University of Southern Queensland
Faculty of Health, Engineering & Sciences

An Investigation into the feasibility of micro scale pyrolysis powered by renewable energy

A dissertation submitted by

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Abstract

This study examined the use of micro scale renewable pyrolysis as a method of distributed waste management. This study aimed to identify if renewable pyrolysis technology could be a potential solution to many of the problems facing the globe today; including resource shortages, pollution and environmental damage being caused by illegal dumping and greenhouse gas emissions.

This study has successfully determined this through the investigation of the technical, financial, social and environmental feasibility of various sized units aimed at servicing individuals, small families and small unit blocks. It identified that the global adoption of renewable micro scale pyrolysis would be a technically and financially feasible process in family homes and small unit blocks where the available renewable energy exceeds the amount of energy required to process the waste generated by those respective areas.

The true benefit of renewable micro scale pyrolysis is not derived from its implementation in a small number of dwellings but rather the global implementation as a method for distributed waste management. Large scale technology adoption would see significant social and environmental benefits. The technology has the potential to eliminate waste and reduce pollution ending illegal dumping and pollution of waterways and oceans while providing significant benefits to the system operator and the economy. Renewable micro scale pyrolysis has the potential to reshape the way that the globe see's and manages waste and should be investigate further as a priority for society and the environment.

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I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

P. Buckley

[redacted]

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

As human kind progresses and rapid technological advancements allow for the ever increasing production and destruction of goods and materials at unprecedented rates, societies are becoming consumer driven by an individual need to have the newest and greatest possessions. This has led manufacturers to design products with built in obsolescence (Gregson & Crang 2015, pg.154).

The waste of humanity extends far beyond consumer products though; never in the history of humanity has food been as accessible to society as it is presently. The ease of access to resources and materials has contributed significantly towards the amounts of waste generated annually across the globe with over one third of the global annual produce being discarded as waste (Yamada et al. 2017, p.g. 1351).

Consumer behaviour has seen significant increases in the amount of waste generated per person annually in all waste streams with generation growing 12% per annum (Pickin et al. 2018, pg. 9). In 2016-17 Australian waste totalled 67 million tonnes; of this waste 54 million tonnes was considered managed waste that would be caught within a municipal waste streams; this totals 2.2 tonnes per capita annually (Pickin et al. 2018, pg. 8) that must be managed to avoid it entering the environment.

Despite considerable efforts by governments and communities across the globe to implement recycling and resource recovery programs significant amounts of the waste generated in society annually ends its life as environmental contamination whether it can be recycled or not. In Australia over the past 11 years recycling rates have increased by 26% (Pickin et al. 2018, pg. 14) however this significant rise has had little impact with 99.9 percent of core waste being generated still reaching landfill (Pickin et al. 2018, pg. 22). Alston et al. (2011) identified that one of the significant waste streams is electronic equipment of which large portions go to landfill wasting precious resources(plastics) that could be converted into useful fuels. (Tuck et al. 2012, pg. 695) makes similar observations identifying that a large portion of the waste generated annually has an unrealised value.

The environmental contamination being caused by human waste is significant with Jambeck et al. (2015) identifying that between 4.8 and 12.7 million Tonnes of plastic waste entered the ocean in 2010. In addition to this Gross (2017, p. 1) identified that plastic waste generation is increasing at 8.4 percent annually and Pickin et al. (2018, pg. 31) identifies that 103kg of plastic are generated per capita annually in Australia. The issue of environmental contamination is even more complicated in developing countries where waste management is not a routine and reliable civic service. (Mia et al. 2018, PG. 503) identifies that Bangladesh only manages to collect and manage around 50% of its municipal waste. Unless immediate action is taken to drastically change consumer behaviour and simplify waste management humanity is heading for an environmental catastrophe.

There has been significant research in recent years towards energy recovery from waste. The energy recovery efforts focus on key areas of landfill methane collection and waste incineration to exploit the high calorific value of waste directly (Pickin et al. 2018, pg. 19). These initiatives have little benefit to the consumer that generated the waste and do nothing to reduce the impact of waste generation and management cycle on the environment, as significant resources are still required to collect, process and store the waste. In addition to this while methods such as incineration have been shown to be economically feasible they have also been shown to be detrimental to the environment releasing pollutants into the atmosphere (Park et al. 2016, pg. 16814).

A long standing concern in society is that its resources will eventually run out and when that happens society will rapidly deteriorate unable to function (Jefferson 2006, pg. 572-573). Demand is rapidly out pacing supply in key energy such as fuel with global reserves falling (Rahman et al. 2018, pg. 32). In a modern society that is so reliant on energy for everyday life this has seen resources extend beyond the physical resource that you can hold with your hand such as food and water into the realm of fuel and electricity. While food and water may be in abundant supply energy is what ensures that an increasingly city bound population is able to access them and rising energy costs have been identified as key concern facing society today (Lior 2010, pg. 3976).

The simplest form of extracting energy from waste and bio-mass is combustion, as previously mentioned this process is in wide use across the globe however it is far from environmentally friendly and also has a low efficiency (Guedes et al. 2018, pg. 134). In response to the identified shortfalls of combustion, pyrolysis, which is considered a clean renewable form of energy (Jaroenkhasemmeesuk & Tippayawong 2015, pg. 951), has been rapidly developing and reaching economic maturity entering commercial operation across the globe. It has been widely recognised as a viable method to derive value from waste traditionally a product seen as having a low or even negative value. The waste to energy and materials recovery market is estimated to have a global industry value in the vicinity of $500 billion (Gregson & Crang 2015, pg.163). This market has developed to the point that developed countries like Italy are exporting in excess of 200 000 tons per year to (Tuck et al. 2012, pg. 695).

The purpose of this project is to identify if it is feasible using renewable energy to eliminate household waste through micro scale pyrolysis. Will micro scale pyrolysis address the global waste crisis, energy and resource shortages being faced by society today?

1.1 Project Aims

The elimination of waste is achieved through changing the nature and perception of what is traditionally considered waste to that of a valuable fuel that can be used to generate electricity, heat homes, cook with or even fuel cars.

The feasibility will be determined through analysing the process outputs, technical investigation, simulation and financial evaluation of micro scale plants used in a single family dwelling and a small unit complex.

1.2 Project Objectives

The key objectives that the project are:

- To investigate the current state of advanced pyrolysis to product e.g. bio-fuel and its use in waste processing and management.

- To investigate global approaches to pyrolysis systems powered by renewable energy.
- Construct a system stimulation's in Chemkin to identify system performance under general household waste loading scenarios.
- Identify the safety, environmental, legislative and standard requirements relevant to consumer operated pyrolysis plants.
- Prepare cost estimates for micro scale plants and perform cost benefit analysis for the systems for implementation into the use cases.
- Determine the technical, social, environmental and financial feasibility of renewable powered micro scale pyrolysis plants for use in the family home or small unit complex.

Chapter 2

Literature Review

Waste generation and management are long standing social issue that has recently seen limited research that attempts to address environmental problems that are developing as the global population develops. Pyrolysis and renewable energy have undergone significant amounts of research over the past four decades as one method to address the waste problem however the technologies are centuries older with much of the recent research focusing on modern applications of the old technology.

2.1 Pyrolysis

Pyrolysis is a well-know thermal decomposition process that involves heating carbon based materials in the absence of oxygen in order to produce desirable outputs of combustible gas, condensate liquid and char (Alston et al. 2011, Arni 2018, pg. 9380-9381, 197) (Bridgwater 2012, pg.68). Since its inception and recent innovations in pyrolysis has focused on processing bio-mass which Alvarez et al. (2014, pg. 10884) identify as being the fourth largest source of renewable energy in the world.

Virtually any type of biomass can be used as pyrolysis feed stock (Bridgwater 2012, pg. 70). Depending on the feed stock usable fuel content derived from the pyrolysis process can be more the 70% of the input feed stock weight (Alston et al. 2011, pg. 9384) (Bridgwater 2012, pg.68) with some studies reporting up to 85% usable fuel outputs. Arni (2018, pg. 201) identifies that both slow and fast pyrolysis process have high conversion rates with process losses as low as 15%.

Alvarez et al. (2014, pg. 10884) identifies that the methods of pyrolysis can be modified depending on the desired outputs of gas, oils or chars. Pyrolysis occurs across a range of temperatures that vary significantly depending on the feed stock mixture and the desired outputs. Alston et al. (2011, pg. 9380) identifies that in the temperate range of 400-500°C gas production averages around 26% but can increase to over 40% at 875°C.

Arni (2018, pg. 201) identifies that higher temperature pyrolysis process favour the production of hydrogen over other less combustible gases. Higher hydrogen content make fast pyrolysis gases more suitable for the production of higher quality energy and fuel oils.

Alston et al. (2011, pg. 9381) identifies that operating at temperatures above 600 °C is essential to avoid the formation of dioxins within the end products.

(Guedes et al. 2018, pg. 138) identifies that the pyrolysis process conversion efficiency increases with temperature but above the oil production optimum 650 °C the oils produced by the reaction reduce and the gases produced increase.

The heat transfer rate plays a key role in the pyrolysis process with (Guedes et al. 2018, pg. 139) highlighting the relation between heat transfer rates and the quality of the bio-oil product. Higher heat transfer rates have been identified to reduce the water and oxygen content of the oil products.

An important characteristic of pyrolysis is that the process produces next to no waste Bridgwater (2012, pg.69). A small amount of ash may be formed and removed from gases and vapours. If the gasses generated during the process are also used to provide the heat required by the pyrolysis reaction then there is also a small amount of clean flue gas containing CO^2 and water that must be managed (Bridgwater 2012, pg. 77).

To improve the desirable outputs of pyrolysis processes, pyrolysis is often performed in the presence of a catalyst which will be further explored later in this review.

Bridgwater (2012, pg.68-69) identifies that lower temperature longer residence reactions are suited for the production of charcoal while high temperatures and short residence times produces higher gas yields. Bridgwater (2012, pg. 69) also identifies that for optimum liquid yield moderate temperatures and short to medium residence times produce superior amounts of condensate liquids. Because of the relation between dwell time or residence to pyrolysis outputs, most pyrolysis processes are classified by their residence time.

Slow pyrolysis also referred to as conventional pyrolysis or cauterisation is characterised by a long residence time usually greater then 1 hour it produces lower gas and liquid condensate increasing the solid yields(Arni 2018, pg. 197). Arni (2018, pg. 198) identify that a typical slow pyrolysis process aims to achieve a temperature of approximately 853K using a heating rate of 45-50 °C/min. As slow pyrolysis is produces higher amounts of char and lower levels of gas and vapours it will not be investigated further in this paper.

Fast pyrolysis residence times usually are less then 10 minutes and heating rates are in the vicinity of 120 °Celsius per minute Arni (2018, pg. 198). However Guedes et al. (2018, pg. 140) identifies the change in oil production from extending residence times is minimal they observed that when extending from 10 to 20 minutes the reduction was less then 1% and at 50 minutes is around 3%. During the residence time the feed materials decompose very quickly generating mostly vapours with a small amount of gases and charcoal (Bridgwater 2012, pg. 69). One of the key challenges to fast pyrolysis in not the temperatures of reaction but achieving the required heat transfer rates to fully process the materials (Bridgwater 2012, pg. 69). Guedes et al. (2018, pg. 135) identifies that fast pyrolysis systems can be set up with low investment costs and are highly efficient.

Flash pyrolysis has a residence time which is generally considered to be less then 2 seconds, the high heating exchange rates required mean material size required is extremely small and the systems are complex (Guedes et al. 2018, pg. 134) flash pyrolysis systems will not be explored further in this paper as it is assessed their technological complexity would prohibit their use in a residential area or a consumer targeted plant.

The end products that are derived from pyrolysis can be directly used or refined in an additional stage to improve their chemical properties for the desired end use applications (Alvarez et al. 2014, pg. 10884) the end products and their uses will be examined in further detail later in this paper.

2.2 Pyrolysis Hazards

The pyrolysis process has several hazards which must be addressed in any plant that uses the pyrolysis process. There will be machine hazards that may lead to crush or dismemberment that must be guarded against.

There are also specific hazards that arise from the pyrolysis process that must be catered for in design. The primary being the handling of combustible end product materials such as gas, oil and char in the vicinity of high heat processes. The char on its own poses a combustion hazard with Bridgwater (2012, pg. 72) identifying that the fresh char is pyrophoric and will spontaneously combust if is exposed to air. This property is short lived and oxidation of active sites neutralises the active sites on the chars surface.

An additional hazard would be the heating processes its self and the potential of it to cause severe burns on individuals that are exposed to hot elements gases or liquids.

Finally there are an output hazard that varies depending on the feed material that may create unintended hazards Alston et al. (2011, pg. 9384) identified one such hazards in that certain types of plastics such as PVC produce dangerous amounts of chlorine gas when they undergo pyrolysis.

2.3 Outputs of pyrolysis

Pyrolysis has three common outputs these are commonly refereed to as bio-gas(syngas, pyrolysis gas), bio-char(char) and bio-oil(pyro-oil, bio-crude).

Bio-Gas or Syngas

Synthetic Gas (Syngas) or Bio-Gas outputs typically makes up around 5% - 30% of the feed material (Bridgwater 2012, pg. 76) however as the temperature elevates so does the amounts of gas that are produced. The gas produced by pyrolysis has a heat value around 6.4-9.8 MJ/Kg however this value is largely dependent on feed materials Joardder et al. (2014, pg.2) and is widely disputed across the industry. Czajczyńska et al. (2017, pg. 391-393) identifies the heat value of pyrolysis gas produced from waste to be between 42 and 50 MJ/Kg. The pyrolysis process has significant benefits over other technologies such as gasification. The pyrolysis process requires the removal of heavy and light condensates from the vapour stream so that only non-condensible gas is left. This process removes tars and other contaminates from the gas that would normally be present in gasification syngas causing damage to burners or engines(Woolcock & Brown 2013, pg. 56-58).

The gas can be stored and transported for direct use, used for production of synthetic fuels and high value chemicals or used in on site energy and heat production (Guedes et al. 2018, pg. 135)

Bio-char or Char

The char outputs account for up to 25% of the feed materials(Bridgwater 2012, pg. 76) (Oasmaa & Peacocke 2010, pg. 26). Mia et al. (2018, pg. 504) identifies that the char has many characteristics making it a valuable resource in agriculture. These include that it improves soil nutrient retention and it increases soil aeration. In addition to these benefits Mia et al. (2018, pg. 505) identifies that bio-char has the ability to absorb CO^2 into its surface area entrapping it.

Joardder et al. (2014, pg.2) indicates that the energy content of the char can be in the vicinity of 17-36 MJ/Kg however this is dependent on the feed materials. Guedes et al. (2018, pg. 135) identifies that energy content of the char means it can be used for heat generation processes as a low quality coal substitute and that it could also be used in the preparation of active carbon materials used in medical procedures and advanced filtration systems.

Condensed liquid or bio-oil

The bio-oil condensed from the vapours of pyrolysis processes are significantly different from crude oil (Oasmaa & Peacocke 2010, pg. 9) however it can be used directly in limited applications or specially designed burners. With upgrading it can be comparable to and compatible with many petroleum products (Guedes et al. 2018, pg. 135). The oil will have an approximate elemental composition to the feed materials and is composed of oxygenated hydrocarbons and a significant portion of water as well as char and ash contaminates if poorly filtered (Bridgwater 2012, pg. 77). Stefanidis et al. (2016, pg. 8261) identifies the high oxygen content of pyrolysis bio-oil as being responsibly for its significant drawbacks such as lower heat value, immicibility with petroleum fuels and its instability in storage. Bridgwater (2012, pg. 77) identifies that Bio-oil typically has a heat value of around 17 MJ/kg however can range as high as 38 MJ/Kg depending on feed materialsJoardder et al. (2014, pg. 2) with around 25% water content. Table 1 is a copy of table 4 from (Bridgwater 2012, pg. 78) it shows the key characteristics of bio-oil and the causes and effects of these characteristics.

Table 2.1: Characteristics of bio-oil. Table 4 from (Bridgwater 2012, pg. 78)

Characteristic	**Cause**	**Effects**
Acidity or Low pH	Organic acids from bio-polymer degradation	Corrosion of vessels and pipework
Ageing	Continuation of secondary reactions including polymerisation	Slow increase in viscosity from secondary reactions such as condensation Potential phase separation
Alkali metals	Nearly all alkali metals report to char High ash feed, Incomplete solids separation	Catalyst poisoning Deposition of solids in combustion Erosion and corrosion Slag formation Damage to turbines
Char	Incomplete char separation in process	Ageing of oil Sedimentation Filter blockage Catalyst blockage Engine injector blockage Alkali metal poisoning
Chlorine	Contaminants in biomass feed	Catalyst poisoning in upgrading
Colour	Cracking of bio-polymers and char	Discolouration of some products such as resins
Contamination of feed	Poor harvesting practice	Contaminants notably soil act as catalysts and can increase particulate carry over.

Table 2.1: Characteristics of bio-oil. Table 4 from (Bridgwater 2012, pg. 78)

Characteristic	**Cause**	**Effects**
Distillability is poor	Reactive mixture of degradation products	Bio-oil cannot be distilled e maximum 50% typically. Liquid begins to react at below 100 °C and substantially decomposes above 100 °C
High viscosity		Gives high pressure drop increasing equipment cost High pumping cost Poor atomisation
Low H:C ratio	Biomass has low H:C ratio	Upgrading to hydrocarbons is more difficult
Materials incompatibility	Phenolics and aromatics	Destruction of seals and gaskets
Miscibility with hydrocarbons is very low	Highly oxygenated nature of bio-oil	Will not mix with any hydrocarbons so integration into a refinery is more difficult
Nitrogen	Contaminants in biomass feed High nitrogen feed such as proteins in wastes	Unpleasant smell Catalyst poisoning in upgrading NOx in combustion
Oxygen content is very high	Biomass composition	Poor stability, Non-miscibility with hydrocarbons
Phase separation or Inhomogeneity	High feed water, High ash in feed, Poor char separation,	Phase separation, Partial phase separation, Layering; Poor mixing, Inconsistency in handling, storage and processing
Smell or odour	Aldehydes and other volatile organics, many from hemicellulose	While not toxic, the smell is often objectionable

Table 2.1: Characteristics of bio-oil. Table 4 from (Bridgwater 2012, pg. 78)

Characteristic	**Cause**	**Effects**
Solids	See also Char Particulates from reactor such as sand Particulates from feed contamination	Sedimentation Erosion and corrosion Blockage
Structure	The unique structure is caused by the rapid depolymerisation and rapid quenching of the vapours and aerosols	Susceptibility to ageing such as viscosity increase and phase separation
Sulphur	Contaminants in biomass feed	Catalyst poisoning in upgrading
Temperature sensitivity	Temperature sensitivity	Irreversible decomposition of liquid into two phases above 100 °C Irreversible viscosity increase above 60 °C Potential phase separation above 60 °C
Toxicity	Bio-polymer degradation products	Human toxicity is positive but small Eco-toxicity is negligible
Viscosity	Chemical composition of bio-oil.	Fairly high and variable with time Greater temperature influence than hydrocarbons
Water content	Pyrolysis reactions, Feed water	Complex effect on viscosity and stability: Increased water lowers heating value, density, stability, and increase pH Affects catalysts

2.4 key components of a pyrolysis processing

Pyrolysis systems are complicated systems with many essential components that can be grouped across four main categories. These categories are Pre processing equipment, Reactors and liquid or gas collection.

2.4.1 Pre-processing equipment dryer, shredder, sorting

While pre-processing of materials for pyrolysis is not essential by reducing feed material size through shredding, moisture content by heating and removing contaminates by sorting, it leads to higher quality process outputs and accelerated material processing.

Typical pyrolysis processes will attempt to recover valuable materials such as ferrous and non-ferrous metals prior to processing as they can damage machines and are of no value in the pyrolysis outputs.

Other materials that may be removed are ceramics and glasses as well as plastics that pose a safety hazard like large amounts PVC if there is no method of handling the gases it produces and materials that damage upgrading catalysts.

2.4.2 Reactors

Bridgwater (2012, pg. 71-72) identifies that most research and commercial reactors focus on the fluid bed reactor because it offers constant performance and high liquid yields compared to other designs for high quantities of material processing.

The air tight nature of the reactor is essential to prevent combustion of the feed materials in addition this the accuracy and consistency of the temperature within the reaction chamber is also essential to maximise the desired yields of the pyrolysis process. Bridgwater (2012, pg. 69) identify that maintaining a reaction chamber temperature at around 500°C is suitable for fast pyrolysis. In addition Bridgwater (2012, pg.69) also identifies that chamber design should allow for rapid removal of gases and char to prevent secondary reactions. However Chen et al. (2019, 155) identify that as pyrolysis temperatures increase the acids and esters produced in the vapours decrease significantly and the phenols increase gradually with better results achieved around 600-700°C.

In recent times there has been a significant amount of reactor development focusing on several designs with different target capacities and heating methods. These are summarised in table 2.2 which shows the types of reactors and their hourly capacity. Many of these commercial designs have been developed of small scale research reactors that have significantly lower capacities which have also been identified in table 2.2.

Table 2.2: Commercial and experimental reactor designs and rated capacities. (Bridgwater 2012, pg. 71-72)

Reactor Type	**Capacity kg/hr**	**Experimental capacities kg/hr**
Fluid bed	20-8000	1-650
Circulating fluid bed	400-4000	1
Rotating cone bed	2000	20
Ablative	250	0.15-20
Auger or screw	200-2083	0.5-30
Microwave	Unknown	<0.1
Moving bed & fixed bed	600	0.5
Vacuum	3500	Unknown

The key designs that were summarised in table 2.2 are further expanded bellow.

Fluid bed reactors

Significant amounts of current research and commercialisation by private enterprise has focused on fluid bed reactors as they offer benefits over simpler designs by increasing the separation of the fluids, gases and char rapidly preventing secondary reactions and providing large processing capacity (Bridgwater 2012, pg. 73). These reactors rely on an inert gas being pumped through a material such as sand to fluidise it giving it a liquid appearance and characteristics. This allows the materials to be engulfed by the fluid for efficient processing. Guedes et al. (2018, pg. 143) identifies the average condensed fuel yield of fluid bed reactors are between 40 and 60%

Circulating fluid bed reactors

More recent research has focused on advanced circulating fluid bed reactors. These are similar to the fluid bed reactors but the fluid is circulated as well as the feed materials.

The key advantage over fluid bed reactors is even higher material processing rates at the trade of of system simplicity (Bridgwater 2012, pg. 73). One of the downsides of circulating fluid bed systems is that char is completely burned off used for heating the sand and will not be an available revenue stream (Bridgwater 2012, pg. 73). As with fluid bed reactors these reactors use an inert gas to to fluidise the bed allowing for the bed material to flow.

Rotating Cone

Rotating cone reactors ingest in a mix of heated sand and feed materials into the reactor cone which rotates using centrifugal force to ensure the feed materials maintain contact with the hot reaction surfaces. The vapours are collected normally and the sand and char are removed for processing and re-circulation after exiting the cone. Typical liquid yields for this design have 60-70% liquid recovery rates (Bridgwater 2012, pg. 73). As with the circulating fluid bed designs the char for this process is completely burned off to heat the sand and will not be an available revenue stream, burning of the char also creates some ash emissions (Bridgwater 2012, pg. 73).

Ablative

Ablative methods of pyrolysis benefit from not being limited by the heat transfer rate of materials and therefore the pre-processing of materials is significantly reduced and the processes doesn't rely on small particle size to be efficient. In ablative processes the material is forced onto a moving heated surface under pressure causing the particles to vaporise leaving char which can be separated in cyclone filters, oil and vapours which yield between 70-75% liquid recovery (Bridgwater 2012, pg. 73-74). Ablative processes generally do not scale well and usually complex to design (Bridgwater 2012, pg. 74).

Vacuum

Vacuum pyrolysis differs from other methods of fast pyrolysis in that it uses lower heat transfer rates however the process has been demonstrated to have significantly lower liquid yields in the vicinity of 35-40%. In combination with lower liquid yields the systems are complex and expensive to produce. The two main advantages are that no inert gas is required and the process doesn't require as much pre-processing of feed materials.

Screw and Auger

Screw and Auger designs move the feed material through the heated pyrolysis zone rather then using fluid to achieve material flow through the system. Due to design conditions it is difficult to achieve residence times as low as circulating fluid bed or other methods of fast pyrolysis.(Bridgwater 2012, pg. 74). For the Screw and Auger designs heat is usually introduced by direct heating of reactor surfaces. Guedes et al. (2018, pg. 143) identifies that these reactors typically have a oil yield rate around 45 to 55%.

2.4.3 Vapour filters

A key challenge facing pyrolysis is removal of contaminants from vapour streams. Hot char acts as a cracking catalyst of vapours which can cause non-desirable products (Bridgwater 2012, pg. 76). The bulk of char is separated out in the reactors however it is inevitable to that some char will persist in the vapour products produces by the pyrolysis process. Removal of the bulk of this material is achieved through cyclone filtration. Failure to remove this product results in rapid liquid degradation (Bridgwater 2012, pg. 76). If the vapour char is not removed from the vapours it may be removed by centrifugation of the collected liquids at a later time (Oasmaa & Peacocke 2010, pg. 13) however presence of char in the liquid will reduce its service life.

2.4.4 Liquid and Gas collection

The vapours produced in pyrolysis reactors must be rapidly cooled to avoid secondary reactions which have significant impacts on liquid yields (Stefanidis et al. 2016, pg. 8261). After filtration as described above they can be condensed into a bio crude or liquid fractions (Bridgwater 2012, pg. 76) for direct fuel applications. Fluid bed reactors pose a significant issue in that the inert gas used to fluidise the bed must be removed and collected separate from the valuable liquids and other combustible gases.

2.5 Feed Materials

The feed materials for the pyrolysis process are extremely diverse with most biological, organic and carbon based materials capable of being pyrolysed. Common feed stocks include household waste, plastics, bio-solids i.e. dry sewerage solids or animal manure, timber, papers, oils and biomass such as rice husk, straw or cuttings (Alston et al. 2011).

There is an increasing amount of research into the use of municipal solid waste as a pyrolysis feed stock with Czajczyńska et al. (2017, pg. 390) identifying that the average calorific value of municipal solid waste is around 27 MJ/Kg. Czajczyńska et al. (2017, pg. 391-393) goes on to identify the heat value of pyrolysis gas produced from municipal solid waste to be between 42 and 50 MJ/Kg and the oil having an unimproved heat value of up to 46.43 MJ/Kg depending on waste composition. Finally the char product was identified to have a heat value of 33.6 MJ/Kg which is comparable with coal. However these values appear to be extremely high when placed into comparison with other researchers findings. With the pyrolysis products obtaining these heat values municipal solid waste is was accessed as a highly suitable feed material for pyrolysis processing and shows high potential.

Solar Assisted Pyrolysis of Plastic Waste: Pyrolysis oil Characterization and Grid-Tied Solar PV Power System Design (n.d., pg. 127) identifies that when pure plastics are the feed material the bio-oil calorific value lies between 35-39 MJ/Kg and that this is between 77-85% of the gross calorific value of diesel fuels making plastic an excellent feed material for fuel production.

Alvarez et al. (2014) identify in their research that the addition of more than 20% plastic material to bio-mass pyrolysis feed materials increases the useful outputs of gas and oil by up to 7% and significantly lowers the CO and CO^2 content of the outputs which is an extremely desirable characteristic for fuels.

Moisture content plays a significant role in the amounts of gas produced by the pyrolysis process with Arni (2018, pg. 198) identifying a correlation between rising moisture content of feed stock materials and reductions in gases produced.

It is important for the process that feed materials are prepared and processed to an appropriate feed size creating a suitable surface area to volume ratio this as it has been identified that this ratio is directly related to oil production by modifying the heat reaction and heat transfer rates (Rahman et al. 2018, pg. 41) Bridgwater (2012, pg. 69). Most studies focusing on achieving feed material sizes from 1mm to 25mm with the predominate particle size being less then 3mm. (Alston et al. 2011)(Bridgwater 2012, pg. 69) (Guedes et al. 2018, pg. 140). However there are some studies suggesting that particle sizes of less then 0.5mm will produce even higher heat transfer rates (Rahman et al. 2018, pg. 41). (Guedes et al. 2018, pg. 140) identifies that these higher rates from particles size less them 2mm is only applicable to fluidised bed reactors and flash pyrolysis processes.

Traditional pyrolysis focuses on single type feed materials like walnut shells of sewerage sludge. However it has been identified the co-pyrolysis of mixed materials where one material has a significantly higher hydrocarbon content such as plastics processed with another bio-mass results is a significant change in high value product yields, with some studies reporting over 50% increases in oils produced (Rahman et al. 2018, pg. 43).

2.6 Make up of waste

To accurately model pyrolysis systems an accurate understanding of the properties, composition and energy content is essential.

Yamada et al. (2017) in their study examined the waste destined for incineration in Kyoto city to identify its composition in figure 2.1 which shows household waste studied and classified across 12 group categories

In a Finnish study Liikanen et al. (2016) identifies through a detailed examination of the composition of municipal solid waste that of the total waste collected 71.5% of it is made up of materials that would be suitable for pyrolysis with only 15.8% being plastics. The mixture of waste poses challenges for processing with 28.5% of municipal solid waste needing to be removed form the processing stream during or prior to pyrolysis. Weather it is removed or not the system must be capable of handling some level of contamination from non-target waste streams.

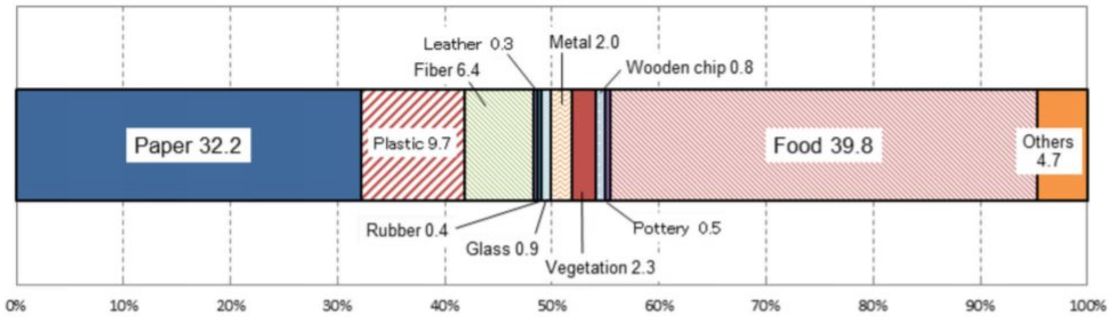


Figure 2.1: Figure 3.a Yamada et al. (2017) detailed composition of household waste

Hla & Roberts (2015, p.g. 18) in their study analyse Brisbane municipal solid waste to determine its composition and and heat values. In their proximate analysis the identified that municipal solid waste after removing moisture is 77.4% volatile matter, 15.1% Fixed carbon and 7.6% Ash. In their ultimate analysis they identified that 52.8% of dry mass is carbon, 6.4% is Hydrogen, 1.29% is nitrogen, 31% is oxygen, 0.18% is silicon and 0.73% is chlorine. There study identified that the dry material heat values to be in the vicinity of 21.81 ± 0.69 Hla & Roberts (2015, p.g. 18) .

Hla & Roberts (2015, p.g. 12) identify there is a significant untapped and valuable resource in the waste of Australia highlighting the immense energy resource that is going unused. Current research indicates that the makeup of municipal solid waste is ideal for pyrolysis with the waste containing up to 63% biomass and 10% plastics which are ideal feed materials for pyrolysis processing (Park et al. 2016, pg. 16815) however this mix must be appropriately dried to remove unwanted moisture from the process prior to pyrolysing.

2.7 Scales of pyrolysis

To date pyrolysis has been proven in small scale research reactors as identified in table 2.2 which were then scaled for commercialisation in large scale applications. There has been little research performed on the benefits, use and application of smaller scale pyrolysis processing in a distributed network or on a per-household basis.

2.8 Pyrolysis energy requirements

Significant amounts of energy are required to prepare the feed materials for pyrolysis and produce the pyrolysis reaction. The main energy concerns when preparing materials is shredding and drying the materials to remove unnecessary moisture. The second significant source of energy consumption is the pyrolysis process itself.

Feed materials have been identified as having an average specific heat capacity of 2.41 J/g K (*Characterization of thermal properties of municipal solid waste landfills* n.d., pg. 218) which will allow for the calculation of energy to remove excess moisture.

Bridgwater (2012, pg. 76) identifies that approximately 15% of the energy in the feed materials is required to provide energy for the pyrolysis process. However this number seems to be quite low and as of yet has not been confirmed in any other research.

Jaroenkhasemmeesuk & Tippayawong (2015, pg. 994) identifies that heat energy losses can have a significant impact on the financial viability and payback periods of pyrolysis projects as such heat management, maximising heat use and insulation are essential components to pyrolysis system designs.

There are many ways for the heat to be introduced into the process as identified in reactor designs one of the key challenges in pyrolysis is sourcing the energy in an appropriate format for the process. With many of the benefits of pyrolysis being offset by the heat generation processes used to carry out the pyrolysis Bridgwater (2012, pg. 74) identifies heat sources may include:

- Renewable energy sources like solar and wind;
- Combustion of pyrolysis char;
- Combustion of pyrolysis gas;
- Combustion of fresh feed materials;
- Combustion of pyrolysis oil;
- Grid electricity; and,
- Fossil fuels.

2.9 Renewable pyrolysis

To date there has been limited research of into the use of renewable energy to conduct the pyrolysis process with most processes focusing on combustion heat generation Joardder et al. (2014, pg.1-10). There are some emerging studies such as the one conducted by *Solar Assisted Pyrolysis of Plastic Waste: Pyrolysis oil Characterization and Grid-Tied Solar PV Power System Design* (n.d.)that focus on using renewable energy(solar PV) to reduce the energy demand of pyrolysis, reducing its emissions and the overall operating cost. *Solar Assisted Pyrolysis of Plastic Waste: Pyrolysis oil Characterization and Grid-Tied Solar PV Power System Design* (n.d., pg. 127-128) identified in their study that a system structured around a grid tie solar PV generated 52% lower greenhouse gases then a comparable pyrolysis system and they also identified a 14% process cost reduction per megawatt hour.

Joardder et al. (2014, pg.1-10) researched if parabolic solar concentrating heating would be a valid method of offsetting the energy required to undertake the pyrolysis process in their research they identified that a solar thermal system on its own wouldn't be able to stably maintain suitable temperatures for the process, instead identifying that solar assisted systems that mixed solar thermal heating with another form of heating had the potential to lower CO^2 emissions and costs by 32.4%.

2.10 Upgrading of pyrolysis oil

For bio-oil to be useful in consumer applications it must be upgraded so that it is compatible with normal fuels and current consumer products. The aim of the upgrading process is the minimise the undesirable properties of bio-oil (Saraçoğlu et al. 2017, pg. 21476) . There are many ways to upgrade bio-oil and indeed they are often combined to achieve desired results.

Physical upgrading Physical upgrading process involve performing direct processes on the pyrolysis system inputs and outputs to improve the quality of outputs.

Filtration

This basic process performed on the hot vapours in addition to cyclone filtration which removes larger particles and has been shown to lower the ash content to less then 0.01% and the alkali content to less the 10 ppm (Bridgwater 2012, pg. 80). Removal of particle contamination increases the quantity and quality of end products. In the case of bio oil filtration also assists in preventing the product from undergoing undesirable secondary reactions (Bridgwater 2012, pg. 80).

Solvent addition

Bridgwater (2012, pg. 80) identifies that the addition of solvents to bio-oils can be beneficial in reducing ageing reactions and increasing oil viscosity.

Emulsions

While bio-oil doesn't mix with hydrocarbon fuels, in low concentrations between 5 and 30% it can be used to form emulsions with diesel fuel and then operated a regular engine with slightly reduced fuel economy (Bridgwater 2012, pg. 80).

Molecular distillation

A recent focus for upgrading of bio-oils has been molecular distillation. Once condensed, bio-oils will break down if high temperature distillation is performed on them. Guo et al. (2010, pg. 52-57) identifies that a potential solution to this is molecular distillation. This process is a low temperature pressurised distillation process that has the ability to be target towards specific molecular compounds. It is used widely in the pharmaceutical industry and has had limited applications in the petroleum industry. Guo et al. (2010, pg. 56) identifies that they were able to successfully reduce the water content of bio-oils from 30.40% to 1.49%. The removal of water significantly increases the energy content, stability and performance of the oils.

Catalytic upgrading

Catalytic upgrading has been identified by Rahman et al. (2018, pg. 38) as a rapidly evolving crucial technology for processing pyrolysis oils removing oxygen and increasing the chemical stability of the final products.

Hydro-treating

In the hydro-treating process oxygen is rejected from the oil as through the catalytic introduction of hydrogen. This process requires high pressures around 20 MPa and temperatures of up to 400 °C and an independent source of hydrogen (Bridgwater 2012, pg. 81) (Wang et al. 2016, pg. 19386).

This process produces a naphtha-like product that would then require further processing to derive a transport fuel like petrol (Bridgwater 2012, pg. 81). The high pressure, high temperatures and high hydrogen consumption rate required for this process will make it not suitable for consumer end use.

Catalytic material Upgrading

In a study of 14 catalysts the Stefanidis et al. (2016, pg. 8265-8267) identifies that most catalysts while producing one desirable outcome do so significantly at the expense of others. Their research that zirconia/titania and ZSM-5 are the most balanced yet effective catalyst for upgrading pyrolysis oil. Current research indicates that Zeolites are the most suitable catalytic materials for upgrading of pyrolysis materials because of their cost effectiveness and performance in pyrolysis (Rahman et al. 2018, pg. 43).

There has been a significant focus on the zeolite upgrading using the ZSM-5 zeolite and in some cases the HZSM-5 zeolite with Rahman et al. (2018, pg. 31 -32) identifying from 40 tested catalysts that those belonging the ZSM-5 family performed best. Recent studies have focused on combining these zeolites with metals to improve their performance Saraçoğlu et al. (2017, pg. 21478). Zeolite upgrading is a combination of cracking and Decarboxylation.

Saraçoğlu et al. (2017, pg. 21482-21483) identifies that ZSM-5 catalyst has a significant impact in material yields with oil yields decreasing by up to 5% however what has also been identified is that char yields remained relatively constant (<0.3% change), gas yields increased in the vicinity of 2.5% and most notably the water yield increased 4%. Recent research has identified that metal doping of ZSM-5 catalysts can increase upgrading performance with better hydrocarbon selectivity and lower coking levels (Yaman et al. 2018, pg. 53) Rahman et al. (2018, pg. 41)

Saraçoğlu et al. (2017, pg. 21483) identified when examining the properties of bio-oil that using of the ZSM-5 catalyst significantly reduced the amount of oxygen in the oil by up to 10% and increased the heating value by 7.7 MJ/kg. The impacts of these changes are significant the removal of water from the oil will improve its stability and allow for the refining of higher quality bio fuels.

Another observation of Saraçoğlu et al. (2017, pg. 21483-21485) is that the undesirable compounds that influence the fuels acidity and reduce its heat value such as ketones, aldehydes and esters have all been reduced by significant amounts while the formation of desirable phenols and aromatics has increased.

One key benefit of zeolite upgrading is that it can be completed directly on the pyrolysis vapours as part of the pyrolysis process. The chemicals that are present after zeolite processing are all precursors to petrol and other consumer fuels (Bridgwater 2012, pg. 81) making this process attractive for consumer level units even though it would require maintenance.

A downside of Zeolite catalysts like ZSM-5 is that they are prone to coking and catalyst deactivation, the effects of deactivation are directly related to temperature with higher temperatures leading to higher rates of deactivation (Galadima & Muraza 2015, pg. 342). Due to the significant benefits of catalysts many companies are currently researching improvements to reduce the impacts of this and expand the lifespan of the catalysts. Galadima & Muraza (2015, pg. 341) identifies that expanding the lifespan by 10-20% across the industry could save millions annually.

Galadima & Muraza (2015, pg. 341) also identifies that heating some catalysts like H-USY between 550 and 650 °C in air can reduce the deactivation affects and expand the zeolites lifespan.

Other catalysts

Other materials for catalytic upgrading and currently being researched however many of them are still in the early stages of research and have been identified as being costly and complex to implement (Bridgwater 2012, pg. 15-21). Kumagai et al. (2015, pg. 695) have identified that a Ni-Mg-Al-Ca catalyst in the pyrolysis process could increase hydrogen gas recovered to 80% while also capturing carbon dioxide in the production.

One study focusing on other materials was conducted by Stefanidis et al. (2016) focused on natural magnesium oxide (MgO) catalysts as an alternative to well studied catalysts like ZSM-5 as a cost effective alternative. They identified that MgO produced comparable output qualities to the ZSM-5 catalyst and still suffered similar problems such as coking and deactivation (Stefanidis et al. 2016, pg. 158-173)

Other methods

There are many other methods of upgrading that are still in early stages of research or not applicable to the micro scale processing that this paper is investigating these include: Aqueous phase processing, mild cracking and gasification.

There are many organisations and research institutes investigating upgrading of pyrolysis oils. However it is clear that presently no one process is suitable to achieve a pyrolysis feed material to consumer fuel product. To achieve this level of refinement would requite a combination of upgrading processes which would increase design complexity, expense and maintenance requirements.

2.11 Fuel testing requirements

Fuels within Australia that are sold to consumers must meet specific fuel standards. The purpose of these standards is two fold. The initial one is to protect the environment and the people that will be in the vicinity of the exhaust fumes from undesirable chemical exposure. The second is to ensure that the consumer is getting what they are paying for and so that a consumer knows that when they buy a specific fuel it will perform in a specific way that is compatible with their car. Validation of the fuel outputs will be essential however if the fuels are not being sold it would not require ongoing legislative testing.

2.12 Benefits of pyrolysis

The benefits of pyrolysis of community waste and plastics can be far reaching. Bio-oil products can be used for transport or power generations fuels (Bridgwater 2012, pg. 86). Life cycle analysis studies around the pyrolysis process have identified that unlike other bio fuels like bio-ethanol pyrolysis has significant potential to reduce net greenhouse gas emission (Kung et al. 2013, pg. 317).

Jefferson (2006, pg. 573-574) identifies an increasing level of global cooperation and regulation to reduce greenhouse gas and specifically carbon dioxide emission however he then identifies that these initiatives are failing with sharp increases in the global CO^2 emissions being seen since 2002 a trend which has continued leading to global CO^2 emissions reaching all time highs in 2018 (Harvey 2018). A key benefit of pyrolysis is that it is a carbon negative process as it removes carbon dioxide from circulation in the form of char which is captured carbon and not released into the atmosphere that has many uses including in agriculture where there char(carbon) is entrapped into the soil.

The pyrolysis gas is a highly valuable output that if used to drive a gas turbine could produce considerable energy that is considered renewable however unlike solar or wind power that are heavily dependent on environmental conditions the gas can be processed and used immediately or stored for a short time and used at a time when it is best suited for the energy user or market.

Saraçoğlu et al. (2017, pg. 21476) identifies that another key benefits of pyrolysis is that its products are significantly easier to transport and store. This benefit is driven by the pyrolysis process reducing significantly the bulk density of feed materials. Because of the ease at which pyrolysis outputs can be transported more value can be derived from the materials if they are centrally processed.

In its report *Enviromental benefits of recycling* (2010, pg. 8) the NSW EPA identifies the waste disposal chain of landfill waste, where waste is collected transported to landfill to be stored to naturally degrade. Much of the waste that is sent to landfill still contains valuable recycling resources that take centuries to break down. Pyrolysis processing of landfill waste will increase the recovery of valuable materials such as concrete and brick, glass and metals allowing these materials to enter the recycling chain while unrecoverable materials are converted into useful energy that can be returned to the consumer. The report *Enviromental benefits of recycling* (2010, pg. 12) by the NSW EPA identifies that to calculate the net benefit of waste management the materials, resources and energy recovered must be subtracted from the resources and energy required to collect and process the waste. Impact of this definition is that pyrolysis has a high net benefit to the society.

The diverse nature of the outputs of pyrolysis make it a valuable process to all of society not to mention it could be a viable method of achieving true zero waste to landfill.

2.13 Modelling pyrolysis

With the promise of being a renewable energy source that can turn bio-mass and waste into valuable fuels in recent years fast pyrolysis has seen an increase in research attention. There have been many models developed attempting to model pyrolysis including the single step, two parallel reaction, three-psudo component and Distributed Activation Energy Model (DAEM) however Bhavanam & Sastry (2014, pg. 126) identifies that the complexity of the pyrolysis reactions makes DAEM most suitable method of modelling

modelling pyrolysis.

Several authors have applied DAEM to model of various materials pyrolysis with a high level of accuracy. Bhavanam & Sastry (2014, pg. 127) identified that there had been no identifiable studies prior to theirs using DAEM to model pyrolysis of municipal solid waste

Bhavanam & Sastry (2014, pg. 127) identifies DAME models are difficult to solve analytically and that DAEM accurately model the total change in volatiles at a given time. A similar but limited model can be constructed in Chemkin pro using the creck modelling mechanism (*The CRECK Modeling Group* 2014) and the ideal reactor models that are provided in chemkin.

2.14 Legislation, Regulations and codes of practice

There is a significant amount of federal and state legislation, regulations, determinations and codes of practice applicable to a consumer level pyrolysis processing plants. Compliance to these legislative instruments is essential however with compliance management in consumer designs, meeting the requirements in these instruments will not be a problem. Importantly there was no legislative instrument identified prohibiting the production and operation of micro scale pyrolysis.

- Work Health and Safety ACT 2011 (of Australia 2017)
- Work Health and Safety Regulations 2011(of Australia 2019*b*)
- Fuel Quality Standards Act 2000 (*Fuel Quality Standards Act 2000* Cwlth)
- Fuel Quality Standards Regulations 2001 (*Fuel Quality Standards Regulations 2001* Cwlth)
- Fuel Standards (Petrol) Determination 2001(*Fuel Standard (Petrol) Determination 2001* Cwlth)
- Fuel Standards (/Automotive Diesel) Determination 2001 (*Fuel Standard (Automotive Diesel) Determination 2001* Cwlth)

- Fuel Standards (Biodiesel) 2003 (*Fuel Standard (BioDiesel) Determination 2003* Cwlth) .
- Ozone protection and synthetic greenhouse Gas Management Act 1989 (of Australia 2003)
- Environment Protection and Biodiversity Conservation Act 1999 (of Australia 2018)
- Excise Tariff Act 1921 (*Fuel Standard (Automotive Diesel) Determination 2001* Cwlth)
- Competition and Consumer Act 2010 (of Australia 2019*a*)

2.15 Standards

There are a significant number of relevant standards that would be applicable to the design of a consumer micro pyrolysis plant that will need to be sourced and managed within future developments and planning.

- AS/NZS 2906:2001 - Fuel containers - Portable-plastic and metal
- AS 4594.1-1999 - Internal combustion engines - Performance - Standard reference conditions, declarations of power, fuel and lubricating oil consumption and test methods
- AS 4603-1999 (R2016) - Flashback arrestors - Safety devices for use with fuel gases and oxygen or compressed air
- AS 1681-2002 (R2013) - Safety requirements for electrically heated Type 1 ovens in which flammable volatiles can occur
- AS 2427-2004 (R2016) - Smoke/heat release vents
- AS 2872-2000 (R2016) - Atmospheric heating of vessels containing fluids - Estimation of maximum temperature
- AS 1359-1998 - Rotating electrical machines - Series
- AS 4024.1-2014 Series - Safety of Machinery
- AS 60034.11-2009 - Rotating electrical machines - Thermal protection
- AS/NZS 3820:2009 - Essential safety requirements for electrical equipment

Chapter 3

Methodology

3.1 Chapter Overview

To feasibility of a micro scale pyrolysis system can be broken into four key components. These are technical, financial, social and environmental feasibility. Technical feasibility will identify if micro scale pyrolysis can process the amounts of waste being generated by the target households within the available energy constraints. This will be determined by modelling the system in Chemkin and determining the process outputs and the estimated energy inputs. Financial feasibility will be determined by using the market values of the model outputs and the estimated system costs to conduct a cost benefit analysis, a key measure of the financial feasibility will be the identification of the dollars generated per Kw of fed energy input the system and if this value exceeds the solar feed in tariffs available to the respective households. Social and environmental feasibility will be determined by evaluating the perceived benefits for society, the specific measures will be evaluating the cost of waste management vs the savings from the adoption of micro scale pyrolysis systems and the quantifiable environmental savings derived from the removal of greenhouse gases.

3.2 Technical Feasibility

The technical feasibility of micro scale pyrolysis will be determined through modelling a micro scale pyrolysis system in Chemkin Pro. Chemkin Pro is an Ansys modelling package that was developed for the analysis of combustion models. The Chemkin program allows you to model complex systems using ideal components of the real world system that is being modelled.

The Chemkin software relies on a reaction mechanism which details all the molecular reactions that occur within predefined chemicals mixtures. For pyrolysis the complete detailed reaction mechanism produced by Creck modelling group was identified as an appropriate mechanism for modelling pyrolysis as it was specifically designed for the complex reactions of pyrolysis and the resultant hydrocarbons produced *The CRECK Modeling Group* (2014). Figure 3.1 shows the three system components of the pyrolysis model in Chemkin; those being the input, reactor and output.

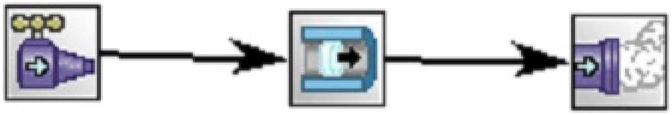


Figure 3.1: Chemkin model showing from left to right inlet, reactor and outlet

While the outputs of systems can be passed through additional processes such as catalysts this will not be included in the model due to the processing requirements and complexity of modelling such systems this study will make conservative estimates of the catalytic outputs.

3.2.1 The pyrolysis model

The modelling of pyrolysis in Chemkin as identified requires the definition of two key elements the process inputs and the reactor. They are then evaluated using the identified constraints and the selected reactor conditions to determine the system outputs.

Model Inputs:

The Chemkin software was not specifically developed to model pyrolysis models because of this the software has some significant limitations when it comes to modelling pyrolysis reactions. One of the significant limitations of Chemkin is that the input materials must be a gas mixture rather then a solid material mixture that represents the actual process inputs.

The gas mixture is determined from the ultimate analysis of Brisbane municipal solid waste conducted by Hla & Roberts (2015, p.g. 18) identified that municipal solid waste has a chemical composition of 52.8% Carbon, 6.4% is Hydrogen, 1.29% is Nitrogen, 31% Oxygen, 0.18% Silicon and 0.73% is Chlorine.

The reaction mechanism is limited to gases that will reach during the pyrolysis process, these include Carbon, Hydrogen and Oxygen. The other gases can be eliminated as they do not react in the reaction mechanism or can be eliminated through operating constraints. It is assumed that users will follow system operating instructions to not place glass into the system which will reduce the the Silicon content seen in municipal solid waste. It is also assumed that users will follow operating instructions to not place PVC plastics into the system which will eliminate Chlorine gases although there must be a method of detecting and managing small quantities of the gas. It has been identified that Nitrogen gas is inert in the pyrolysis process and will be entered into the reaction mechanism. Table 3.1 details the input gases entered into the Chemkin model.

Table 3.1: Model Gas Inputs

Chemical	**Quantities %**
Carbon	52.8
Hydrogen	6.4
Oxygen	31

The Chemkin model input allows for the specification of an input flow rate. The intent is to study flow rates from 10 to 80 cm^3/s identifying the optimal flow rates for the specified reactor sizes.

Plug Flow Reactor

Based of the information identified during the literature review, the best reactor for a micro scale renewable household pyrolysis system is a screw or auger reactor design. Figure 3.2 shows how a screw or auger reactor is integrated into a pyrolysis system in industrial applications. A household auger reactor would need to follow similar principles but on a smaller scale.

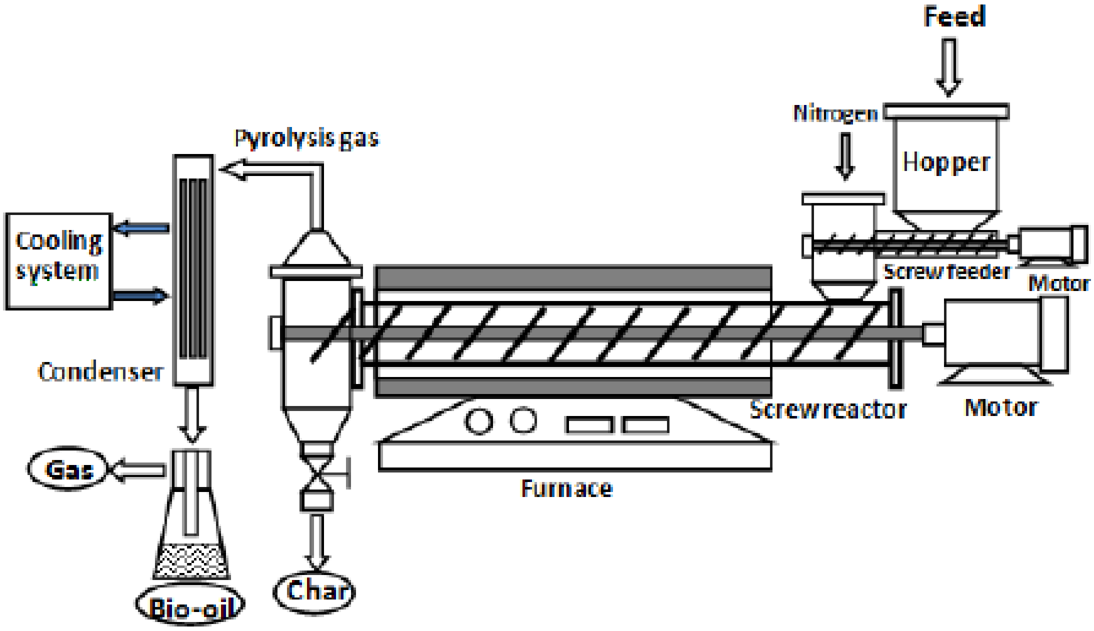


Figure 3.2: Typical industrial pyrolysis auger reactor configuration (Pichestapong et al. 2013)

There are many aspects that make the auger reactor most suited to micro scale renewable pyrolysis including its ability to handle a wide range of capacities form small to extremely large quantities, its simplicity, the ability to heat it electronically with affordable off the shelf components and its ability to operate as part of a continuous process not requiring operator intervention to load and unload the reactor at each process step.

It was identified that the closest ideal reactor to the screw or auger reactor is the plug flow reactor. The plug flow reactor is an ideal when there is no mixing between plugs as as they progress along the reactors length. It is considered to be perfectly stirred with all properties within a plug having the same materiel preterites such as density and viscosity. In addition to this once a reactor is at steady state all plugs that pass through the system will have the same residence time. This is the time from when a plug enters the reactor to when it exits as a process output (Ancheyta 2017, pg. 50-51). An ideal plug flow reactor is shown in 3.3. The figure shows rector inputs on the left and the plug as it processes along the reactors length. Heat is uniformly applied to the reactor as shown.

The plug flow reactor in Chemkin allows for the completion of a parameter study to identify model performance across a large range of conditions including the inlet conditions previously mentioned. This study has constrained the reactor length to 50 cm minimising secondary reactions in the gas mixture which are undesirable. The study will vary the reactor diameter from 20 to 50 mm identifying the optimal flow rates for reactor dimensions

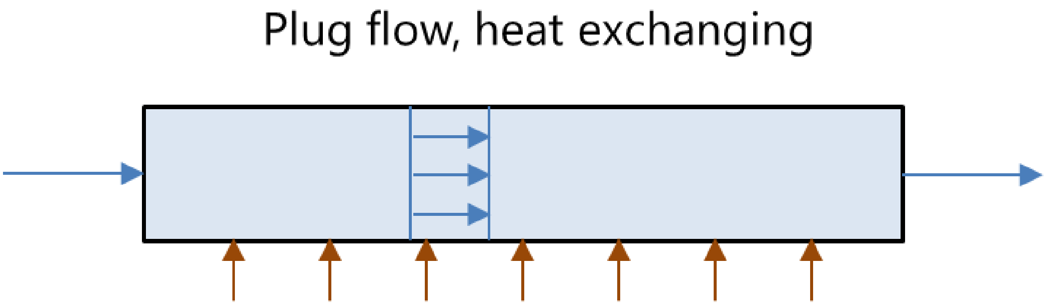


Figure 3.3: Ideal Plug flow reactor (Fogler 1999)

through the analysis of outputs.

3.2.2 Model Constraints:

The literature review, model requirements and design considerations have identified a number of constraints or operating conditions that the system model must satisfy.

Operating Time:

A key aim of the system is to identify the feasibility of using renewable energy to power the micro scale pyrolysis system because of this aim the operating duration required to process the daily waste generated for the target systems.

The Bureau of Meteorology *Average annual and monthly sunshine duration* (2019) identifies that depending on the location in Australia the average daily sunshine hours range from five to 10 hours. To cater for the largest portion of Australia the systems minimum processing capacity should exceed the daily processing capacity in under five hours.

Temperature:

The literature review indicates that pyrolysis can be conducted across a wide range of temperatures from 400 to over 1000 °C however lower temperatures produce more char and undesirable dioxins in the process outputs while higher temperatures increase the levels of gas produced. Because of this, this study will use the temperature of 650 °C for all simulations.

One identified limitation of the Chemkin model is that for the plug flow reactor simulation does not used a linear temperature profile from input to exit at the target temperature. Realistic system modelling would use an input temperature of just above 100 °C simulating feed material having just undergone a moisture removal process which would increase in a linear progression to the target temperature. This is expected to have an impact on the model results.

Pressure:

Sharuddin et al. (2016) identified that pressure of the reactor vesicle can have an impact on the outputs of the pyrolysis reaction increasing the liquid and gas outputs. The micro pyrolysis system is intended for consumer household use because of this high pressure systems are not desirable and would increase the complexity and cost of the overall system. With the impact of pressure playing an important role it was determined that a lower pressure of 5 KPa would be suitable for the model simulations.

Processing quantity:

Hla & Roberts (2015) identified that in Brisbane Australia 660kg of waste are generated per capita per year this correlates to 1.8 kg per day. Park et al. (2016) identified that 73% of the waste generated per capita is suitable for pyrolysis meaning that micro scale systems must cope with 1.32 kg/person/day. A 4 person family home would need to process 5.28 kg/day and a small unit complex of 20 people would need to process 26.4 kg/day.

3.2 identifies the defined minimum processing requirements from one to five hours for each of the three system capacities. The daily processing required was rounded up to 1.5 Kg allowing for fluctuations and surges in waste generated by the target demographics.

Model Outputs

The Chemkin simulation outputs a large number of variables including residence time, Volatile organic compounds(ppm), Unburned Hydrocarbons(ppm), the molecular conversion rates and the reactor gas phase mole fractions which are of specific interest . This paper will focus on the residence time to identify that the desired amounts of waste can be processed by the designed systems it will also use the presence of unburned hydrocarbons at the reactor end point to confirm that the pyrolysis process has been successful.

Table 3.2: Minimum system processing capacities from one to five hours

	Capacity kg/hr(g/s)		
Hours	1.5 kg	6 kg	30 kg
One	1.5(0.42)	6(1.67)	30(8.33)
Two	0.75(0.21)	3(0.83)	15(4.17)
Three	0.5(0.14)	2(0.56)	10(2.78)
Four	0.375(0.10)	1.5(0.42)	7.5(2.08)
Five	0.3(0.08)	1.2(0.33)	6(1.67)

Jin et al. (2019) identifies that the gas phase mole fractions of interest for the generation of energy include Hydrogen(H2), Methane (CH4), Ethylene (C2H4), Acetylene (C2H2), Ethane (C2H6), Propene (C3H6) and Propane (C3H8) as these compositions are key building blocks of fuels such as diesel. The identification of these fractions in the process outputs will also aid in confirming that the waste pyrolysis has been successful.

Additional compounds of interest include combustibles like Carbon monoxide (CO).

3.2.3 Energy Calculations

Support Energy:

The main support energy required for the system is material shredding. Availability of waste shredders that are appropriately sized for the feed material and capacity of a micro scale pyrolysis system is limited however research indicates that for a cutting capacity of 40 mm and a throughput between 90 and 215 kg per hour up to approximately 2300 watts of power is required *Bosch Shredders* (2019). This indicates that subject to testing a 1000 watt shredder would provide adequate capacity for a micro scale pyrolysis unit.

Drying Energy:

The specific energy requirements municipal solid waste was identified as 2.41 J/g K. Assuming an average environmental temperature of 20 °Celsius this equates to 216.9 J/g of material to heat it too 110 °C facilitating the removal of excess moisture from the waste materials.

Pyrolysis Energy:

A limitation that has been identified in Chemkin is that it was not able to directly determine the amount of heat energy required to complete the pyrolysis reaction. This results in significant challenges when determining the energy required to undertake the pyrolysis process because of the significant number of chemical and phase changes that occur during the process.

For this study an estimation of the energy required for pyrolysis can be estimated based on appropriately sized heating equipment for the process. Supplier research indicates that appropriately sized heating elements to maintain the required temperatures would draw between 1200 and 1800 watts of energy *RS Components Cartridge Heaters* (2019). This will be combined with the daily processing time of the pyrolysis reaction to determine the total operation energy.

The technical feasibility is of a micro scale system will be reliant on the system being able to be operated from the renewable energy that is being input into the system or excess energy that can be used as a result of the process. Table 3.3 identifies the solar energy input that has been identified as reasonable for respective systems and their corresponding dwelling sizes.

Table 3.3: Renewable energy input for systems

System Size KG	Solar System KW
1.5	1
6	5
30	20

3.3 Financial Feasibility

The evaluation of financial feasibility will be done by identifying the perceived value of the outputs to households, estimating the total system costs through the identification of suppliers of the main components. A key assessment of the financial feasibility will be the calculation of the return on investment and evaluating the return on investment period of a pyrolysis system vs a solar system. The feasibility study will also compare the energy generation capability of the pyrolysis systems vs a similarity sized solar system to the renewable energy being fed into the system.

3.3.1 Perceived value of outputs:

The determination of direct pyrolysis outputs values is relatively simple as they all have an immediate value to the end user. To asses the value to end users current market values of pyrolysis outputs will be used. There may also be other incentives or markets that system owners may be able to participate in such as carbon emission trading or renewable energy feed in tariffs as these vary significantly depending on location they will not be evaluated in this study.

Electricity:

Electricity can be generated from unused solar energy and the direct combustion of pyrolysis in a small gas turbine. The best guidance for electricity value to the customer feeding electricity back into the grid is the currently available feed in tariffs that are offered by various energy companies. These tariffs vary from state to state but average out to be 9c per kWh *Solar feed-in tariffs - ACT NSW QLD SA VIC - Origin Energy* (2019).

Pyrolysis Fuel:

The direct use of pyrolysis fuel in small quantities can be achieved without catalytic upgrading through mixing small amounts directly as a fuel additive. The current market value of diesel will be used to determine the fuel value for the end user. *Global petrol Prices* (2019) identified that on September 16 2019 the average Australian Diesel fuel price was $1.47 per L

Carbon Black:

Carbon Black or char has limited use in to the household user but there is a significant commercial market for the product as an agricultural supply, a pigment or as a precursor material for making advanced filtration devices. Li et al. (2017) identify that the cost of carbon black fluctuates significantly but a stable wholesale price has traditionally been around $0.20 per kg. However if with appropriate testing materials sold as activated carbons may have significantly higher market values.

3.3.2 Estimated system costs

The system cost will be estimated through the cost identification of the main system components after the completion of the Chemkin Simulation. This will allow for the identification of appropriately sized components.

The key system components that will be costed include the shredder, a dryer unit, the main pyrolysis unit and an energy system that includes solar and gas electricity generation.

3.3.3 Cost benefit analysis

A standard cost benefit analysis will be conducted where system purchase will be accounted in the first year and then benefits will be accounted for over the estimated 10 year life of a system. The systems would require reoccurring annual services and maintenance of any proposed filters at recommended intervals without completing a system prototype the value of these is a pure estimate as such a conservative amount of $400 per annum has been applied to the smaller system and this was respectively multiplied by two and three for the larger systems.

This analysis also relies on the assumption that the waste material has a cost value of $0 as it is waste and would traditionally be getting disposed off.

This rudimentary analysis doesn't account for changes in energy costs of or the value of the process outputs over that lifespan or other benefits such as higher government rebates or carbon credits that system operators may be eligible for. Because of this the actual returns over a 10 year period may be significantly higher if market values of the process outputs increase at rages beyond the rate of standard inflation.

The key measures for the feasibility of the pyrolysis system will be comparing the return on investment period of a solar system of similar value VS the proposed pyrolysis system.

3.4 Social and Environmental Feasibility

The determination of the social and environmental feasibility of micro scale pyrolysis systems is largely subjective and is difficult to quantify as it is dependent on the technology uptake by end users. However some inference can be taken from estimating the waste captured per single person system one the scale of 1,000, 10,000, 100,000 and 1,000,000 people and the impact that the removal of this waste from the system would have in the reduction in landfill and waste management costs. *Economic effects of the South Australian solid waste levy* (2015) identifies that to cost of landfill life cycle management is $28.77 per tonne.

As this system is designed to operate entirely from collected solar energy the system will operate in a carbon negative or carbon capture state a finding that was observed as desirable by Li et al. (2017). Zhou et al. (2014) in their study of Chinese power generation identify that the depending on the fuel source and quality the CO^2 generated can vary significantly form 0.0482 kg per MJ to 0.219 kg per MJ.

The assessment of the environmental benefit can also have a dollar value assigned to it based of the CO^2 generated per MJ for this assessment a mid range value of 0.1336 will be used with the values identified by the Grantham Research Institute (*Economic co-benefits of reducing CO2 emissions outweigh the cost of mitigation for most big emitters* 2017) who identified that the social cost of CO^2 emissions presently lies between $50 and $100 per tonne. A value of $50 will be used to assess the benefit for this project.

In addition to the CO^2 saved in power generation there is also the consideration that there would be a significant reduction in the communities reliance on garbage collection services. It was identified that the average Australian garbage truck has the capacity to transport on working days 3,152,880 kg of waste per year *Gold Coast Garbage Truck Design* (N.D) when this information is combined with the the work if Sandhu et al. (2014) who was able to identify that the average garbage truck under operational conditions products 55.42 tonnes of CO^2 per year will allow for the calculation of waste collection emissions savings.

An additional environmental benefit from the reduction in waste going to landfill is the significant reduction in methane generation which is considered to have a 23% greater impact on global warming then the same mass of CO^2 (Themelis & Ulloa 2007). Methane is generated at a rate of 417kg/tonne of municipal solid waste. Heikkinen (2017) identifies that the United States Interior Department Bureau of Land Management has established an interim value of $162 per tonne when converted to Australian dollars this rounds to $240 per tonne.

Chapter 4

Results

4.1 Chapter Overview

The determination of the feasibility of micro scale pyrolysis has been broken into three key components. These are technical, financial, social and environmental feasibility. Technical feasibility identified if small micro scale pyrolysis can process the amounts of waste being generated by the target households within the available energy constraints through the construction of a system model in Chemkin. A cost benefit analysis was conducted to determine the Financial feasibility of a micro scale renewable pyrolysis system using estimated costs and the current market values of the process outputs. Social and environmental feasibility has been assessed against the quantifiable financial benefits for the society and environment that the system offers including the capture of carbon, removal of greenhouse gases and the removal of waste from the environment.

4.2 Technical Feasibility

Establishing the technical feasibility of the micro scale pyrolysis system was not completely successful using the method outlined in chapter three several attempts were made at modelling the system and results of the 4th model have been detailed bellow. The results indicate that pyrolysis was successful however the model was unstable and failed to identify target compounds.

As a result of this a different approach to modelling was attempted using proxy compounds which were identified through an analysis of the materials present in municipal solid waste mix. Final simulations using the proxy substitution were successfully completed and were able to identify the target compounds required for the production of combustible fuels and gases.

The model outputs were then used to confirm that the pyrolysis reaction had completed within the reactor vessel and that the system was producing the expected hydrocarbons. System through puts were calculated mathematically to determine the total operating time per day allowing for the identification of if there was sufficient energy available for the systems operation.

4.2.1 Pyrolysis Model

The construction of this model proved to be significantly challenging with the model solver requiring configuration changes to achieve convergence on the system design. It is believed simulating systems with such low flow rates requires increases the number of decimal places that the simulation was trying to compute which increased the processing power and model complexity. However after the solver sensitivities were reduced to $1x10^3$ the model was able to successfully solve in the majority of simulations without errors.

The initial simulations accessed volumetric flow rates across 10 to 80 cm^3/sec in increments of 10 these flow rates were evaluated using reactor diameters from 20 to 50 mm in increments of 10 mm. Using the gas input combination and constrains identified in table 4.1.

Table 4.1: Model Gas Inputs

Chemical	**Quantities %**
Carbon	52.8
Hydrogen	6.4
Oxygen	31

It was identified that the residence times that these simulations produced correlated with the literature for fast and flash pyrolysis reactions however for screw and auger reactors these residence times seen with the highest flow rates may not be achievable. Figure 4.1

shows the change of residence time with respect to the volumetric flow rate.

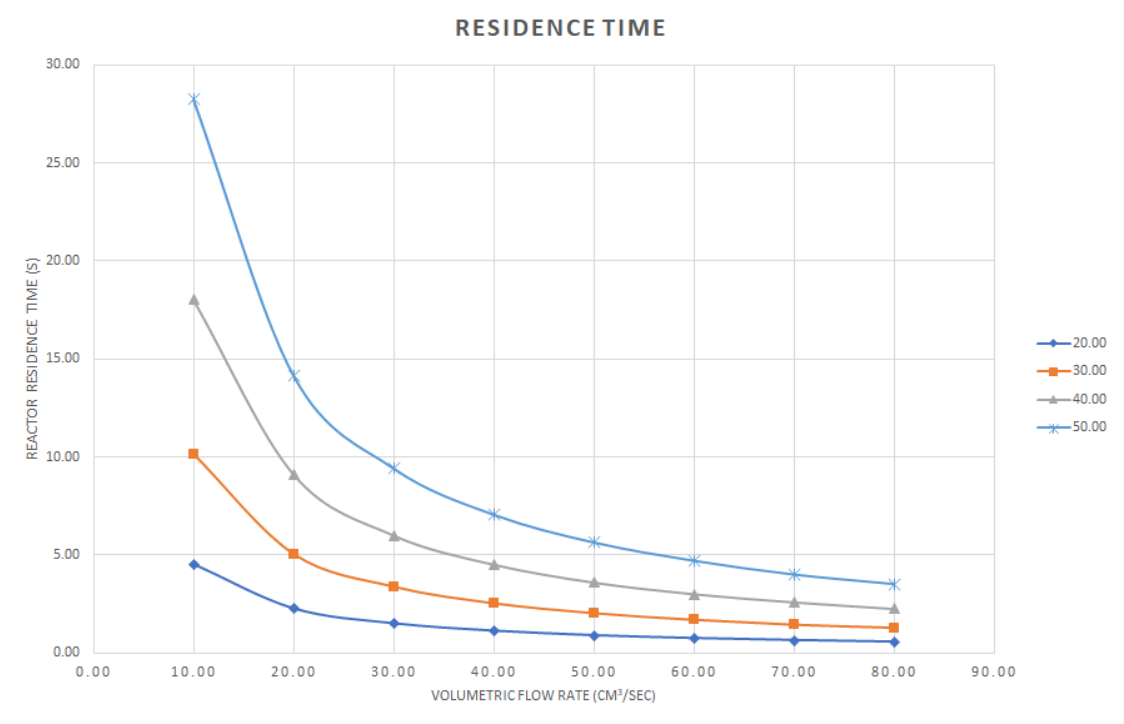


Figure 4.1: Residence time Vs. volumetric flow rate

Examining the initial simulation results it was identified that the volatile organic compounds and unburned hydrocarbons at the reactor endpoint have high level of correlation with the values in all initial simulations runs differing by less then 0.1%. This is expected with the ideal pyrolysis process and shows that almost all outputs of the pyrolysis process are volatile compounds and also valuable hydrocarbons.

Figure 4.2 plots the unburned hydrocarbons in parts per million vs the reactor residence time on a logarithmic scale across the target reactor sizes. The initial result that is clear from this graph across the reactors is that shorter residence times lead to higher levels of hydrocarbon production which was supported by the reviewed literature.

The results shown in the figure 4.2 also provide indications of ideal flow rates for the different sizes of reactors however the flow sample size isn't large enough to confirm this finding. This chart provided the first indication that there was something wrong with this simulation the results are inconsistent and it was clear that the simulations results would be questionable.

The strong presence of the unburned hydrocarbons in the simulation was considered as a reliable indication that the pyrolysis reaction of the input materials has been successful.

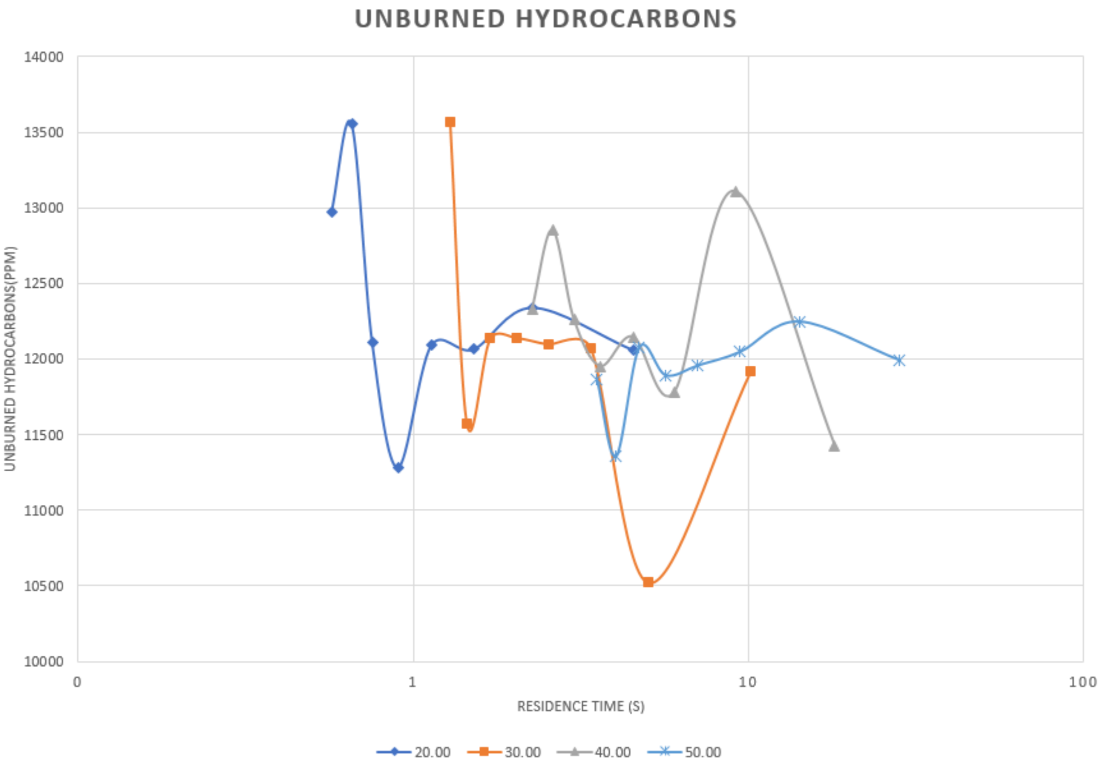


Figure 4.2: Pyrolysis Chemkin unburned hydrocarbons Vs. volumetric flow rate

A further analysis of the identified chemical compounds failed to identify all the chemical compounds of interest however it was able to identify that the process produced high levels of energy rich combustible fuels. The outputs had a higher then expected level of hydrogen but Arni (2018) identified that shorter duration pyrolysis processes produce higher levels of hydrogen rich outputs will lead to higher quality fuels so it is not expected that this is a problem. It is expected that the cause of the models failure to identify all target compounds of interest is the reduced accuracy of the model that was required in order for it to converge with available resource.

The output fractions presented in figures 4.3 to 4.9 account for 99.96% of process outputs with the remaining fractions being outside the accuracy bonds of the model.

Figures 4.3, 4.4, 4.6, 4.7 and 4.8 form the significant portion of the detected unburden hydrocarbon outputs of the simulation with all graphs having a similar structure to the unburned hydrocarbons graph presented in figure 4.2. The exception to this general trend was carbon and methane CH4. The methane which had was only detected in small amounts on four of the simulations and the it is expected that the carbon would have a different graph to the unburned hydrocarbons as it is collecting as char not in the gas mixture. The presence of significant amounts combustible outputs indicates that the process is chemically feasibly but the simulation results are extremely unstable and further investigation is required.

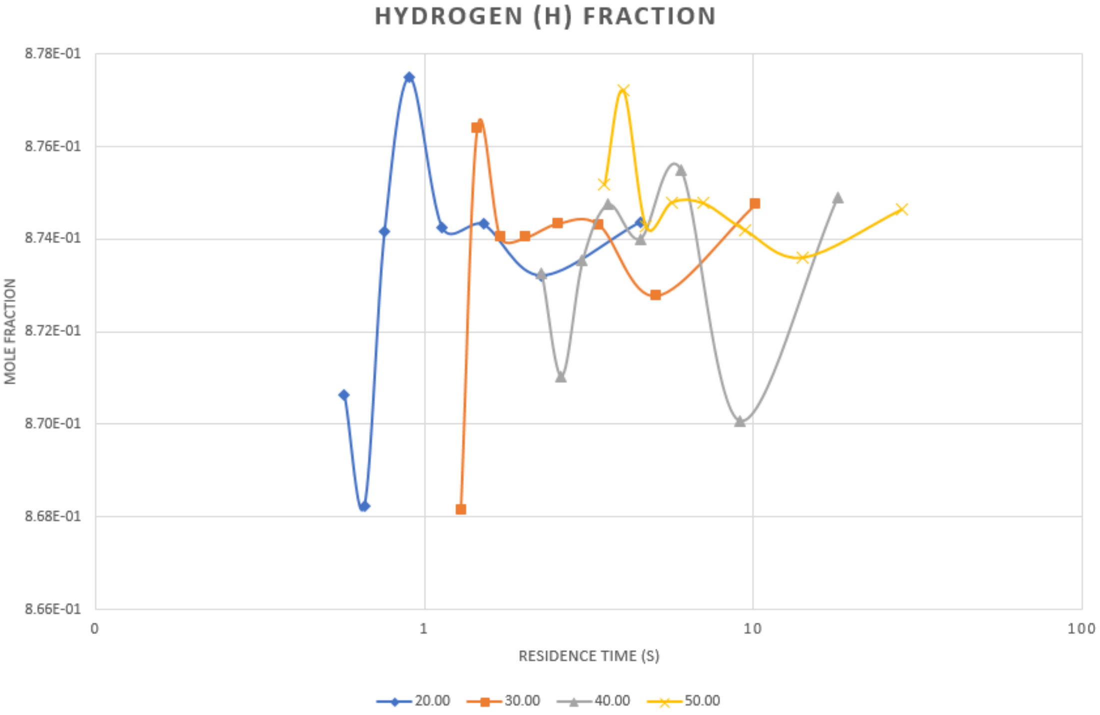


Figure 4.3: Identified Hydrogen Fraction

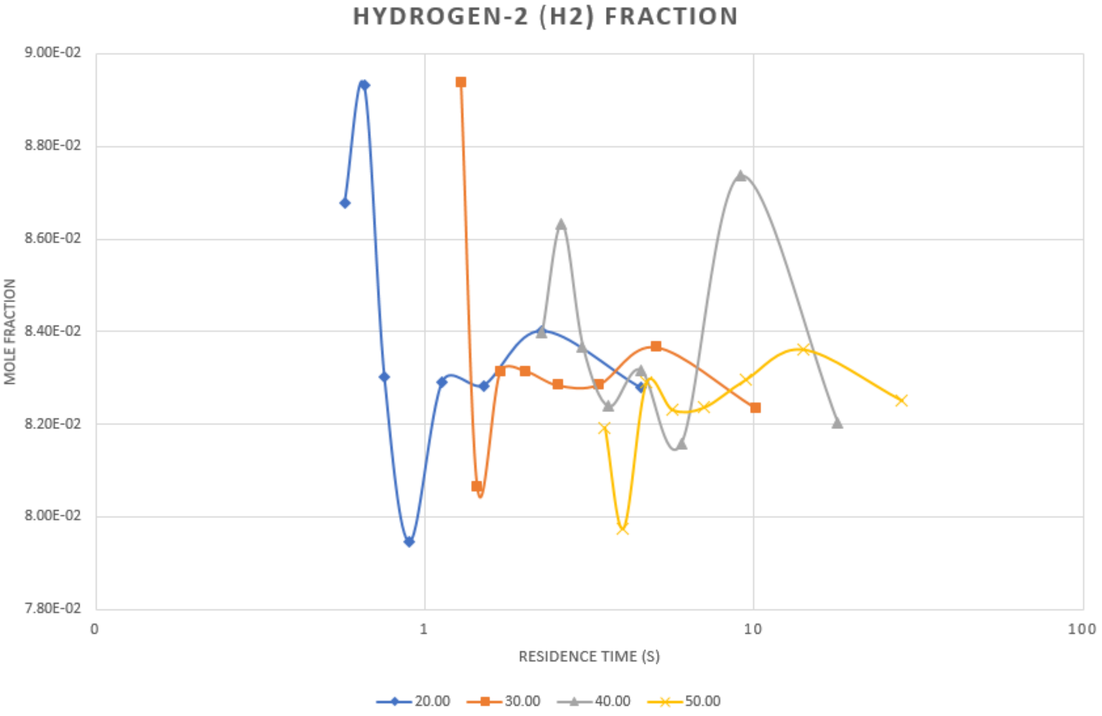


Figure 4.4: Identified Hydrogen-2 Fraction

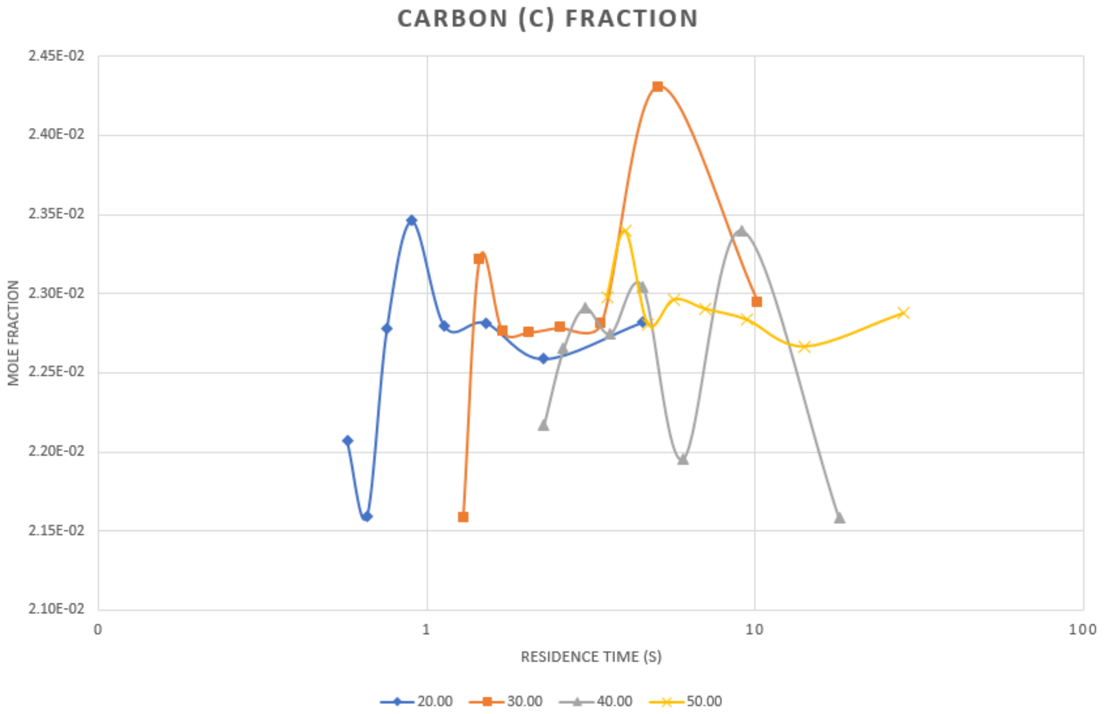


Figure 4.5: Identified Carbon Fraction

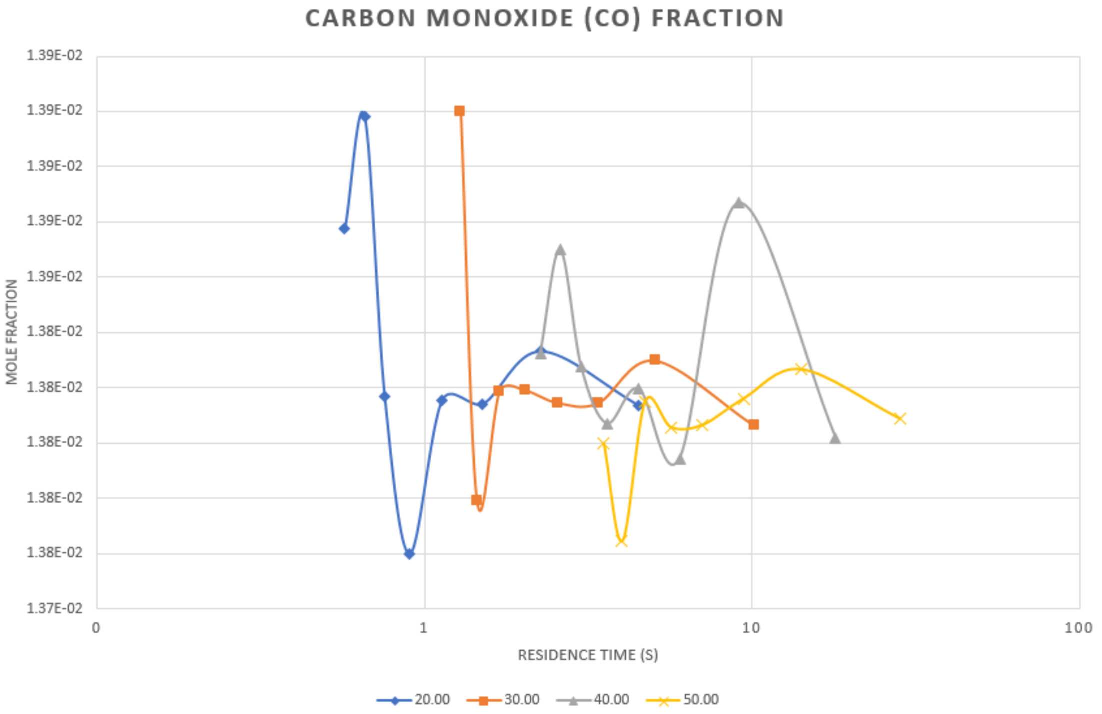


Figure 4.6: Identified Carbon Monoxide Fraction

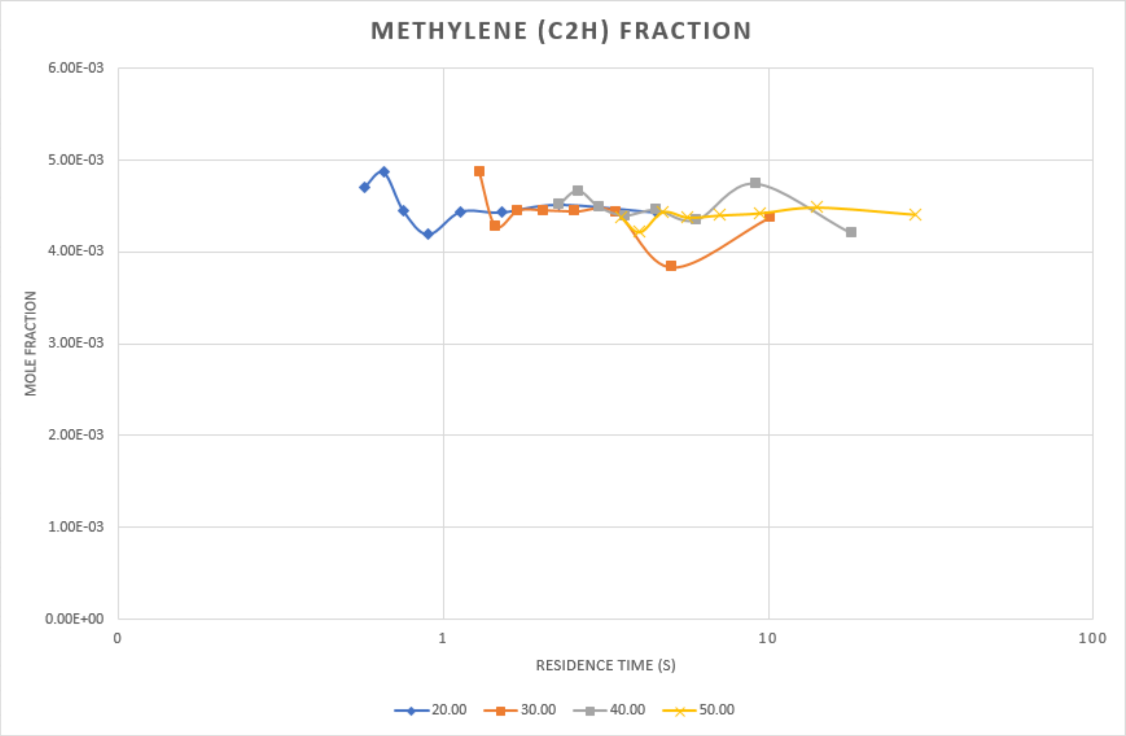


Figure 4.7: Identified Methylene Fraction

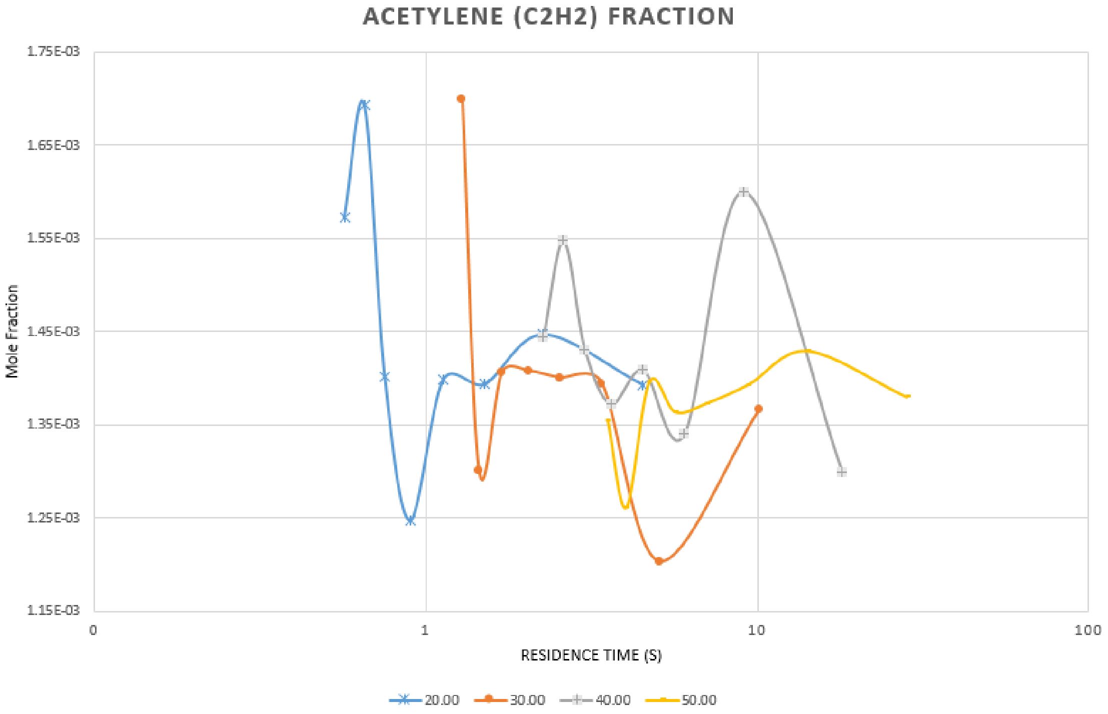


Figure 4.8: Identified Acetylene fraction

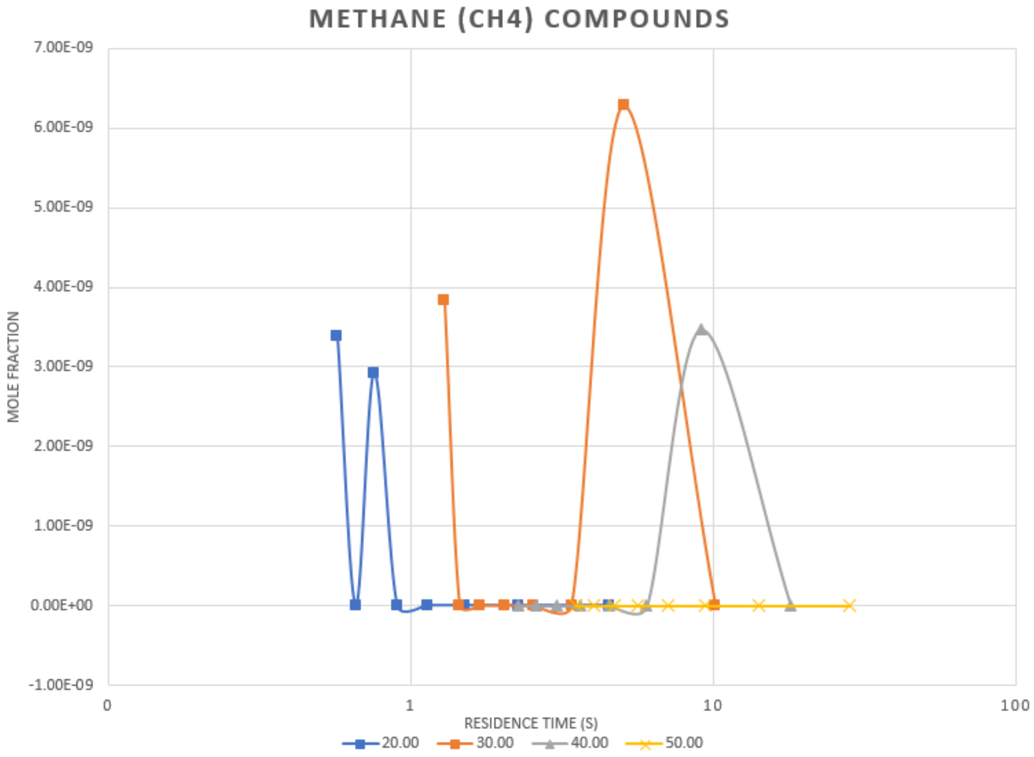


Figure 4.9: Identified Methane Fraction

Following the assessment that results obtained through initial simulations were unreliable but successfully showed outputs of interest and significant amounts of target compounds it was determined that further simulations were required. Options for further simulations are limited with many of the processing variables being fixed due to system or software constraints. However it was identified that a viable alternate simulation would be to use the chemicals identified in municipal solid waste or proxy's of the chemicals that are present in the reaction mechanism. In addition to the chemical change the proxy studies were conducted across a wider range of input flow rates from 10 to 80 cm^3/sec to assist in identifying trends.

Using the composition of waste identified by Yaman et al. (2018) the chemical make up of municipal solid waste determined and chemicals that were present in the reaction mechanism were identified. Where a chemical couldn't be identified a proxy of similar structure was used. The proxy simulation inputs are summarised in table 4.2.

It was identified that the largest component in waste was Cellulose which is seen in paper, food waste and vegetation. Following this the next largest group identified was sugars, starches and food acids which is not unexpected due to the high amount of food scraps seen in waste. The final main group was plastics that were identified in the reaction mechanism as PET, polyethe and styren.

Table 4.2: Proxy Gas Inputs

Chemical	**Quantities %**
Celulose	52.34
PET	3.56
Polyethe	3.56
Styren	3.56
Phenol	7.31
Ligniis	7.31
Glucose	7.31
Starch	14.61

The Conduct of the proxy simulation was extremely successful although the simulation still required a reduced accuracy level to achieve convergence as in the previous simulation run. The simulation was able to identify significant quantities of all target chemicals after the pyrolysis process. The proxy simulation run produced significant results that were largely consistent.

Figures 4.10 and 4.11 show the simulated volatile organic compounds and vs flow rate and residence time. These charts identify clear trends that for all flow rates smaller reaction vessels with lower residence times produced higher amounts of volatile organic compounds. This finding corresponds directly with previous studies and is an important finding in planning system capacity for end users. To the aim of the system design must be to achieve the best performance for the users waste needs. These charts indicate that if a user buys a system that exceeds their waste needs then they will see lower system performance and in turn lower user benefits.

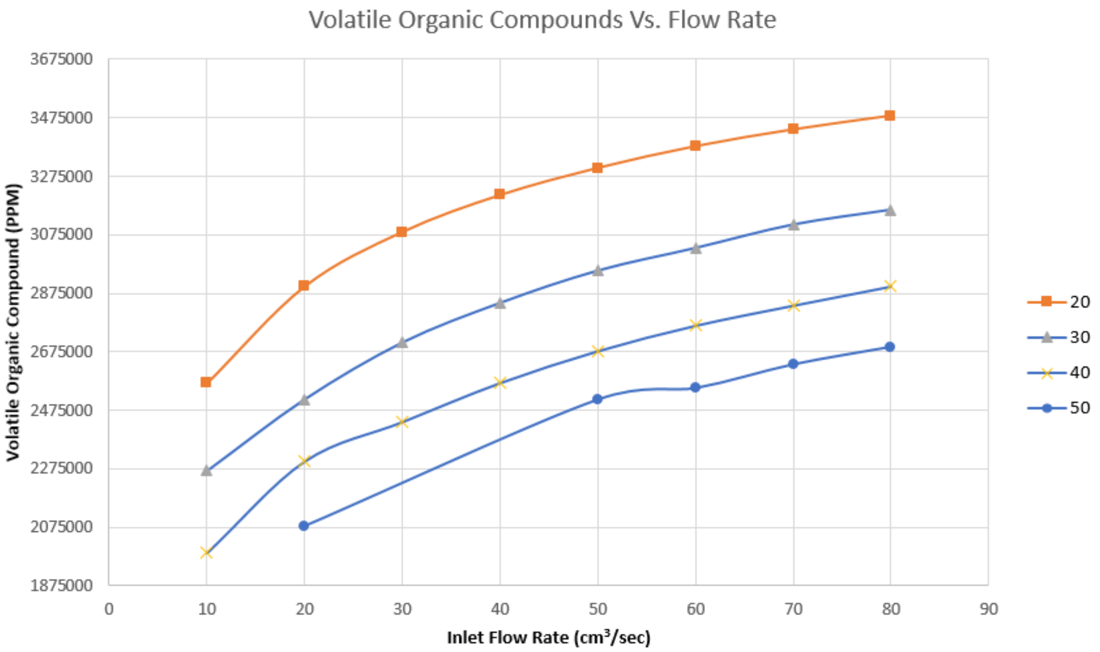


Figure 4.10: Identified Methane Fraction vs flow rate

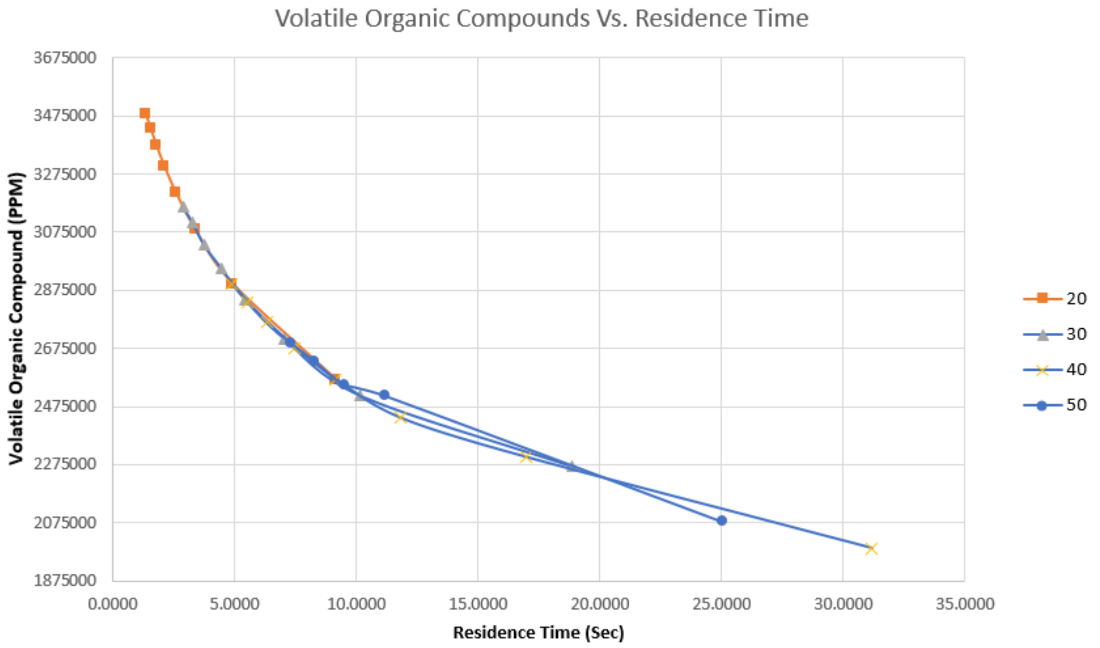


Figure 4.11: Identified Methane Fraction vs residence time

Figures 4.12 to 4.27 show the Mole fractions vs flow rates and residence times of the target chemicals that were identified in the Proxy simulation outputs. These graphs have a high level of correlation with the volatile organic compounds. However when analysing target chemical outputs it can clearly be identified that controlling gas residence time is critical to achieving the desired outputs. This could be used to control the development of undesirable gases but could also be used with a high level of accuracy to target specific chemicals that may be more desirable. A clear demonstration of this is that the C2H4 peek production is seen in systems with residence times bellow 5 seconds but C2H6 Peek production is seen in systems with longer residence times. This may allow for users to target their system operation towards the production of more gas and direct electricity and lower levels of fuels. However this would require significant further investigation.

All graphs appear to display largely similar behaviours trending towards longer or shorter residence times in a liner trend, however C3H6 as seen in figures 4.20 and 4.21 has a non uniform trend and undergoes significant variations as residence times increase beyond the three to four second mark. It is expected that the cause of this is secondary reactions along the length of the reactor this is generally supported by literature in Chapter 2.

In addition to the target chemicals bellow the simulation was also able to identify that outputs contained a small quantities of C4H4, C4H6, C6H6, C10H10 and CH2C0 all chemicals that have been identified as contributing to the pyrolysis outputs.

The presence of the highly combustible target chemicals supports the use of the outputs as a fuel energy source this is supported by the ultimate and proxy simulations. Micro scale renewable pyrolysis systems are chemically feasible and there is the strong possibility that the technology may have a wider range of applications then initially thought if the size of the system can be exploited to provide a high level of control over residence times the system could be tailored to deliver the desired outputs of the end user favouring gas or condensible materials.

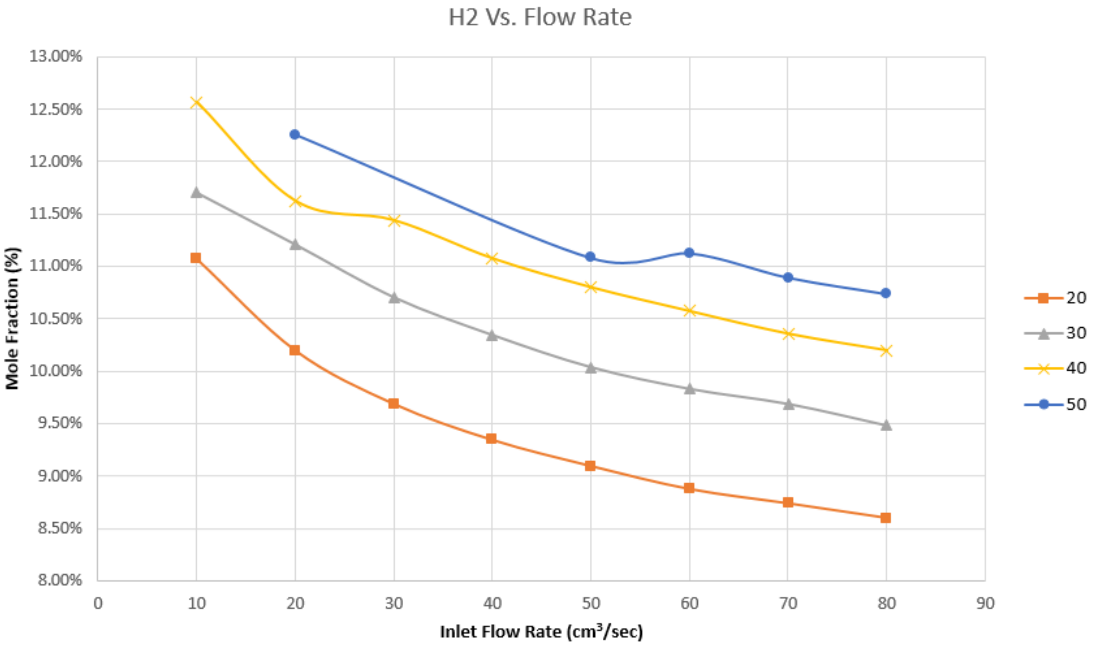


Figure 4.12: Identified Hydrogen Fraction vs flow rate

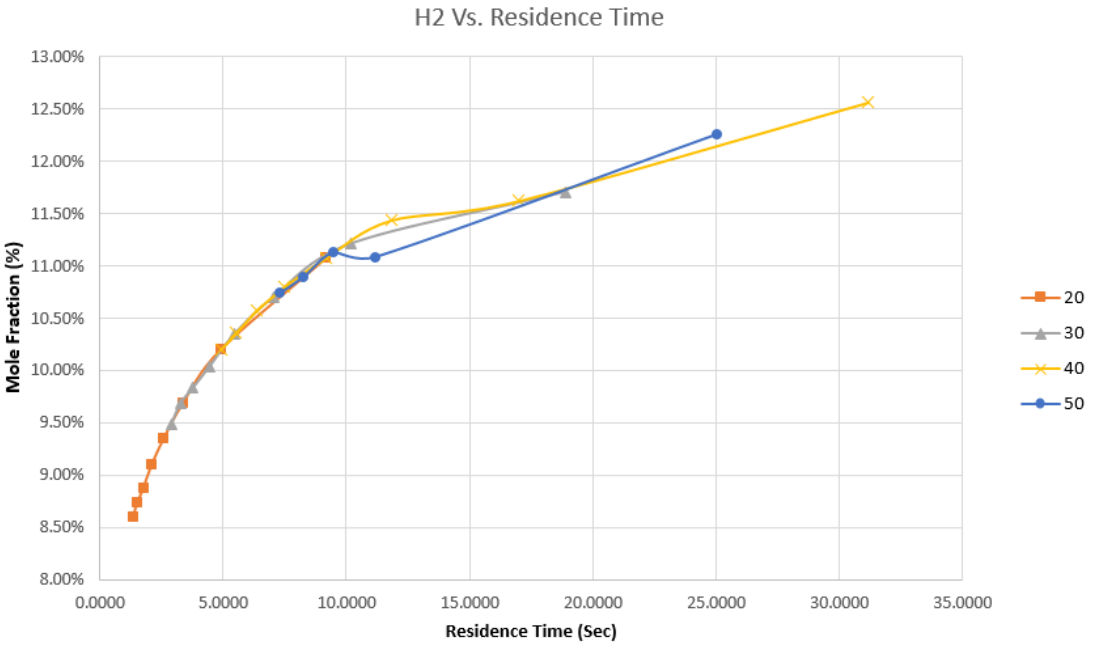


Figure 4.13: Identified Hydrogen Fraction vs residence time

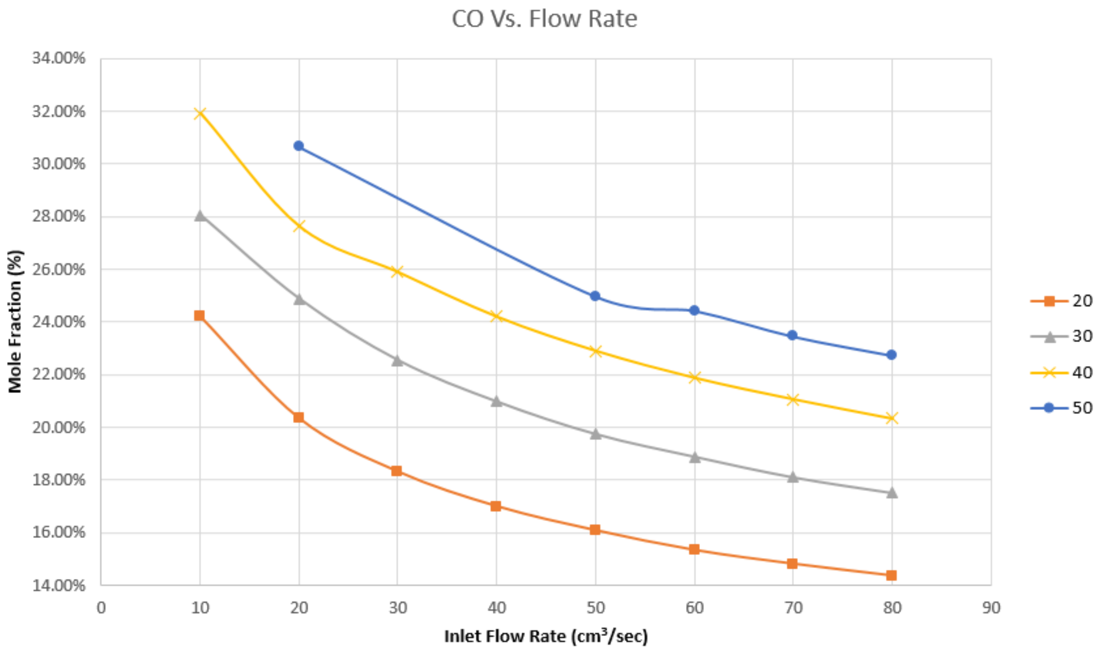


Figure 4.14: Identified Carbon Monoxide Fraction vs flow rate

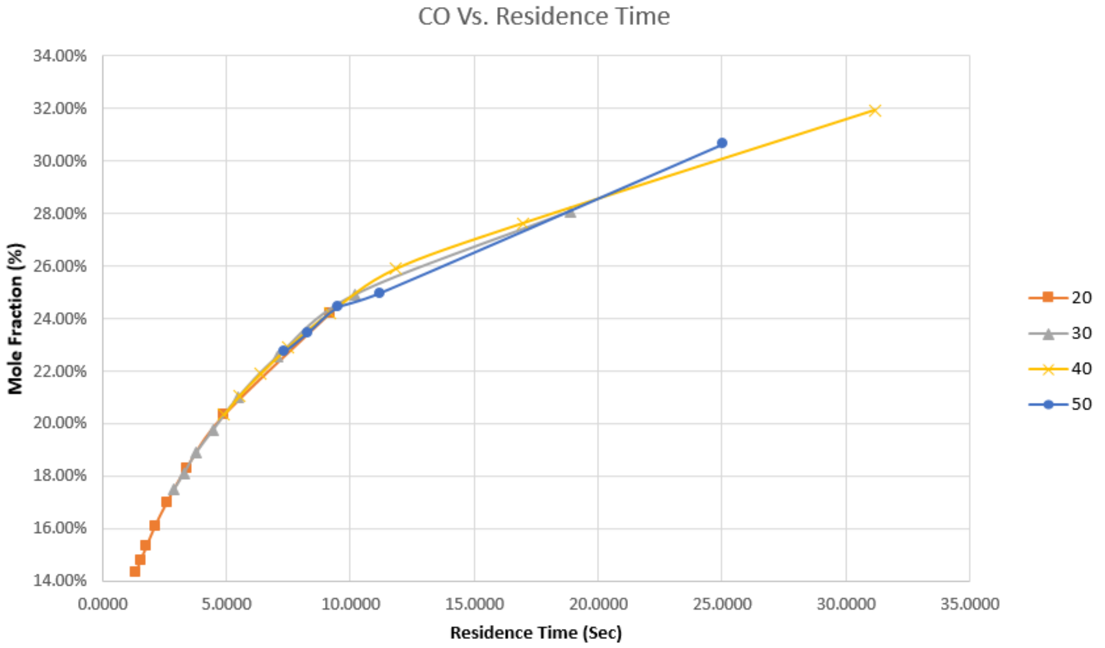


Figure 4.15: Identified Carbon Monoxide Fraction vs residence time

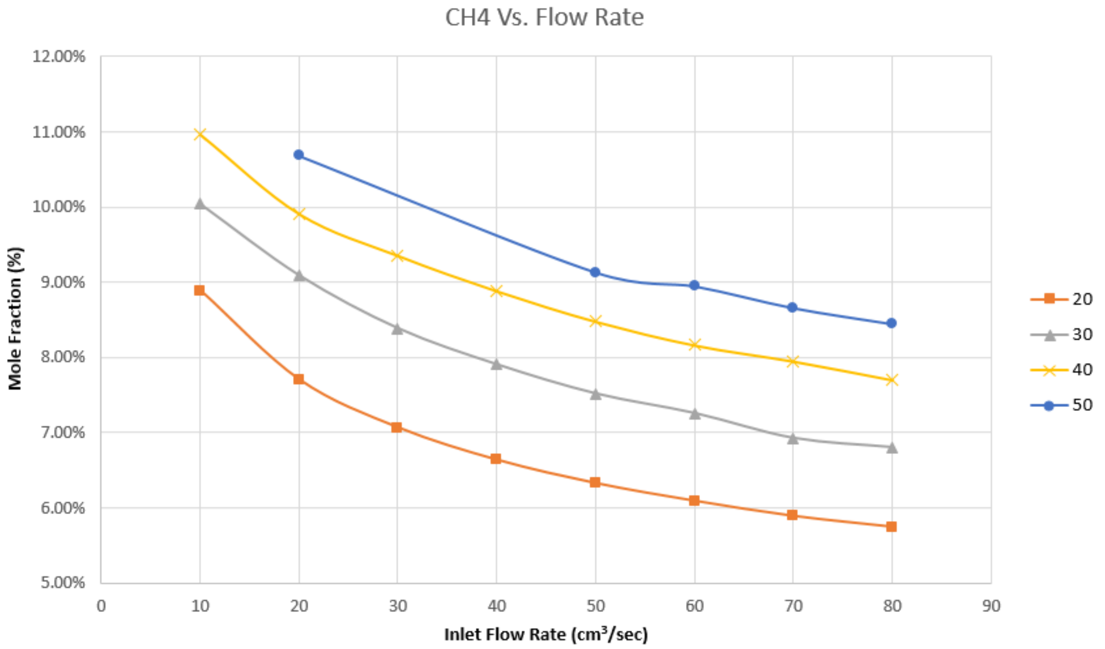


Figure 4.16: Identified Methane Fraction vs flow rate

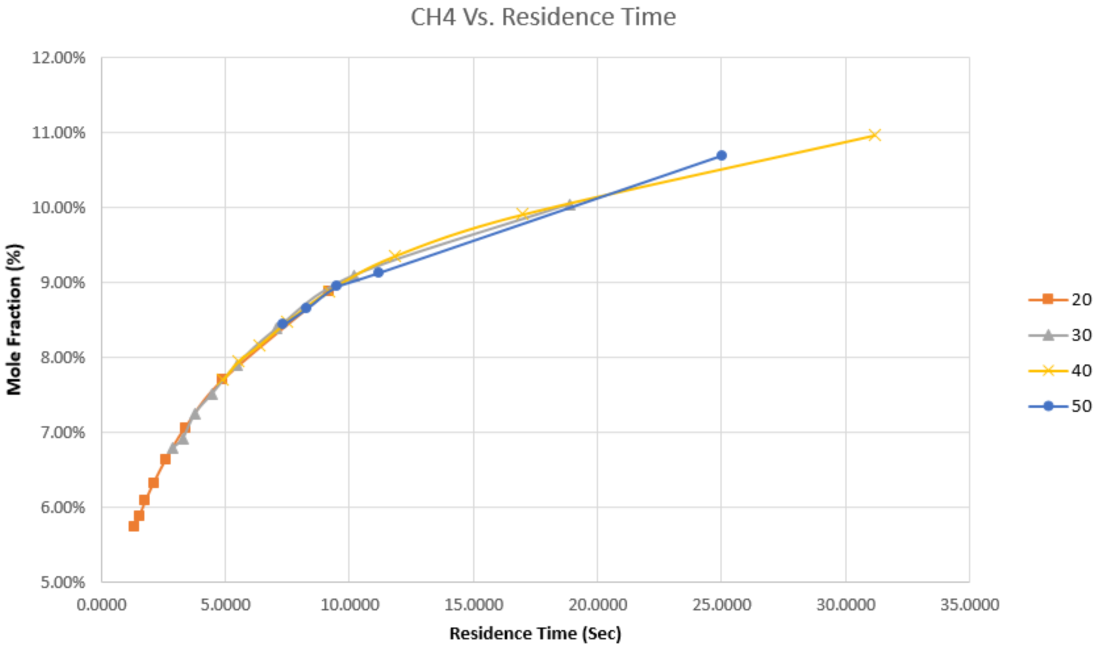


Figure 4.17: Identified Methane Fraction vs residence time

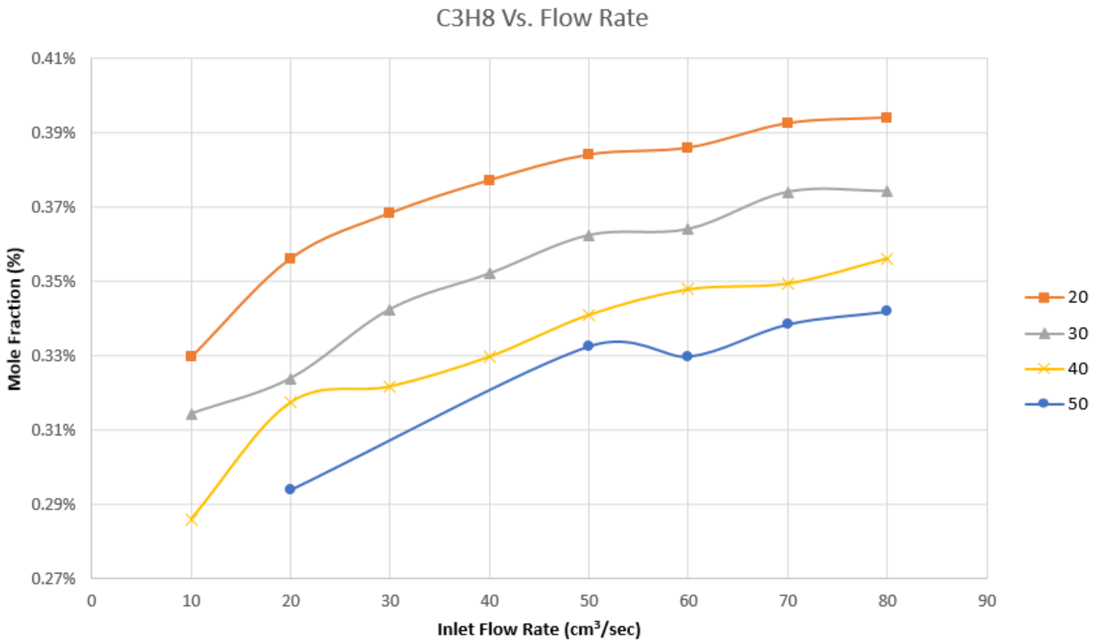


Figure 4.18: Identified Propane Fraction vs flow rate

Figure 4.19: Identified Propane Fraction vs residence time

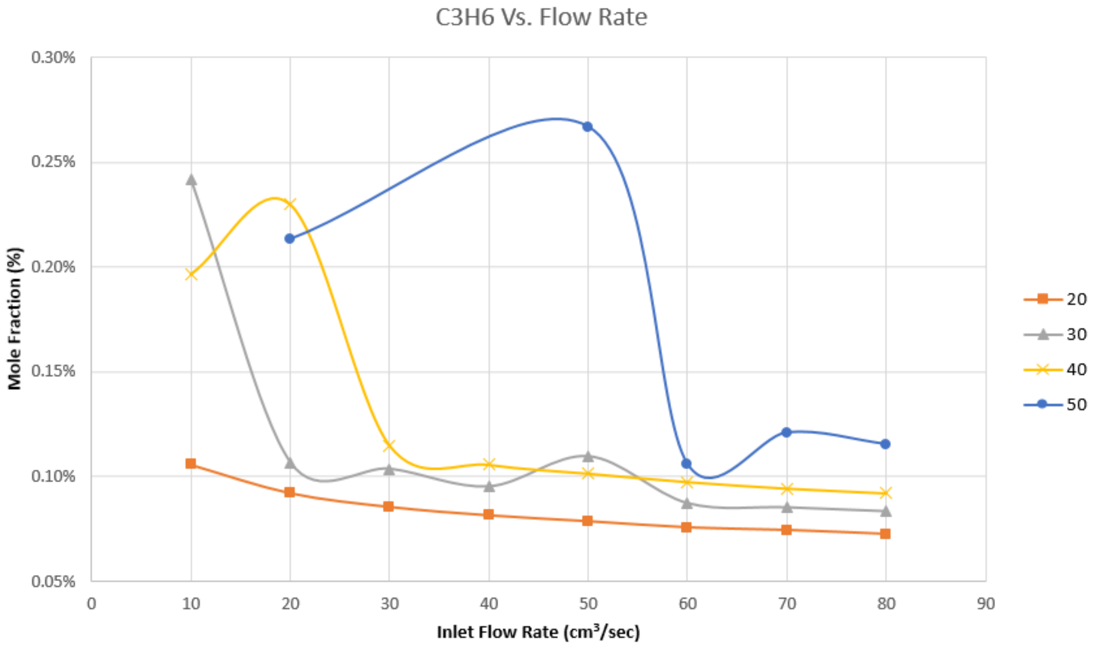


Figure 4.20: Identified Cyclopropane Fraction vs flow rate

Figure 4.21: Identified Cyclopropane Fraction vs residence time

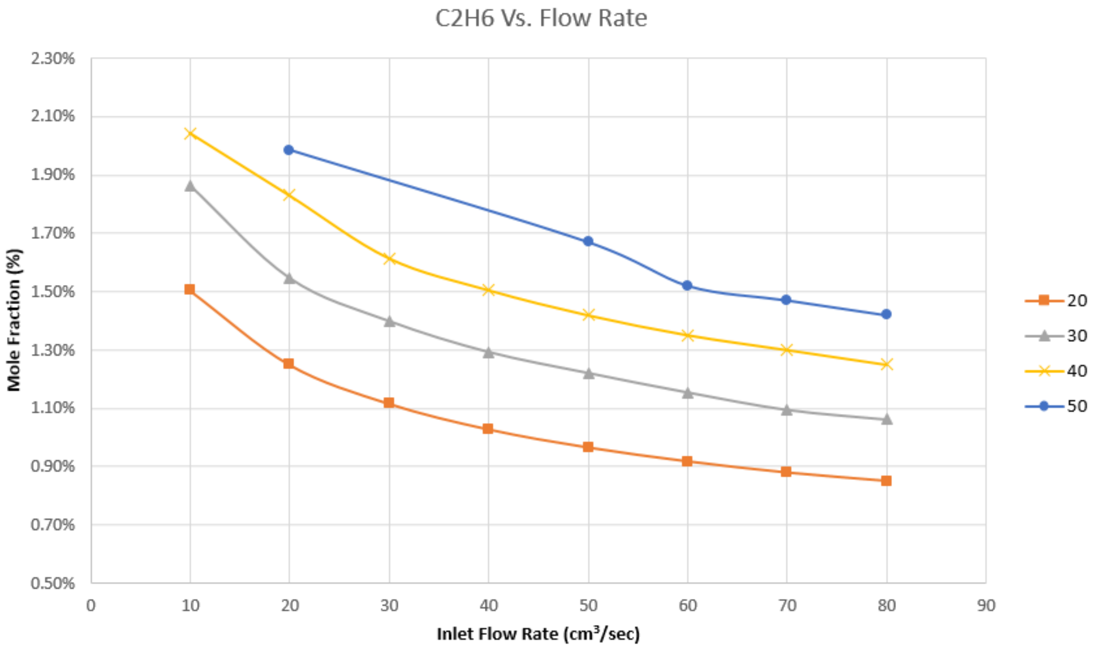


Figure 4.22: Identified Ethane Fraction vs flow rate

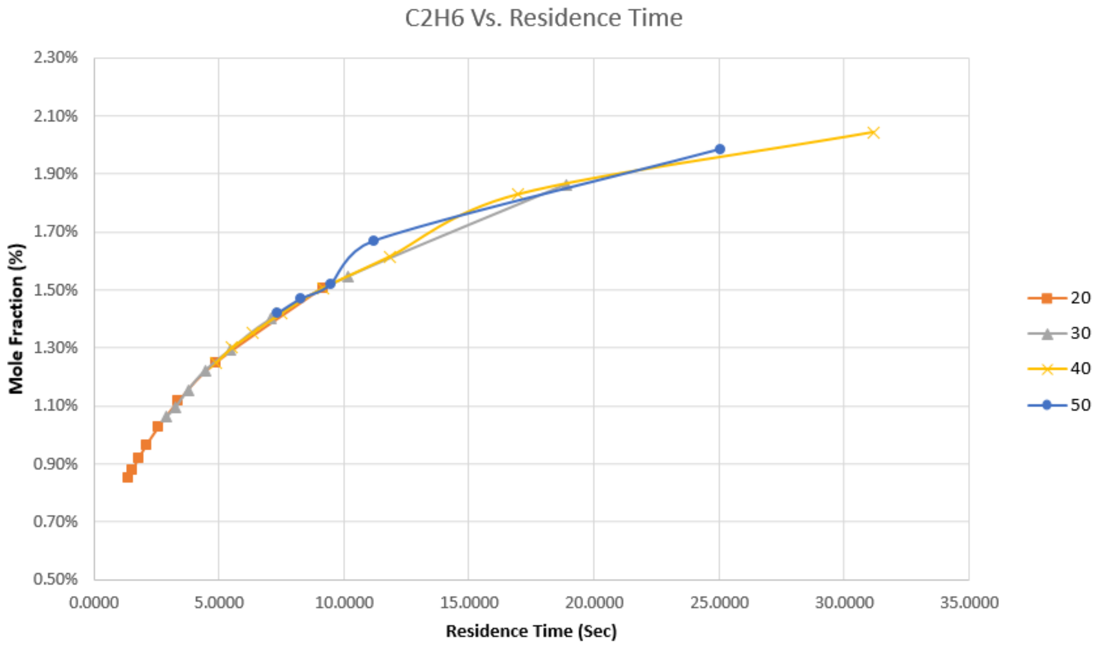


Figure 4.23: Identified Ethane Fraction vs residence time

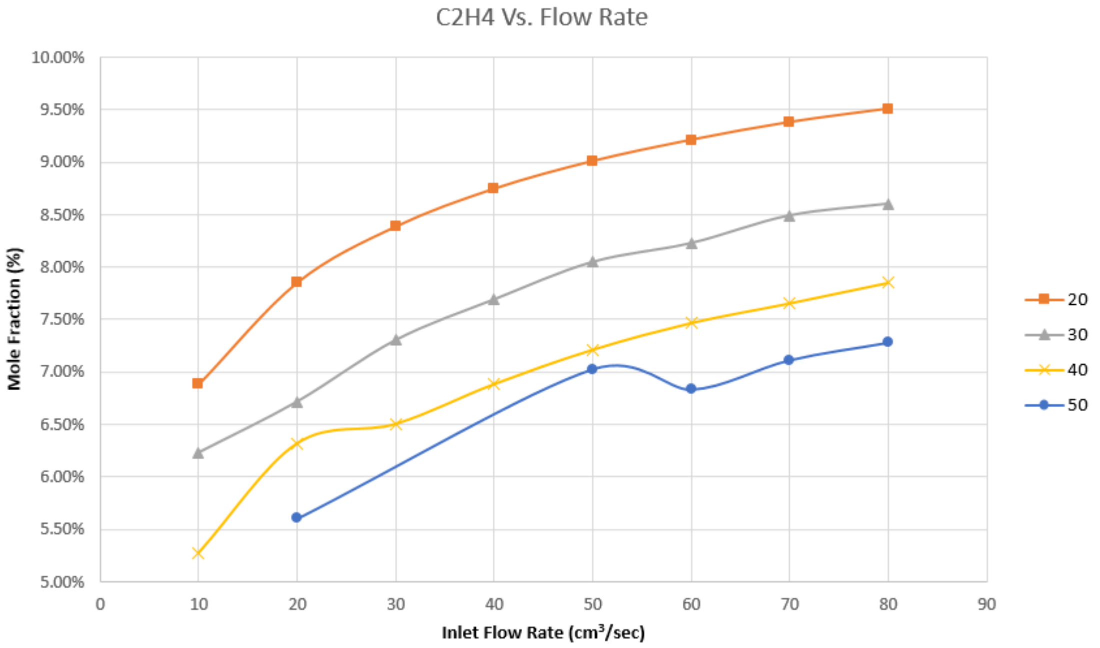


Figure 4.24: Identified Ethylene Fraction vs flow rate

Figure 4.25: Identified Ethylene Fraction vs residence time

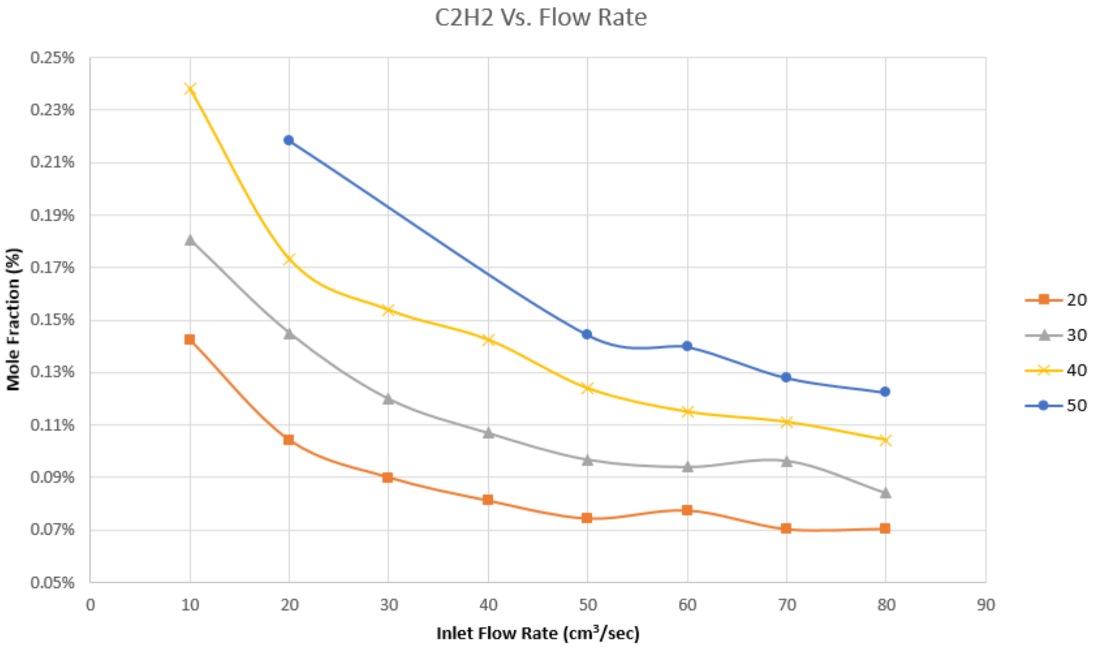


Figure 4.26: Identified Acetylene Fraction vs flow rate

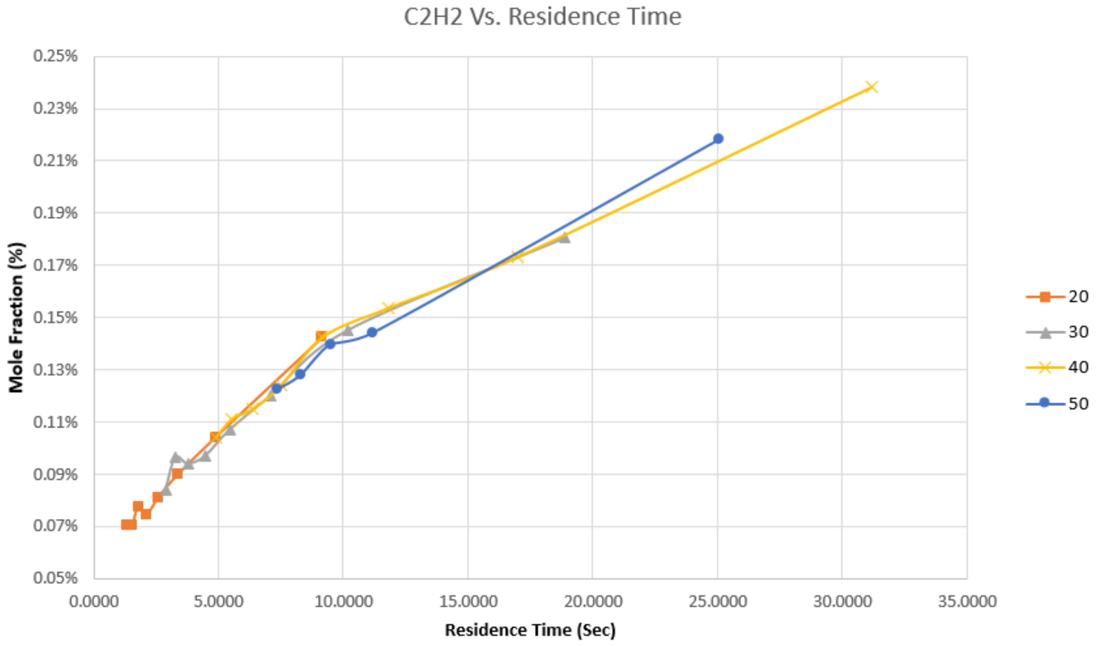


Figure 4.27: Identified Acetylene Fraction vs residence time

4.2.2 System throughput

The system throughput was established using the average density of municipal solid waste 0.37767 g/cm ^{3} (*Waste Materials Density Data* n.d.). Using the know densities estimating the system hourly throughput is relatively simple. The throughput is shown in table 4.3

in Kg/hr for each of assessed volumetric flow rates that were analysed in the simulation. The expanded flow rates identified in the proxy studies were not examined in assessing the system through puts as they were intended to assist in identifying trends not system capacities.

Table 4.3: System hourly mass throughput in Kg

Reactors	**30 cm^3/sec**	**40 cm^3/sec**	**50 cm^3/sec**	**60 cm^3/sec**
All (Kg/hr)	40.79	54.38	67.98	81.57

Based on the calculated hourly throughput shown in table 4.3 the reactors will be able to process the sufficient materials for all system designs. To maximise the processing efficiency flow rates of 50 and 60 cm ^{3} /sec will not be evaluated further because they are far beyond capacities required for the system design and it is expected that these designs would increase the costs.

4.2.3 Energy requirements

Based off the reactor flow rates it is possible to calculate the time in hours to process the waste for the defined system sizes. Table 4.4 provides a summary of the time to process the material specified for each system size using the input flow rates.

Table 4.4: Reactor processing time in hours

Processing requirement (kg)	**30 cm ^{3} /sec (Hours)**	**40 cm ^{3} /sec (Hours)**
1.5	0.03139	0.02758
6	0.1255	0.1103
30	0.6277	0.5517

Table 4.5 indicates that total expected annual operating time for the various sized units across the two flow rates. It highlights the significant benefit that the distributed waste processing offers. Because the waste is not concentrated in one location to processing energy and workload is spread out among many nodes therefore making it effective to be processed using low density energy generation methods like solar PV.

Using the power requirements defined in the methodology it is possible to estimate the

Table 4.5: Annual processing time in hours

Processing requirement (kg)	30 cm ^{3} /sec (Hours)	40 cm ^{3} /sec (Hours)
1.5	11.46	10.07
6	45.81	40.26
30	229.1	201.37

low and high power usage required by the system for operation. These low and high power values are identified in table 4.6.

Table 4.6: Total System power requirement

Power bracket	Power (Kilowatts)
Low	2.4169
High	4.3169

The information identified in tables 4.4 and 4.6 was then used to estimate the total kilowatt hours required for to run the system and process the waste for each size of system. It was identified that the systems would require a period of warm up time prior to operation, to account for this and other energy losses the total power estimate includes a 25% margin for losses, warm up energy and controller requirements. These values have been summarised in table 4.7

Table 4.7: Total System power estimate

System size	Power	Power (kWh)	
(kg)	bracket	30 (cm^3/sec)	40 (cm^3/sec)
1.5	Low	0.0948	0.0833
	High	0.1694	0.1488
6	Low	0.3798	0.3333
	High	0.6775	0.5954
30	Low	1.8965	1.6667
	High	3.3874	2.9769

The power usage identified in table 4.7 shows that the total identified power draw required to operate the system is well within the total solar system capacity that was identified in table 3.3. It is expected that this excess capacity will have a significant impact on the system cost and it would be appropriate to size the solar system appropriately for the peek requirements of the of the pyrolysis unit. This analysis could be expanded to include energy lost from the system in the phase conversions of the pyrolysis process and as hot materials leave the reactor. The energy analysis also at present doesn't account to efficiency losses in the systems although there is enough capacity to account for significant losses in the systems.

The assessment of the technical feasibility has been limited by the modelling capacity of the software examining micro scale pyrolysis systems. However initial results indicate that a renewable energy powered micro scale pyrolysis system is technically feasible. With chemical outputs consistent with large scale pyrolysis and an energy draw that is significantly lower then the available power supplied by solar systems that correspond to the that size of dwelling.

4.3 Financial Feasibility

The determination of financial feasibility has been determined through the conduct of a cost benefit analysis assessing the return on investment for money invested into the systems. The conduct of a cost benefit analysis required the identification of the estimated system cost prior to conducting the analysis.

4.3.1 Identified costs

The identification of system costs was completed though costing of major system components. The system costings were prepared based on the smallest and largest proposed systems with the medium system being a scaled down system of the largest system. A more detailed breakdown and websites of potential suppliers from which components could be sources are detailed in appendix C these costings are summarised in table 4.8. A 40% margin was also applied to the cost of the system components to replicate a suppliers potential profit on the end product pyrolysis unit. This margin also allows for variance in system costs or the cost of unidentified minor components.

Table 4.8: Total System cost estimate

	System Capacity		
Component	**1.5kg**	**6kg**	**30kg**
Shredder	69.00	135.00	399.00
Dryer	112.09	211.19	607.57
Reactor	212.06	271.16	507.57
Power System	12573.44	4932.20	55098.00
Margin	934.18	5276.32	22644.86
Total Cost	3269.63	18467.10	79275.00

4.3.2 Identified benefits

The benefits that have been identified from a micro scale pyrolysis unit include char, fuel and electricity generated from gas. An additional benefit that has been considered is excess electricity that may be generated from unused solar power. The calculated products were multiplied by the values identified in table 4.9 to determine the total benefits per year.

Table 4.9: System benefits

Benefit	**Value ($)**
Char	0.20
Fuel	1.47
Gas Electricity	0.09
Solar Electricity	0.09

The model was not able to determine the exact output quantities however the literature review indicates that 10% of product is char, 60% condensible fuels and 30% non-condensible combustible gases is a suitable benchmark. The total yearly throughput was determined as the daily system design capacity multiplied by 365 days in the year.

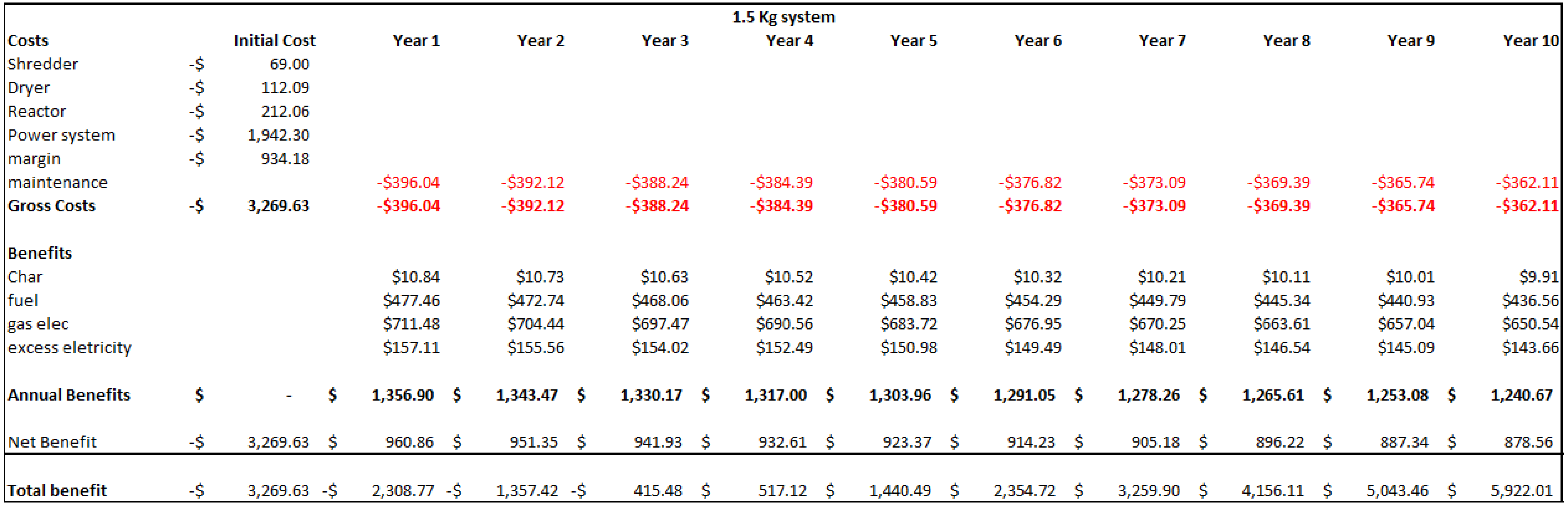
The determination of gas electricity capacity required the conversion of gas energy to kWh of electricity. This was determined by multiplying the calculated mass produced by energy density of 45 MJ/kg which was identified in the literature review. To total MJ of gas was then converted to kWh.

Excess electricity was calculated based of the highest demand scenario by subtracting the high total system power estimates from the total available solar power over the constrained 5 hour period across 365 days. Table 4.7 shows the total solar power generated over a year, the small amount of power used by the pyrolysis system and the surplus that will be returned to the grid.

Table 4.10: Excess system power

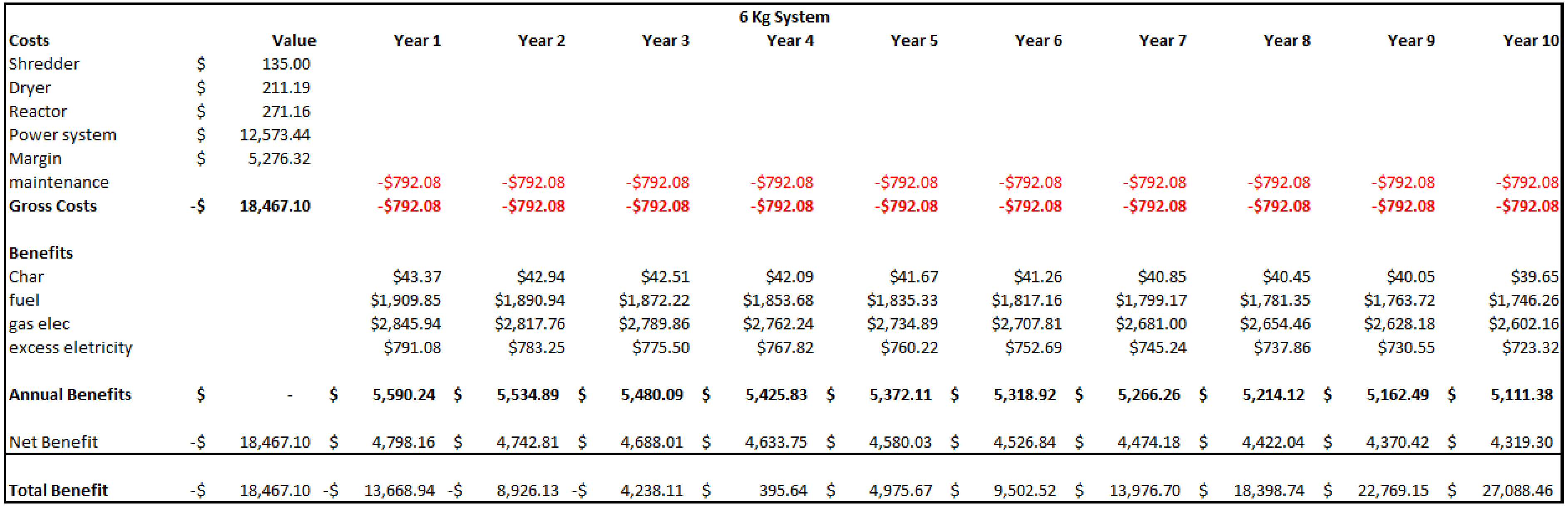
System size	**Power (kWh)**		
(kg)	**Generated**	**Used**	**Surplus**
1.5	1825	61.8	1763.2
6	9125	247.3	8877.7
30	36500	1236.4	35263.6

Using the total system costs, the system benefits and the identified annual maintenance costs the the cost benefit analysis was conducted for each system. These are presented in figure 4.28 to 4.30 these figures indicate that all systems have significant financial benefits to the operator.



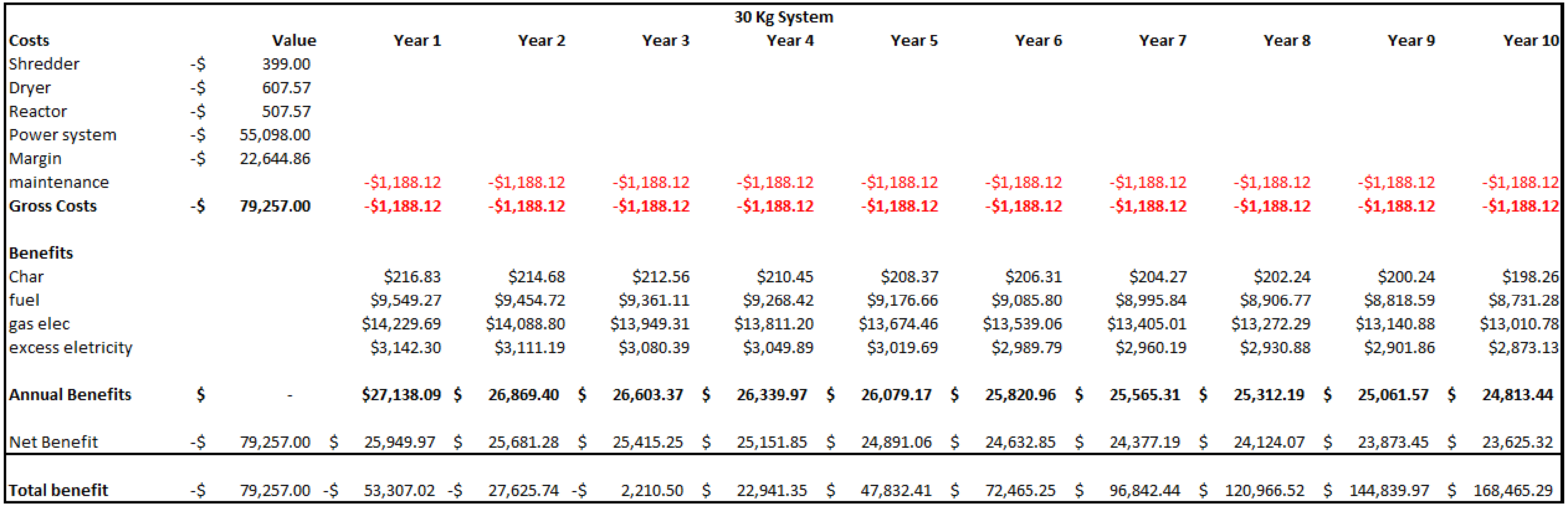
					1.5 Kg system						
Costs	**Initial Cost**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Shredder	-$ 69.00										
Dryer	-$ 112.09										
Reactor	-$ 212.06										
Power system	-$ 1,942.30										
margin	-$ 934.18										
maintenance		-$396.04	-$392.12	-$388.24	-$384.39	-$380.59	-$376.82	-$373.09	-$369.39	-$365.74	-$362.11
Gross Costs	**-$ 3,269.63**	**-$396.04**	**-$392.12**	**-$388.24**	**-$384.39**	**-$380.59**	**-$376.82**	**-$373.09**	**-$369.39**	**-$365.74**	**-$362.11**
Benefits											
Char		$10.84	$10.73	$10.63	$10.52	$10.42	$10.32	$10.21	$10.11	$10.01	$9.91
fuel		$477.46	$472.74	$468.06	$463.42	$458.83	$454.29	$449.79	$445.34	$440.93	$436.56
gas elec		$711.48	$704.44	$697.47	$690.56	$683.72	$676.95	$670.25	$663.61	$657.04	$650.54
excess eletricity		$157.11	$155.56	$154.02	$152.49	$150.98	$149.49	$148.01	$146.54	$145.09	$143.66
Annual Benefits	**$ -**	**$ 1,356.90**	**$ 1,343.47**	**$ 1,330.17**	**$ 1,317.00**	**$ 1,303.96**	**$ 1,291.05**	**$ 1,278.26**	**$ 1,265.61**	**$ 1,253.08**	**$ 1,240.67**
Net Benefit	-$ 3,269.63	$ 960.86	$ 951.35	$ 941.93	$ 932.61	$ 923.37	$ 914.23	$ 905.18	$ 896.22	$ 887.34	$ 878.56
Total benefit	-$ 3,269.63	-$ 2,308.77	-$ 1,357.42	-$ 415.48	$ 517.12	$ 1,440.49	$ 2,354.72	$ 3,259.90	$ 4,156.11	$ 5,043.46	$ 5,922.01

Figure 4.28: 1.5 kg per day cost benefit analysis



					6 Kg System						
Costs	**Value**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Shredder	$ 135.00										
Dryer	$ 211.19										
Reactor	$ 271.16										
Power system	$ 12,573.44										
Margin	$ 5,276.32										
maintenance		-$792.08	-$792.08	-$792.08	-$792.08	-$792.08	-$792.08	-$792.08	-$792.08	-$792.08	-$792.08
Gross Costs	**-$ 18,467.10**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**	**-$792.08**
Benefits											
Char		$43.37	$42.94	$42.51	$42.09	$41.67	$41.26	$40.85	$40.45	$40.05	$39.65
fuel		$1,909.85	$1,890.94	$1,872.22	$1,853.68	$1,835.33	$1,817.16	$1,799.17	$1,781.35	$1,763.72	$1,746.26
gas elec		$2,845.94	$2,817.76	$2,789.86	$2,762.24	$2,734.89	$2,707.81	$2,681.00	$2,654.46	$2,628.18	$2,602.16
excess eletricity		$791.08	$783.25	$775.50	$767.82	$760.22	$752.69	$745.24	$737.86	$730.55	$723.32
Annual Benefits	**$ -**	**$ 5,590.24**	**$ 5,534.89**	**$ 5,480.09**	**$ 5,425.83**	**$ 5,372.11**	**$ 5,318.92**	**$ 5,266.26**	**$ 5,214.12**	**$ 5,162.49**	**$ 5,111.38**
Net Benefit	-$ 18,467.10	$ 4,798.16	$ 4,742.81	$ 4,688.01	$ 4,633.75	$ 4,580.03	$ 4,526.84	$ 4,474.18	$ 4,422.04	$ 4,370.42	$ 4,319.30
Total Benefit	-$ 18,467.10	-$ 13,668.94	-$ 8,926.13	-$ 4,238.11	$ 395.64	$ 4,975.67	$ 9,502.52	$ 13,976.70	$ 18,398.74	$ 22,769.15	$ 27,088.46

Figure 4.29: 6 kg per day cost benefit analysis



		30 Kg System									
Costs	**Value**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Shredder	-$ 399.00										
Dryer	-$ 607.57										
Reactor	-$ 507.57										
Power system	-$ 55,098.00										
Margin	-$ 22,644.86										
maintenance		-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12	-$1,188.12
Gross Costs	**-$ 79,257.00**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**	**-$1,188.12**
Benefits											
Char		$216.83	$214.68	$212.56	$210.45	$208.37	$206.31	$204.27	$202.24	$200.24	$198.26
fuel		$9,549.27	$9,454.72	$9,361.11	$9,268.42	$9,176.66	$9,085.80	$8,995.84	$8,906.77	$8,818.59	$8,731.28
gas elec		$14,229.69	$14,088.80	$13,949.31	$13,811.20	$13,674.46	$13,539.06	$13,405.01	$13,272.29	$13,140.88	$13,010.78
excess eletricity		$3,142.30	$3,111.19	$3,080.39	$3,049.89	$3,019.69	$2,989.79	$2,960.19	$2,930.88	$2,901.86	$2,873.13
Annual Benefits	**$ -**	**$27,138.09**	**$ 26,869.40**	**$ 26,603.37**	**$ 26,339.97**	**$ 26,079.17**	**$ 25,820.96**	**$ 25,565.31**	**$ 25,312.19**	**$ 25,061.57**	**$ 24,813.44**
Net Benefit	-$ 79,257.00	$ 25,949.97	$ 25,681.28	$ 25,415.25	$ 25,151.85	$ 24,891.06	$ 24,632.85	$ 24,377.19	$ 24,124.07	$ 23,873.45	$ 23,625.32
Total benefit	-$ 79,257.00	-$ 53,307.02	-$ 27,625.74	-$ 2,210.50	$ 22,941.35	$ 47,832.41	$ 72,465.25	$ 96,842.44	$ 120,966.52	$ 144,839.97	$ 168,465.29

Figure 4.30: 30 kg per day cost benefit analysis

4.31 graphs the cost and benefit returns over the expected 10 year system life. The 1.5 kg system has an internal rate of return equal to 5%, a payback period of 8 years and the system had a return on investment of 26% over 10 years. The 6kg system had an internal rate of return equal to 6%, a payback period of 8 years and a return on investment of 37% over the 10 year system life. The 30 kg system has an internal rate of return equal to 13%, a payback period of 6 years and a return on investment over 10 years of 85%.

The world bank *ANNEX: ECONOMIC AND FINANCIAL APPRAISAL to Sindh Solar Energy Project (P159712)* (2018) conducted a financial study of a large scale solar project in Pakistan worth in excess of 100 million USD they identified that this project can expect an return on equity of 15% per year. In another study Melbourne industry leader sustainable has published their market analysis on their website where they identify that the return on investment for solar systems with and without batteries across Australian states varies between 8.1% and 30.8% (*Australian solar ROI - should you be installing it?* 2018). Additional industry analysis by *Australian Solar Index - Investment Return And Ranking* (2019) identifies that the internal rate of return for solar systems varies considerably across Australia ranging from as low as 10% to as high as 30%. This variation is significantly influenced by federal and state government incentives for solar energy which varies form state to state and is artificially inflating the profitability of these systems.

Based on the internal rate of return the single person and four person households would be better off investing their money in other investments or pooling with other single person households to achieve better returns on investment. The 30 kg system is a sound investment with return rates that significantly exceed solar only investment returns.

While the smaller two systems do not show favourable returns on investment the costs of all systems could be reduced significantly by lowering the size and capacity of the electrical systems which in this study greatly exceed the energy capacity required for processing the waste and account for around 60% of the system costs. An additional problem that was identified with this analysis post its completion was that an underlying assumption is that the smallest system will use the smallest components and the largest system will use the largest components. The 6 and 30 kg systems potential capacities far exceeds what would be required for the number of people and it is identified that this would also have a significant impact on the cost and investment returns.

This initial cost benefit analysis indicates that there is significant financial benefit investing in renewable powered micro scale pyrolysis systems in multi-person households for distributed waste processing and management.

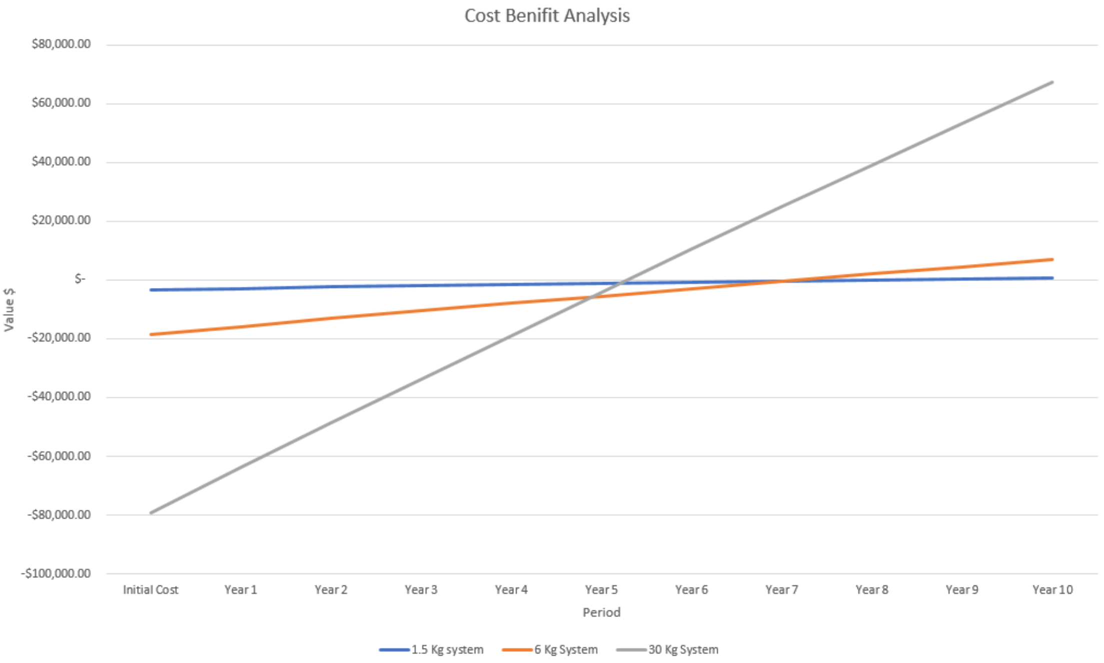


Figure 4.31: Standard Cost Benefit Analysis

However an interesting opportunity may arise if the systems gas electricity was stored through the day and returned to the grid in the peek daily demand period where energy prices can be up to 3.5 times higher then standard feed in tariffs. This would have a significant impact on the returns with internal rates on return experiencing in all systems a boost of between 21 and 35% which can be seen in the peek cost benefit analyse detailed in figure 4.32. This would make renewable micro scale pyrolysis an appropriate investment for all sizes of households with returns that far exceed standards grid feed solar. This would have an impact on system complexity and cost however and would require further analysis.

The distributed peek energy generation capacity of micro pyrolysis systems could have substantial implications on the wider energy market costs during peek periods in all cases the systems are profitable however for a single person household investing in a system should be driven by factors beyond simple financial as better returns can be achieved with standard solar systems or in other investments.

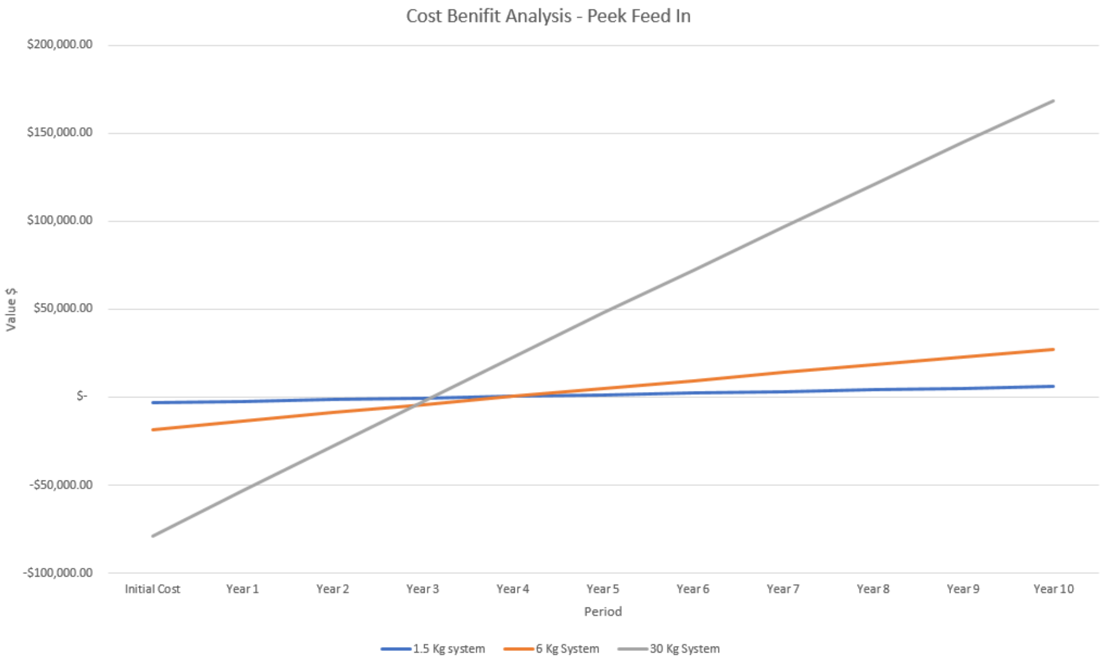


Figure 4.32: Cost Benefit Analysis using peek demand feed in

4.4 Social and Environmental Feasibility

The Social and environmental feasibility was examined through analysing the results and evaluating their impact on the broader population from the perspective of waste management and the generation of carbon dioxide.

Table 4.11 identifies the simple local waste management savings that would be experienced by population groups ranging from 1000 one million people implementing renewable micro scale pyrolysis.

Table 4.11: Total System management savings

	1,000	**10,000**	**100,000**	**1,000,000**
Total saved ($)	28,770	287,700	2,877,000	28,770,000

The cost savings is significant for these communities and would see considerable social benefit across the community from lower rates and levies to increased services. In addition to the local fiscal social benefit that the community would experience there is also the flow on impacts to the community that systems would being including broader economic growth.

The implementation of renewable micro scale pyrolysis waste management systems may also have significant impacts in addressing developing social and health issues such as climate anxiety which was identified by (*Climate anxiety is real, but there's something you can do about it* n.d.).

The direct environmental benefits were identified as carbon dioxide and methane emission reductions. Table 4.12 identifies the significant environmental benefits that would be experienced from the introduction of micro scale renewable pyrolysis waste management into population groups ranging from one thousand to one million. The table identifies that a significant portion of the environmental benefit would be realised through the energy generated from the pyrolysis process.

Table 4.12: Total CO^2 and Methane emissions prevented and their value

	1,000	**10,000**	**100,000**	**1,000,000**
Generation CO^2 (Tonnes)	789.98	7,899.77	78,997.68	789,976.8
Transport CO^2 (Tonnes)	12.83	128.31	1,283.09	12,830.9
Total CO^2 (Tonnes)	802.81	8,028.08	80,280.77	802,807.77
Total CO^2 ($K)	40.141	401.404	4,014.039	40,140.389
Total Methane (Tonnes)	12.831	128.309	1,283.09	12,830.9
Total Methane ($K)	3.079	30.794	307.941	3,079.416
Total Emission saving ($K)	43.22	432.195	432,1.98	43,219.805

The wide scale adoption of micro scale pyrolysis will have significant benefits for the environment which has been quantifiable shown in table 4.12. The expansion beyond population figures shown into a significant portion of Australia's 24 million person population would also have a significant impact if half the country was to adopt the technology there would be a 1.81% reduction in Australia's greenhouse gas emissions base of current Department of Environment and Energy emission figures (*Australia's National Greenhouse Accounts* 2019).

Due to variations in how waste is managed from country to country expansions beyond the population of Australia are not likely to be accurate however estimations if half the global population was to adopt the technology there would be a direct emissions reduction of 3.14 Billion Tonnes annually and a financial saving of $166 Billion AUD. This equates to an 8.1% reduction in global CO^2 emissions and an 8.66% reduction in global methane emissions.

In addition ot the identified direct environmental benefits that were analysed in table 4.12 it is anticipated that the introduction of micro scale renewable pyrolysis would also have significant flow on effects in other industries that would lead to a number of additional indirect emission savings. One clear industry area is a lower demand of fuel, gas and electricity would see emissions reductions in those industries.

The social and environmental benefits have a clear and quantifiable benefit to the individual, society and the world beyond the quantifiable benefits resulting from the introduction of the technology various additional benefits can be established that are more difficult to quantify theoretically. These include, reductions in landfill, reduction in waste management traffic, reduction or elimination of pollution and illegal dumping, reduction in ocean pollution and improvements in marine life, global health improvements and the development of a true circular economy where goods are taken from raw materials and returned to raw materials with zero waste. The overwhelming quantifiable social and environmental benefit combined with the presently un-quantifiable benefits provide adequate support to determine that the implementation of renewable micro scale pyrolysis systems is socially and environmentally feasible.

Chapter 5

Conclusions and Further Work

5.1 Conclusions

In conclusion this study has examined the use of micro scale renewable pyrolysis as a method of distributed waste management. This study aimed to identify if renewable pyrolysis technology could be a potential solution to many of the problems facing the globe today; including resource shortages, pollution and environmental damage being caused by illegal dumping and greenhouse gas emissions.

The purpose of this study was to identify if the elimination of waste could be achieved through changing the nature and perception of what is traditionally considered waste to that of a valuable fuel that can be used to generate electricity, heat homes, cook with or even fuel cars. The major objective of this study that was required to meet these aims was to determine if renewable micro scale pyrolysis was technically, financially and also the social and environmental feasible to achieve this objective several other objectives were identified as follows.

The current state of advanced pyrolysis to product applications

The literature review in chapter 2 allowed for the investigation of the current application of advanced pyrolysis and its use in the generation of customer ready products. During this review it was identified that many commercial pyrolysis systems are in service across the globe and that depending on technology there is varying levels of product readiness with many systems requiring that oils being produced be centrally processed and upgraded or co-processed in traditional petroleum refineries.

It was identified that low cost ZSM-5 catalysts may be suitable for in place catalytic upgrading of pyrolysis products in small systems such as the renewable powered micro scale pyrolysis systems studied in this paper. It was identified in chapter 2 that there was no identifiable off the shelf product currently aimed at consumers for pyrolysing waste and that the technology is at a maturity level where this would be possible.

Investigate global approaches to pyrolysis systems powered by renewable energy

The literature review in chapter 2 identified that there is currently some research being conducted in the use of renewable energy to offset the energy required to complete the pyrolysis process. This research was able to identify significant benefits in using renewable energy in support of pyrolysis including lower emissions and increased cost viability of projects.

However the identified research did not investigate if the process could be done using only renewable energy as it was focusing on processing large centralised repositories of waste. This is because of the significant quantities of waste being processed requires a higher energy density then the that that was available from renewable energy.

This paper investigated the if the energy density of residential solar was able to be used to conduct the complete pyrolysis of residential waste. When the waste generated is processed on an individual or small group level this paper was able to identify that it is possible to conduct the complete pyrolysis waste management process using the available renewable energy.

Construct a system stimulation's in Chemkin

A simulation was conducted in Ansys Chemkin of the pyrolysis reaction. The Creck reaction mechanism (*The CRECK Modeling Group* 2014) was used in Chemkin to determine the reaction species and intern the process outputs. The simulation used the ultimate analysis of municipal solid waste as the feed in material to determine the technical feasibility of the pyrolysis process.

While the simulation returned significant results confirming the processes technical feasibility it was significantly limited by the modelling software. These constraints included limited temperature profiles, unrealistic feed in material properties and a limited interoperability as part of a larger model.

The ideal model for the micro scale pyrolysis must be able to accurately model the input materials, thermal properties along the length of the reactor and to integrate as a part of a larger process model that simulates materials from raw input to product output. It is expected that the ideal model would be able to accurately determine the energy required for the pyrolysis reaction and to accurately determine the quantities of consumer products that are produced.

Identify the safety, environmental, legislative and standard requirements relevant to consumer operated pyrolysis plants.

The literature review in chapter 2 identified that a consumer product is subject to a significant amount of legislation, regulations and standards that vary significantly across the country. The key compliance requirements that were identified include:

- The plant must be safe;
- The plant must operate as specified;
- The plant must include appropriate user protection features;
- The plant must comply with appropriate standards as identified in section 2.15;
- Some elements of the plant may need certification and registration i.e. pressure vessels;
- The plant must include appropriate shields and guards;
- The plant must provide accurate guidance on output use;
- The plant must be verified and validated to ensure that it is not emitting uncontrolled environmental pollutants, and;
- Fuel Products can not be sold without testing, licensing and taxing.

After investigating the legislative requirements it was identified that with appropriate due diligence the compliance burden was management and it was not expected that it would have financial impacts that would render the systems non-viable.

The implementation of specific measures such as using materials and equipment that have already achieved appropriate levels of certification during the design phase would also ensure that the compliance burden is minimised.

Prepare cost estimates form micro scale plants and perform cost benefit analysis for the systems for implementation into the use cases

Using the information identified in chapter 2 - literature review, chapter 3 Methodology and during the technical feasibility study cost estimates of the three micro scale renewable pyrolysis systems were prepared through the identification of major system components and their costs. Benefits were identified as the primary system outputs and were valued at today's market rates.

The identified benefits and costs were then used in a cost benefit analysis over 10 years to determine the financial feasibility of the system and make inference on investment returns when compared to solar energy projects.

Determine the technical, social, environmental and financial feasibility of renewable powered micro scale pyrolysis plants for use in the family home or small unit complex.

The core of this study and its modelling was the study of the technical, financial and social and environmental feasibility of renewable micro scale pyrolysis for distributed waste management.

The modelling was completed on the basis of a single person household, a four person household and a unit complex of 20 people. It was able to successfully identify that micro scale pyrolysis can be conducted in these households both on a chemical level, in that it produces useful and expected unburned hydrocarbons. It was also successful in identifying that the energy available from solar systems associated with households of these sizes was sufficient to completely power the pyrolysis systems required to process the amounts of waste generated in these households.

The financial feasibility was determined through the conduct of a cost benefit analysis. The cost benefit analysis was able to identify that the internal rate of return on a system sized for a single person and a four person household was bellow that of typical solar system install. The 20 person system was identified as having internal rates of return that are higher then typical solar system returns without government subsidies that solar systems receive. It is expected that if the system sizes were optimised for the required processing capacities then all systems would deliver significant returns to end users. The rates of return for systems should they achieve subsidies like those that the solar industry receives would also see significant increases in their rates of return.

An additional finding of the cost benefit analysis was that if the system was used as a energy storage device feeding electricity into the grid at peek demand periods it has the potential to increase internal rates of return by 21 to 35%. This would result in the smallest system being financially viable and a better investment then a similar solar system.

Finally this study looked at the social and environmental feasibility of renewable micro scale pyrolysis. It was able to quantify a significant social benefit in the reduction local government waste management costs. In addition to this the study identified several un-quantifiable benefits such addressing health and well being issues like climate anxiety.

The study accessed environmental impact based on the total direct greenhouse gas emission savings using the social impact value of the gases carbon dioxide and methane. The study was able to identify that adoption of the technology by half of Australia's population could be attributed to a 1.81% reduction in Australian green house gas emissions. Although a less accurate measure due to the differences in waste management strategies the adoption of the technology by half the global population would result in a saving of $166 Billion Australian Dollars annually equivalent to an 8.1% and 8.6% reduction in global carbon dioxide and methane emissions respectively.

The global adoption of renewable micro scale pyrolysis would be a technically and financially feasible process in family homes and small unit blocks where the available renewable energy exceeds the amount of energy required to process the waste generated by those respective areas. The true benefit however of renewable micro scale pyrolysis is not derived from its implementation in a small number of dwellings but rather the global implementation as a method for distributed waste management. Large scale technology adoption would see significant social and environmental benefits. The technology has the potential to eliminate waste and reduce pollution ending illegal dumping and pollution of waterways and oceans while providing significant benefits to the system operator and the economy. Renewable micro scale pyrolysis has the potential to reshape the way that the globe see's and manages waste.

5.2 Further Work

In order to maximise the feasibility of renewable micro scale pyrolysis additional work is required in several areas to ensure that the technology can be implemented as a consumer product where the end user can directly apply the output products. Additional work required includes:

- Model refinement and validation;
- investigate the integration of catalytic upgrading;
- further study on the financial benefits and cost implications of using gas as energy storage and peek demand feed in system;
- prototype development and testing;
- Engage with government for development funding;
- Lobby government for the expansion of renewable incentives to include micro scale pyrolysis;
- Engage with community to identify true demand for systems and benefits;

With the completion of the further work identified it is envisioned that renewable micro scale pyrolysis will have a rapid consumer uptake and that it will have a significant and beneficial impact for the globe.

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Appendix A

Project Specification

ENG 4111/2 Research Project

Project Specification

For:	**Paul Buckley**
Topic:	An Investigation into the feasibility of micro scale pyrolysis plants powered by renewable energy for use in residential areas.
Supervisors:	A. Wandel
Sponsorship:	Faculty of Health, Engineering & Sciences
Project Aim:	To assess the feasibility of renewable energy powered micro scale pyrolysis plant's for use in a single dwelling or block of residential units

Program: Bachelor of Mechanical Engineering (Honours)

1. Research the background information on pyrolysis to bio-fuel conversion.
2. Construct system models identifying key components to optimise sizing and calculations.
3. Using Chemkin analyse the performance of systems with proposed feed stocks.
4. Prepare cost estimates of proposed systems.
5. Compare implementation methods and benefits.

6. Assess the systems feasibility across technical, chemical, safety and financial domains.

As time and resources permit:

1. Survey community to identify interest in process and cost acceptability.
2. Use Survey results to reduce assumptions validate and expand feasibility.

Agreed:

Student Name:	Paul Buckley
Date:	March 2019
Supervisor Name:	Andrew Wandel
Date:	March 2019

Appendix B

Safety and Risk Assessment

In order to complete a risk assessment for the project it was necessary to determine the risk management objectives that the process is aiming to address. The objectives were identified as:

- Safe and on time project completion;
- Project and research safety;
- Maintain risk levels within or bellow identified target zones,
- Incorporate risk management into research and publications.

Acknowledging that not all risks are equal risks were then identified on and accessed against Project critical success factors as identified in the table B.1 bellow:

Table B.1: Project Risk Targets.

	acceptable residual risk level			
Critical success Factor	LOW	Medium	High	Very high
Project completion		X		
Safety		X		
Legislative Compliance		X		

All project risks will be assessed in accordance with the likelihood criteria as outlined in table B.2.

Table B.2: Likelihood Criteria.

Rating	Descriptors
Almost Certain	All risk associated controls are week and/or non-existence. Without control improvement there is almost no doubt that the risk will occur.
Likely	The majority of the controls associated with the risk are weak. Without control improvement it is more likely then not that the risk will occur.
Possible	There are some controls in place that could be improved. However without improvement there is no certainty that the risk will occur.
Unlikely	The majority of controls are strong with few gaps. This strength means that the it is not likely for the risk to occur as a result of action or inaction within the organisation.
Rare	All controls are in place and functioning with no control gaps. The strength of controls mean that the risk will not eventuate as a result of something that is within the organisations control.

The risk consequences are detailed in table B.3. It is important to note that the safety and legislative compliance consequences extend beyond the completion of the project and to potential end users.

Table B.4 identifies the risk rating in accordance with the likelihood and consequences as identified in tables B.2 and B.3.

There are three key risks identified for the this research project they are identified in table B.5.

- Failure to complete project;
- Illness or injury as a result of project;
- Negative short term legislative change.

As all risks fall within or bellow the medium risk rating no additional controls are required. However risks will need to be monitored and reviewed to ensure that their status doesn't change throughout the course of the project.

Table B.3: Risk Consequences.

Consequence	Critical success factor		
	Project Completion	Safety	Legislative Compliance
Severe	Unable to complete project program failure	Death or permanent disability	Project fails to comply with unidentified legal requirements
Major	Failure to submit project subject failure	Major injury unable to work	project fails to comply with identified legal requirement
Moderate	project submitted late <5 days	Major injury return to work <12 weeks	Major negative Regulatory changes after project completion
Minor	Requirement to make major modification	Minor injury return to work <6 weeks	Major negative regulatory change during project completion
Insignificant	Requirement to make minor modification	Minor injury no time of	Minor positive or negative regulatory changes

Table B.4: Risk Rating.

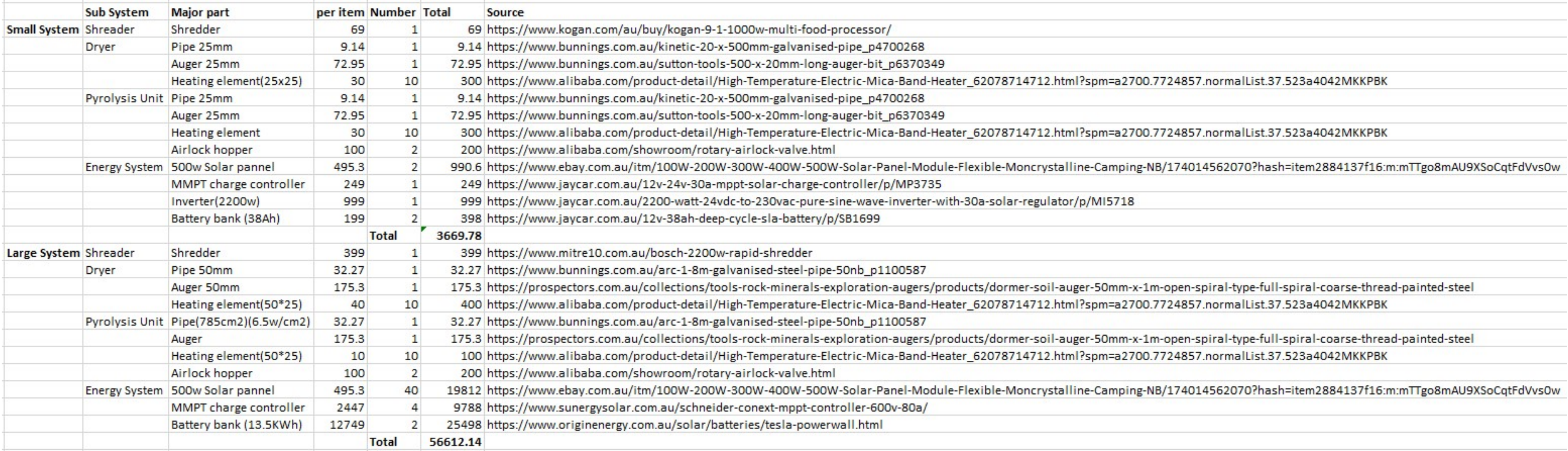
Likelihood	Consequence				
	Insignificant	Minor	Moderate	Major	Severe
Almost Certain	Low	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Possible	Low	Medium	Medium	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Medium	Medium

Table B.5: Risk assessment.

Risk	Cause	Consequence	Likelihood	Risk Rating
Failure to complete project	Illness, Loss of work, poor time management	Major	Rare	Medium
Illness or injury as a result of project	Poor research application	Major	Rare	Medium
Negative short term legislative change	Community pressure, Lobbying, safety incident	Moderate	Possible	Medium

Appendix C

Costing Spreadsheet



	Sub System	Major part	per item	Number	Total	Source
Small System	Shreader	Shredder	69	1	69	https://www.kogan.com/au/buy/kogan-9-1-1000w-multi-food-processor/
	Dryer	Pipe 25mm	9.14	1	9.14	https://www.bunnings.com.au/kinetic-20-x-500mm-galvanised-pipe_p4700268
		Auger 25mm	72.95	1	72.95	https://www.bunnings.com.au/sutton-tools-500-x-20mm-long-auger-bit_p6370349
		Heating element(25x25)	30	10	300	https://www.alibaba.com/product-detail/High-Temperature-Electric-Mica-Band-Heater_62078714712.html?spm=a2700.7724857.normalList.37.523a4042MKKPBK
	Pyrolysis Unit	Pipe 25mm	9.14	1	9.14	https://www.bunnings.com.au/kinetic-20-x-500mm-galvanised-pipe_p4700268
		Auger 25mm	72.95	1	72.95	https://www.bunnings.com.au/sutton-tools-500-x-20mm-long-auger-bit_p6370349
		Heating element	30	10	300	https://www.alibaba.com/product-detail/High-Temperature-Electric-Mica-Band-Heater_62078714712.html?spm=a2700.7724857.normalList.37.523a4042MKKPBK
		Airlock hopper	100	2	200	https://www.alibaba.com/showroom/rotary-airlock-valve.html
	Energy System	500w Solar pannel	495.3	2	990.6	https://www.ebay.com.au/itm/100W-200W-300W-400W-500W-Solar-Panel-Module-Flexible-Moncrystalline-Camping-NB/174014562070?hash=item2884137f16:m:mTTgo8mAU9XSoCqtFdVvs0w
		MMPT charge controller	249	1	249	https://www.jaycar.com.au/12v-24v-30a-mppt-solar-charge-controller/p/MP3735
		Inverter(2200w)	999	1	999	https://www.jaycar.com.au/2200-watt-24vdc-to-230vac-pure-sine-wave-inverter-with-30a-solar-regulator/p/MI5718
		Battery bank (38Ah)	199	2	398	https://www.jaycar.com.au/12v-38ah-deep-cycle-sla-battery/p/SB1699
				Total	**3669.78**	
Large System	Shreader	Shredder	399	1	399	https://www.mitre10.com.au/bosch-2200w-rapid-shredder
	Dryer	Pipe 50mm	32.27	1	32.27	https://www.bunnings.com.au/arc-1-8m-galvanised-steel-pipe-50nb_p1100587
		Auger 50mm	175.3	1	175.3	https://prospectors.com.au/collections/tools-rock-minerals-exploration-augers/products/dormer-soil-auger-50mm-x-1m-open-spiral-type-full-spiral-coarse-thread-painted-steel
		Heating element(50*25)	40	10	400	https://www.alibaba.com/product-detail/High-Temperature-Electric-Mica-Band-Heater_62078714712.html?spm=a2700.7724857.normalList.37.523a4042MKKPBK
	Pyrolysis Unit	Pipe(785cm2)(6.5w/cm2)	32.27	1	32.27	https://www.bunnings.com.au/arc-1-8m-galvanised-steel-pipe-50nb_p1100587
		Auger	175.3	1	175.3	https://prospectors.com.au/collections/tools-rock-minerals-exploration-augers/products/dormer-soil-auger-50mm-x-1m-open-spiral-type-full-spiral-coarse-thread-painted-steel
		Heating element(50*25)	10	10	100	https://www.alibaba.com/product-detail/High-Temperature-Electric-Mica-Band-Heater_62078714712.html?spm=a2700.7724857.normalList.37.523a4042MKKPBK
		Airlock hopper	100	2	200	https://www.alibaba.com/showroom/rotary-airlock-valve.html
	Energy System	500w Solar pannel	495.3	40	19812	https://www.ebay.com.au/itm/100W-200W-300W-400W-500W-Solar-Panel-Module-Flexible-Moncrystalline-Camping-NB/174014562070?hash=item2884137f16:m:mTTgo8mAU9XSoCqtFdVvs0w
		MMPT charge controller	2447	4	9788	https://www.sunergysolar.com.au/schneider-conext-mppt-controller-600v-80a/
		Battery bank (13.5KWh)	12749	2	25498	https://www.originenergy.com.au/solar/batteries/tesla-powerwall.html
				Total	**56612.14**	

Figure C.1: Spreadsheet of costs found from local suppliers for key components.