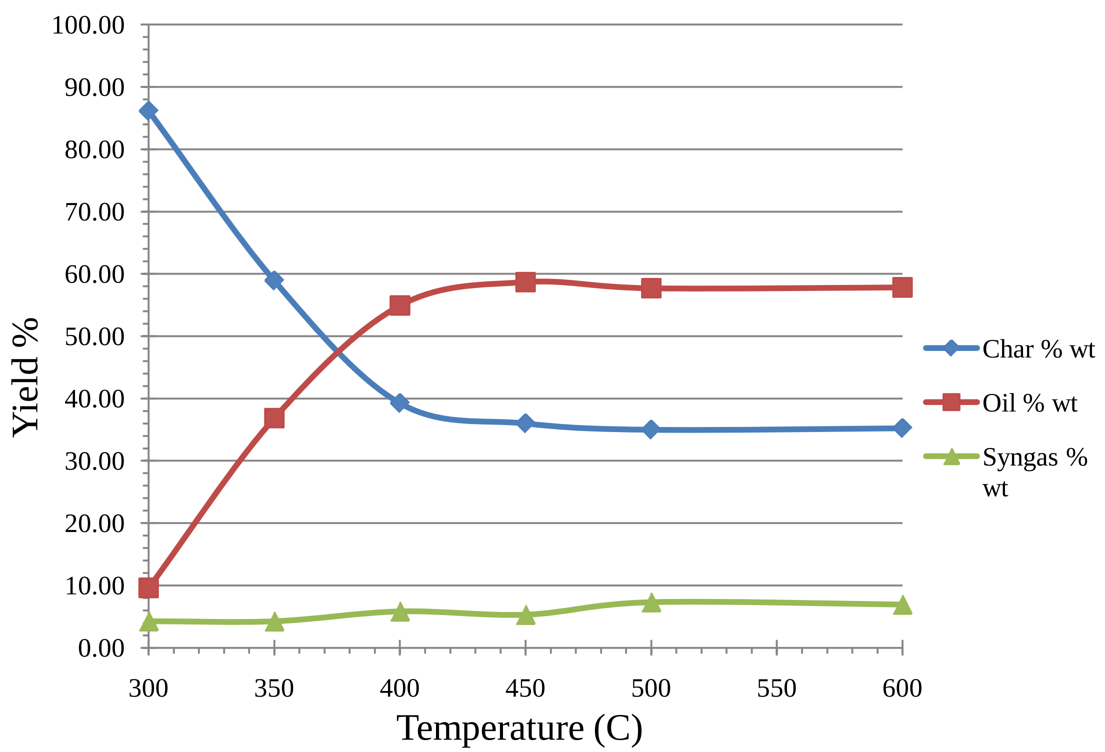


Figure 4-2: Pyrolysis product yields from experimental set 1.

The second set of results examined the effect of different sized tyre feed on product yields and quality. Smaller tyre crumb samples were used and results are shown in a table and graphs below. Comparing the previous results using the larger tyre samples with results obtained from the second set of experiments shows a slight reduction in oil yield at the same process conditions. This decrease in oil produced suggests that there is a decrease in thermal degradation of tyre which is supported by the increased char yields shown in the graphs on the next page.

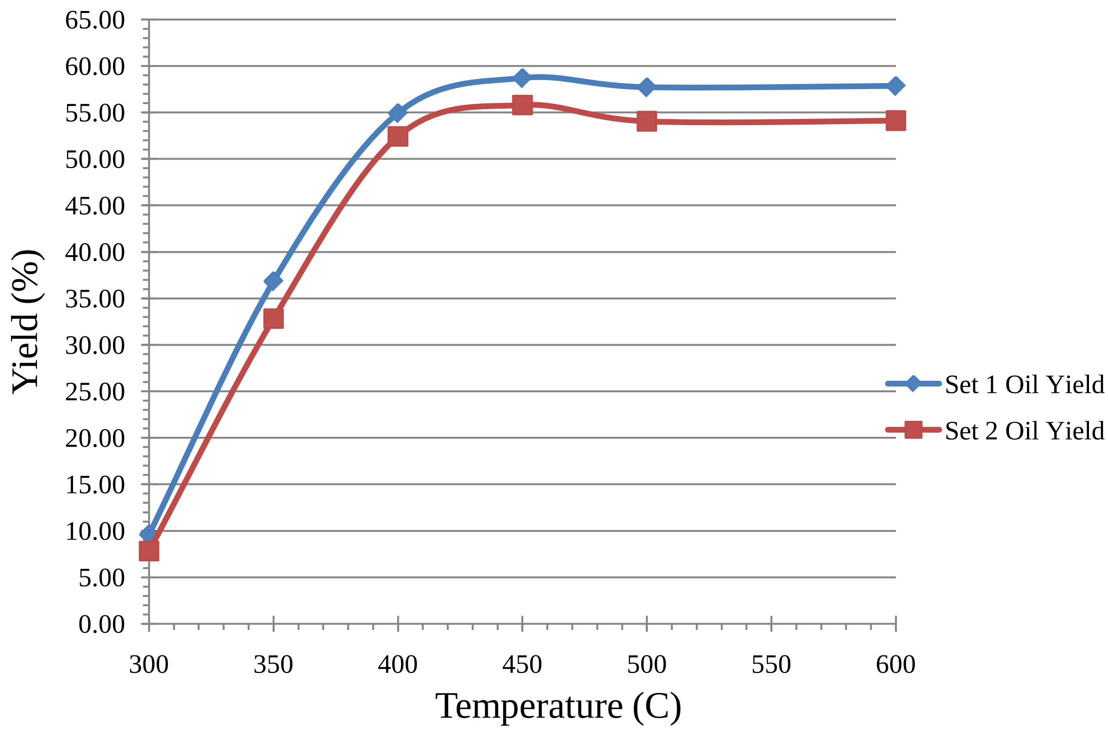


Figure 4-3: Pyrolysis oil yields (% weight).

This change in oil and char yield is quite unusual because it was expected that finer crumb samples will improve heat transfer due to increased surface area. However this has proven not to be the case. The effect of reduced feed size on heat transfer of pyrolysis is reversed and this could be because of the way larger samples are positioned inside the reactor. Bigger particles will not be as densely packed, taking the larger volume inside the reactor which results in more surface area being in direct contact with hot walls of the reactor and larger voids between the particles itself. Both of these could improve the heat transfer with the increased surface area being exposed to heat provided by walls of reactor and also the hot pyrolysis gases moving through the voids exposing more rubber to degradation process.

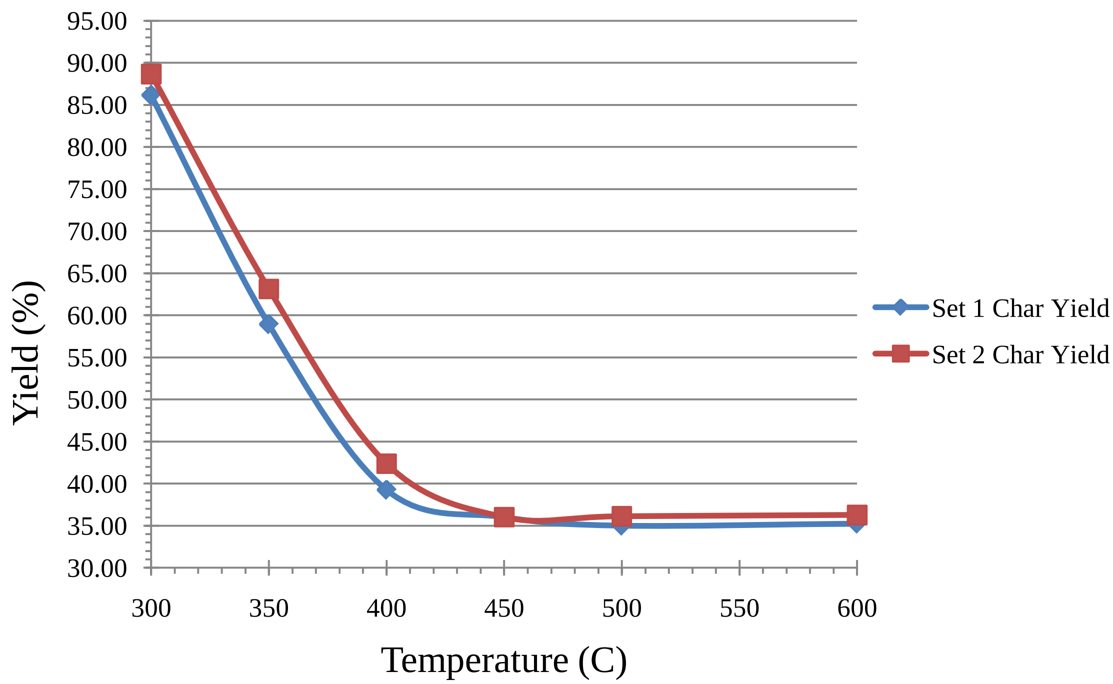


Figure 4-4: Pyrolysis char yields (% weight).

In the second set of experiments the samples are tightly packed together which makes it more difficult for gases to escape quickly from the reactor. Additional time spent inside the reactor will cause further cracking of liquid fraction produced and more gaseous products will be formed as a result. This is supported by decreased oil production and increased syngas yield in the second set of experiments. Also, additional proof of this could be the fact that the syngas production is nearly equal in the two cases up until the 400 °C when the difference becomes considerable. The reason for this could be that the liquid fraction produced is much lower at temperatures prior to 400 °C and this is why we do not notice any difference in syngas yields obtained. In this pyrolysis period there is not much liquid product that could be further cracked into gas and this is why the syngas yield is much lower. However, beyond this temperature there is an increase in the liquid yield present within the system, therefore increasing the potential for liquid to gas thermal cracking. This results in more gaseous product being formed at process end.

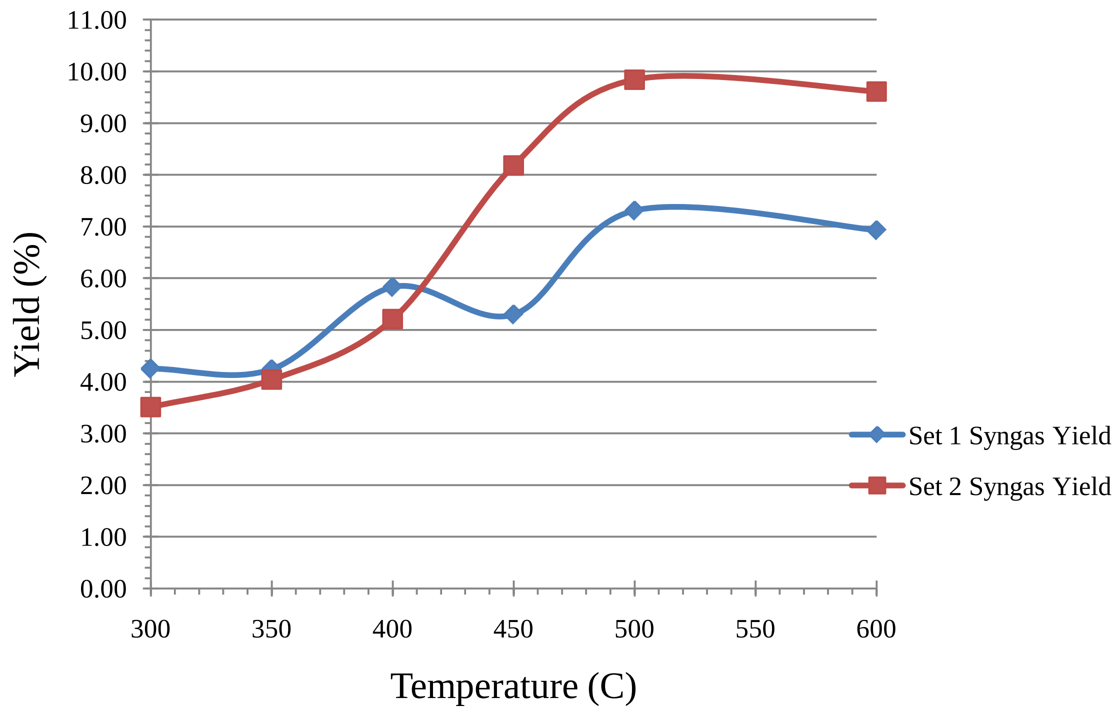


Figure 4-5: Pyrolysis syngas yields (% weight).

From the second set of experiments it can be concluded that reducing the size of the tyre feedstock will increase the total cost of the process without improving the product yield. However, this might not be the case with the commercial scale projects. The reason for this is that most of the process economics on a commercial scale largely depend on the throughput of the system and the economies of scale. If reducing the size of the feedstock can significantly improve the throughput of the system by packing the reactor more tightly with the tyre crumb, total product volumes of the facility will be increased. This is where economies of scale might justify any extra energy and capital spent on reducing the size of the tyre feed further. However, this will have to be studied at some other instance as this is not the focus of the current research.

Table 4-5: Experimental set 2 (wt % is mean value ± standard deviation of 3 repeat experiments).

Temperature (C)	Char	s.d.	Oil	s.d.	Syngas	s.d.
	% wt	±	% wt	±	% wt	±
300	88.66	3.75	7.82	1.79	3.51	1.99
350	63.13	3.18	32.82	2.81	4.04	0.46
400	42.37	2.03	52.42	1.11	5.21	1.12
450	36.02	0.70	55.80	0.73	8.18	0.75
500	36.11	0.48	54.05	0.68	9.84	1.00
600	36.27	0.33	54.12	0.36	9.61	0.69

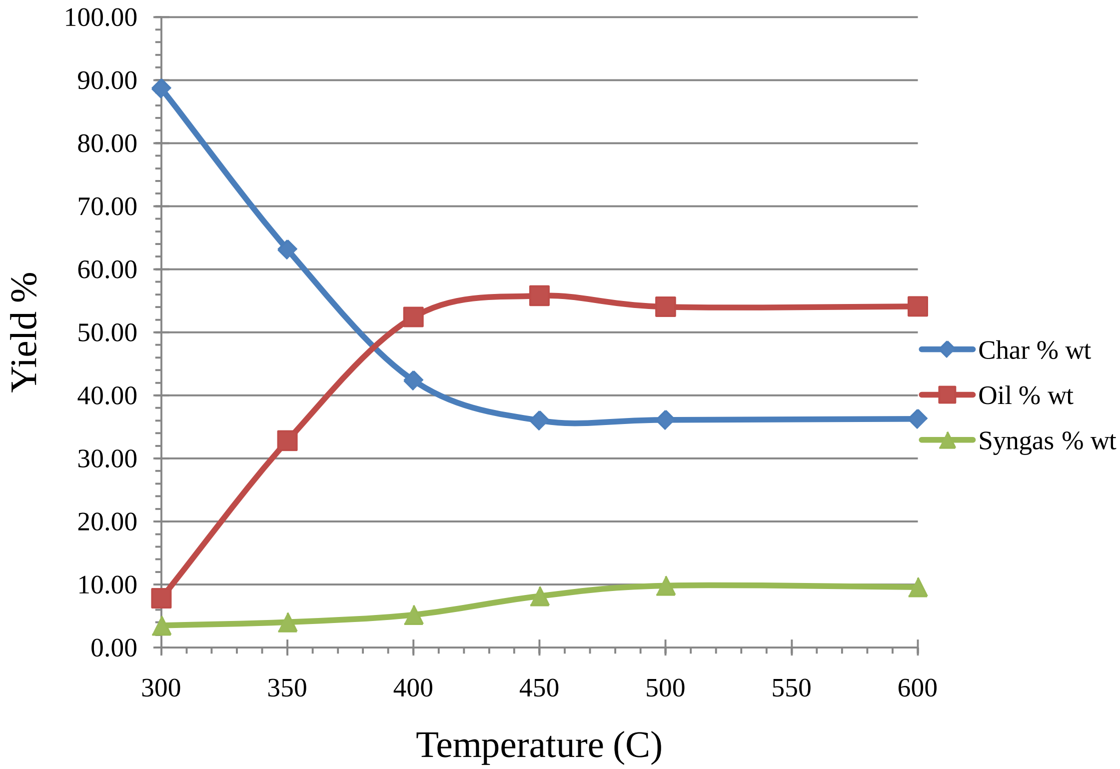


Figure 4-6: Pyrolysis product yields from experimental set 2.

Finally, the third set of experiments was carried out under the same process conditions as the first set, with the retention rate being the only exception. In order to study the effect varying residence time within the reactor has on the product yield and quality, tyre samples remained inside the reactor for 180 minutes from the moment the specified process temperature was reached. This was compared to the results obtained from the first set of experiments which were performed using 60 minutes as the retention time. The results are presented in a table and graph below.

Table 4-6: Experimental set 3 (wt % is mean value ± standard deviation of 3 repeat experiments).

Temperature (C)	Char	s.d.	Oil	s.d.	Syngas	s.d.
	% wt	±	% wt	±	% wt	±
300	83.44	3.28	8.05	1.49	8.51	2.12
350	57.58	3.19	35.98	1.52	6.44	1.68
400	37.77	2.00	53.08	1.39	9.15	0.73
450	35.03	0.67	55.08	0.71	9.89	0.13
500	33.98	0.26	55.64	0.38	10.38	0.65
600	34.21	0.26	56.62	0.23	9.17	0.49

From the results shown above we can see that the oil yield is slightly lower, as is the amount of char recovered from the reactor. On the other hand, syngas fraction is nearly doubled which suggests that the extended retention time provides stronger thermal cracking resulting in some liquid product being further processed and added to gaseous fraction. The same behaviour is noticed in the Set 2; however the fraction of char recovered is lower this time around. This suggests that long retention time not only increases the liquid to gas thermal cracking, but some of the gaseous product arrives as a result of stronger thermal cracking directly from char to gas.

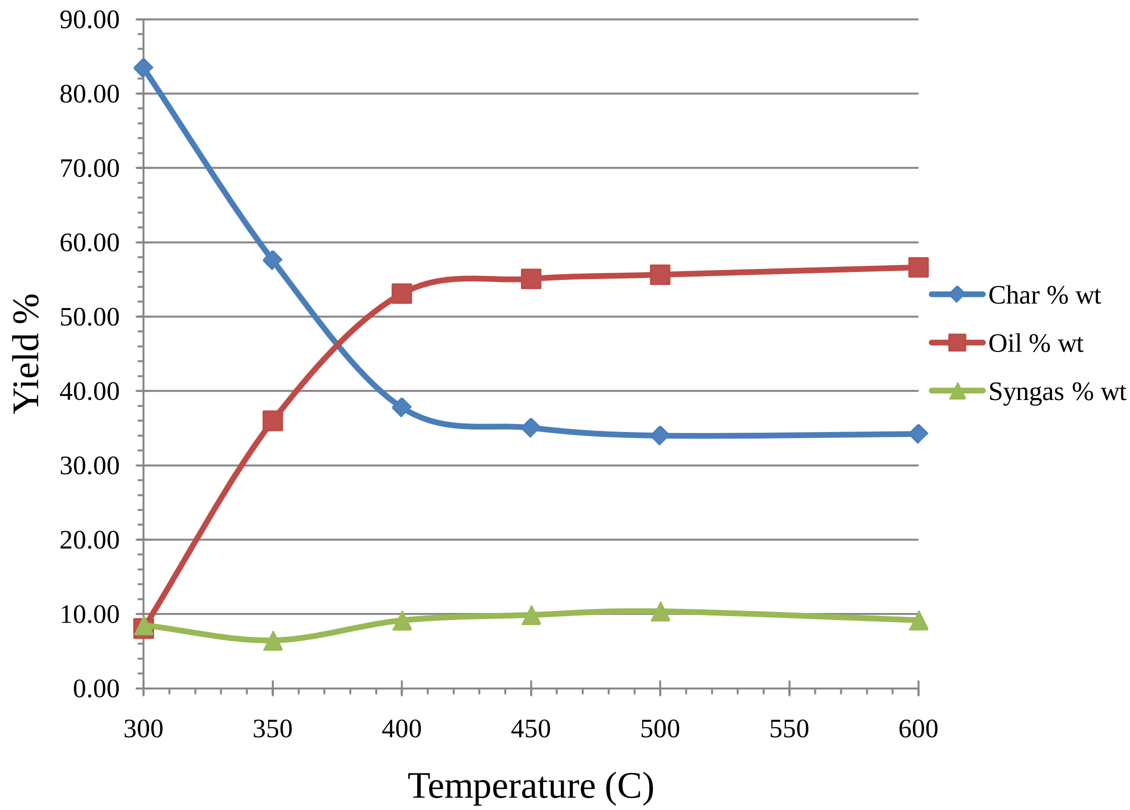


Figure 4-7: Pyrolysis product yields from experimental set 3.

The change in product yields obtained using longer retention time is not significant enough to justify additional energy necessary in order to achieve the specified process conditions. Increase in energy costs is enormous and it is recommended that the maximum retention time for pyrolysis of tyres should not exceed 60 minutes. Furthermore, it is suggested that any future pyrolysis research includes the study of retention times shorter than one hour, possibly 30 to 45 minutes. It is important to notice that the retention time will be different on a commercial scale due to significant increase in the material being processed, therefore possibly increasing the overall time for the completion of thermal degradation of tyres.

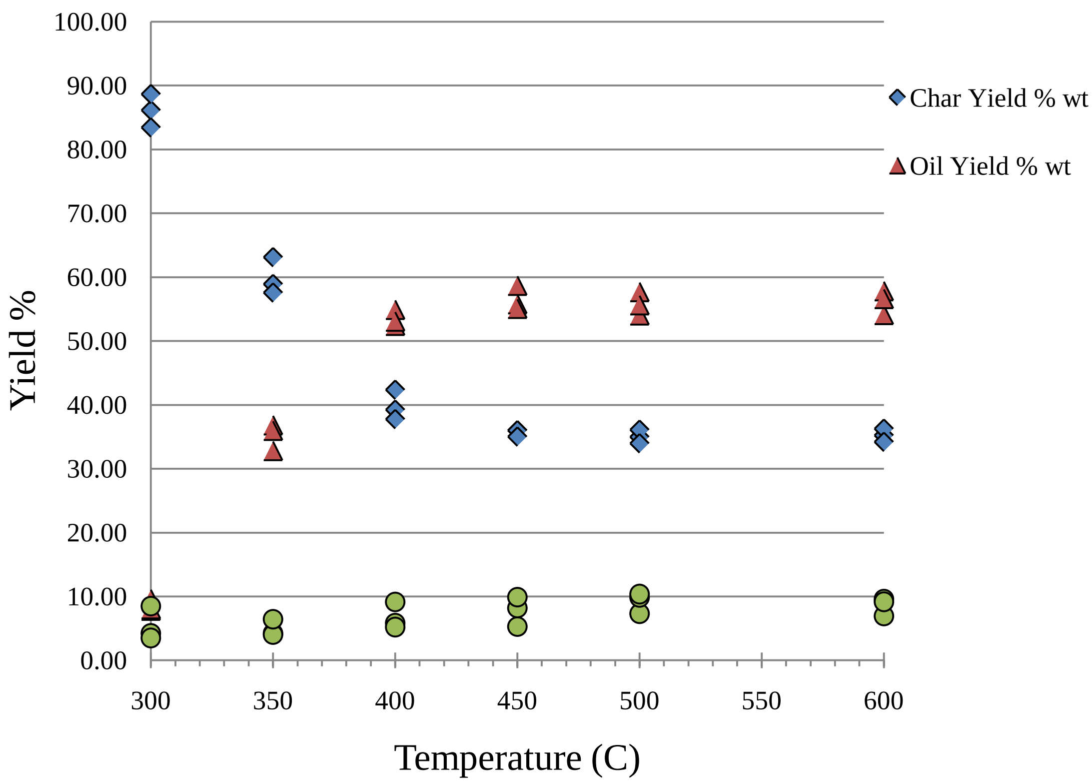


Figure 4-8: Pyrolysis product yields from all experimental runs (54 in total).

The above graph shows a summary of char, oil and syngas yield of all 54 experiments completed under different process conditions. Even though some process parameters have been changed in the experiments, the difference in product yields is not great but rather very minimal. The only major change in product yields occurs when the process temperature is altered. Another key point that this graph is able to depict is that the results obtained from the experiments are reproducible and therefore indisputable.

4.3.2 Tyre pyrolysis char

The char obtained from the pyrolysis experiments at 300 °C and 350 °C consisted of very sticky, partially degraded tyre crumbs. The "gummy" appearance of the tyre crumbs suggests that further increase in temperature is necessary to complete the cracking process. All of the char produced at temperatures above 350 °C was very brittle, black in colour and easily crumbled to fine powder. The crumbs retain their original shape, however at slightly smaller proportions. The char samples have been stored under cool and dry conditions before being sent to HRL Technology laboratory in Melbourne for proximate and ultimate analysis. The quality analysis of char samples is presented in the table below.

Table 4-7: Qualitative analysis of char samples.

			PROXIMATE ANALYSIS (%DB)			ULTIMATE ANALYSIS (%DB)							
HRL Sample ID CMM/08/0596 No.	Sample Description	Total Moisture (%)	Ash Yield	Volatile Matter	Fixed Carbon	Carbon (%db)	Hydrogen (%db)	Nitrogen (%db)	Sulphur (org)	O (by diff)	Gross Dry Calorific Value (MJ/kg)	Gross Wet Calorific Value (MJ/kg)	Net Wet Calorific Value (MJ/kg)
1	Char 19/05/08 600C	0.90	16.30	1.92	81.8	80.4	0.3	0.37	3.11	0.0	28.07	27.8	27.7
2	Char 24/04/08 450C	1.00	17.40	2.24	80.4	79.0	0.2	0.35	2.93	0.2	27.67	27.4	27.3
3	Char 12/05/08 450C	0.50	16.30	2.34	81.4	78.6	0.2	0.34	3.04	1.6	28.45	28.3	28.3
4	Char 05/05/08 350C	0.70	9.70	39.91	50.4	82.9	4.8	0.33	2.24	0.1	34.5	34.3	33.3

In order to compare the quality of pyrolytic char with the typical carbon black used in the manufacture of tyres, elemental composition of carbon black is included in the table above. The most noticeable discrepancy between the two sets of results is the amount of ash present in char. Tyre manufacturers will not use any type of carbon black unless it has ash content below 0.5 % wt [52]. The proportion of ash in the pyrolytic char reaches staggering 17.4 %. Rodriguez et al suggested that this large quantity of ash comes from all the inorganic fillers, excluding steel, which are used in the manufacture of new tyres [51].

Table 4-8: Elemental composition of typical carbon black.

	Carbon (% wt)	Hydrogen (% wt)	Nitrogen (% wt)	Sulphur (% wt)	O + others (% wt)	Ash (% wt)
Commercial Tyre carbon black	**97.1**	**0.2**	**0.2**	**1.0**	**1.1**	**0.4**

Sulphur concentration in the pyrolytic char is nearly 3 times higher than the amount found in commercial carbon black. This is because tyres originally contain around 1.5% wt. sulphur, and considering that only 35% of char remains after the pyrolysis is complete at 450 °C and 600 °C, this would mean that the total amount of sulphur left behind in the remaining char is around 60 %. This is a considerable amount and could pose a big problem in trying to market the char as a high value product. On the positive side, the calorific value of pyrolytic char is very high, much higher than that of coal and could be used as a solid fuel.

Looking at the relationship between process conditions and char quality it seems that there is not much difference in the elemental composition, apart from the hydrogen concentration at 350 °C. The reason for such a high hydrogen concentration is the fact that degradation of a tyre is not complete at this temperature. This is further supported by higher GCV values at lower temperatures. Therefore it can be concluded that the quality of pyrolytic char is not influenced by either the size of the feedstock or the retention time. The only process parameter affecting the elemental composition of char is the temperature, however this is only evident between the low and the high values.

The potential use for the char obtained from tyre pyrolysis is mainly limited by high concentrations of ash and sulphur. The new tyre manufacturers will not consider using char containing such extreme ash concentrations which narrows the market considerably. One possible use in the future could be the in replacing the lower quality carbon black in playground surfacing, footwear, conveyor belts and possibly sporting facilities. Another potential use is further processing of char into activated carbon. This would be a great source of income as activated carbon is a very high value product. However, further work needs to be done in order to fully understand the potential for this prospect.

4.3.3 Tyre pyrolysis oil

The oil recovered from the condenser is very viscous and dark brown - black in colour. In order to extract all of the oil from the condenser coils, a solvent solution made up of chloroform and methanol mixture was used. Only a small fraction of oil was recovered without any solvent, and this was mainly oil which accumulated inside the tar trap. In order to obtain accurate results only the solvent-free oil samples were used for the GC-MS analysis, as they would be free of any contamination. However, out of 52 samples, only a few of them were obtained in such a manner while the others had to be recovered using the solvent. The oil samples containing solvent were heated to 35 °C and left inside the fume cabinet in order to evaporate the chloroform and methanol mixture. It was important to control the temperature under 35 °C because of the possible loss of some lighter hydrocarbons present in the oil samples.

The table below shows the results of the elemental analysis carried out on the oil samples as well as their GCV. Oil obtained at 450 °C has the highest concentration of hydrogen and carbon and this was anticipated since at this temperature secondary cracking of liquids is not as strong as in higher temperatures, therefore no additional carbon and hydrogen are lost to syngas product. There is also a large difference in the fraction of oxygen and other elements found in the four oil samples. Such a discrepancy can only be explained by different levels of chloroform or methanol present in the oil due to an inadequate removal of solvent.

Gross calorific value of pyrolytic oil is rather high but not as impressive as in some similar works done previously and this again could be the cause of some solvent remaining in the samples reducing the total average GCV of the oil. Different levels of solvent present in each of the four samples are also a possible reason behind different

GCV's obtained. Even with the solvent present in the samples, the GCV of the pyrolytic oil is still very high, making it a perfect candidate for a liquid fuel, mainly used for heating purposes.

Table 4-9: Qualitative analysis of oil samples.

			PROXIMATE ANALYSIS (%AR)	ULTIMATE ANALYSIS (%AR)					
HRL Sample ID CMM/08/0596 No.	Sample Description	Total Moisture (%)	Ash Yield	Carbon	Hydrogen	Nitrogen	Sulphur (org)	O (by diff)	Gross Dry Calorific Value (MJ/kg)
5	Oil 19/05/08 600C		0.00	74.4	9.9	0.51	0.92	14.3	37.8
6	Oil 450C Large		0.06	77.4	10.8	0.61	0.80	10.3	39.4
7	Oil 450C		0.00	80.6	11.0	0.50	1.12	6.8	40.5
8	Oil 350C		0.00	70.9	9.5	0.47	0.91	18.2	36.2
9	Moisture Sample	3.90							

A single 50 ml sample was used to analyse the moisture of the pyrolytic oil produced. As seen in the table above, the moisture concentration is just below 4 %. This is a small amount but still significant if taken into account the fact that this moisture will have to be removed by heating it at 110 °C before the oil can be used in any engine. This is because of the water clogging the filters and fuel lines by freezing at lower conditions, while at higher temperatures it will promote rusting.

The current acceptable limit for sulphur concentration for diesel fuel is 1.2 %. The sulphur present in pyrolytic oils is below this value, however one of the samples obtained at 450 °C reaches 1.12 % sulphur content. This is one area which will have to be closely monitored as high sulphur content increases the wear of engine parts due to increased corrosion. In case this proves to be an issue, a recommended solution would be to use the pyrolytic oil as a fuel blend, therefore reducing the total concentration of both the moisture and the sulphur present.

The four oil samples presented in Table 4-3 were analysed by gas chromatography/mass spectrometry (GC-MS). The results obtained suggest that the recovered oil is a complicated mixture of many different organic compounds, ranging anywhere from C_5 to C_{20} hydrocarbon isomers, including a great proportion of aromatics. These compounds have been identified by matching the retention times and mass spectrum measured against the standard in the NBS library. Only the compounds with high quality match (≥90%) have been published in this report. It is worth mentioning that high quality match compounds only make up 5% of the total number of compounds present inside the oil samples. However these are usually the compounds having the biggest presence as shown by area underneath the peaks presented in TIC (total ion chromatographer) trace diagrams in Figure 4-7 and Figure 4-8. The list of the high quality match compounds and their respective area percentage is shown in Table 4-10.

It is interesting to note that compounds identified by GC-MS analysis mainly belong to aliphatic, aromatic and hydroxyl groups. Of these three groups, aromatics is the most common and this is mainly due to the reactions that take place among aliphatic and aromatic free radicals as well as the cyclation of aliphatic chains. Tyre pyrolysis oils have been identified as being strongly aromatic by other authors performing similar work in the past. It is interesting to note that sample obtained at 600 °C contained much higher proportion of aromatic compounds compared to samples obtained at 450 °C. This is particularly evident with benzene, benzothiazole and quinoline. Cunliffe and Williams explain that at lower temperatures, the free-radical fragments are generated due to much slower cracking of the polymer and in order to become stable they accept hydrogen from potential H-donor structures [53]. On the other hand temperatures closer to 600 °C generate much more free radicals at faster rates causing them to recombine with one another, which results in more aliphatic compounds being connected to aromatics. This will explain a slight decrease in many aliphatic compounds as the temperature increases to 600 °C.

The summary of composition analysis of oil samples using GC-MS can be found on the next page.

Table 4-10: Composition analysis of oil samples using GC-MS.

	AREA %			
Compound (High Quality Match)	Sample 1 (600 °C)	Sample 2 (450 °C)	Sample 3 (450 °C)	Sample 4 (450 °C)
				-
Cyclobutane - 1-methylethylidene	2.55	0.89	-	-
Toluene	2.52	1.17	-	-
p-Xylene	5.34	2.55	-	-
Styrene	-	0.82	-	-
Benzene - 1-methylethyl	8.70	1.70	1.29	1.75
Benzene, - 1,2,3-trimethyl	-	1.18	-	-
cis-2,6-Dimethyl-2,6-octadiene	-	1.17	-	-
Cyclohexene	-	0.68	-	-
D – Limonene	3.50	0.93	-	-
Limonene	47.73	33.93	11.21	15.01
4-Carene	3.98	2.24	-	-
o-Isopropenyltoluene	2.81	-	-	-
Caprolactam	-	-	3.52	-
1,2,3-Trimethylindene	-	0.88	1.76	1.36
Naphthalene - 2,7-dimethyl	2.90	1.20	2.37	1.95
Naphthalene- 2,3,6-trimethyl	-	1.68	3.96	3.85
Quinoline - 1,2-dihydro	7.41	3.18	4.86	7.50
Quinoline- 2,4-dimethyl	-	0.74	2.02	1.21
Phenol - 1,1,3,3-tetramethylbuty	-	0.76	1.53	1.67
Heptadecane	-	-	1.57	-
Heptadecanenitrile	-	0.74	-	-
Pentadecanenitrile	-	-	1.67	-
Octadecanenitrile	-	-	1.85	-
n-Hexadecanoic acid	-	0.94	2.31	-
Octadecanoic acid – methyl ester	-	-	1.53	-
Di-n-octylphthalate	-	-	6.15	-
Nonacosane	-	-	1.56	1.22
Tricosane		-	1.57	-
Benzothiazole	4.16	1.01	2.06	-
1,4,5,8-Tetramethylnaphthalene		-	-	1.23
1,4-Benzenediamine	5.75	4.66	-	3.12

Limonene has by far the most notable presence in the pyrolytic oil mixture. This compound accounts for nearly 50% of the total liquid product distribution at 600 °C, making it the biggest single factor in deciding the final use for oil derived from tyre pyrolysis. It is suggested that limonene is produced as the result of the dimerization of isoprene, a main constituent of natural rubber [54]. According to United States Department of Health and Human Services isoprene vapour is considered very carcinogenic and conversion to limonene could be a key in favouring pyrolysis of tyres over the standard combustion and incineration. Additional to this, limonene is widely used in manufacturing some industrial solvents, resins and adhesives, which could be another potential market for pyrolytic oil.

Other major compounds that have been identified in pyrolysis oils are benzene, toluene, p-xylene, styrene, 4-Carene, naphthalene, quinoline, phenol, benzothiazole and benzenediamine. Most of these are labelled on the TIC diagrams below and all of them are included in the table of high quality match compounds. Similar compounds have been identified in previous works done by other authors.

As mentioned before, process temperature has an effect on the proportions of the compounds present in the oil mixture, with aromatics increasing as the temperature increases at the expense of decreasing aliphatic chains. At 450 °C we see compounds such as heptadecane, pentadecanenitrile, octadecanenitrile, hexadecanoic acid, octadecanoic acid, Di-n-octylphthalate, nonacosane, tricosane and other aliphatics, which are not present at all at 600 °C. However the presence of aromatics at higher temperatures becomes more significant.

The effect of longer residence time on the composition of product oil is analysed by comparing the results obtained from oil samples 2 and 4. It is evident that the effect of prolonged residence time is very similar to the effect of increased process temperature. However this time the change in the proportions of the aromatic and aliphatic compounds present is much smaller than the change caused by temperature increase. This is expected as further cracking is induced by tyre being exposed to heat for longer periods of time, however the cracking is not as extensive as when tyre is exposed to a higher temperature. Apart from converting into aromatic chains as is the case when temperature is increased, some aliphatic hydrocarbons are further cracked only into different isomers. This is shown in the GC-MS table. You can notice a much larger number of isomers present in the sample which was collected from extended residence time experiment.

Finally, the effect of feed size on the composition of oil is not very significant. Most of the compounds present exhibit the same proportions within the mixture, however few of the aliphatic hydrocarbons present in sample 3 are not found in sample number 4. This could be due to different reasons such as some of these compounds evaporating when the solvent was extracted from the sample. However, a more realistic reason is because some of these compounds did not make the high quality match list. They are possibly present, however could not be identified with certainty due to such a low quality match in the NBS library. This could also be one significant source of error when trying to compare all of the samples. Just because certain compounds could not be identified does not mean they are not present in the mixture. However, the analysis performed for this particular study was sufficient to recognize the trends in changing compositions of products due to variation of process conditions.

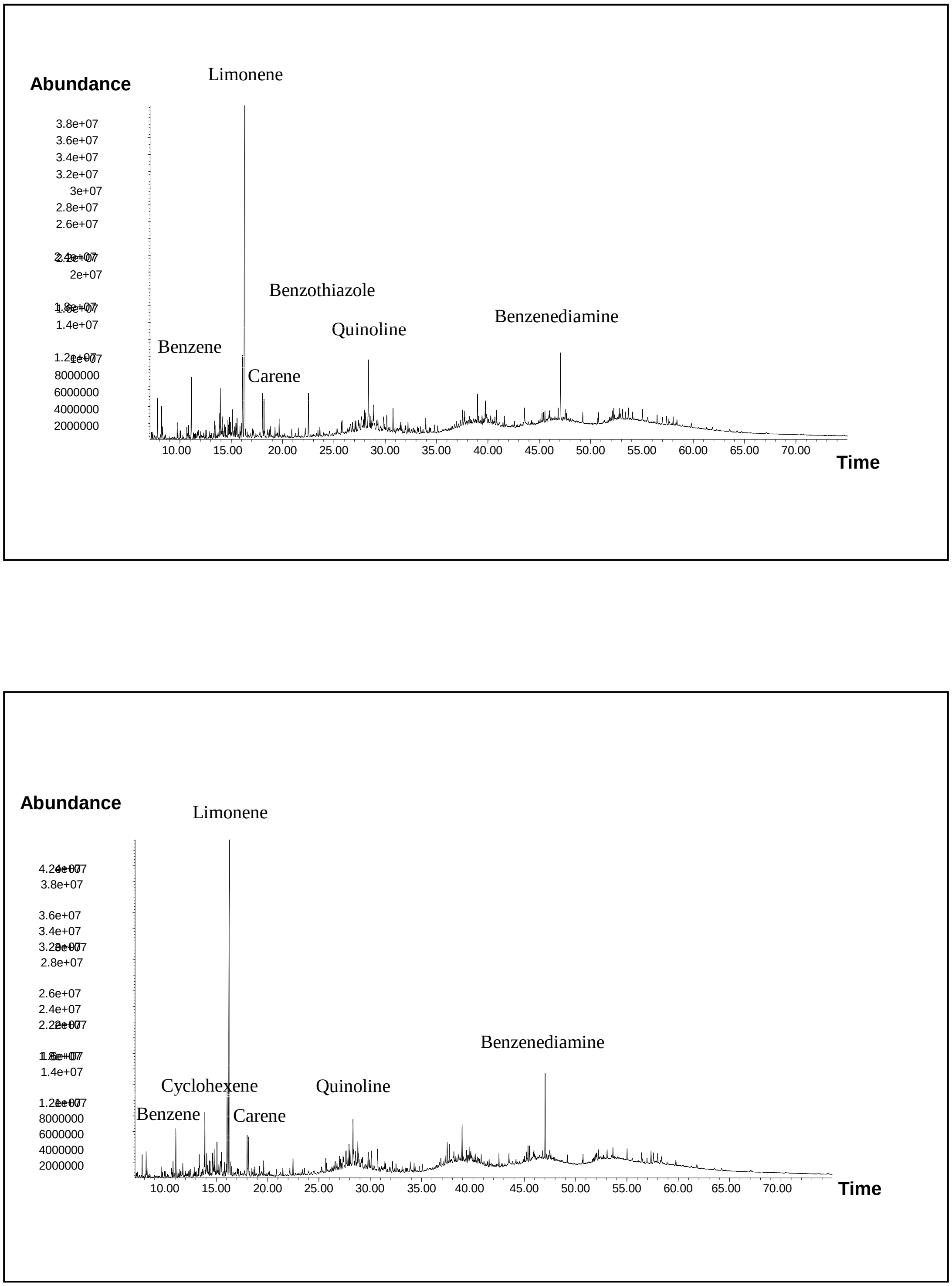
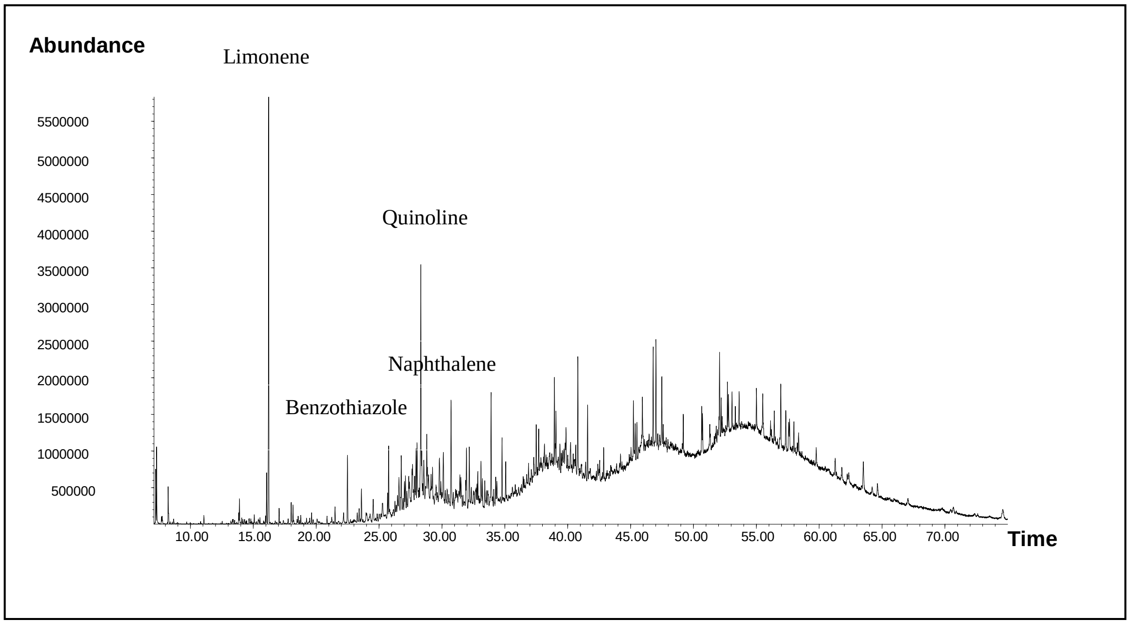


Figure 4-9: Total ion chromatographer (TIC) trace diagrams for a) oil sample 1 (19/05/2008, 600 C) and b) oil sample 2 (02/08/2008, 450 C).



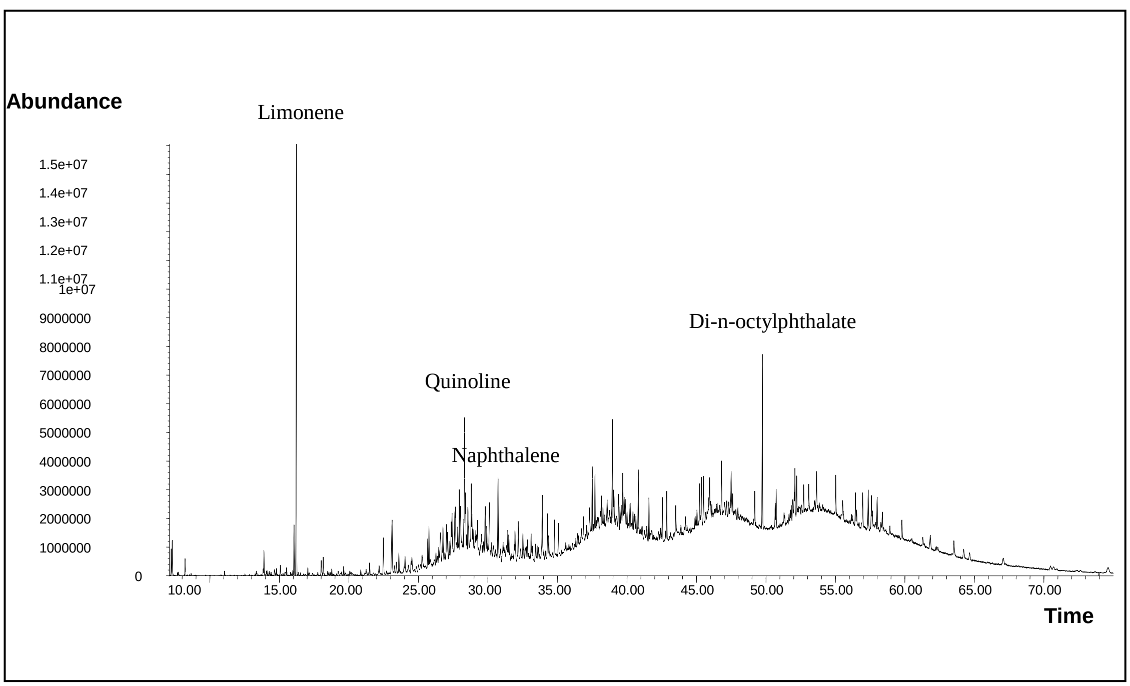


Figure 4-10: Total ion chromatographer (TIC) trace diagrams for a) oil sample 3 (12/05/2008, 450 C) and b) oil sample 4 (24/04/2008, 450 C).

Chapter 5 : Economic Analysis

A preliminary stage 1 economic analysis was conducted for a waste tyre pyrolysis plant producing pyrolytic oil, steel and char. A number of different models, including further processing of char into activated carbon or carbon black, have been developed and compared using cashflow analysis for the purpose of this research report. Basis for the cost analysis were similar facilities which have either been built in the past or are going to be constructed in the near future. The in-depth feasibility studies completed for these projects contain viable information which has been used for the purpose of this economic analysis.

The main purpose of this economic study is to explore the financial viability of waste tyre pyrolysis process on a commercial scale. It is important to note that up to date there has been no commercially viable solution to operating waste tyre pyrolysis plants which resulted in all of the previous projects being scrapped within a few years after starting up. Financial problems have been noted as the main cause of these plants being shut down. This has increased the uncertainty within the investors over the true value of pyrolysis processing and has resulted in lower number of interested parties willing to support the development of similar projects in the future. The main objective of this economic analysis is to explore some of these issues and provide a proposal for improving the overall financial attractiveness of the waste tyre pyrolysis process.

5.1 Design Basis and Process Description

The following economic analysis was based on a pyrolysis PFD shown in Figure 5-1. Operating process conditions were derived from the experimental results obtained in previous chapter which provided accurate results of product recovery. This is very important as it will provide clear picture of the revenue generated by the sale of products and it will assist in the development of economic analysis.

Waste tyres are delivered onsite where they are sorted and stored in bulk before being processed. The feed preparation step includes loading waste tyres onto conveyor belt and reducing them to small chips (2-3 cm across) in industrial sized chippers before passing them through magnetic separator where 99 % of the steel is removed. The cost of feed preparation such as chipping and steel removal is included in the final cost analysis.

Tyre shreds are then loaded into a large and cylindrical rotary pyrolysis reactor where they are processed into char, fuel and synthesis gas. Nitrogen is used as the inert carrier gas. The number of reactors required will be directly related to the size of the plant. Products are separated and further processed in order to obtain high value products capable of generating significant revenue. Operating temperature inside the reactor was set at 450°C as this will give the best yield of pyrolytic oil and char while providing enough syngas to support the process itself and significantly reduce the energy requirements. Experimental results in Chapter 4 have shown that at 450°C, final product yields of the process are as follows: 15% steel, 8.5% syngas, 29.75% char and 46.75% oil. Pyrolytic oil is stabilised and classified as a number 6 fuel oil while char is steam activated or sold as carbon black. In the later case, capital and operating costs are lower as no carbon activation is necessary. However, the total revenue is significantly lower as activated carbon is the product with a much higher value. Different economic models have been developed and evaluated against each other in order to determine the best possible option.

Syngas generated from the pyrolysis of waste oil is not produced at significant quantities to provide a saleable product stream. In order to maximise the value of this product, the syngas is used to provide necessary heat and energy requirements for the pyrolysis process, which significantly reduces the operating costs and in turn has an effect on project’s overall profitability.

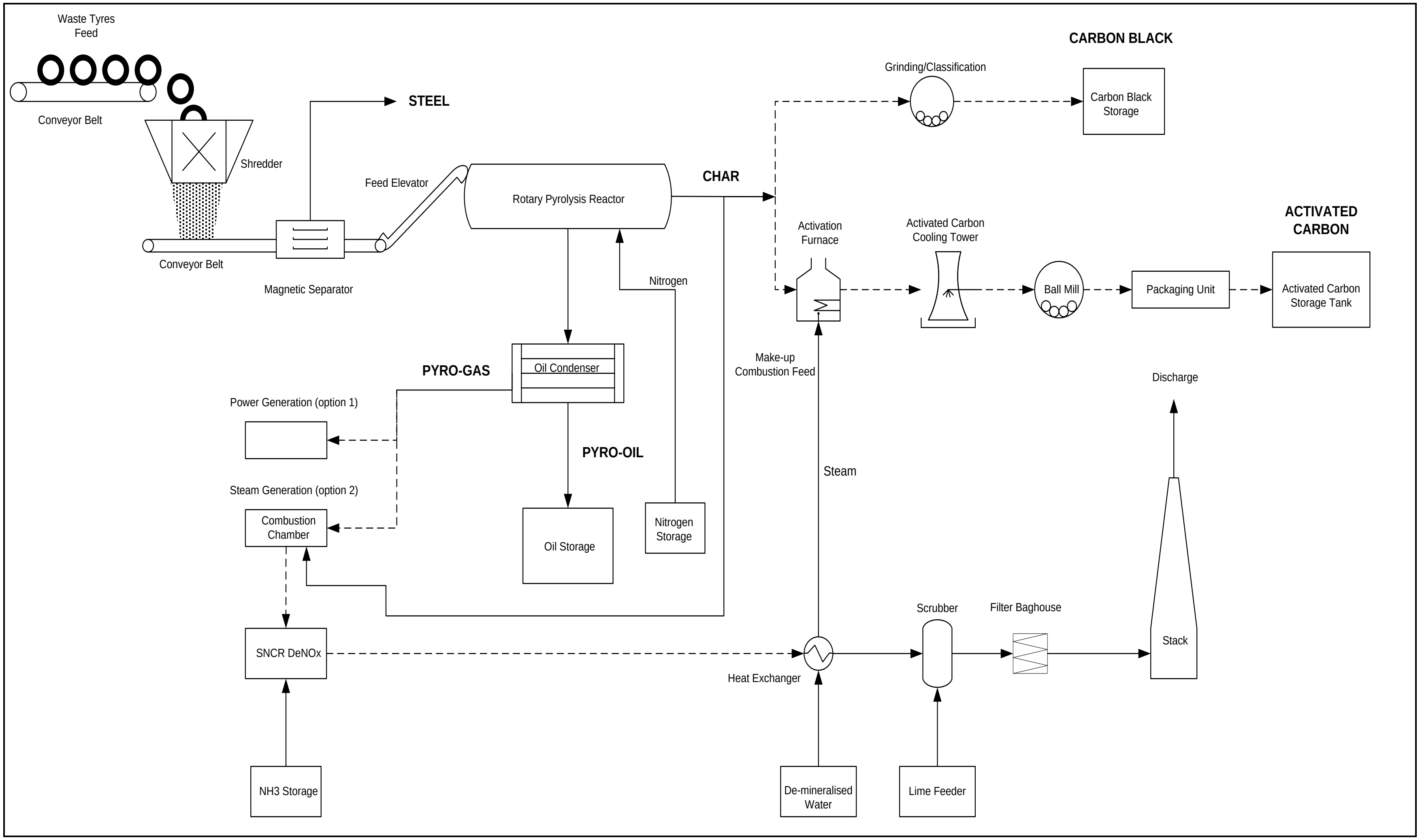


Figure 5-1: Process Flow Diagram

5.2 Plant Location

For the purpose of this report it was important to choose a single location for the waste tyre processing facility. The main reason for this is to keep the consistency between different models and enable accurate comparison between the same. Therefore, it was assumed that Hughes Environmental Solutions Pty Ltd, who has been the main sponsor of this research, requires a waste tyre pyrolysis plant in Wales, UK.

Exact location of the proposed plant depends on the availability of feedstock, in this case passenger waste tyres. As transport of waste tyres is a significant cost to the project, it was important that the plant was located so that the overall distance to collection points is minimised.

It was decided that the port city of Swansea would be strategically ideal location for the waste tyre pyrolysis plant. It is a deep water port and it has good rail and road links to major population centres of South Wales as shown in Figure 5-1. This will ensure that the transportation costs are minimised and major waste tyre collection points are easily accessible. It will also assist in generating revenue by providing the necessary market access for the final products.

The port of Swansea is ideally located for maritime trade with north-west Europe, Ireland and the Mediterranean. It is a deep water port and it caters for ships up to 30,000 tonnes. All of the heavy-duty modern cargo handling equipment as well as large open and sheltered storage areas are available at the docks.

The map presented in Figure 5-2 displays the location of Swansea and the 50 mile radius surrounding the city. This area is used in our economic analysis as an average distance of waste tyre collection points. Cardiff, the capital city of Wales is approximately 46 miles from Swansea and is within the 50 mile radius as seen on the map. This is very significant because majority of the waste tyres in South Wales are being generated in Cardiff city and its neighbouring area, which is expected considering the high population count in this region.

It is estimated that in South Wales alone a total of 115,000 tonnes of waste tyres are generated each year, of which 100,000 tonnes is considered suitable for recycling and processing [56]. From the map in Figure 5-2 it can be seen that the 50 mile radius nearly covers the whole area of South Wales, suggesting that approximately 80,000 to 90,000 tonnes of waste tyres are generated in this region annually. This will be used as the basis for the economic analysis presented in the next section of this report.

The specific site for the processing plant has not been identified as this is not within the scope of this study.

Figure 5-2: The proposed location of the waste tyre processing facility and 50 miles collection radius shown on the map of Wales.

5.3 Collection vs. Disposal of waste tyres

One of the biggest factors influencing the success of a waste tyre business is the level of company's involvement within the industry. Some companies choose to remain at the collection level, while others decide to be more involved at the disposal end of waste tyres. However, a possible integration of these two could potentially provide an ultimate solution for a successful business within the industry. This is one of the areas this economic analysis explores, by comparing the stand alone disposal facility with the facility which incorporates the waste tyre collection service as well.

New tyre retailers in UK charge their customers EDC (Environmental Disposal Charge), which is a charge levied for the disposal of waste tyres [57]. In theory, EDC should be used to cover the costs of collection charge, which is the charge applied by the collectors to remove and transport the waste tyres to a disposal facility or other end user. Apart from collection charge, EDC should cover the cost of the disposal fee or gate fee, which is a charge paid by the collector to the disposal facility in order to accept the waste tyres for processing or other end use. The table below summarizes the average charges in South Wales as of 2007.

Table 5-1: Average charges of waste tyre collection and disposal in South Wales.

£ per tyre	EDC to consumer (average)	Collection charge (average)	Disposal fees/Gate fees (average)
Passenger car	0.94	0.86	0.55

The charges shown in Table 5-1 represent average figures of passenger car waste tyres and some of them vary considerably across the country. Most of the new tyre retailers have standard EDC charges and these differ only slightly. However, when it comes to collection and disposal charges, the difference can be significant depending on the geographical area and its supply and demand situation. Charges are also subject to contract terms and volumes. For example, lower volumes will be charged prices at the higher end of the scale and vice versa. The average values presented here are generated as a result of survey performed in 2007 throughout UK, with South Wales being one of the ten regions included in this study.

Even though collection charges are there to cover the cost of transportation and handling of waste tyres, this is not always the case. Many collectors realise that the costs of collection, sorting and transportation of waste tyres are very significant and often larger than the collection fees they charge. This is due to long distances between the collection points and the processing facility, as well as the fact that because of their high bulk, full loads of waste tyres can’t achieve the maximum weight allowed in any truck load. This means additional trips are required, therefore increasing the transportation cost.

For the purpose of this report, quantities of waste tyres are presented as either a tonnage or “car tyre equivalent” where the average truck tyre is represented as six car tyres [57]. Information gathered in 2007 survey of collectors has confirmed that the conversion factor for car tyres (including the 4x4 vehicles and LCV) is 120 tyres per tonne [57]. This figure is going to be used throughout this report and will not vary.

The cost of collection and transportation of waste tyres has been modelled based on the results obtained from the 2007 survey completed by WRAP (Waste & Resource Action Programme), in which over 200 collectors throughout UK participated in [57]. On the following page is the estimation of a typical collection model developed from the results obtained in the WRAP study.

Basis for Collection Models (estimated vales) [57]:

- 18 tonne rigid vehicle (with 2 drivers) can load up to 300 car tyres per trip;
- Assume 3 collection trips per day;
- Assume 60 mile round trip per collection;
- The all up cost of operating the vehicle with 2 operators is £281 per day (obtained from WRAP study).
- The cost of sorting is £3.50 per tonne of tyres

Therefore the cost of collection and transportation per tonne or per car tyre is:

Weight of tyres collected / day	*= (300 tyres x 3 trips) ÷ 120 tyres/tonne*
	= 7.5 tonnes per day
Cost per tonne of tyres collected	*= £281 ÷ 7.5 tonnes*
	= £37.50 per tonne
Adding the cost of sorting	*= £3.50 per tonne*
Total cost of collection-sorting	*= £41.00/tonne or £41.00 ÷ 120 = £0.34 per tyre*

The WRAP study also estimates that the shorter collection rounds will be as low as £22 per tonne while the longer routes can be as high as £54. This information is used throughout the economic model where longer routes of 80 and 100 mile round trip are required.

5.4 Assumptions used in economic analysis

Some additional assumptions used in developing waste tyre processing economic models are:

1. Conversion factor of 120 car tyres per tonne of waste.
2. Plant operating on average 335 days per year.
3. Only car tyres are used (some truck tyres are collected and they are accounted for by using the “car tyre equivalent” conversion factor, 6 car tyres = 1 truck tyre).
4. Steel content recovered from tyre is approximately 15 %.
5. Pyrolysis yields at 450 °C from exp results are: C = 35%, O = 55% and SG = 10% (after steel removal).
6. Activated carbon burnoff rate approx 40% (only models with activated carbon capabilities).
7. Cost of waste product disposal is negligible.
8. Syngas generated is utilised in the process as heat and energy (no revenue generated, but assists in cost reduction).

These assumptions are used throughout this economic analysis and any changes are noted accordingly.

5.5 Fixed Capital Investment Estimate

The Fixed Capital Investment of the waste tyre pyrolysis plant is estimated by using the capital cost of similar facility as the basis. Recently, UK based company PYReco has announced its plans to construct a tyre pyrolysis plant capable of processing 60,000 tonnes of waste tyres annually. The plant will be located in Wales and the total cost of the facility is estimated at £80 million, excluding the cost of activated carbon production facility which has not been included in the original plant design [66]. This capital figure was obtained through Metso, who has performed an initial design of the entire facility. This information will be valuable in getting a pretty close estimate of the FCI in our economic models.

In order to estimate the capital cost of the facility with carbon activation capability, an additional capital cost has been added on top of PYReco's financial estimate. This value has been estimated using the study completed by Conti et al. in 2002 where an economic analysis was performed showing the difference in CAPEX between the charcoal production facility and activated carbon facility [65]. This ratio in CAPEX difference was the best basis for estimating the cost of adding the activation process to PYReco plant in Wales. In this study the initial CAPEX of charcoal production facility was estimated at $4 million while the addition of activation facility increased this cost to nearly $9 million. This would indicate that close to $5 million was required in order to upgrade a 36 tpd charcoal production plant to a fully integrated activated carbon facility [65].

In order to get a more accurate estimate, the CAPEX values of basis facilities have to be adjusted in order to account for various factors such as inflation, capacity and location. Therefore the following formula is used to obtain the capital cost of different economic models,

Cost 2 = Cost 1 x (Inflation Index2/Inflation Index1) x (Location index2/Location index1) x (Size2/Size1) ^R

For example, let's say that we would like to estimate the CAPEX of 50 tpd facility using the PYReco plant as the basis. On the next page is the table summarizing the factors used for capital cost adjustment.

Table 5-2: Capital cost (CAPEX) estimate of 50 tpd plant.

	CAPEX
Cost 1 [66] PYReco Plant	**£80,000,000**
M&S Inflation Index 1 (2008) [62]	**1469.5**
M&S Inflation Index 2 (2008) [62]	**1469.5**
Aspen Richardson Location Index 1 (UK) [61]	**1**
Aspen Richardson Location Index 2 (Wales, UK) [61]	**1**
Size 1 (tpd)	**180**
Size 2 (tpd)	**50**
Cost capacity factor (R) [59]	**0.9**
Exchange rate (£ to £)	**1**
COST 2	***£25,259,092***

In order to estimate the cost of activated carbon production facility add on, identical adjustment method is used in order to account for varying capacity, inflation and location factors. Therefore CAPEX estimate for the required upgrade is presented in Table 5-3.

It is important to note that 15 tpd production of activated carbon was calculated from the 50 tpd waste tyres pyrolysis plant, which estimated the annual production of charcoal to be 4983 tonnes. Daily charcoal production rate is obtained by dividing this by 335 working days in a year as was estimated at the start of this chapter. Since all of the charcoal is going to be activated, this daily production rate of 15 tpd of charcoal is used as the capacity of the activated carbon facility and the cost is adjusted according to original model developed by Conti et al.

Using this method it was possible to estimate the Total Capital Investment required for 50 tpd waste tyre processing facility with integrated activated carbon production. The same method is used for all of the remaining models developed in this economic study.

Table 5-3: Capital cost (CAPEX) estimate of upgrading to activated carbon production facility with 15 tpd charcoal feed.

	CAPEX
Cost 1 [65]	**$5,000,000**
M&S Inflation Index 1 (2002) [62]	**1104.2**
M&S Inflation Index 2 (2008) [62]	**1469.5**
Aspen Richardson Location index 1 (Italy) [61]	**1.12**
Aspen Richardson Location index 2 (Wales, UK) [61]	**1.25**
Size 1 (tpd)	**36**
Size 2 (tpd)	**15**
Cost capacity factor (R) [59]	**0.9**
Exchange rate ($ to £)	**0.672314**
COST 2	***£2,256,042***

5.6 Operating Cost Estimate

Operating costs or manufacturing costs of a plant are considered to be all of the costs which are directly incurred as a result of manufacturing operation. For the purpose of this economic analysis, operating cost is divided in three subsections: Direct Production Costs, Fixed Charges, and General Expenses. All of the estimates included in operating cost analysis are performed using the general rules of thumb for waste processing facilities. The reason for this is shortage of specific information and records regarding the operating costs from similar projects and facilities in the past.

5.6.1 Direct Production Costs

Transportation and Collection of Feedstock

For the cost estimate associated with the collection and transportation of waste tyres to the facility please refer to section 5.3 in this chapter.

Operating Labour and Supervision

In a preliminary cost analysis such as the one performed here, it is often satisfactory to estimate the total operating labour requirements using the information from similar projects with previous experience. Since capital cost of the plant is estimated using the information obtained from PYReco, it is acceptable to refer to the same project for further information regarding the number of employees this plant is expecting to employ.

PYReco's 180 tpd facility is expecting to employ around 50 permanent employees of which not all are going to be part of operating labour [66]. Some of them will include the management and supervisory positions associated with running the plant. R. K. Sinnott (2005, p.265), states that in a processing plant on average, one supervisor would be required for every 4-5 operators. Using this as a guide, one fifth of the permanent number of employees at PYReco's facility will be supervisors. The rest will be considered as operating labour. Therefore for a plant with 180 tpd capacity the estimated staffing plan is as follows.

$$\text{Supervisory: } 1/5^{th} \text{ of } 50 = 10 \text{ supervisors}$$

$$\text{Operating Labour: } 4/5^{th} \text{ of } 50 = 40 \text{ employees}$$

The cost of operating labour is usually calculated on the basis of total number of hours multiplied by the hourly rate. In order to convert the number of operating labour employees into equivalent hours some assumptions have to be made:

1. Labour employees will work in 3 shifts.
2. On average each employee will work 8 hours per day.

Taking the above assumptions into account it is easy to calculate the annual labour hours required to operate 180 tpd facility. Therefore,

$$40 \text{ employees} \times 8 \text{ hours a day} = 320 \text{ hours}$$

$$320 \text{ hours} \times 335 \text{ days} = 107{,}200 \text{ hours per annum}$$

Total number of hours is multiplied by average hourly rate for processing plant labour, which is obtained from 2008 UK Annual Survey of Hours and Earnings [69]. For the purpose of this report the 2008 hourly rate used is £25. It is important to note that operating costs for hours spent during the plant shut down period due to repairs or upgrades is not included in this estimate. This is considered as a separate cost and is discussed in the later sections.

The only discrepancy between the PYReco staffing plan and the pyrolysis facility economically evaluated in this report is the additional staff requirement for activated carbon production line. In order to account for this a separate section called *plant overhead cost* has been added to total operating cost. The estimate for this is presented in sections to follow.

For plants with different capacities Peters, Timmerhaus and West (2003, p.263) recommend using a specific power of the capacity ratio in order to estimate the labour requirements when the plant is scaled up or down. This is because the relationship between labour requirements and capacity is not a liner one. The value which is recommended is 0.2 to 0.25 power of the capacity ratio. For the purpose of this report 0.25 will be used. Therefore,

Labour 2 = Labour 1 x (Capacity 2/Capacity 1) ^0.25

Estimating total cost of supervisory positions is a little bit different then estimating labour costs. Instead of calculating annual number of hours required to operate a plant supervisory positions are based on the typical salaries. Each supervisory position will receive the average salary amount equal to annual salary reviews published by the Institution of Chemical Engineers and found on IChemE website [71]. The average supervisory salary in 2008 was £35,000 and this will be used as the basis in estimating costs associated with this operating requirement.

Other staffing costs such as executive salaries, clerical wages and IT support are included in Administrative Costs which is explained in more detail later on in the section.

Utilities

Due to the lack of detailed information regarding the exact utility requirements for the waste tyre processing facility, it was necessary to obtain the best possible estimate by using the figures from ordinary chemical processes. Peters et.al (2003, p.267) explains that as a rough estimate, utility cost is often between 10 and 20 % of the overall operating cost. However, for the purpose of this report a lower margin of 10% will be used because of possible energy recovery due to availability of syngas as a by product of tyre pyrolysis. Syngas can significantly reduce energy requirements either by being utilised for power or steam generation for both pyrolysis and activation processes in the plant. Therefore utility cost is estimated as 10 % of the total operating cost in the plant.

Maintenance and Repairs

Annual cost for plant maintenance and repairs in processing industry ranges anywhere between 2 and 10 percent of the FCI (Fixed Capital Investment). Using Table 6-16 from Peters et.al (2003, p.268) as a guide, simple chemical process such as processing of waste tyres is between 2-6 percent, with 4 percent being a reasonable value.

Operating Supplies

This category includes most of the consumables such as lubricants, test chemicals and other supplies which are not part of the feedstock or maintenance and repair items. Usually the value recommended by Peter et.al (2003, p.268) is 15 % of the maintenance and repairs cost, however this might be a little bit excessive considering the simplicity of the process and lack of rotating equipment such as compressor and pumps. According to R. K. Sinnott (2005, p.267), this value should be closer to 10 rather than 15 percent.

Patents and Royalties

Since there is no royalties which will be charged to current pyrolysis process, the only cost associated with this section will be the annual patent fee, which ranges anywhere between 1 and 3 percent of total operating cost depending on the patent type [70]. For the purpose of this analysis a minimal value of 1 % is used.

Plant Overhead Cost

Plant overhead costs include things such as general plant upkeep and overhead, payroll overhead, medical services, safety and protection, recreation, cafeteria, laboratories and storage facilities. The common value associated with this cost is 50 % of operating labour and supervision costs together [70].

5.6.2 Fixed Charges

Loan Repayments (Interest Only)

If the project is financed externally, through a bank loan or bonds, there will be a direct cost associated with these borrowed funds in the form of interest paid. This is why the annual interest paid will be included in the operating costs of the project. The exact method of calculating this amount is explained in more detail in later sections.

Local Taxes

Local property taxes vary with each individual location and are very different in highly populated areas compared to remote locations. It is assumed that the location of Swansea plant in South Wales will be in an industrial area, mainly due to government rules and regulations which will try to keep it away from highly populated areas. Therefore using this as a guide a rough approximation of the local property taxes is about 1 percent of the fixed capital investment [70].

Insurance

Property insurance rates usually amount to approximately 1 percent of the FIC [70]. This value can vary depending on level of protection facilities as well as type of processes being carried out and the risk it poses.

5.6.3 General Expenses

Administrative Cost

Apart from costs associated with direct running of the plant, there is a significant cost associated with executive and administrative activities as well. Peters et.al. (2003, p.270) lists things such as wages and salaries for administrators, secretaries, accountants, legal personnel are all part of administrative cost. Additional to this there are costs incurred by stationary supplies as well as communication, administrative buildings and any other overheads. The administrative cost in the processing industry ranges anywhere between 15 to 25 percent of operating labour cost, and it mainly depends on the project requirements [70]. For the waste tyre processing facility this value is estimated at a lower margin of 15 % due to low requirements for separate administration support. Hughes Environmental Solutions Pty Ltd has an existing administrative and legal department capable of taking most of the workload required for the running of the plant.

Distribution and Marketing Costs

General expenses due to marketing and distribution are very easy to overlook but they play an important part in the overall success of the project. In order to sell all of the products manufactured by the facility buyers must be found and products successfully delivered to them. This category includes everything from cost of containers, advertising, shipping, commissions to travel expenses for sales representatives. The cost of distribution and marketing for most projects is in the range of 2 to 20 % of the total operating cost [70]. However, the lower end figures will apply to projects which sell their products in bulk and deal with smaller number of customers. Since this is the case with the waste tyre recycling business in general, the overall value is estimated at 5 % of total operating cost.

Research and Development Costs

The overall cost of the research and development will be mainly dependent on company's commitment towards developing new methods and technologies. Therefore there is no single rule to follow, however Peters et.al. (2003, p.271) recommends approximate value of 5 percent of total operating cost. Considering that the research and development commitment in waste tyre industry is not as significant as in some other processing and chemical industries, it is fair to say that 3 % is a reasonable estimation.

5.6.4 Financing and Loan Repayments

Due to such high investment capital being needed to support projects such as this one, it is very likely that some sort of borrowed funds will be required. Interest paid on the amount borrowed will be considered as part of the cost of doing business. Therefore, this has been included in the cash flow analysis under the fixed charges. The principal repayments of the loan have not been included in the operating cost and cannot be used to offset the income tax; however it is still included in the total annual expenses.

Different economic models in the following section will explore the effect of financing the capital cost from different sources as well as the repayment methods.

The method of calculating loan repayments is based on a fixed interest rate of 8% compounded annually, which is the recommended value used for the bank or other loans [70]. Length of the loan is varied throughout the economic models as to provide the comparison and evaluate the different borrowing options. The same method is used for the total loan amount as different investors will be in different financial situations. An investor borrowing a full amount to support the high cost of capital will have a different cash flow performance than someone who requires a very little borrowing funds. This difference is worth exploring as it can mean a difference between a successful project and a failed one.

5.7 Estimation of Revenue and Operating Benefits

Correct estimate of the revenue generated by plant operation is essential in obtaining a good economic analysis. Most of the revenue in waste tyres processing facility will come from direct sales of the end products, however a very significant contribution will come from either a collection or disposal fees for waste tyres. This economic analysis will explore different options and look at optimizing the profits by mixing and matching different income streams together. Some economic models will be based on marketing activated carbon while others will resort to selling basic carbon black. Alternatively, some models will explore the collection and transportation of waste tyres while others will rely exclusively on charging disposal fees or perhaps combining the two feedstock options together. Financial performance of each model will be evaluated at the end, with the optimum solution becoming a recommended course of action for future investors.

Collection vs. Gate Fees

The waste disposal facility will have two options when it comes to the source of feedstock and the revenue generated through it. As mentioned in section 5.3 the level of involvement in waste tyre collection and delivery is very crucial from both the financial and operating point of view. If the company decides to charge collection fees and transport all of the waste tyres itself, additional planning needs to be done in order to supervise such a daunting task. Collecting and transporting 7 million tyres is not going to be easy and it will require significant amount of resources, both people and equipment. On the positive note the benefits associated with this type of feedstock supply include the potential for better revenue as well as the additional security associated with constant provision of feedstock. On the other side relying on other collectors to deliver your feedstock means possible threat of supply shortage and loss of production. In order to avoid this problem, large quantities of tyres need to be kept on site as contingency which requires additional space and presents a serious fire hazard. Both options require significant amount of resources and the final recommendation will therefore depend on the financial performance of each. Another possibility will be to integrate both models and have a facility which will receive part of its feedstock from independent collectors, while also being reliant on its own collection activities throughout the region.

Table 5.1 in Section 5.3 summarizes the collection and gate fees which will be used to estimate the additional revenue in the cash flow analysis. In case that collection fees are charged, the total revenue amount will be offset by the cost of transportation and handling while the gate fees can be added straight to the total revenue generated from the sale of products.

Steel Sales

Steel is a valuable commodity in today’s world and marketing this product should be straight forward. If we consider that steel makes up about 15% of the total weight of waste tyres which are delivered to the site it is easy to see that this could be a very good source of income. At £190 per tonne, steel sales will generate significant revenue for the business and will be relatively easy to market. The current prices of steel are retrieved from the *Chemical Market Reporter* and have been used for the purpose of this economic study.

Carbon Black Sales

Good quality carbon black can be marketed easily and can generate significant amounts of revenue while requiring minimal processing. In today's market carbon black can be used in many different industries and is fairly straight forward to market. However, price varies with the quality of the carbon black and it is expected that up to £205 per tonne is achievable from the pyrolysis of waste tyres. This is the current price that Advanced Pyrotech is currently marketing their product from the continuous pyrolysis process.

Activated Carbon Sales

Activated carbon is by far the most valuable of all the products derived through the pyrolysis process. However, this comes at a significant cost of having to upgrade the current plant by adding the activation unit. Depending on the activation process itself and the burnoff rate, different quality activated carbon is achievable. It is anticipated that the quality of activated carbon manufactured from the pyrolysis of waste tyres is capable of generating revenue stream in order of £930 per tonne. This is considered to be a very average quality activated carbon considering that top of the range products generate anywhere from £1100 to £1200 per tonne.

Pyrolysis Oil Sales

The oil derived from the pyrolysis process is classified as number 6 fuel oil and it requires further refining. The oil is therefore stabilised and sold to refining industry at mere £170 per tonne. This is a disappointing figure considering that oil is the most dominant product in the pyrolysis of waste tyres.

5.8 Income Tax Calculation

Income taxes paid are usually based on the corporate wide basis and the taxable income is defined as the total gross profit. This is represented by subtracting all of the costs associated with manufacturing the product from the overall revenue generated. It is important to note that any interest paid on financing capital cost of the plant is considered as the operating cost, while the principal loan repayments are excluded from offsetting the income tax.

Depreciation

Another very important factor in calculating the income tax paid by the company is the level of depreciation charged on the physical contents of the facility. The depreciation is considered as the significant operating cost and is used to reduce the total taxable income. There are different ways of estimating the depreciation with the most common one being the straight line method in which a value of the facility decreases linearly with time. A briefing document from the Institute of Fiscal Studies (IFS), complied by S. Bond and A. Klemm, suggest that UK taxation system provides capital allowance of 25% for most plant and machinery [72]. From experience the capital allowance is very similar to what most organisation use as their depreciation rate and this rule of thumb will be used throughout the paper.

Losses

UK taxation system also makes provisions for losses within the company. These loses can be used in a similar matter as depreciation in order to offset profits in the previous or future years. A loss incurred in a specific year can be either carried back up to 3 years or carried forward for up to 5 years in order to offset future profits [73]. This is a very important factor when calculating the overall taxable income of the company.

Corporate Taxation Rates

HM Revenue and Taxes website keeps updated information on the current corporate taxation rates used throughout the UK and they vary according to the size of the business. Small companies whose annual profits do not exceed £300,000 are taxed at the rate of 19% while main rate for corporation tax is 28% as of 2008 [73]. Since waste tyre processing facility does not fall in the small business category, the taxation rate used for the purpose of this study will be 28%.

5.9 Time Value of Money

5.9.1 Discounted Cash Flow

In order to obtain a clear representation of the projects financial performance it is important to bring the net cash flow in each year to its “present worth” at the start of the project. This concept is crucial because the money earned can be reinvested and start earning come kind of return. This means that the money earned in the early stage of the project is more valuable than the money acquired at later stages. Therefore, some type of compound interest or discount rate has to be used to represent this. The following formula is used to adjust the net cash flow in each year and convert it into present worth cash flow in that particular year.

$$\text{PWF (year } n\text{)} = \frac{Net\ Cash\ Flow\ in\ year\ n}{(1+r)^n}$$

where *r* is the discount rate used.

For the purpose of this study a recommended value of 8% is used as the annual discounting rate (*r*) [68].

5.9.2 Annual Escalation of Costs and Revenues

In order to account for annual increase in manufacturing costs as well as the revenues generated from the sale of products and collection of waste tyres a specific escalation factor is used in the cash flow analysis. This escalation factor also represents estimated inflation rate which is likely to occur over the period of years. For the annual increase in operating costs a suggested factor of 2.0% is used while for the annual escalation of revenues this factor is slightly higher, around 2.5% as recommended by Peters, Timmerhaus and West [70].

5.10 Profitability and Investment Analysis

5.10.1 Net Present Worth (NPW)

In order to evaluate different economic models the total net present worth (NPW) is used extensively throughout the industry. The NPW represents the difference between the present worth of all cash inflows and outflows of a project. It projects the overall worth of the project at the end of a specific time period. This NPW is calculated by deducting the present worth of all capital investments from the present worth of all cash flows. The following formula applies,

$$\mathbf{NPW = \sum PWF - PW\ Capital\ Investment}$$

Evaluating the overall profitability of an investment through NPW analysis is pretty straight forward. The magnitude of the NPW will determine if the project is considered to be attractive investment opportunity. If the NPW is positive, then the project should be accepted. If this value is negative, this investment opportunity should not be pursued. Finally, if the NPW is equal to zero, the project does not make any difference economically and money should be invested somewhere else. If comparing the performance of two separate projects against one another it is recommended to use NPW as the main measure. The project with the highest NPW has the best financial performance and should be the chosen ahead of the other alternatives.

Please note that NPW (Net Present Worth) and NPV (Net Present Value) represent the same method of evaluating the profitability of a project.

5.10.2 Internal Rate of Return (IRR)

Internal rate of return on investment or IRR is a good indication of project's profitability. It is a discounted rate of return and it is used to evaluate an investment by comparing the gains that the project will bring over the specified period of time versus the cost of the investment over the same period. Since the scope of this study includes only a simple level 1 economic analysis, an annual IRR calculation will be applied at this stage. Annual ROI is expressed as the discount interest rate for which the present worth of all cash inflows equals the present worth of all cash outflows. Therefore, the NPW is equal to zero. The following formula is used to calculate the annual IRR (*r*):

$$\text{NPW} = \sum_{n=0}^{N} \frac{Cn}{(1+r)} = 0$$

Where *n* is the period and *N* is the total number of periods.

IRR is solved through a series of iterations. For the purpose of this study a special function for calculating IRR was used in Microsoft Excel 2007.

5.10.3 Minimum Acceptable Return on Investment

In order to evaluate if IRR of the project is acceptable, there has to be a basis against which it can be compared. Many financial experts use what is known as minimum acceptable ROI (Return on Investment) as the basis in their comparison with calculated return values. However, this minimum acceptable ROI is only a guide and is very different from project to project. This variation is mainly due to a level of risk undertaken by project. Some companies use the table below to help them identify minimum acceptable ROI.

Table 5-4: Minimum acceptable ROI classification [63].

If risk of project is	*Then minimum acceptable ROI is*
Low	10%
Medium	15%
High	20%

Furthermore, the risk of project can be assessed by the following table:

Table 5-5: Assessing the risk of the project [63].

	For		
Marketing know-how	*Manufacturing know-how*	*Product Demand*	*Risk is*
Weak	**Weak**	Weak	High
Strong	Strong	**Strong**	Low
	Therefore risk is : **Medium**		

** Note that the processing of waste tyres is identified and highlighted in bold text.*

The processing of waste tyres is considered to be a project with a medium risk level mainly due to the fact that both the demand and marketing of the products remains a at relatively strong level, while the actual manufacturing process has limited previous experience in the industry. Therefore the waste tyre processing project has a minimum acceptable ROI of 15% and this will be used as the basis for evaluating the financial performance of the investment in the following section.

5.11 Economic Models

In order to find the best economic model there are many factors which need to be considered and different variables which need to be explored. Optimising the financial performance of the project will be the key driver in attracting potential investors. This section presents different case studies and explores alternative options in search of the "perfect" economic model. In order to assist with the economic evaluations a twenty year cash flow analysis is performed outlining the NPW (Net Present Worth) and IRR (Internal Rate of Return) of the project. Using these parameters it was possible to evaluate the investment for its economic feasibility and to construct the best economic model under the given circumstances. It is important to note that all of the figures obtained are based on the assumptions outlined in the report and are in no way definite performance indicators.

5.11.1 The Basic Economic Model 1

The basic economic model 1 is developed as the reference case study which could be optimized by restructuring the setup of the business and exploring different options. Each of the new models are evaluated against each other using a tool known the life cycle cost analysis. The life cycle cost analysis looks at how well the project performs over the specified period of time (usually the life of the project) and it also takes into account the time value of money which is a crucial concept in determining the overall profitability of the investment. Identifying all of the possible scenarios and comparing the financial performances of each enables an investor to select the investment which maximizes the return from the capital available. The objective is to simply develop the best possible economic model at this point in time and with the current available resources.

Table 5-6 presents a brief summary of the economic model. It includes details such as the overall capacity of the plant, type of feedstock, production rates of products together with market price for each, the total fixed capital investment required as well as the factors used to arrive at this estimate. All of the methods used to make these estimates are explained in detail in the previous sections of this chapter.

Table 5-6: Summary table of basic economic model 1.

Life Cycle Cost Analysis: Summary Table of Economic Model 1			
Plant Type: Low Temp Pyrolysis of Waste Tyres			
Feedstock:		**Product Sales:**	
Type:	Waste Tyres	Steel Sales:	9,045 tonnes/year
Annual Feedrate:	60300 tonnes	Carbon Black Sales:	tonnes/year
Annual Waste Tyres:	7,240,000 tyres	Oil sales:	28,190 tonnes/year
Collected	7,240,000		
Delivered	0		
Plant Operating Time:	335 days/year	Activated Carbon Sales:	10,764 tonnes/year
Daily feed rate:	180 tpd	A.C. burnoff rate:	40 %
		Steel Price:	£190 per tonne
		Carbon Black Price:	£205 per tonne
		Pyrolytic oil Price:	£170 per tonne
		Activated Carbon Price:	£930 per tonne
			source: ***WRAP (Aug 08)***
Fixed Capital Investment Estimate:			
Pyreco Pyrolysis Plant CAPEX Basis (2008):	£80,000,000	Activated Carbon Facility CAPEX Basis :	$5,000,000 ref: Conti et al.
Pyreco Capacity Basis:	180 tpd	A.C. Capacity Basis:	12,000 tonnes/year = 36 tpd
Cost Capacity Factor:	0.9	M&S Inflation Index 2002:	1104.2
Pyrolysis Plant (FCI):	£80,000,000	M&S Inflation Index 2008:	1469.5
Activated Carbon Facility:	£7,145,282	Aspen Richardson Location Index - Italy:	1.12
Total Fixed Capital Investement:	***£87,145,282***	Aspen Richardson Location Index - Wales:	1.25
Project Start Year:	2008	Exchange rate ($ to £):	0.67
Length of Construction:	18 months		
Loan Amount:	£67,000,000	Discount Rate:	8.00%
Length of Loan:	10 years	Cost Escalation Rate:	2.00%
Loan Interest Rate:	8.00%	Revenue Escalation Rate:	2.50%

As you can see from the table above the basic economic method assumes that the plant can process up to 180 tonnes per day of waste tyres with the entire feedstock being collected internally by the company. After the total fixed capital investment or FCI has been estimated, a careful analysis of the annual operating costs is performed. Table 5-7 shows the itemized operating cost estimate. In addition to the operating cost, this economic analysis attempts to provide some insight into the cost of financing the investment from the external sources. Table 5-8 presents the annual loan repayments together with the amount of interest charged on the borrowed sum. For the purpose of this basic economic model 1 it was assumed that the potential investor will finance up to £20 million from the internal sources with the remaining amount being supplied through a commercial bank loan over the period of 10 years.

Table 5-7: Operating cost estimate for basic economic model 1.

Operating Cost Estimate			
Plant Type: Low Temp Pyrolysis of Waste Tyres			
Feedstock:	Waste Tyres	FID:	£87,145,282
Annual Feedrate:	60,300 tonnes		
Annual Waste Tyres:	7,240,000 tyres		
Plant Operating Time:	335 days/year		
Daily feed rate:	180 tpd		
Manufacturing Cost:	Rate or quantity per year	Cost per rate (£) or quantity unit	Total Cost
Direct Production Cost:			
1. Operating Labour (hrs/year)	107,200	25	£ 2,680,000
2. Supervisory and Clerical Positions	10	35,000	£ 350,000
3. Utilities	10%	of Operating Cost	£ 1,299,296
4. Maintenance and Repairs	4%	of FCI	£ 3,485,811
5. Operating Supplies	10%	of Item 4	£ 348,581
6. Patents and Royalties	1%	of Operating Cost	£ 129,930
7. Plant Overhead Costs	50%	of Item 1+2	£ 1,515,000
Fixed Charges:			
1. Loan Repayments (Interest only)	Varies every year		See Loan Repayments
2. Local Taxes	1%	of FCI	£ 871,453
3. Insurance	1%	of FCI	£ 871,453
General Expenses:			
1. Administrative Cost	15%	of Item 1	£ 402,000
2. Distribution and Marketing	5%	of Operating Cost	£ 649,648
3. Research and Development Cost	3%	of Operating Cost	£ 389,789
Total Operating Cost			***£ 12,992,961***

Table 5-8: Loan repayments schedule for basic economic model 1.

Loan Repayments

Loan Amount:	£67,000,000	Monthly Repayments:	£812,895
Length of Loan:	10 years	Annual Repayments:	£9,754,739
Periods:	120		
Periods per year:	12		
Annual Interest:	8.00% fixed		

Calculation of Payments:

End of Year:	Interest Rate	Period		Balance	Interest	Principal	Repayments
0		0		£ 67,000,000			
1	8%	1	12	£ 62,440,486	£ 5,195,224	£ 4,559,514	£ 9,754,739
2	8%	13	24	£ 57,502,534	£ 4,816,787	£ 4,937,952	£ 9,754,739
3	8%	25	36	£ 52,154,735	£ 4,406,939	£ 5,347,799	£ 9,754,739
4	8%	37	48	£ 46,363,071	£ 3,963,075	£ 5,791,664	£ 9,754,739
5	8%	49	60	£ 40,090,702	£ 3,482,369	£ 6,272,369	£ 9,754,739
6	8%	61	72	£ 33,297,729	£ 2,961,766	£ 6,792,973	£ 9,754,739
7	8%	73	84	£ 25,940,943	£ 2,397,953	£ 7,356,786	£ 9,754,739
8	8%	85	96	£ 17,973,548	£ 1,787,343	£ 7,967,396	£ 9,754,739
9	8%	97	108	£ 9,344,862	£ 1,126,053	£ 8,628,686	£ 9,754,739
10	8%	109	120	-£ 0	£ 409,876	£ 9,344,862	£ 9,754,739
Total				***-£ 0***	***£ 30,547,386***	***£ 67,000,000***	***£ 97,547,386***

Table 5-9: Depreciation schedule estimate for basic economic model 1.

Depreciation Estimate:

Year	Y0	1	2	3	4	5	6	7	8	9	10
Net Capital Investment	£ 87,145,282										
Depreciation Rate (UK)											
Reducing Balance		25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Depreciation Expense		***£ 21,786,321***	***£ 16,339,740***	***£ 12,254,805***	***£ 9,191,104***	***£ 6,893,328***	***£ 5,169,996***	***£ 3,877,497***	***£ 2,908,123***	***£ 2,181,092***	***£ 1,635,819***
Present Capital Value											
- After Depreciation Expense		£ 65,358,962	£ 49,019,221	£ 36,764,416	£ 27,573,312	£ 20,679,984	£ 15,509,988	£ 11,632,491	£ 8,724,368	£ 6,543,276	£ 4,907,457

Year	11	12	13	14	15	16	17	18	19	20	21
Net Capital Investment											
Depreciation Rate (UK)											
Reducing Balance	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Depreciation Expense	***£ 1,226,864***	***£ 920,148***	***£ 690,111***	***£ 517,583***	***£ 388,188***	***£ 291,141***	***£ 218,355***	***£ 163,767***	***£ 122,825***	***£ 92,119***	***£ 69,089***
Present Capital Value											
- After Depreciation Expense	£ 3,680,593	£ 2,760,445	£ 2,070,333	£ 1,552,750	£ 1,164,563	£ 873,422	£ 655,066	£ 491,300	£ 368,475	£ 276,356	£ 207,267

Life Cycle Cost Analysis: Economic Model 1 | **Statement of Cashflow** | **Date:** **Aug-08**

Plant Type: Low Temp Pyrolysis of Waste Tyres

Feedstock:	Waste Tyres	**Cost of Pyrolysis Plant:**	£ 80,000,000	**Cost Escalation Factor:**	2.00%		
Annual Feedrate:	60,300 tonnes	**Cost of Activ. Carbon Facility:**	£ 7,145,282	**Benefit Escalation Factor:**	2.50%		
Annual Waste Tyres:	7,236,000 tyres			**Income Tax Rate:**	28.00%	http://www.uktax.demon.co.uk/	HM Revenue and Taxes
1. Collected	7,236,000	**Total Capital Investment:**	£ 87,145,282	**Discount Rate:**	8.00%	http://www.hmrc.gov.uk/index.htm	
2. Delivered	0	**Total Amount Financed:**	£ 67,000,000				
Plant Operating Time:	335 days/year						
Daily feed rate:	180 tpd						

	Y0 Project Year	1 2010	2 2011	3 2012	4 2013	5 2014	6 2015	7 2016	8 2017	9 2018	10 2019	11 2020	12 2021	13 2022	14 2023	15 2024	16 2025	17 2026	18 2027	19 2028	20 2029	TOTAL
Operating Costs																						
Direct Production Cost:																						
1. Transportation of Feedstock		£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	£ 3,256,200	**£ 65,124,000**
2. Operating Labour (hrs/year)		£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	**£ 53,600,000**
3. Supervisory and Clerical Labour		£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	**£ 7,000,000**
4. Utilities		£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	**£ 25,985,921**
5. Maintenance and Repairs		£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	**£ 69,716,226**
6. Operating Supplies		£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	**£ 6,971,623**
7. Patents and Royalties		£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	**£ 2,598,592**
8. Plant Overhead Costs		£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	**£ 30,300,000**
Fixed Charges:																						
1. Loan Repayments (Interest Only)		£ 5,195,224	£ 4,816,787	£ 4,406,939	£ 3,963,075	£ 3,482,369	£ 2,961,766	£ 2,397,953	£ 1,787,343	£ 1,126,053	£ 409,876	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ 30,547,386**
2. Local Taxes		£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	**£ 17,429,056**
3. Insurance		£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	**£ 17,429,056**
General Expenses:																						
1. Administrative Cost		£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	**£ 8,040,000**
2. Distribution and Marketing		£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	**£ 12,992,961**
3. Research and Development Cost		£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	**£ 7,795,776**
Depreciation		£ 21,786,321	£ 16,339,740	£ 12,254,805	£ 9,191,104	£ 6,893,328	£ 5,169,996	£ 3,877,497	£ 2,908,123	£ 2,181,092	£ 1,635,819	£ 1,226,864	£ 920,148	£ 690,111	£ 517,583	£ 388,188	£ 291,141	£ 218,355	£ 163,767	£ 122,825	£ 92,119	
Annual Escalation of Costs:		£ 324,983	£ 656,466	£ 994,579	£ 1,339,453	£ 1,691,226	£ 2,050,033	£ 2,416,017	£ 2,789,321	£ 3,170,090	£ 3,558,475	£ 3,954,628	£ 4,358,704	£ 4,770,861	£ 5,191,262	£ 5,620,070	£ 6,057,455	£ 6,503,587	£ 6,958,642	£ 7,422,798	£ 7,896,237	**£ 77,724,889**
																						£ -
TOTAL OPERATING COST		£ 43,555,689	£ 38,062,154	£ 33,905,484	£ 30,742,793	£ 28,316,084	£ 26,430,956	£ 24,940,627	£ 23,733,947	£ 22,726,396	£ 21,853,331	£ 21,430,653	£ 21,528,013	£ 21,710,133	£ 21,958,006	£ 22,257,418	£ 22,597,756	£ 22,971,103	£ 23,371,569	£ 23,794,784	£ 24,237,517	**£ 520,124,412**
Loan Repayments (Principal)		£ 4,559,514	£ 4,937,952	£ 5,347,799	£ 5,791,664	£ 6,272,369	£ 6,792,973	£ 7,356,786	£ 7,967,396	£ 8,628,686	£ 9,344,862	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ 67,000,000**
																						£ -
TOTAL EXPENSES		£ 48,115,203	£ 43,000,106	£ 39,253,283	£ 36,534,457	£ 34,588,453	£ 33,223,929	£ 32,297,413	£ 31,701,343	£ 31,355,082	£ 31,198,194	£ 21,430,653	£ 21,528,013	£ 21,710,133	£ 21,958,006	£ 22,257,418	£ 22,597,756	£ 22,971,103	£ 23,371,569	£ 23,794,784	£ 24,237,517	**£ 587,124,412**
Revenue and Operating Benefits																						
1. Collection Fees		£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	£ 6,222,960	**£ 124,459,200**
2. Gate Fees		£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ -**
3. Steel Sales		£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	**£ 34,371,000**
4. Carbon Black Sales		£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ -**
5. Activated Carbon Sales		£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	**£ 200,202,030**
5. Pyro Oil Sales		£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	**£ 95,846,850**
Annual Escalation of Revenues		£ 568,599	£ 1,151,413	£ 1,748,797	£ 2,361,116	£ 2,988,742	£ 3,632,060	£ 4,291,460	£ 4,967,345	£ 5,660,128	£ 6,370,230	£ 7,098,085	£ 7,844,136	£ 8,608,838	£ 9,392,658	£ 10,196,073	£ 11,019,574	£ 11,863,662	£ 12,728,852	£ 13,615,672	£ 14,524,663	**£ 140,632,101**
TOTAL REVENUE		£ 23,312,553	£ 23,895,367	£ 24,492,751	£ 25,105,070	£ 25,732,696	£ 26,376,014	£ 27,035,414	£ 27,711,299	£ 28,404,082	£ 29,114,184	£ 29,842,039	£ 30,588,090	£ 31,352,792	£ 32,136,612	£ 32,940,027	£ 33,763,528	£ 34,607,616	£ 35,472,806	£ 36,359,626	£ 37,268,617	**£ 595,511,181**
Gross Profit before Depreciation Charge		£ 1,543,185	£ 2,172,953	£ 2,842,072	£ 3,553,381	£ 4,309,941	£ 5,115,054	£ 5,972,284	£ 6,885,475	£ 7,858,778	£ 8,896,672	£ 9,638,250	£ 9,980,225	£ 10,332,770	£ 10,696,189	£ 11,070,796	£ 11,456,912	£ 11,854,868	£ 12,265,004	£ 12,687,668	£ 13,123,219	**£ 162,255,694**
Gross Profit after Depreciation Charge		-£ 20,243,136	-£ 14,166,787	-£ 9,412,733	-£ 5,637,723	-£ 2,583,387	-£ 54,942	£ 2,094,787	£ 3,977,352	£ 5,677,686	£ 7,260,853	£ 8,411,386	£ 9,060,077	£ 9,642,659	£ 10,178,606	£ 10,682,609	£ 11,165,772	£ 11,636,513	£ 12,101,237	£ 12,564,843	£ 13,031,100	**£ 75,386,769**
Income Tax Calculation																						
1. Depreciation Expense		£ 21,786,321	£ 16,339,740	£ 12,254,805	£ 9,191,104	£ 6,893,328	£ 5,169,996	£ 3,877,497	£ 2,908,123	£ 2,181,092	£ 1,635,819	£ 1,226,864	£ 920,148	£ 690,111	£ 517,583	£ 388,188	£ 291,141	£ 218,355	£ 163,767	£ 122,825	£ 92,119	**£ 86,868,926**
2. Operating Cost		£ 21,769,368	£ 21,722,414	£ 21,650,679	£ 21,551,689	£ 21,422,756	£ 21,260,960	£ 21,063,130	£ 20,825,824	£ 20,545,304	£ 20,217,512	£ 20,203,789	£ 20,607,865	£ 21,020,022	£ 21,440,422	£ 21,869,231	£ 22,306,615	£ 22,752,748	£ 23,207,803	£ 23,671,959	£ 24,145,398	**£ 433,255,486**
3. Operating Benefits		£ 23,312,553	£ 23,895,367	£ 24,492,751	£ 25,105,070	£ 25,732,696	£ 26,376,014	£ 27,035,414	£ 27,711,299	£ 28,404,082	£ 29,114,184	£ 29,842,039	£ 30,588,090	£ 31,352,792	£ 32,136,612	£ 32,940,027	£ 33,763,528	£ 34,607,616	£ 35,472,806	£ 36,359,626	£ 37,268,617	**£ 595,511,181**
4. Losses Claims							£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	
Taxable Income		£ -	£ -	£ -	£ -	£ -	£ -	£ 2,094,787	£ 3,977,352	£ 5,677,686	£ 7,260,853	£ 8,411,386	£ 9,060,077	£ 9,642,659	£ 10,178,606	£ 10,682,609	£ 11,165,772	£ 11,636,513	£ 12,101,237	£ 12,564,843	£ 13,031,100	**£ 127,485,477**
Net Income Taxes		£ -	£ -	£ -	£ -	£ -	£ -	£ 586,540	£ 1,113,659	£ 1,589,752	£ 2,033,039	£ 2,355,188	£ 2,536,822	£ 2,699,944	£ 2,850,010	£ 2,991,130	£ 3,126,416	£ 3,258,224	£ 3,388,346	£ 3,518,156	£ 3,648,708	**£ 35,695,934**
Net Profit After Taxes		£ 1,543,185	£ 2,172,953	£ 2,842,072	£ 3,553,381	£ 4,309,941	£ 5,115,054	£ 5,385,743	£ 5,771,816	£ 6,269,026	£ 6,863,633	£ 7,283,062	£ 7,443,404	£ 7,632,825	£ 7,846,180	£ 8,079,666	£ 8,330,496	£ 8,596,645	£ 8,876,657	£ 9,169,512	£ 9,474,511	**£ 126,559,761**
Net Cash Flow	-£ 87,145,282	£ 23,329,505	£ 18,512,693	£ 15,096,878	£ 12,744,485	£ 11,203,269	£ 10,285,050	£ 9,263,240	£ 8,679,939	£ 8,450,118	£ 8,499,452	£ 8,509,926	£ 8,363,552	£ 8,322,937	£ 8,363,763	£ 8,467,853	£ 8,621,637	£ 8,815,000	£ 9,040,424	£ 9,292,337	£ 9,566,630	**£ 213,428,687**
																						£ -
Discounted Cash Flow (After Tax)		£ 21,601,394	£ 15,871,651	£ 11,984,388	£ 9,367,577	£ 7,624,756	£ 6,481,326	£ 5,405,012	£ 4,689,501	£ 4,227,163	£ 3,936,891	£ 3,649,761	£ 3,321,281	£ 3,060,327	£ 2,847,535	£ 2,669,421	£ 2,516,574	£ 2,382,421	£ 2,262,357	£ 2,153,147	£ 2,052,503	**£ 118,104,985**

Business Case Results:	
NPW of Cash Flow	***£ 30,959,703***
IRR	***13.9%***
ROR	***12.2%***

Figure 5-3: Statement of cash flow for basic economic model 1.

Another important cost which is included in the overall cash flow analysis is the expense associated with the depreciation of the operating facility. The depreciation estimate is presented in Table 5-9 on the previous page. It uses the reducing balance method to provide the 20 year depreciation schedule at the annual rate of 25%.

Finally, the most important part of the life cycle cost analysis is presented in Figure 5-3. The statement of cash flow for a 20 year period presents the complete overview of the financial performance of the investment. At the very end of the spreadsheet there is a brief summary of the business case results which are used to evaluate the profitability of the project and are in turn key indicators of projects economic feasibility. NPW, IRR and ROR are all summarized in this section and highlighted in a light red colour.

5.11.2 Economies of Scale and Minimum Plant Capacity

Identifying the optimum capacity feed for the facility is the first step in obtaining the overall optimization of the system. The concept of “economies of scale” relates directly to the notion that as the capacity increases the cost per unit will decrease, therefore increasing the overall profitability of the investment. In order to examine if this claim stands for the waste processing plant as well, life cost analysis was performed for the following capacities: 60, 90, 120, 150, 180, 210 and 230 tonnes per day. All of the other variables are kept unchanged from the basic economic model 1. The following graphs illustrate the relationship between the plant capacity and both NPW and IRR.

As you can see from the Figure 5-4 the NPW analysis shows a significant gradient as the capacity of the plant increases and discovers the lower limit of 95 tpd for the plant to be classified as profitable. This is due to negative NPW values for plants with capacity below 95 tpd. Also, slight bumps displayed in both trend lines are due to increased average cost of waste tyre transportation as the capacity requirements increase. For example, it was estimated that at lower capacities the collection radius will be relatively small, meaning that the average length of transport will remain the same. However, if this radius increases, this will automatically increase the average transportation distance, in turn affecting the average cost per tyre and overall operating cost. This is clearly demonstrated by these small upsets in the trend line. Also, the reason that these step changes do not occur every time the capacity is increased is due to the fact that the collection radius only increases when all of the available resources have been exhausted from the current collection area.

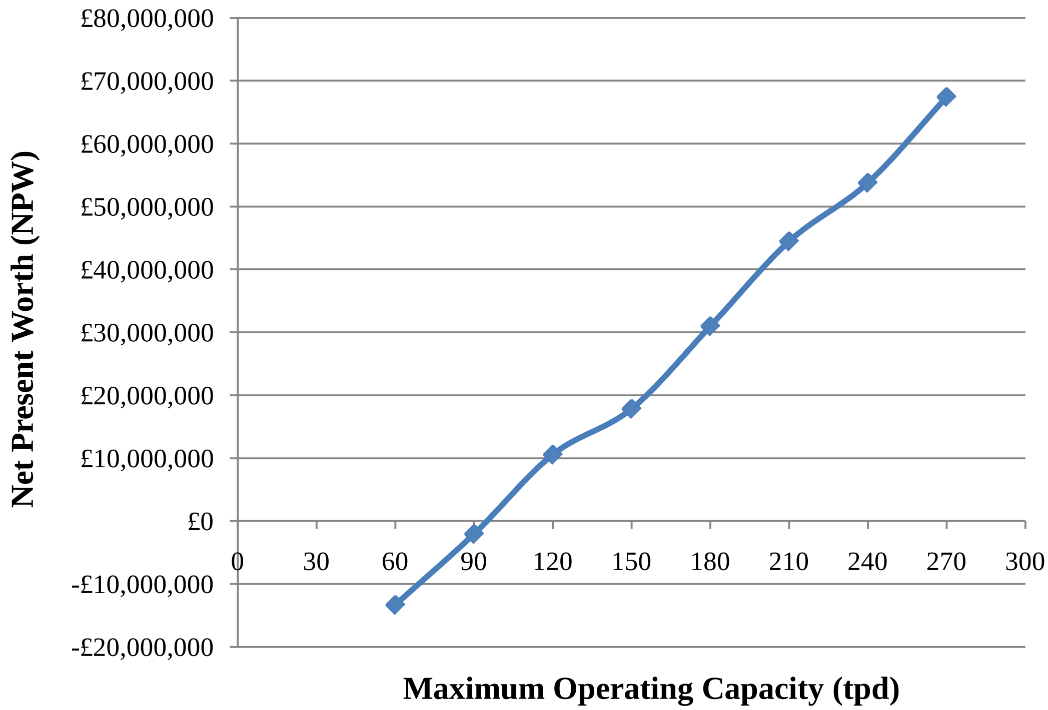


Figure 5-4: NPW vs. Maximum Operating Capacity

On the other hand the Figure 5-5 displays an interesting trend where the internal rate of return on the investment increases at slower rates as the capacity of the plant grows larger. Also, this graph identifies any capacities which display an IRR above 15% and will be considered as an attractive investment as this is the minimum acceptable rate of return for the waste processing plant. Plant capacities above 210 tonnes per day are classified as the only suitable investment if using the basic economic model 1.

It is also interesting to note that the gradient of IRR gets smaller and smaller as the capacity reaches the upper limit of 270 tpd. It will be fair to assume that at some point this gradient will be close to zero and any further increase in production capacity will not have any further effect on the internal return of return.

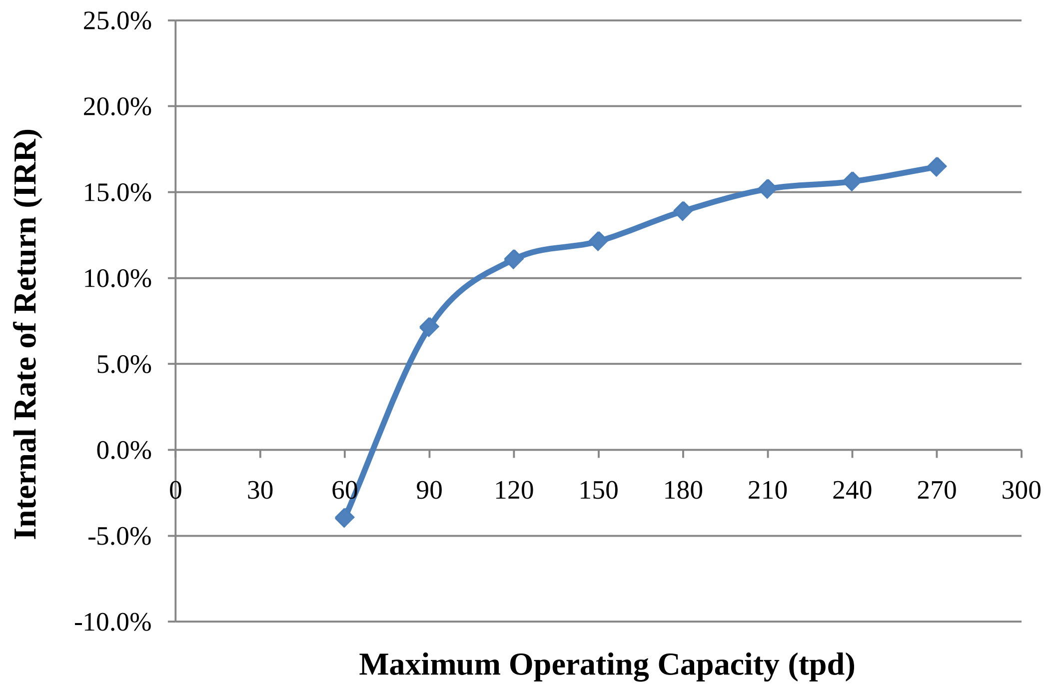


Figure 5-5: IRR vs. Maximum Operating Capacity

By looking at these two graphs it is easy to draw following conclusions:

1. Any waste tyre pyrolysis plants with maximum operating capacity below 210 tonnes per day are deemed as poor investment and will not attract any potential investors. These projects should not be pursued.
2. Increasing the collection radius of waste tyres will slightly slow down the financial growth of the project as this will cause the average cost of single tyre transportation to increase, therefore causing the operating cost to increase in non-linear fashion.

Note: *The above statements are only true for the projects which are based on the current assumptions. These figures will be revisited again at the end of the chapter once the business cases have been evaluated and the optimisation is complete.*

For the purpose of this study the upper limit of plant's capacity is kept at 270 tonnes per day which amounts to around 90,000 tonnes per annum, as this is the maximum amount of waste tyres generated in South Wales each year. Any capacity greater then this will require extended network of collection and transportation of tyres making it uneconomical for its delivery and use as the plant's feedstock.

5.11.3 Activated Carbon vs. Carbon Black

One of the key business decisions a potential investor is going to be facing is the final product selection. This refers mainly to carbon black versus activated carbon dilemma. The carbon black can be marketed at its current state and without any further processing, while the same can't be said for the activated carbon. However, activating the carbon black will produce a much higher value product which means higher revenue. But this comes at the price of increased CAPEX and OPEX as additional facility will be required. This is why it is important to complete a lifecycle cost analysis for both cases and identify a more attractive option.

Figure 5-6 displays two separate trend lines, one representing the NPW of the carbon black producing facility and the other one the investment with activated carbon as the final product. After examining the graph it is very clear that activated carbon facility will substantially outperform the plant producing the carbon black instead. What is even more amazing is the fact that the NPW of carbon black producing facility is negative for all capacities within the scope of this study (60 to 270 tpd). By analysing even bigger capacities it was concluded that overall capacity of the carbon production facility has to be close to 400 tpd before a positive NPW is recorded. The plant with this capacity will require close to 16 million tyres to be processed annually which is way above the maximum amount of waste tyres generated in South Wales region. See **Appendix xxx** for the complete table of results.

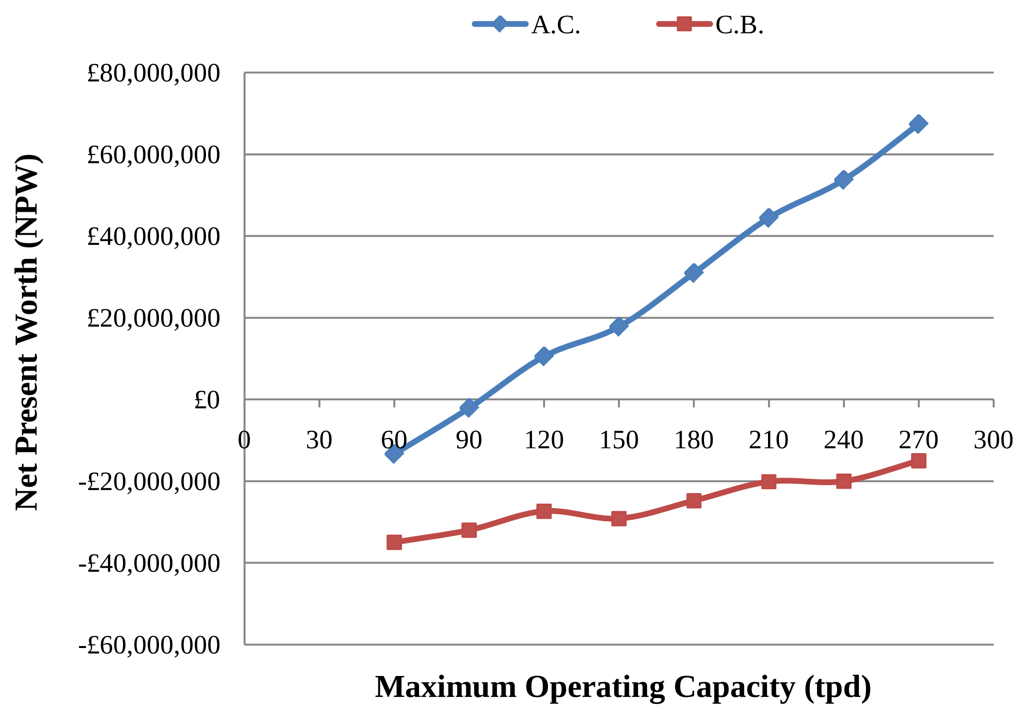


Figure 5-6: NPW Analysis of Activated Carbon vs. Carbon Black.

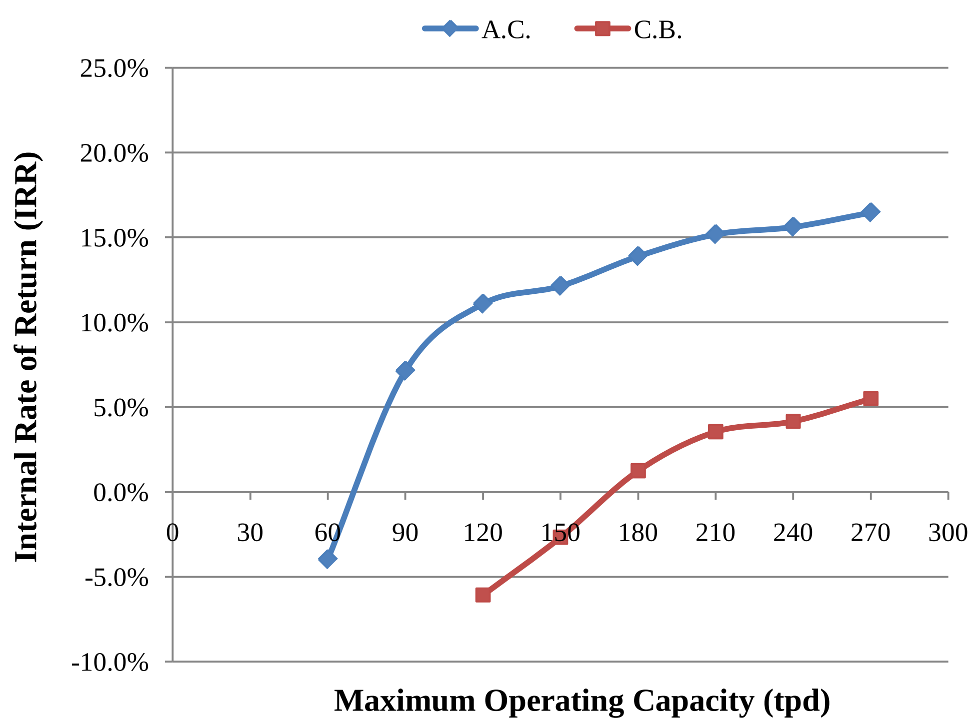


Figure 5-7: IRR Analysis of Activated Carbon vs. Carbon Black.

As the IRR analysis is closely related to NPW, the results presented in Figure 5-7 come as no surprise. Again, the IRR of the activated carbon production outperforms the carbon black and the differences in overall financial performance are significant. This is why the recommendation of this paper is to pursue the production of activated carbon instead of carbon black.

5.11.4 Collection vs. Delivery of Feedstock

Processing of waste tyres and successful marketing of end products are not the only two areas affecting the overall financial performance of the project. Many economic studies concentrate only on optimising the processing steps and forget that for the waste processing projects a significant portion of revenue comes from obtaining the feedstock itself. In most industries feedstock comes at a considerable cost while for the majority of waste processing facilities this is not the case. In fact, these facilities are paid money to process someone else's waste. However, transporting and sorting this feedstock does incur some costs.

Currently there are two options for obtaining feedstock for the waste tyre processing plant. The waste tyres can either be collected by the company itself which will earn a considerable amount of revenue due to collection fees charged or the company can simply contract other businesses to deliver their own waste tyres and charge them a disposal fee at the gate. Both options have their own pros and cons with collection fees being higher then gate fees, but incurring extra cost due to transportation and handling of the tyres.

Basic economic model 1 is using collection strategy as means of securing the feedstock for the processing facility. This is presented in Figures 5-8 as "Collection Fees" series. Alternatively, other two options evaluated include the disposal fee charged at the gate or the third option which will include equal ratio of collection and disposal fees.

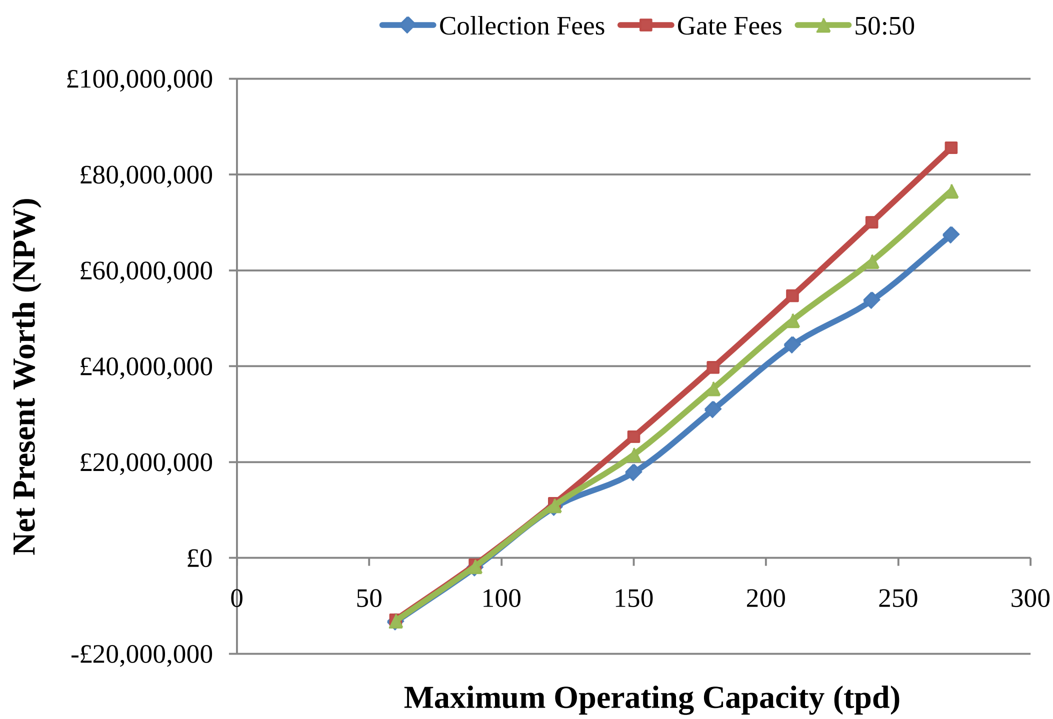


Figure 5-8: NPW analysis of different feedstock delivery options.

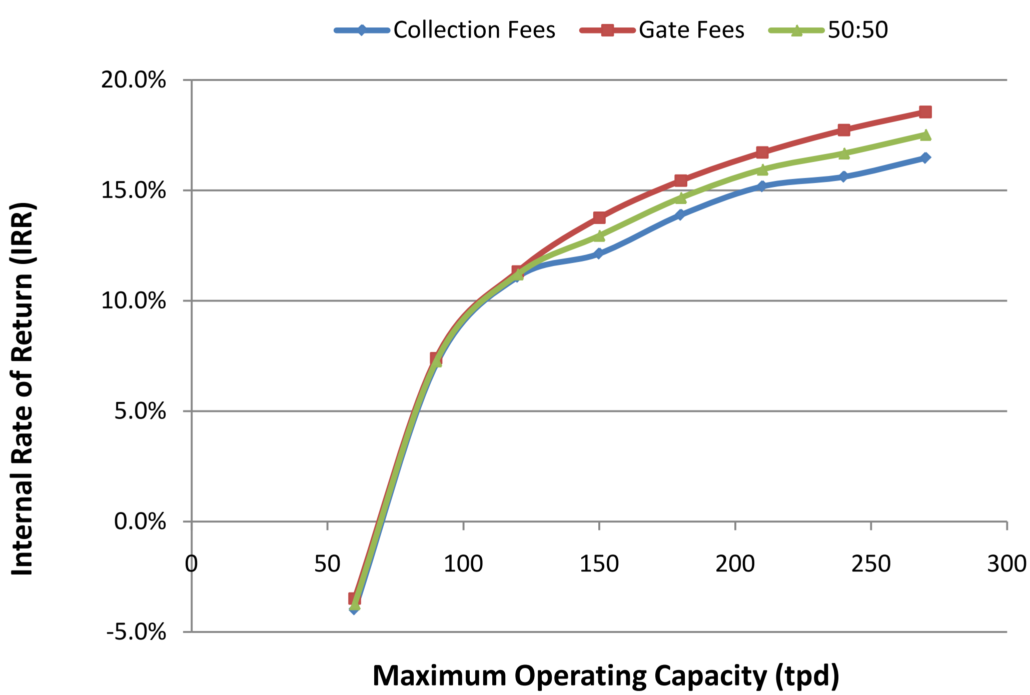


Figure 5-9: IRR analysis of different feedstock delivery options.

As we can see from both figures the financial performance of the plants with capacities lower than 120 tpd are nearly identical which leads to a conclusion that at low capacities the choice comes down to operating factors rather than financial. However, as the capacity increases so does the performance of different feedstock options. At high capacity, charging disposal fees at the gate seems like the best option. This is attributed to the fact that as the feedstock demand increases so does the average cost of transporting. Companies have to travel further to obtain more feedstock which increases the cost of transport while the collection fee remains constant. On the other hand this is not the issue with the contracted deliveries. Gate fees remain constant regardless of where the feedstock comes from. Therefore, it would seem that having feedstock delivered is far more attractive from both operating and financial level and should be pursued as the best option for obtaining the feedstock.

However, this might not be so straight forward. It is fair to assume that there will be a maximum limit of waste tyres being available through self-delivery system from other collection companies and this will be directly related to the distance tyres have to be transported. Collection companies will not be willing to travel large distances if there is another disposal facility which might be closer or if the overall cost of transport exceeds the collection charge. Therefore, even though this might be the best option financially, there is a big uncertainty if it is achievable in reality due to reasons mentioned above. Another shortcoming which has to be considered is the high risk of relying purely on external resources for feedstock delivery. If the processing facility doesn’t have any type of its own collection and delivery system, it is risking a possible reduction in productivity due to potential lack of supply caused by unreliable source of feedstock. This is much less likely to happen if the risk is shared and some of the tyres are self-collected by the facility. This would provide an optional increase in self-supply in case that one of the other independent collectors fails to meet its quota. Therefore, both scenarios have pros and cons regarding the sustainability of feedstock supply. This is why it will be up to investor’s discretion on which model they will use and it will very much depend on the amount of risk they are prepared to take.

Considering all of the arguments above and taking them into account when setting up the business, it is the recommendation of this paper that a mixture of self-collection and contract delivery of feedstock is used for future waste tyres processing facilities. The exact ratio will depend on the available contracts within the region. It is important to secure contracts which provide the delivery of feedstock from longest distances and only after those contracts are secured should the remainder of the waste tyres be collected internally. The objective is to collect the closest feedstock while contracting the one furthest away.

5.11.5 Loan vs. Internal Finances

The interest charged on financing the capital cost of a project such as the waste tyre processing, presents a significant portion of the total operating cost. This is why it is important to evaluate different financing options and their influence on the overall financial performance of the investment. Basic economic model 1 assumes that the project has been partially financed from internal sources while the remainder of the money will come from a bank loan. In contrast to this a life cycle cost analysis was performed for projects fully financed by the investing company or alternatively fully financed by a bank loan. It is expected to see an improvement from the self-financed option, however it will be interesting to note at what operating plant capacities are other two options considered acceptable.

From the two figures it can be seen that the benefits of internal financing grow as the maximum operating capacity of the plant increases. NPW analysis shows that if the project is solely financed by the bank loan then the minimum capacity of the plant has to be 120 tpd. On the other hand, internally financed project can be profitable above 80 tpd. However, the true benefit of self-financing can be seen at much higher capacities as this is directly attributed to higher interest paid on increased capital expenditure.

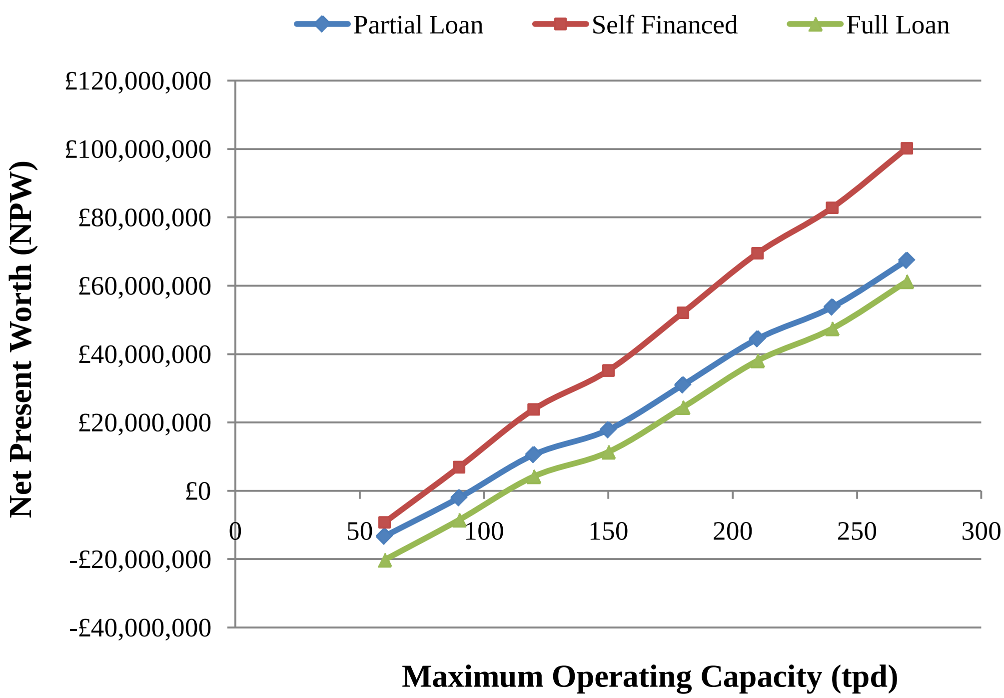


Figure 5-10: NPW Analysis of Loan vs. Internal Financing.

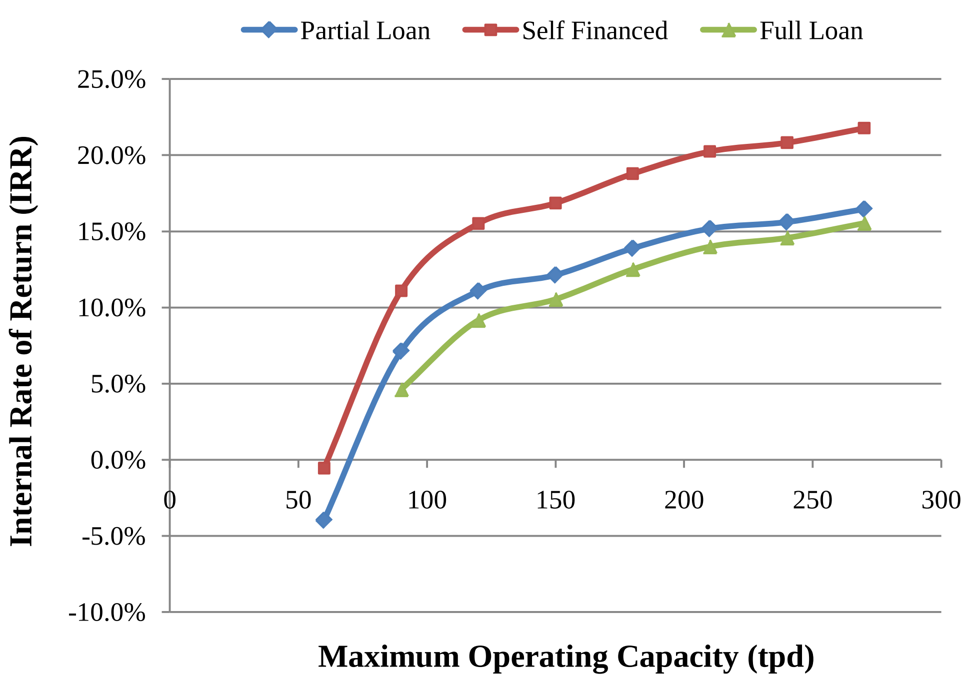


Figure 5-11: IRR Analysis of Loan vs. Internal Financing.

The IRR analysis shows that if the basic economic model 1 is fully financed through a bank loan, the waste tyres processing facility has to be as large as 250 tpd in order to meet the minimum acceptable rate of return. On the other hand a self financed project can be as small as 120 tpd, making this investment suitable in regions with limited supply of waste tyres.

5.11.6 Length of the Loan

If the only option of financing capital investment remains long term bank loan it is important to decide on the length of such a borrowing. This brief analysis outlines the benefits of acquiring the loans on shorter periods of time providing that the higher repayments can be managed. Again, the main conclusion from NPW analysis is that the benefits of the shorter loan period are more notable as the capacity increases, therefore reaffirming the notion of economies of scale.

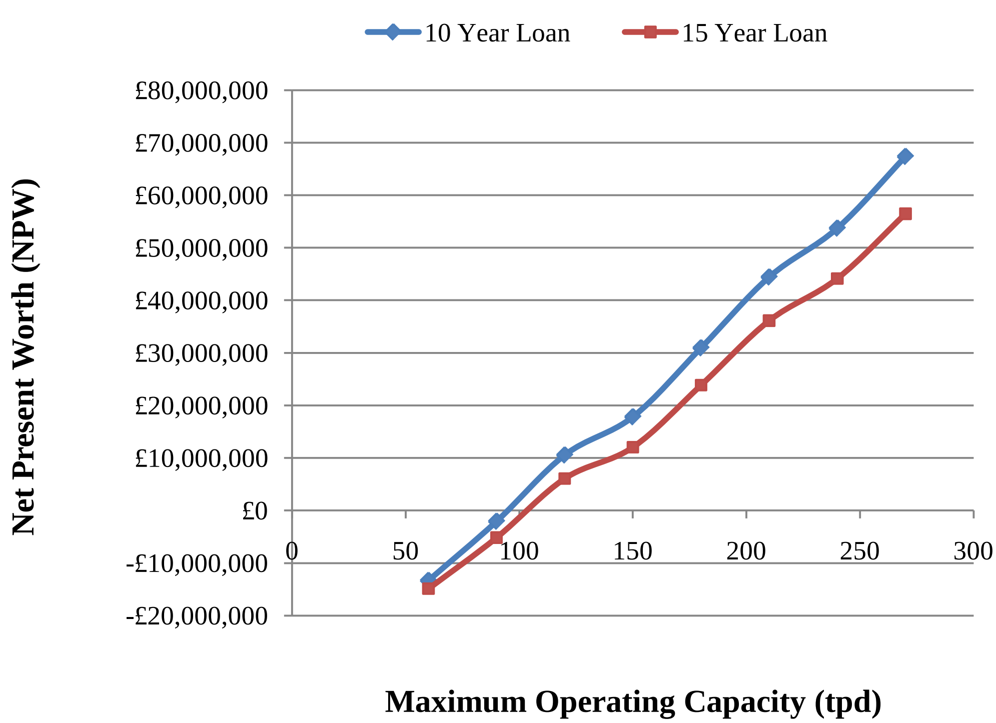


Figure 5-12: NPW analysis for different loan periods.

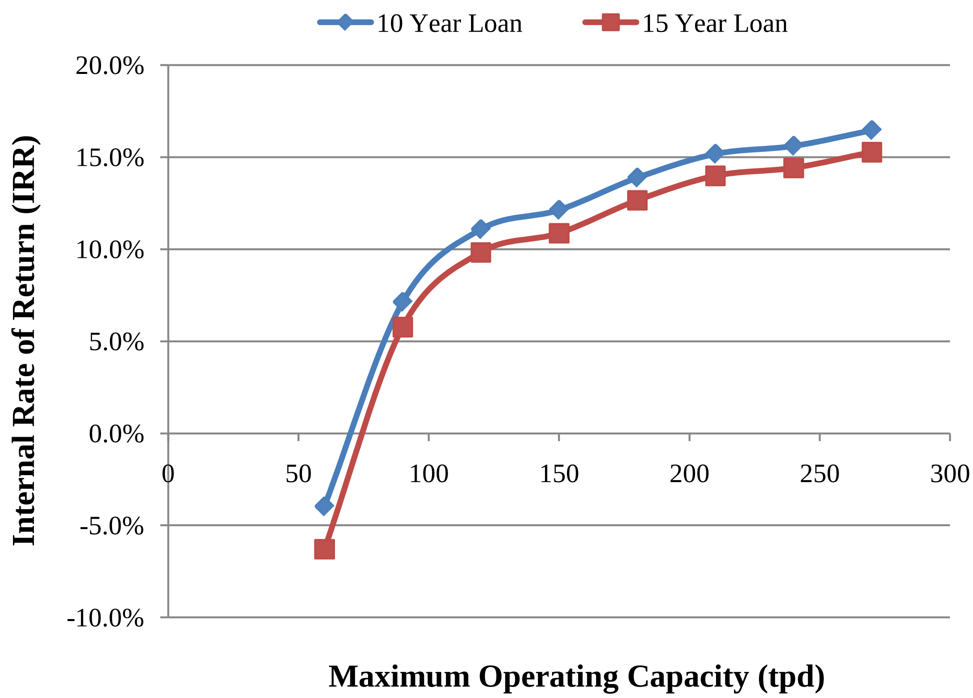


Figure 5-13: IRR analysis for different loan periods.

5.11.7 Optimising the system – "A Perfect Economic Model"

After careful analysis of the key variables within the basic economic model 1, it is safe to say that optimisation of the waste tyre pyrolysis is very dependent on the external forces. In a perfect scenario, the economic performance of waste tyre pyrolysis plant looks very promising. However, it is important to understand that there are some limitations when making realistic assumptions during the economic analysis.

The following is the summary of the best achievable economic model using reasonable assumptions. These assumptions are based on key findings established through a series of individual economic models presented in the earlier sections.

Optimum Economic Model for Waste Tyre Pyrolysis Plant:

1. The maximum operating capacity of the plant will be kept at 180 tonnes per day or 60,300 tonnes per annum of processed waste tyres. Even though South Wales region generates close to 90,000 tonnes of waste tyres annually, it is not reasonable to assume that the whole lot will be collected by a single company. A more in-depth analysis of available feedstock should be performed before any key decisions are made regarding the size of the investment.
2. The waste tyre pyrolysis plant will include the activation facility for the manufacture of activated carbon. This will be the product of choice, as it clearly outperforms carbon black production facilities at current market prices. Market demand for activated carbon is far greater than standard carbon black making the overall investment far more attractive for any potential investors.
3. Waste tyre feedstock will be partially collected internally by the company, while the remaining amounts will be secured through various contracts. The waste tyres delivered onsite will attract the gate disposal fee while the collected feedstock will be generating revenue through collection fees. The exact ratio of the collected tyres versus the delivered feedstock can't be provided, however for the purpose of this study it is estimated to be 50:50.
4. Even though it is difficult to secure investors who will be able to fully finance the project from their own resources, this type of financing option is still the most preferable. This is why the optimum economic model will assume that the total capital cost of the project will be financed from internal sources, by the investor itself.

Therefore, using the above assumptions the overall life cycle cost analysis of the investment is presented below.

Table 5-10: Summary table of optimum economic model.

Life Cycle Cost Analysis: Summary Table of Economic Model			
Plant Type: Low Temp Pyrolysis of Waste Tyres			
Feedstock:		**Product Sales:**	
Type:	Waste Tyres	Steel Sales:	9,045 tonnes/year
Annual Feedrate:	60300 tonnes	Carbon Black Sales:	0 tonnes/year
Annual Waste Tyres:	7,236,000 tyres	Oil sales:	28,190 tonnes/year
Collected	3,618,000		
Delivered	3,618,000		
Plant Operating Time:	335 days/year	Activated Carbon Sales:	10,764 tonnes/year
Daily feed rate:	180 tpd	A.C. burnoff rate:	40 %
		Steel Price:	£190 per tonne
		Carbon Black Price:	£205 per tonne
		Pyrolytic oil Price:	£170 per tonne
		Activated Carbon Price:	£930 per tonne
			source: WRAP (Aug 08)
Fixed Capital Investment Estimate:			
Pyreco Pyrolysis Plant CAPEX Basis (2008):	£80,000,000	Activated Carbon Facility CAPEX Basis :	$5,000,000 ref: Conti et al.
Pyreco Capacity Basis:	180 tpd	A.C. Capacity Basis:	12,000 tonnes/year = 36 tpd
Cost Capacity Factor:	0.9	M&S Inflation Index 2002:	1104.2
Pyrolysis Plant (FCI):	£80,000,000	M&S Inflation Index 2008:	1469.5
Activated Carbon Facility:	£7,145,282	Aspen Richardson Location Index - Italy:	1.12
Total Fixed Capital Investement:	***£87,145,282***	Aspen Richardson Location Index - Wales:	1.25
Project Start Year:	2008	Exchange rate ($ to £):	0.67
Length of Construction:	18 months		
Loan Amount:	none	Discount Rate:	8.00%
Length of Loan:	10 years	Cost Escalation Rate:	2.00%
Loan Interest Rate:	8.00%	Revenue Escalation Rate:	2.50%

From the table above it is easy to notice that the total capital investment for the waste tyre pyrolysis project is just above £87 million. The facility also has ability to manufacture activated carbon and the feedstock supply is equally divided between independent contractors and the company itself who will perform the waste tyre collection as well. The project is fully financed from internal sources and no external funding. The total amount of steel manufactured is around 9,000 tonnes per year, pyrolytic oil 28,000 tonnes per year and activated carbon production reaches 10,000 tonnes annually. The plant is operated 335 days a year, with remaining time being spent on annual maintenance or any other planned turnaround activity. At maximum operating capacity the plant will be able to process around 7.2 million waste tyres annually which works out to about 21,600 waste tyres per day.

Table 5-11: Operating cost estimate of optimum economic model.

Operating Cost Estimate			
Plant Type: Low Temp Pyrolysis of Waste Tyres			
Feedstock:	Waste Tyres	FID:	£87,145,282
Annual Feedrate:	60,300 tonnes		
Annual Waste Tyres:	7,236,000 tyres		
Plant Operating Time:	335 days/year		
Daily feed rate:	180 tpd		
Manufacturing Cost:	Rate or quantity per	Cost per rate (£) or quantity unit	Total Cost
Direct Production Cost:			
1. Operating Labour (hrs/year)	107,200	25	£ 2,680,000
2. Supervisory and Clerical Positions	10	35,000	£ 350,000
3. Utilities	10%	of Operating Cost	£ 1,299,296
4. Maintenance and Repairs	4%	of FCI	£ 3,485,811
5. Operating Supplies	10%	of Item 4	£ 348,581
6. Patents and Royalties	1%	of Operating Cost	£ 129,930
7. Plant Overhead Costs	50%	of Item 1+2	£ 1,515,000
Fixed Charges:			
1. Loan Repayments (Interest only)	Varies every year		See Loan Repayments
2. Local Taxes	1%	of FCI	£ 871,453
3. Insurance	1%	of FCI	£ 871,453
General Expenses:			
1. Administrative Cost	15%	of Item 1	£ 402,000
2. Distribution and Marketing	5%	of Operating Cost	£ 649,648
3. Research and Development Cost	3%	of Operating Cost	£ 389,789
Total Operating Cost			***£ 12,992,961***

The annual operating cost of a 180 tpd plant in this economic model is £13 million. The biggest portion of this operating cost goes towards maintenance and repairs as well as the operating labour required in running the plant. The cost of utilities is not as large as it might have been expected and this is mainly due to the fact that a good portion of energy requirements and heat is supplied through the pyrolysis process itself which generates significant amounts of synthetic gas which can be used to cut some of the costs. Depreciation schedule estimate on the following page represents the annual expense which is added to total operating cost in the cash flow analysis. This depreciation is also used to reduce the overall income tax which will improve overall performance of the economic model.

Table 5-12: Depreciation schedule estimate of optimum economic model.

Depreciation Estimate:

Year	Y0	1	2	3	4	5	6	7	8	9	10
Net Capital Investment	£ 87,145,282										
Depreciation Rate (UK) Reducing Balance		25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Depreciation Expense		***£ 21,786,321***	***£ 16,339,740***	***£ 12,254,805***	***£ 9,191,104***	***£ 6,893,328***	***£ 5,169,996***	***£ 3,877,497***	***£ 2,908,123***	***£ 2,181,092***	***£ 1,635,819***
Present Capital Value - After Depreciation Expense		£ 65,358,962	£ 49,019,221	£ 36,764,416	£ 27,573,312	£ 20,679,984	£ 15,509,988	£ 11,632,491	£ 8,724,368	£ 6,543,276	£ 4,907,457

Year	11	12	13	14	15	16	17	18	19	20	21
Net Capital Investment											
Depreciation Rate (UK) Reducing Balance	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Depreciation Expense	***£ 1,226,864***	***£ 920,148***	***£ 690,111***	***£ 517,583***	***£ 388,188***	***£ 291,141***	***£ 218,355***	***£ 163,767***	***£ 122,825***	***£ 92,119***	***£ 69,089***
Present Capital Value - After Depreciation Expense	£ 3,680,593	£ 2,760,445	£ 2,070,333	£ 1,552,750	£ 1,164,563	£ 873,422	£ 655,066	£ 491,300	£ 368,475	£ 276,356	£ 207,267

Life Cycle Cost Analysis: Economic Model — **Statement of Cashflow** — **Date:** Aug-08

Plant Type: Low Temp Pyrolysis of Waste Tyres

Feedstock:	Waste Tyres	**Cost of Pyrolysis Plant:**	£ 80,000,000	**Cost Escalation Factor:**	2.00%
Annual Feedrate:	60,300 tonnes	**Cost of Activ. Carbon Facility:**	£ 7,145,282	**Benefit Escalation Factor:**	2.50%
Annual Waste Tyres:	7,236,000 tyres			**Income Tax Rate:**	28.00%
1. Collected	3,618,000	**Total Capital Investment:**	£ 87,145,282	**Discount Rate:**	8.00%
2. Delivered	3,618,000	**Total Amount Financed:**	£ 67,000,000		
Plant Operating Time:	335 days/year				
Daily feed rate:	180 tpd				

http://www.uktax.demon.co.uk/ HM Revenue and Taxes
http://www.hmrc.gov.uk/index.htm

	Y0 Project Year	1 2010	2 2011	3 2012	4 2013	5 2014	6 2015	7 2016	8 2017	9 2018	10 2019
Operating Costs											
Direct Production Cost:											
1. Transportation of Feedstock		£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100
2. Operating Labour (hrs/year)		£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000
3. Supervisory and Clerical Labour		£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000
4. Utilities		£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296
5. Maintenance and Repairs		£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811
6. Operating Supplies		£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581
7. Patents and Royalties		£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930
8. Plant Overhead Costs		£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000
Fixed Charges:											
1. Loan Repayments (Interest Only)		£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
2. Local Taxes		£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453
3. Insurance		£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453
General Expenses:											
1. Administrative Cost		£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000
2. Distribution and Marketing		£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648
3. Research and Development Cost		£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789
Depreciation		£ 21,786,321	£ 16,339,740	£ 12,254,805	£ 9,191,104	£ 6,893,328	£ 5,169,996	£ 3,877,497	£ 2,908,123	£ 2,181,092	£ 1,635,819
Annual Escalation of Costs:		£ 292,421	£ 590,691	£ 894,926	£ 1,205,246	£ 1,521,772	£ 1,844,628	£ 2,173,942	£ 2,509,842	£ 2,852,460	£ 3,201,931
TOTAL OPERATING COST		£ 36,699,802	£ 31,551,492	£ 27,770,792	£ 25,017,410	£ 23,036,160	£ 21,635,685	£ 20,672,500	£ 20,039,026	£ 19,654,613	£ 19,458,810
Loan Repayments (Principal)		£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
TOTAL EXPENSES		£ 36,699,802	£ 31,551,492	£ 27,770,792	£ 25,017,410	£ 23,036,160	£ 21,635,685	£ 20,672,500	£ 20,039,026	£ 19,654,613	£ 19,458,810
Revenue and Operating Benefits											
1. Collection Fees		£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480
2. Gate Fees		£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900
3. Steel Sales		£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550
4. Carbon Black Sales		£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
5. Activated Carbon Sales		£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102
5. Pyro Oil Sales		£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343
Annual Escalation of Revenues		£ 540,559	£ 1,094,633	£ 1,662,558	£ 2,244,681	£ 2,841,358	£ 3,452,951	£ 4,079,834	£ 4,722,389	£ 5,381,008	£ 6,056,093
TOTAL REVENUE		£ 22,162,933	£ 22,717,007	£ 23,284,932	£ 23,867,055	£ 24,463,732	£ 25,075,325	£ 25,702,208	£ 26,344,763	£ 27,003,382	£ 27,678,467
Gross Profit before Depreciation Charge		£ 7,249,452	£ 7,505,255	£ 7,768,945	£ 8,040,749	£ 8,320,899	£ 8,609,636	£ 8,907,205	£ 9,213,860	£ 9,529,861	£ 9,855,476
Gross Profit after Depreciation Charge		-£ 14,536,869	-£ 8,834,485	-£ 4,485,860	-£ 1,150,355	£ 1,427,571	£ 3,439,640	£ 5,029,708	£ 6,305,738	£ 7,348,769	£ 8,219,656
Income Tax Calculation											
1. Depreciation Expense		£ 21,786,321	£ 16,339,740	£ 12,254,805	£ 9,191,104	£ 6,893,328	£ 5,169,996	£ 3,877,497	£ 2,908,123	£ 2,181,092	£ 1,635,819
2. Operating Cost		£ 14,913,482	£ 15,211,751	£ 15,515,986	£ 15,826,306	£ 16,142,832	£ 16,465,689	£ 16,795,003	£ 17,130,903	£ 17,473,521	£ 17,822,991
3. Operating Benefits		£ 22,162,933	£ 22,717,007	£ 23,284,932	£ 23,867,055	£ 24,463,732	£ 25,075,325	£ 25,702,208	£ 26,344,763	£ 27,003,382	£ 27,678,467
4. Losses Claims							£ -	£ -	£ -	£ -	£ -
Taxable Income		£ -	£ -	£ -	£ -	£ 1,427,571	£ 3,439,640	£ 5,029,708	£ 6,305,738	£ 7,348,769	£ 8,219,656
Net Income Taxes		£ -	£ -	£ -	£ -	£ 399,720	£ 963,099	£ 1,408,318	£ 1,765,607	£ 2,057,655	£ 2,301,504
Net Profit After Taxes		£ 7,249,452	£ 7,505,255	£ 7,768,945	£ 8,040,749	£ 7,921,179	£ 7,646,537	£ 7,498,887	£ 7,448,254	£ 7,472,206	£ 7,553,972
Net Cash Flow	-£ 87,145,282	£ 29,035,772	£ 23,844,996	£ 20,023,751	£ 17,231,853	£ 14,814,507	£ 12,816,533	£ 11,376,384	£ 10,356,377	£ 9,653,298	£ 9,189,791
Discounted Cash Flow (After Tax)	-£ 87,145,282	£ 26,884,974	£ 20,443,240	£ 15,895,499	£ 12,665,926	£ 10,082,505	£ 8,076,590	£ 6,638,011	£ 5,595,228	£ 4,829,052	£ 4,256,651
Business Case Results:											
NPW of Cash Flow	***£ 56,404,035***										
IRR	***19.6%***										
ROR	***14.3%***										

	11 2020	12 2021	13 2022	14 2023	15 2024	16 2025	17 2026	18 2027	19 2028	20 2029	TOTAL
Operating Costs											
Direct Production Cost:											
1. Transportation of Feedstock	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	£ 1,628,100	**£ 32,562,000**
2. Operating Labour (hrs/year)	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	£ 2,680,000	**£ 53,600,000**
3. Supervisory and Clerical Labour	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	£ 350,000	**£ 7,000,000**
4. Utilities	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	£ 1,299,296	**£ 25,985,921**
5. Maintenance and Repairs	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	£ 3,485,811	**£ 69,716,226**
6. Operating Supplies	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	£ 348,581	**£ 6,971,623**
7. Patents and Royalties	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	£ 129,930	**£ 2,598,592**
8. Plant Overhead Costs	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	£ 1,515,000	**£ 30,300,000**
Fixed Charges:											
1. Loan Repayments (Interest Only)	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ -**
2. Local Taxes	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	**£ 17,429,056**
3. Insurance	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	£ 871,453	**£ 17,429,056**
General Expenses:											
1. Administrative Cost	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	£ 402,000	**£ 8,040,000**
2. Distribution and Marketing	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	£ 649,648	**£ 12,992,961**
3. Research and Development Cost	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	£ 389,789	**£ 7,795,776**
Depreciation	£ 1,226,864	£ 920,148	£ 690,111	£ 517,583	£ 388,188	£ 291,141	£ 218,355	£ 163,767	£ 122,825	£ 92,119	
Annual Escalation of Costs:	£ 3,558,391	£ 3,921,980	£ 4,292,840	£ 4,671,118	£ 5,056,962	£ 5,450,522	£ 5,851,954	£ 6,261,414	£ 6,679,064	£ 7,105,066	**£ 69,937,170**
											£ -
TOTAL OPERATING COST	£ 19,406,315	£ 19,463,188	£ 19,604,012	£ 19,809,762	£ 20,066,210	£ 20,362,724	£ 20,691,370	£ 21,046,241	£ 21,422,949	£ 21,818,246	**£ 449,227,307**
Loan Repayments (Principal)	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ -**
											£ -
TOTAL EXPENSES	£ 19,406,315	£ 19,463,188	£ 19,604,012	£ 19,809,762	£ 20,066,210	£ 20,362,724	£ 20,691,370	£ 21,046,241	£ 21,422,949	£ 21,818,246	**£ 449,227,307**
Revenue and Operating Benefits											
1. Collection Fees	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	£ 3,111,480	**£ 62,229,600**
2. Gate Fees	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	£ 1,989,900	**£ 39,798,000**
3. Steel Sales	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	£ 1,718,550	**£ 34,371,000**
4. Carbon Black Sales	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	**£ -**
5. Activated Carbon Sales	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	£ 10,010,102	**£ 200,202,030**
5. Pyro Oil Sales	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	£ 4,792,343	**£ 95,846,850**
Annual Escalation of Revenues	£ 6,748,054	£ 7,457,315	£ 8,184,307	£ 8,929,474	£ 9,693,271	£ 10,476,162	£ 11,278,625	£ 12,101,150	£ 12,944,238	£ 13,808,404	**£ 133,697,064**
TOTAL REVENUE	£ 28,370,428	£ 29,079,689	£ 29,806,681	£ 30,551,848	£ 31,315,645	£ 32,098,536	£ 32,900,999	£ 33,723,524	£ 34,566,612	£ 35,430,778	**£ 566,144,544**
Gross Profit before Depreciation Charge	£ 10,190,977	£ 10,536,649	£ 10,892,780	£ 11,259,670	£ 11,637,622	£ 12,026,953	£ 12,427,985	£ 12,841,049	£ 13,266,488	£ 13,704,651	**£ 203,786,163**
Gross Profit after Depreciation Charge	£ 8,964,113	£ 9,616,501	£ 10,202,669	£ 10,742,086	£ 11,249,435	£ 11,735,812	£ 12,209,629	£ 12,677,283	£ 13,143,663	£ 13,612,532	**£ 116,917,237**
Income Tax Calculation											
1. Depreciation Expense	£ 1,226,864	£ 920,148	£ 690,111	£ 517,583	£ 388,188	£ 291,141	£ 218,355	£ 163,767	£ 122,825	£ 92,119	**£ 86,868,926**
2. Operating Cost	£ 18,179,451	£ 18,543,040	£ 18,913,901	£ 19,292,179	£ 19,678,022	£ 20,071,583	£ 20,473,015	£ 20,882,475	£ 21,300,124	£ 21,726,127	**£ 362,358,382**
3. Operating Benefits	£ 28,370,428	£ 29,079,689	£ 29,806,681	£ 30,551,848	£ 31,315,645	£ 32,098,536	£ 32,900,999	£ 33,723,524	£ 34,566,612	£ 35,430,778	**£ 566,144,544**
4. Losses Claims	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	
Taxable Income	£ 8,964,113	£ 9,616,501	£ 10,202,669	£ 10,742,086	£ 11,249,435	£ 11,735,812	£ 12,209,629	£ 12,677,283	£ 13,143,663	£ 13,612,532	**£ 145,924,806**
Net Income Taxes	£ 2,509,952	£ 2,692,620	£ 2,856,747	£ 3,007,784	£ 3,149,842	£ 3,286,027	£ 3,418,696	£ 3,549,639	£ 3,680,226	£ 3,811,509	**£ 40,858,946**
Net Profit After Taxes	£ 7,681,026	£ 7,844,029	£ 8,036,033	£ 8,251,885	£ 8,487,780	£ 8,740,925	£ 9,009,288	£ 9,291,410	£ 9,586,262	£ 9,893,142	**£ 162,927,217**
Net Cash Flow	£ 8,907,890	£ 8,764,177	£ 8,726,144	£ 8,769,469	£ 8,875,968	£ 9,032,066	£ 9,227,644	£ 9,455,177	£ 9,709,087	£ 9,985,260	**£ 249,796,143**
											£ -
Discounted Cash Flow (After Tax)	£ 3,820,441	£ 3,480,375	£ 3,208,585	£ 2,985,662	£ 2,798,075	£ 2,636,374	£ 2,493,946	£ 2,366,149	£ 2,249,713	£ 2,142,320	**£ 56,404,035**

Figure 5-14: Optimised statement of cash flow for waste tyre pyrolysis plant.

The above life cycle cost analysis shows that the current economic model of waste tyre pyrolysis has NPW of £56 million and IRR of 19.6%. By looking at these business case results it can be concluded that this type of investment is considered profitable and will be very attractive to potential investors.

In previous section a minimum acceptable return on investment for a waste tyre processing plant was defined as 15%. The IRR of the optimum economic model was obtained through life cycle cost analysis and is clearly higher than specified minimum value of 15%. Therefore it can be said that at 19.6% annual IRR, this project is considered a very good investment.

5.12 Summary

After completing the analysis of the optimum economic model it was pleasing to see that the overall performance of the project did improve which was anticipated from the start. Above all, this economic model led to a discovery of some very important findings which could be very useful in future studies. The next section explores potential for further improvements in the financial performance of a waste tyre processing facility. There is a potential for some added benefits of investing in waste tyre processing industry and hopefully these can be implemented in the near future which will further increase the interest from investors all over the world.

Chapter 6 : Conclusions and Recommendations

6.1 Future of waste tyre processing industry

In the above economic analysis, it was only looked at the possibility of changing and improving those aspects of business which can be controlled, such as the plant's capacity, feedstock supply and final products produced. However in the future there will be more opportunities and threats arising from other external factors. These external factors are those which are not in our control, but still have a very significant effect on the overall performance of the project. Some of these factors may have a positive or negative outcome on the overall business. Potential opportunities and threats may come from factors such as the market price of the products, collection as well as the disposal fees, a more rigorous laws and regulations regarding the safe disposal of tyre etc. This section will look at only one of these external factors which can be crucial in the growth of waste tyre processing industry in the near future.

If there is a single external factor which would have the biggest impact on the overall performance of the plant that would be the change in collection and disposal fees. The reason for this is that a very small change in the fees allocated for collection and disposal could generate a significant increase in the project's revenue. For example, if the collection fees were to increase from £0.86 to a single pound (£1), which is only a 16 % increase, the overall increase in revenue generated would increase by staggering £800,000 for a plant processing 180 tpd. Now, imagine if these fees were to be doubled or even tripled (100% or 200% increase), the overall increase in the revenue would be very significant. This significance is further enhanced by the fact that an increase in collection and disposal fees has no real effect on the overall cost of the project, meaning that the increased revenue carries over directly into a profit. To continue further this chain reaction an increase in profit will greatly improve the project's NPW and IRR, which is the ultimate goal of this economic model.

Now that the key element of the "perfect model" has been identified, there is a much more difficult task of finding a way to implement this change. It is clear that tyre retailers will not be willing to pay any additional fees which would bump up the overall revenue since this will cause them large financial losses. Currently the new tyre retailers charge their customers what is known as Environmental Disposal Charge. This levy is charged on top of the price for new tyres in order to cover the costs of waste tyres disposal. Is it possible to work together with the retailers and raise the EDC to a more significant amount, say maybe £5? Let's hypothesize that this becomes the case, and retailers raise the levy to £5 for the collection and disposal of tyres. At first, the problem of disposing waste tyres within environmental regulations becomes solved. The companies would be able to commit higher investments and install highly advanced technology in order to process these tyres and still manage to obtain sufficient returns on their investment. However, the truth is that things are far from being that simple. What this increase in EDC will do is increase the profit margin of all tyre processing and recycling processes. This means that the investor has no real motive to invest in new and high risk technology, when already existing technology such as gasification or even simple dumping of the tyres illegally, will bring him now even bigger profits. If the suggested path is taken there will be more motives to continue the current trend of poor disposal of tyres which is as shown in Chapter 1 fatal for the environment that we all live in. A more careful and controlled approach needs to be undertaken in order to successfully implement the newly increased levy.

The waste tyre industry is going to be "frozen" without further assistance from the government. What this industry needs is for United Kingdom and other governments to step up and become an equal partner in solving this enormous problem called waste tyres. In order to promote environment friendly technologies such as pyrolysis, the government needs to recognise the effort of many companies which are prepared to take a massive risk in order to get this "show on the road". Instead of letting the tyre retailers call the shots, the government should impose a very different and selective type of tax on new tyres. This tax will be selective in a way that only those companies which can prove that their technology is environmentally friendly and it meets all the necessary rules and regulations are eligible to apply for the additional benefits. For example, if the UK government decides to impose a £5 tax for every new tyre manufactured or imported to the country, this will be more than enough to improve the overall plant performance which will help promote the new technology. However, as mentioned previously this will only apply for environmentally friendly projects while the current levy fees will remain for the other disposal technologies. This way we are more likely to see a much bigger interest from the investors and their willingness to be the part of the higher risk projects.

It is important to note that processing facilities will not be able to claim the full amount generated by this new tax. The reason for this is that there is a high cost in setting up and running such a system, so it is reasonable to assume that government will decide to keep a good portion of this in order to cover these costs. Therefore, in such an economic model a key assumption will have to be made where for every tyre collected the facility will be able to claim £3, while for every tyre which has been delivered to the facility by the independent collector and disposed of, £2 claim will apply. The reason for the difference in the two is mainly because it is assumed that in order to attract more tyres to be delivered to the processing facility the company will have to pay up to £1 to independent collectors. This way the facilities which don’t have their own collection of tyres can still remain competitive in the market against the more profitable technologies and ensure steady availability of feedstock.

It is a recommendation of this study for the waste tyre industry as a whole to approach the UK government with a proposal similar to the one presented above. This is going to be crucial in helping to make projects such as the one studied in this report more attractive for the investors. Other external factors such as the market price of the products present a very long shot because they depend on other industries and cannot be influenced in any way. However, the increased fees resulting from government tax imposed on the new tyres is much more achievable, but at the same time very difficult. Therefore, a good strategic plan will need to be developed and presented to UK government in order to raise the awareness of the current status of the industry and improve the attractiveness of the high risk technologies. The author of this report authorizes the use of this document as the reference in any further attempts to develop a proposal for the UK government and present the ideas presented above.

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