Performance Study and Validation of the Downdraft Biomass Gasification Process for Combined Heat & Power Plants from Under-utilised Biomass and Bio – Waste

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Abstract

Improved energy generation methods are required to guarantee sustainable energy sources for the future. Gasification technology allows for waste and low-quality biomass materials to be converted into a producer gas, which can in turn be utilised in a CHP system for sustainable heat and electricity generation. To improve the downdraft gasification process, blends of biomass materials were investigated for their impact on process parameters such as producer gas lower heating value, conversion efficiency, tar production and producer gas application processes. This work was carried out through a combination of experimental and simulation analysis.

Novel work analysing agricultural residues such as poultry litter and anaerobic digestate, along with the bioenergy crop miscanthus showed improvement in gas lower heating value when using blended feedstocks. From previous feedstock blending literature, the blending ratios of interest were identified as 80/20, 60/40 and 40/60 by weight percentage, with wood pellets the blending feedstock introduced. Small – scale experimental analysis was carried out on the Fluidyne downdraft gasification system in Ulster University, using the results collected to validate the computational simulations generated with ECLIPSE simulation software.

Experimental results from the blended feedstocks displayed improvements up to 12.9% in producer gas lower heating value, from the 24% increase in carbon content of the feedstock after the introduction of wood pellets. Increases in the combustible portion of the producer gas led to a 6.1% improvement in thermal efficiencies along with 2.5% increase in electrical efficiency of the simulated CHP process. A cradle to grave life cycle assessment carried out using SimaPro software to evaluate the environmental impact that blending feedstocks for downdraft gasification and the application process had showed improvements in environmental impacts when compared to traditional energy generation methods. Further ECLIPSE software was used to carry out the techno – economic analysis of the process and using financial indices to evaluate the impact of blends, decreases in net present value, break even selling price and payback period were found due to the purchasing cost of the wood pellet feedstock.

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Table of Contents

List of Figures

List of Tables

List of Publications and Conferences

	Manuscripts				
	Title	Journal	Status	Date	Co-Authors
1	Modelling and Experimental Investigation of Small-Scale Gasification CHP Units for Enhancing the Use of Local Biowaste	Waste Management	Published	Dec-21	Valentina Gogulancea, Caterina Brandoni, Neil Hewitt, Chris Johnston, George Onofrei, Ye Huang
2	Gasification of Biowaste Based on Validated Computational Simulations: A Circular Economy Model to Handle Poultry Litter Waste	Waste and Biomass Valorization	Published	May - 22	Caterina Brandoni, Valentina Gogulancea, Mohammad Jaffar, Neil J. Hewitt, Kai Zhang, Ye Huang

	Conferences			
	Name	Location	Work	Date
1	Engineering the Energy Transition: Technological and Industrial Opportunities and Challenges	Titanic Hotel Belfast	Poster Presentation	Feb-20
2	Energy Technology Partnership 9th Annual Conference 2020	Virtual	Presentation	Nov-20
3	THESSALONIKI 2021 8th International Conference on Sustainable Solid Waste Management	Virtual	Presentation	Jun-21

List of Abbreviations

AD	Anaerobic Digestion
AGT	Advanced Gasification Technologies
Ar	Argon
BEIS	Department for Business, Energy and Industrial Strategy
BESP	Break Even Selling Price
°C	Degrees Celsius
$CaCO_3$	Calcium Carbonate
CCL	Climate Change Levy
CH_4	Methane
Cl	Chlorine
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAF	Dry, Ash Free
DCFR	Discounted Cash Flow Rate
DETI	Department for Enterprise, Trade and Investment
DGS	Downdraft Gasification System
ECS	Energy Crop Scheme
EPC	Engineering, Procurement and Construction
ER	Equivalence Ratio
FIT	Feed in Tariff
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HHV	Higher Heating Value
H_2	Hydrogen
ICE	Internal Combustion Engine
IEA	International Energy Agency
IED	Industrial Emissions Directive
K	Potassium
ktoe	kilo tonnes of oil equivalent
kWh_e	kilowatt-hour electrical

kWh_{th}	kilowatt-hour thermal
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
LPG	Liquid Petroleum Gas
MCS	Microgeneration Certification Scheme
MJ/Nm^3	Megajoule per normal cubic metre
M.C%	Moisture Content
N	Nitrogen
NAP	Nutrient Action Programme
NAPR	Nutrient Action Programme Regulations
NI	Northern Ireland
NPV	Net Present Value
N_2	Nitrogen
N_2O	Nitrous Oxide
odt	Oven Dry Tonne
ORC	Organic Rankine Cycle
P	Phosphorus
PAH's	Polycyclic Aromatic Hydrocarbons
PBP	Payback Period
RHI	Renewable Heat Incentive
RPM	Revolutions Per Minute
SEG	Smart Export Guarantee
SO_2	Sulphur Dioxide
SRC	Short Rotation Coppice
UK	United Kingdom
Vol. %	Volumetric Percentage
WFD	Water Framework Directive
wt.%	Weight Percentage

Chapter 1 - Introduction

1.1 Introduction to the Topic

Energy is currently one of the most important global research topics, due to the continued growth of global population. The waste-to-energy nexus is central to sustainable development (Sharma et al., 2020). Based on the principles of reducing, reusing, recycling, recovering and restoring, it focuses on simultaneously reducing waste and producing energy. With supply and demand for both commodities increasing globally, a coherent integrated approach is required to ensure a sustainable future for all nations. The current climate crisis with issues such as environmental pollution and increasing global temperature has brought this nexus to the forefront of many peoples thinking. This is due to an increase in severe weather events, rising sea tides displacing some of the most vulnerable communities, along with the prevalence of famine in some communities. These extreme conditions have sped up the transition of nations and industries from harmful fossil fuel energy sources, to more sustainable and renewable alternatives. Governments are implementing strategies to utilise resources which are closer to home, rather than relying on the import of oil or gas which may need to travel over long distances. Renewables in the form of solar and both on and offshore wind have become much more attractive options. They are capable energy generators with reducing capital costs and greater access the wider public (ISEA, 2016). Biomasses universal availability and potential sustainability means that through thermochemical conversion, it can become a staple of the future energy mix globally. This thesis will cover the most efficient of these biomass thermochemical conversion technologies, gasification and the advantages associated with it over other conversion methods. The research will focus on utilising sustainable and waste biomasses for energy conversion, blending these materials for increased system performance and efficiency, and using the producer gas in downstream equipment for heat and electricity production.

The term biomass is used to describe any material consisting of recently living plant or animal-derived material. This can be divided into three groups; energy crops, primary residues and wastes. Energy crops can be both conventional crops such as cereals, oil seed rape or sugar beet and perennial energy crops such as short rotation coppice (SRC) willow, poplar and miscanthus. Primary residues include forestry residues for example brash and short rotation forestry, and agricultural crop residues in the form of straw from cereals. Wastes covers a wide range of secondary and tertiary residues such as by-products from sawmills and arboricultural arisings. Tertiary residues include organic wastes, sewage sludges and animal manures (Slade et al., 2010). Biomass is one of the oldest energy generation methods known to man. The combustion of woody biomass for heat and food preparation has been carried out for thousands of years. More recently conversion methods have been optimized to increase the efficiency of this energy extraction, through methods such as gasification and pyrolysis. The use of biomass and biowastes as an energy source has become a much more attractive proposal since the environmental damage caused by fossil fuels became apparent. Sustainable biomass is widely available, in many different forms, with each having its optimum conversion method. To ensure a robust and reliable grid, a mixture of technologies will be required. A move away from large scale energy plants which traditionally combust fossil fuels will be necessary. In their place should be a system of micro-generation, where small scale energy generation is carried out close to the end user. This avoids the issues of long-distance transport of energy through overhead power lines or similar. Biomass holds the distinct advantage over other energy generation methods of being available year-round, and not dependent on the weather as is the case with solar and wind power (Elsner et al., 2017). This allows biomass to be a programmable source of energy, which causes less issues for the grid. Many conversion methods for biomass exist, each with its own optimum application.

For successful application of biomass for energy usage, biomass materials need to go through an applicable conversion process. Biomass conversion for energy generation can be split into two groups, biological conversion and thermochemical conversion. The common biological conversion methods currently in use are hydrolysis, fermentation, and anaerobic and aerobic digestion (Goswami et al., 2020). These conversion methods can produce many primary and secondary products, such as sugars, solvents, alcohols, methane and electricity to name a few. These methods are more commonly used for materials with a high moisture content such as food waste in the United Kingdom.

This research is focused on the 2nd group of conversion methods, thermochemical conversion as shown in Figure 1.1 Thermochemical Conversion Methods including fuels, chemicals and powers. These conversion techniques include combustion, pyrolysis, liquefaction and gasification (Brown, 2019). They are much more suited to drier feedstocks, with a moisture content below 20% for optimum application. These each produce their own distinct products such as charcoal, bio-oil, fuel gas, heat and electricity.

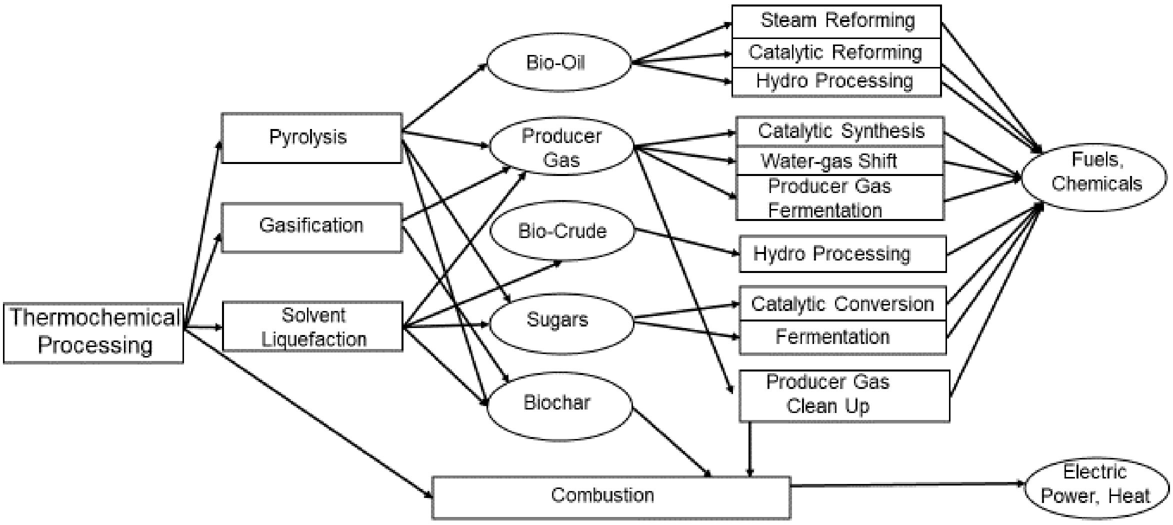


Figure 1.1 Thermochemical Conversion Methods including fuels, chemicals and powers

Combustion occurs at temperatures between 800 - 1600°C, generating thermal energy which can be suitable for heating or power. This happens through the fast reaction of oxygen and fuel. Parameters influencing combustion include fuel heating value, moisture content, the stoichiometric ratio of fuel to air and the furnace design. Gasification can take place at lower temperatures than combustion and occurs under conditions where the stoichiometric ratio of oxygen to fuel is less than one. The primary products are a producer gas containing a mixture of carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2) and nitrogen (N_2). By-products include tars, chars and ash. This producer gas, depending on the gas quality, can then be applied to an engine for heat and electricity generation. Parameters influencing gasification include fuel heating value, moisture content, chemical composition of biomass and equivalence ratio. Pyrolysis can be either the first step in the combustion or gasification process, or a conversion method to generate biofuel products on its own. Biomass in an oxygen free environment in converted into bio-oils at a different speed depending on the set up. A reaction temperature of between 300 - 900°C is standard, and the bio-oil can be further refined to replace petroleum products. Finally, solvent liquefaction occurs at lower temperatures of between 105 - 400°C. Through a mix of increased pressure and temperature another bio-oil product can be produced from the process. Of the four thermochemical conversion techniques, solvent liquefaction is the furthest from commercial application (Brown, 2019).

Significant benefits are associated with the use of biomass materials as a method of energy generation. These include:

- Abundantly available: various types of biomass can be found in almost every region of the world. From coconut and rubber seed shell to willow and forestry residues (Widjaya et al., 2018).
- Versatility: biomass materials can come in many forms (solid, liquid or gaseous biofuels) and can be converted through many processes. This means that a suitable feedstock and conversion method can be found for every application (Pérez et al., 2013).
- Adding value to material: many materials previously seen as waste can now be used as an energy source thanks to the many available conversion methods. Waste previously discarded now has an inherent value as a fuel (Sansaniwal et al., 2017).
- Additional income: This income can benefit whoever generates the biomass, whether it be a waste from a farm (manure or crop residues) or by-products from a factory (off-cuttings).
- Fuel security: many countries are currently relying on importing of fossil fuels over long distances. Using locally available biomass can provide fuel security to these areas.
- Diverting Waste from Landfill: Many waste biomasses, or biowastes as they are known are currently disposed of through landfilling as no other solution exists. This material can be converted to energy through its inherent carbon content.
- Employment: the switch from fossil fuels to biomass will open new trade and business, creating new employment within many communities.

- Carbon Neutrality: many biomass materials are carbon neutral due to their sustainable growth or classification as a waste which would otherwise be disposed of (Jangsawang et al., 2015).
- Effective Energy Carrier: biomass is a reliable source of energy with a good energy to weight ratio, which can be easily stored for use when required (Mutlu and Yucel, 2018).

Biomass offers many opportunities to many communities. Through the variety of conversion methods available for it, biomass can be used to substitute for fossil fuels in all the major energy demand sectors; heat, electricity and transport. Rural communities are the ones who will benefit most from a switch to biomass, as they are the ones who grow, produce and harvest these materials.

Circular Economy

The circular economy is a sustainability approach that is being heavily promoted by academia, industry and policy makers alike (WRAP, 2019a). The idea is to change consumer attitude and work towards a more sustainable and resource efficient economy. Currently many products are fabricated or purchased with the intention of disposal after one use. Not only is this incredibly harmful to our environment, it is also wasteful in terms of resources such as energy and raw materials in the production of said product. If we can move away from this single use system, the benefits are a sustainable future where the faith of all raw materials is guaranteed. This approach operates through the extraction of all uses out of a material before final disposal occurs. This will divert a large amount of waste from landfill. Between 2015 – 2020 recycling in Northern Ireland increased by 50.6%, through application of the circular economy approach (WRAP, 2020). Through using wastes and by-products for energy production not only are we ensuring a more sustainable energy mix, but we are also promoting a healthy waste management strategy and increase recycling in line with a circular economy approach.

The availability of biomass around the globe in all its different forms is one of the most attractive characteristics of the material. Biomass and biowastes are homogenously distributed all over the world in many different forms including solid, liquid and gas. Current best estimations are conservative but put global biomass resources between

100 – 200 EJ per year (Ladanai and Vinterbäck, 2009; Shunichi Nakada, Deger Saygin, 2014; WBA, 2016). This is equal to approximately 3,582,688 ktoe, or 25% of the entire energy supplied by all sources in 2018 (IEA, 2020). By using more waste biomass resource and optimization of current technology for improved efficiencies, this percentage could increase further. Wholesale changes to the current system of where we source our energy from and how it is produced is required though if we are to utilise global biomass resources to their full potential, as current global energy from biomass resources stands at approximately 10%.

The 10% of global energy from biomass resources represents 1,327,127 ktoe, but this is dwarfed by the primary sources of energy being utilised altogether. The most common source of energy is from oil with 4,496,998 ktoe, followed by coal and natural gas with 3,838,326 and 3,261,595 ktoe respectively (IEA, 2020). These can be seen along with all other sources of energy in Figure 1.2 Total Global Energy Supply by Source 1990 - 2018. This reliance on fossil fuels is the cause of climate change, and the primary source of the harmful greenhouse gases (GHG's) being emitted. Globally this equates to over 81% of energy from non-renewable sources in 2018. This is clearly an unsustainable amount, as fossil fuel resources are depleting and the damage to the environment is immeasurable. To decrease this percentage and make the swap to sustainable sources of energy, governments need to take drastic action. This could include large incentives to introduce new technology or legislating for the removal of large GHG emitters within the next decade. Biofuels globally made up approximately 9.3% of the energy mix in 2018. This is interesting as even though the amount of energy generated from these resources has almost doubled in the last 30 years, as a percentage of overall energy produced it has decreased by over 1% in the same time period. This can be put down to the increase in global energy demand, and the filling of that demand with other sources, particularly natural gas that seen a 3% increase, and other technologies such as wind and solar that saw a 1.5% increase when comparing current usage to 1990 levels.

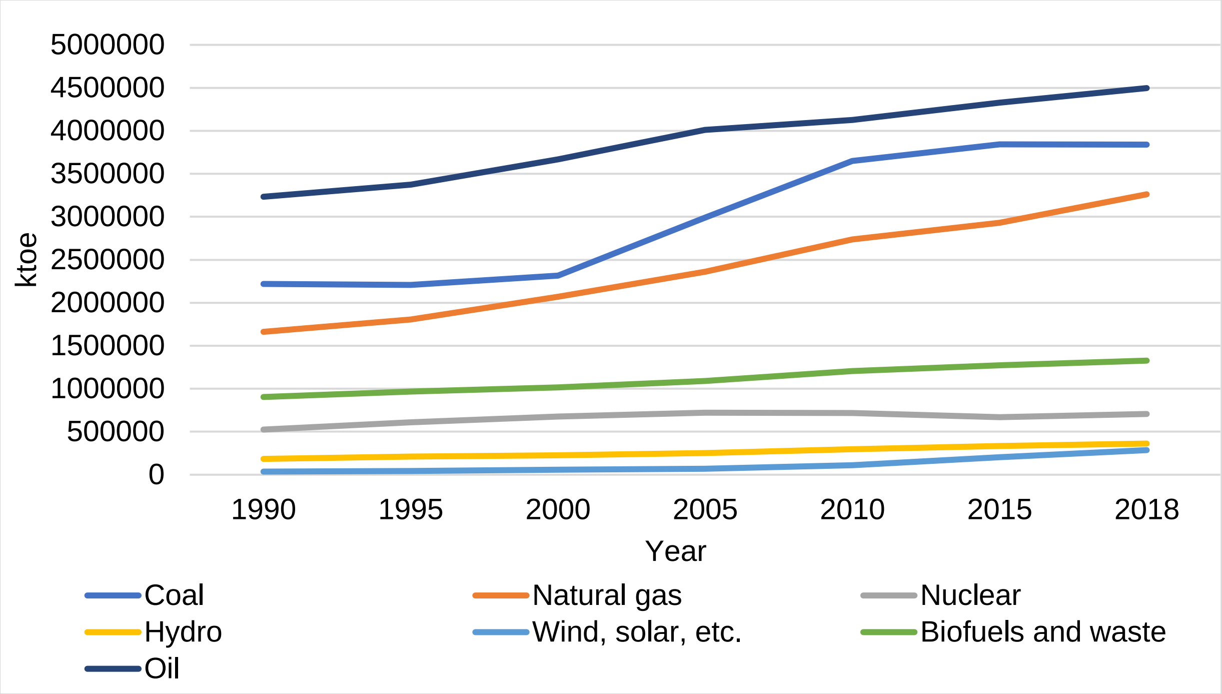


Figure 1.2 Total Global Energy Supply by Source 1990 - 2018

Looking closer to home, within the EU 28 (2018), biofuels and waste made up 160,262 ktoe of the energy consumed, as seen in Figure 1.3 Total EU-28 Energy Supply by Source 1990 - 2018 (IEA, 2020). This equates to 10% of the EU-28 energy mix, which is in line with the global average. The use on non-renewables in the EU-28 has dropped by approximately 10% also during this time period to just over 71%. This is mainly down to the increase in renewable sources being used, with biofuels and waste making up the greatest portion of the increase. The level of nuclear power being utilised, has stayed mostly consistent. Significant research and development will need to be carried out by the EU if they are to reach their target of over 50% of energy sourced from biomass (European Biomass Associtation, 2013). A mere 7% increase in energy from biofuels and waste between 1990 and 2018 means that the substantial work still needs to be undertaken by the EU to reach this goal.

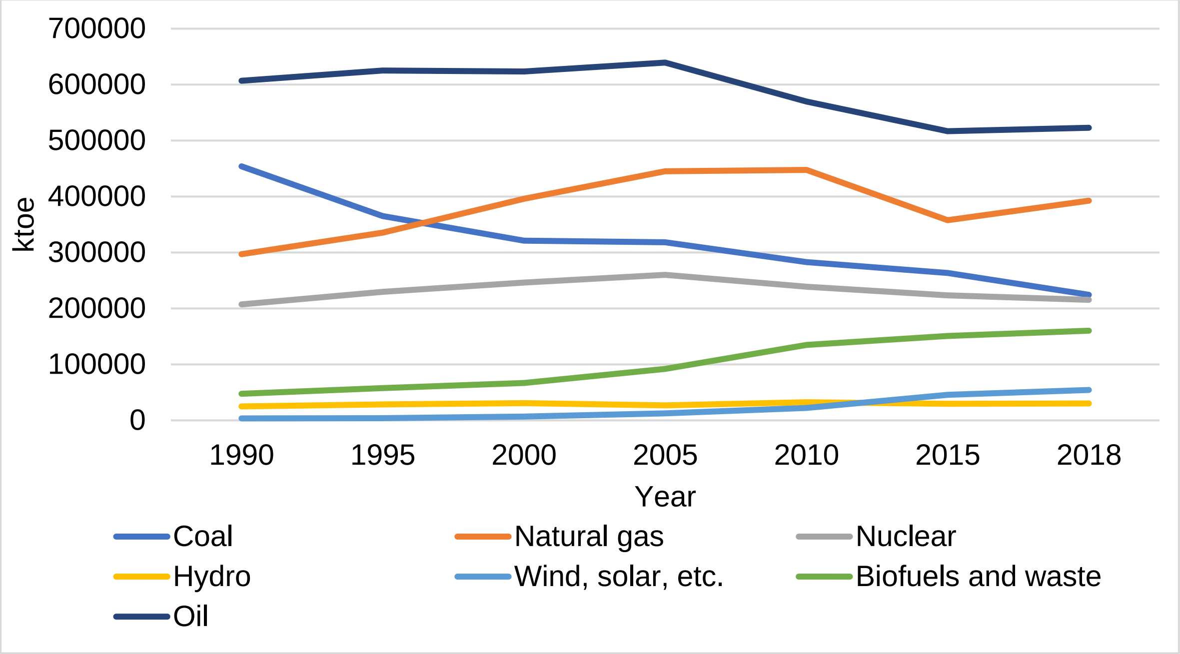


Figure 1.3 Total EU-28 Energy Supply by Source 1990 - 2018

Within the UK, there is also significant room for growth of the bioenergy sector. Figure 1.4 Total UK Energy Supply by Source 1990 – 2019 shows that biomass and waste contribute to 15,670 ktoe of the energy supply in 2019, or 9.2%, continuing the global trend (IEA, 2020). Unlike the global or EU-28 average, the UK's main source of energy is natural gas, with 67,308 ktoe or 39.7% of energy supplied. During this time period of 1990 – 2019, the renewable sources of energy grew by almost 13%. This is mainly due to its low starting point at 0.5% of the total energy mix in 1990. Coal is the major casualty here, with a huge drop from close to 31% of the energy mix to almost 3%. This equates to a 91% reduction in coal usage, and with 0.333 $kgCO_2/kWh_e$ from coal compared to 0.015 $kgCO_2/kWh_e$ for wood chip the environmental benefits are over 20 times greater (DEFRA, 2020).

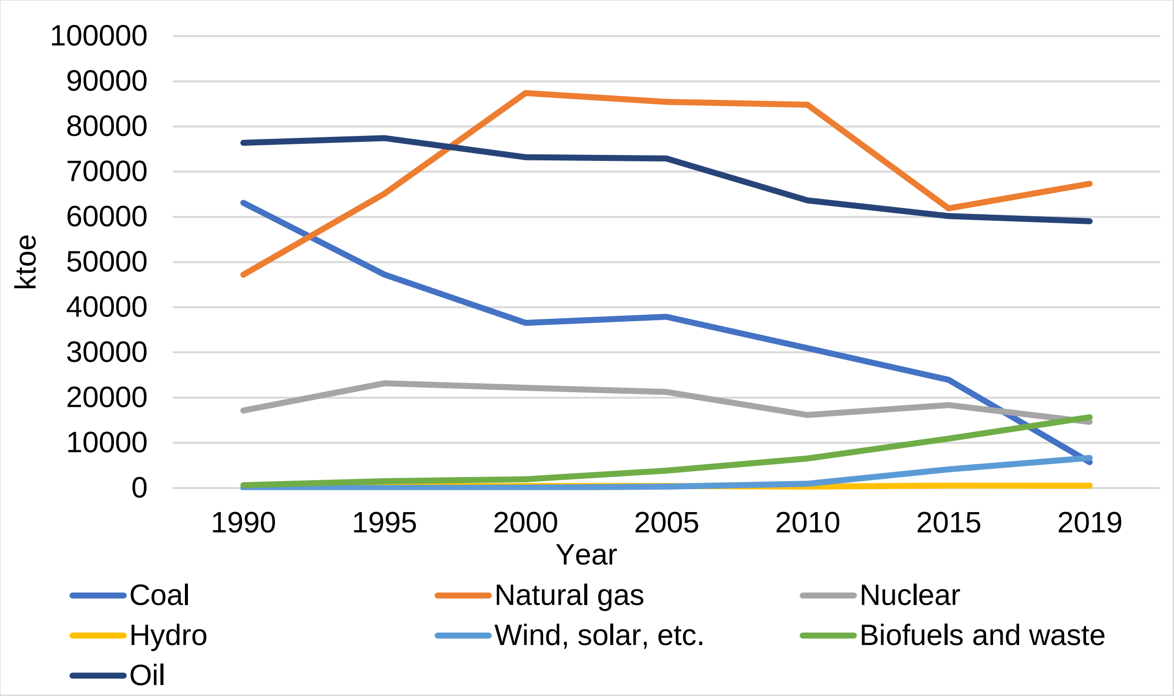


Figure 1.4 Total UK Energy Supply by Source 1990 – 2019

To further understand the current market for bioenergy, and its potential to grow within the UK, we can look at the current usage of biomass and waste materials for energy generation. Within Figure 1.5 UK Electricity generation from Biofuels and Waste by Source 1990 - 2019 we can see the total electricity generated from these materials (IEA, 2021). A total of 38,120 GWh of renewable electricity was generated from these sources in 2019, with 67% of this from primary solid biofuels. Primary solid biofuels are the sum of a few different materials grouped together such as fuel wood, wood residues and by-products such as chip and pellet, along with some vegetal materials (Eurostat, 2021). This electricity generation has room for growth as predictions carried out by Shepherd estimate miscanthus yields of 12 t ha^{-1} year^{-1}, which could supply 0.09 EJ/year or approximately 65% of current bio-electricity yields from one source alone (Shepherd et al., 2020). An obvious example of where growth will come from is the energy sourced from industrial wastes. Currently industrial wastes supply 1,568 GWh of energy, or 4% of the total electricity from biomass. We can expect to see a large increase here when more industries begin to adopt the circular economy approach to their business model and identify potential waste to energy conversion routes for their materials. For the UK to achieve their sustainability target of net zero emissions by 2050, a seismic shift in energy generation methods will need to take place. The largest portion of electricity generated in 2019 still came from non-renewables sources. 43.6% of the total, or 141,191 GWh came from coal, oil and natural gas. Renewables aren't far behind making up 39.03% of the total, or 126,333 GWh, with nuclear making up the difference of 17.3% or 56,184 GWh in 2019. Discussions on whether nuclear energy should be classified as renewable or not continue within the EU today, with two of its main economies, Germany and France, on opposing sides in this argument (Cohen, 2022).

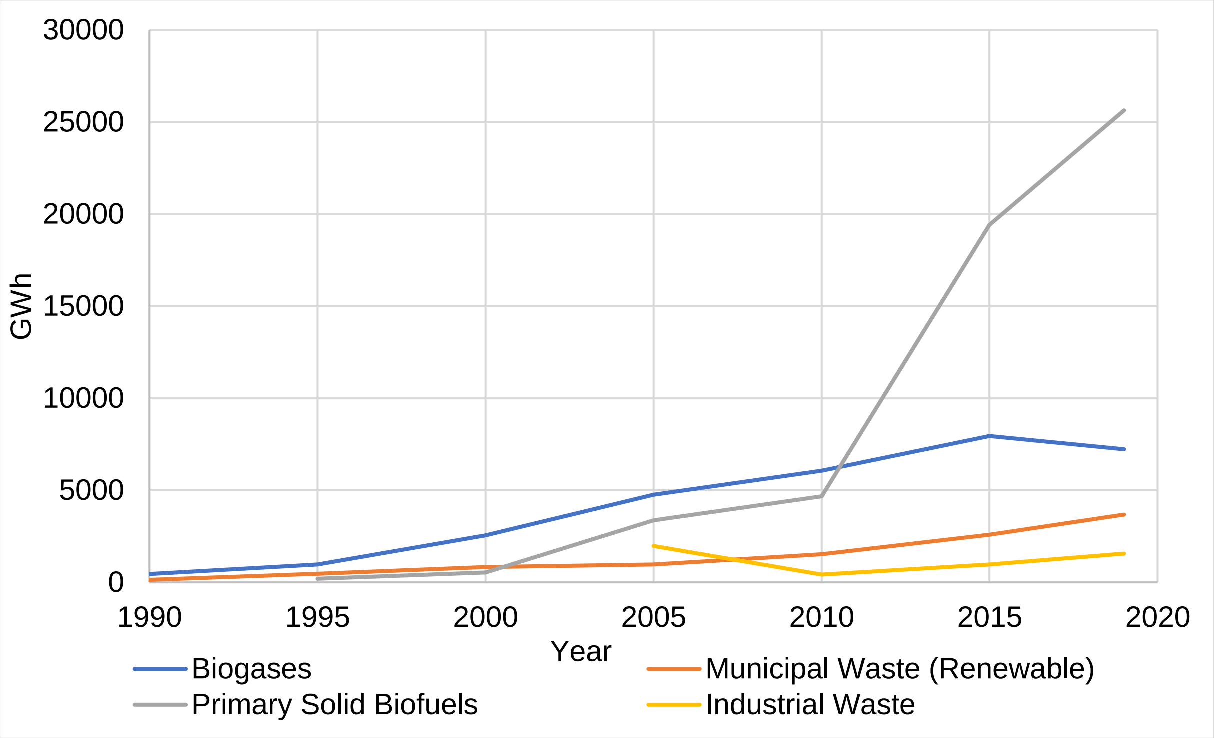


Figure 1.5 UK Electricity generation from Biofuels and Waste by Source 1990 - 2019

One of the issues with trying to increase the level of biofuels in the national energy mix, is that of supply vs. demand. International policy has concluded that an increase in biomass usage is required to meet sustainability and climate change targets. Who makes the first move is the question? Governments will not provide funding for sustainable biomass conversion projects if a guaranteed source is not available. Similarly, farmers or other suppliers of biomass won't commit to producing the required biomass if contracts are not in place for purchasing, it's too great a financial risk to burden. It's a chicken and egg situation, where you ask which one comes first. How can we ever hope to achieve the lofty targets set out if the supply chain cannot guarantee the feedstock? Energy will be required, whether the biomass can be sourced sustainably or not. Currently the regions with the highest demand for biomass are also ones with the lowest resource availability (Welfle, 2017). This isn't to say that biomass isn't available in these regions, but the type of biomass required isn't available. This can be attributed to the fact that large scale biomass combustion plants have been designed with pellets or chip in mind as the feedstock of choice. This design has led to an increase in international trade of biomass pellets, with Europe at one point importing 30% of all biomass it consumes (Welfle, 2017). This figure has reduced to approximately 4% recently (European Commission, 2019). Transcontinental transport of feedstocks off sets any emission savings achieved by member states, if they are still relying on it. These pelleted and chipped material arrive through shipping or long-distance haulage, which is at fault for a significant proportion of GHG emissions. To avoid this issue more emphasis should be placed on the use of sustainable biomass materials. This includes production of biomass locally and using resources readily available as feedstocks, avoiding reliance on international trade of biomasses. Potential feedstocks could include agricultural wastes, industry wastes such as forestry waste or sludges from wastewater treatment plants. To further increase the sustainability of biomass, certain industries could utilise their wastes or by-products as an energy source. An example of this is the potential for the poultry industry to use the litter generated to provide the heat and electricity required by the sheds through gasification and downstream application of the producer gas. This research will focus on this circular economy approach to energy production.

For a change in human behaviour to occur, an incentive or catalyst for change must exist. The main driver of this change has been and will continue to be policy introduced by governments at all levels. The change from a fossil fuel based economy to a sustainable fuel’s economy could not occur if it were not for government intervention as most people would remain content with the status quo. A significant amount of this legislation for change has already been introduced both nationally and internationally to try and tackle the issues of global warming, along with ensuring more stringent environmental protection. These can come in the form of international accords that large numbers of countries sign up to, right down to policy introduced by a local town or city council. With the overall goal of protecting the environment from further harm, they each have their own important part to play.

The most important pieces of international policy that have been adopted in the past 25 years are the international protocols brought into existence by the UN. These include the Kyoto Protocol in 1997 and more recently the Paris Climate Accord, signed off in 2016. These protocols were introduced to try curb what had been rising levels of GHG's, mainly CO_2, CH_4 and nitrous oxide (N_2O). The Kyoto Protocol committed industrialized countries to limit their GHG emissions by an agreed amount, with each agreeing to individual targets. The burden was placed upon developed countries, as it was agreed they had been responsible for a large portion of the then emissions. An example of the commitment required by the Kyoto Protocol was the UK's legally bound target of reducing their emissions by 12.5% compared to 1990 levels, by the year 2012. A more recent international agreement to tackle climate change and its effects is the Paris Climate Accord. It is another legally binding agreement that sets a goal of limiting global warming to below 2, and preferably 1.5 degree Celsius. The Paris accord differs from Kyoto, as it allows the individual signatory countries to decide on how they can best assist with reaching this target. This allows for each country to develop their own climate strategy. Individual countries can therefore adopt technologies and put systems in place that will have the greatest affect, and not be burdened by being told what to do. This allows each signatory to forge their own approach, using local customs and resources to their benefit.

The European Union has implemented its own climate change focused legislation. In 2009 the Renewable Energy Directive (2009/28/EC) was introduced (European Parliament, 2009). This directive outlined plans for the union to achieve 20% of its energy requirements from renewables by the year 2020, as well as committing individual countries to achieve 10% of transport fuels from renewable sources. Member states were required to transpose this into their own national law. This piece of legislation was enough when first introduced, but once the Paris Climate accord was adopted, the EU realised an increase in efforts was required if its position as a global leader in renewables was to be held. Therefore in 2018 the EU introduced the recast Renewable Energy Directive (2018/2001/EU) with new binding targets for member countries (European Parliament, 2018). This was to achieve 32% of energy from renewable sources by 2030 and 14% of transport fuel from renewables as well. The EU also reserves the right to further increase these targets in 2023.

Environmental protection policy that the EU have introduced is the Waste Incineration Directive which was introduced in 2000 and replaced in 2010 by the Industrial Emissions Directive (IED)(2010/75/EU). The IED is the main method through which the EU can monitor and regulate emissions from industrial applications, with the aim of keeping adequate air quality throughout Europe (European Parliament, 2010). IED is based off an integrated approach for the entire environmental performance of a plant and the use of best available technology for optimum environmental performance. The introduction of this catch all legislation allowed for the thermochemical treatment of certain waste products, such as poultry litter, if in an IED compliant system. For protection of waterways and soil across Europe, the EU introduced the Water Framework Directive (WFD) as Directive 2000/60/EC. This was first adopted in the year 2000 and took on the problem of managing water quality throughout Europe for surface and ground waters (European Parliament, 2000). This like other EU legislation was done through an integrated approach of manging water from a river basin unit and not based on political or administrative boundaries. This legislation set out limits on minimum water quality, as well as a timeline for achieving good quality water status for all waters within the EU by a set deadline. The integrated approach covering all of Europe streamlined vast amounts of legislation in the field and paved the way for member states to improve their own water quality.

The UK has its own policy in place to deal with climate change and the issues surrounding it. They had originally taken instruction from the EU, but now since Brexit has taken place, they are no longer required to comply with EU based directives. The main policy to tackle climate change and environmental protection in the UK was the 2008 Climate Change Act, through which the UK committed to reducing GHG emissions by 80% by the year 2050 compared to 1990 levels, through 5 yearly carbon budgets (DEFRA, 2008). Renewables Obligations was introduced in 2002 across England, Wales and Scotland and in 2005 in Northern Ireland (Ofgem, 2021a). It replaced the Non-Fossil Fuel Obligation which ran from 1990. It encouraged the production of renewable electricity and placed an obligation on licensed suppliers to provide increasing amounts of it. In 2019 the UK government became the first major economy to commit to net zero emissions by the year 2050. This was done through an amendment to the climate change bill and shows an increase on previous commitments of 80% reduction. The UK met its targets for the first two carbon budgets, 2008-12 and 2013-17, but achieving the goals of future budgets isn’t as certain.

As a member of the UK, Northern Irelands (NI) policy is heavily influenced by the government in Westminster. Even though the UK government introduced the 2008 Climate Change Act, NI's devolved government has yet to adapt it into national legislation. As of December 2020, a consultation on the NI Executives first ever climate change bill was launched. NI had seen a reduction in GHG's of 20% compared to 1990 levels, but to achieve the net zero goal by 2050 as set out by the UK government, a robust and coherent strategy must be put in place soon or the opportunity will be missed. Even though no climate change bill exists within the legal framework of Northern Ireland, there is important legislation in place in terms of environmental protection. One of the most noteworthy of these is the Nutrient Action Programme Regulations (NAPR) (DAERA, 2019). This programme puts measures in place to ensure the protection of waters against pollution from agricultural sources. Over application of farm or industrial wastes for nutrient replacement in the soil can lead to harmful effects such as eutrophication or local waterways. With the ever-increasing industrialisation of farming, these regulations provide a basic level of protection to all waterways from the adverse effects of agriculture. Northern Ireland is no longer a member of the EU, but the NAPR would have been influenced by the WFD that was introduced prior to its exit. For clarification, Northern Ireland remains in the EU's single market for goods, and therefore must follow EU rules on customs and agri-food products for goods arriving in the country (Assembly, 2021). Whether this will have any impact on policy is yet to be seen.

1.2 Novelty

The novelty associated with this research, as discussed in the following chapter (Chapter 2), is the use of blends of various biomass and biowaste materials to increase the overall efficiency and performance of the downdraft gasification system with engine application. A techno-economic and environmental assessment of the system will also be carried out to add further evidence and justification to the research. Using novel blends of previously unresearched materials, the downdraft system with engine applications can be optimised in terms of conversion efficiency, producer gas lower heating value (LHV), gas yield and by-product generation. Using the 3 different blend ratios, 80/20, 60/40 and 40/60, their influence on the downdraft gasification system will be evaluated with a focus on the application of the technology within both Northern

Ireland and across Europe for both financial and environmental impact. Identifying possible users of the technology will demonstrate the potential of the proposed new system.

1.3 Justification and Objectives

It is clear from the information above that there is a significant opportunity for biomass to be used as a sustainable alternative to fossil fuels for heat and electricity production around the globe. Gasification has the potential to become the biomass conversion method of choice through higher conversion efficiencies than direct combustion for some practises, and versatility in its application through the production of a producer gas.

The aim of this project is to develop a comprehensive performance analysis of an entire biomass gasification system with novel blended feedstocks. This includes an economical concept for biomass supply chain management, pre-treatment, production of producer gas and utilisation of biomass/waste, by means of biomass gasification for electricity and heat production. This overall aim will be achieved through 4 objectives:

1. *Process Modelling* – develop the feedstock supply chain and gasification process models for the integrated biomass gasification and CHP system. The models developed will be used to evaluate technical, economic and environmental performance of micro – generation fuelled by biomass
2. *Experimental Study and Model Validation* – Experimental work and analysis of selected feedstocks for a range of process conditions, leading to pilot test results
3. *Process Integration* – Producer gas generated by a downdraft gasifier will be cleaned, analysed and fed to an internal combustion engine for the application of combined heat and power
4. *Assessment* – Techno-economic and environmental assessment of the full bioenergy production chain carried out through LCA and techno-economic analysis of the system

1.4 Thesis Structure

This thesis will be structured into 9 chapters, each dedicated to a different aspect of the research. The present introduction chapter covers the background to the research project, explaining the justification of the work, defines the novelty of the work and the potential applications. It discusses the history and current availability of biomass, and the various pieces of legislation and policy which are the driving forces behind it.

Chapter 2 is a comprehensive literature review, covering the entire scope of biomass gasification and highlighting the gaps in the literature that justifies the work carried out. It includes literature from every aspect of the research project including biomass selection, experimental parameters, gas cleaning, modelling techniques and application of the producer gas in downstream equipment.

Chapter 3 will discuss the methodology chosen to carry out the various analysis included in this research. It will be heavily influenced by the literature review. The methodology will assist with reaching the overall aim, through a set of achievable objectives. Material analysis, modelling techniques and producer gas generation are some of the topics covered.

Chapter 4 is on the results generated from experimental analysis. This is carried out through practical analysis of the feedstocks of interest in a pilot scale fixed bed downdraft gasifier. Feedstock experiments are ran in triplicate to ensure accuracy of results. A complete feedstock elemental and proximate analysis was carried out to understand the composition.

Chapter 5 is on the simulation and modelling carried out to represent the various gasification reactions, as well as the application of the producer gas in downstream equipment and techno economic analysis of the system. The software used to carry this out is ECLIPSE simulation package. Some of the important modelling parameters are gas composition, LHV and yield (Nm^3/kg).

Chapter 6 covers the life cycle analysis of the entire system from feedstock collection, material processing, downdraft gasification and application of the producer gas. All relevant emissions will be calculated using the ECLIPSE simulation software and compared using SimaPro LCA software. The environmental impact of heat and electricity generated from the producer gases of different feedstocks will be compared to traditional generation methods.

Chapter 7 will discuss the finances associated with the research. It will cover the net present value (NPV) and break-even selling price (BESP) of electricity generated and propose a potential payback period (PBP) for users who would install the suggested technology. The economics will cover the cost of purchasing equipment, the potential money saved on disposal of waste products and fossil fuel displacement, as well as any incentives that the system may be eligible for.

Chapter 8 is the discussion section, where the results that have been generated are discussed in detail and interpreted. Understanding the results and the impact that blending had on them is the important section of this work. Changes if I were to repeat the analysis or how to continue the work will also be discussed.

Chapter 9 draws the conclusions from the entire research. It clarifies the scientific outcomes of the research, as well as suggesting potential policy which could be proposed to support the introduction of downdraft gasification feedstock blending.

Chapter 2 – A Review of Fuel Gas Production from Biomass and Bio – Waste

2.1 Introduction

This chapter will provide a comprehensive overview of the research previously carried out in the field of biomass downdraft gasification, identifying the important parameters which will influence the experimental analysis to be carried out, as well as explicitly identifying the gap in the knowledge which this thesis aims to fill. The need for this research is because the demand for energy globally has been steadily rising, and the means to meet this demand is in jeopardy. Traditional energy sources such as fossil fuels, which have been negatively impacting the environment in the form of climate change, are depleting to the point where an alternative is required. (Baruah and Baruah, 2014).

Alternative energy sources and technologies must be utilised to ensure energy security into the future. Renewable technologies have proliferated in recent years, with solar and wind experiencing significant increases in their utilisation across the U.K. Installed capacity for solar across the UK reached over 13,200MW by March 2019, while combined on and offshore wind energy has an approximate operational capacity of over 20,000MW as of April 2019 (DECC, 2019; RenewableUK, 2019). Another renewable energy source that hasn’t seen the same level of installation but has significant scope for growth is biomass, with substantial amounts of sustainably sourced biomass and waste materials available for energy production.

The overhaul of current energy generation methods is being supported by all stakeholders, such as industry, governments and the general public for a variety of reasons. Many renewable targets have been set by a variety of policies. The 2009 Renewable directive sets the UK a target of 15% of energy to be produced from renewable sources by 2020, as well as a commitment to 30% emissions reduction by 2020 as set out in the National Renewable Energy Policy (DECC, 2009). These commitments are all part of a more long term plan that the U.K government has agreed to for 2050, where the government wants to reach net zero carbon emissions (Government, 2019). Northern Ireland’s obligations were to generate 40% renewable electricity and 10% renewable heat by 2020 (Department of Energy & Climate Change

(DECC), 2011). New targets are yet to be ratified by the NI assembly. To achieve these new targets, emerging renewable technologies must be incorporated.

The technology of interest for this research has great potential to increase renewable heat and electricity across Northern Ireland and the rest of the U.K. This is biomass gasification coupled with a combined heat and power (CHP) system. Due to the significant agricultural economy and large biomass resources available, gasification could become a major part of the renewables sector. The agricultural industry across the UK contributes to approximately 1% of the entire national economy and employs 1.53% of the national workforce (DEFRA, 2019). Utilising resources from this industry will encourage sustainability and further growth, as well as protecting what is a vital employer of people. This project will focus on identifying the best available waste and sustainable biomass for gas production, modelling the process to identify potential energy, cleaning of the producer gas to ensure successful application can take place and ensuring the entire life cycle of the process is both economically and environmentally sustainable.

2.2 Feedstock Preparation

The gasification of biomass material is becoming an ever more popular source of energy globally, as many people are trying to minimise their fossil fuel use and look for more environmentally friendly methods of generating energy. This method of energy production isn’t without its complications, and many of these need to be tackled before any material is introduced to the gasifier. Biomass varies in physical and chemical structure geographically, so to ensure a consistent performance, pre-treatment or pre-processing of the various materials may need to take place (Sansaniwal et al., 2017). Due to the non-uniform nature of biomass’ and their associated physical characteristics, feedstock preparation becomes an important step in the process to ensure a consistent fuel source for the system (Widjaya et al., 2018). The most appropriate methods of pre-treatment for biomass gasification are physical pre-treatment methods such as drying, size reduction and densification (Sansaniwal et al., 2017). The quality of producer gas generated from the gasification process is directly affected by the physical biomass characteristics (Susastriawan et al., 2017).

Achieving the ideal characteristics for each is therefore crucial for the success of the overall process.

2.2.1 Drying

Depending on the biomass materials of interest, high moisture content may be an issue that requires resolving. Waste and non-woody biomass may contain significant amounts of moisture, up to 50wt.%, which will need to be removed before gasification (Asadullah, 2014a)(Kumar et al., 2009). The calorific value of the producer gas can be negatively affected by high moisture content, resulting in a gas with a low calorific value (Susastriawan et al., 2017). This occurs when energy is spent evaporating excess energy from the biomass material, detracting from the net energy produced (Ruiz et al., 2013). An ideal moisture content for gasification is in the 10 – 15 % range. Drying can be an energy intensive step in the process, which can decrease the overall efficiency of this energy production method. To avoid this occurring, excess heat from the gasification process can be recovered to dry fresh biomass (Widjaya et al., 2018). This would avoid using approximately 20% of the energy produced for material processing (EPC, 2021a).

2.2.2 Size Reduction

The irregular shapes and sizes of various biomass materials can lead to significant issues when feeding the material into the gasification system. These characteristics can lead to problems during the gasification process such as bridging and throat blocking of the gasifier (Susastriawan et al., 2017). Increased gas yields and overall increase in process efficiencies have been identified when particle size is reduced (Kumar et al., 2009). A smaller particle size gives a much larger surface area for heat transfer activity, which increases the gasification efficiency, and the production of better quality producer gas (Asadullah, 2014a). Grinding or milling are common methods of particle size reduction with Tub Grinders, Hammer-Mills and Knife Mills some of the equipment of choice for carrying this out (Sansaniwal et al., 2017). Optimum particle size for pellet production is between 0.5 – 2.0mm (Puig-Arnavat et al., 2016).

2.2.3 Densification

Many biomass materials have irregular shapes combined with low bulk and energy density (Widjaya et al., 2018). These characteristics also lead to the issues of throat blocking and bridging (Susastriawan et al., 2017). To avoid these issues, densification of the low bulk and energy dense material needs to take place. Common methods of biomass densification include balling, briquetting and pelleting (Asadullah, 2014a). For gasification technology, pelleting is often the method of choice, using pellets 1 – 2cm in size with fixed bed designed gasifiers (Widjaya et al., 2018). Pelleting of material has also been seen to lower the amount of ash generated, as well as increasing the overall efficiency of the process, due to removal of variability in the feedstocks (Ruiz et al., 2013). Pelleting often requires a binding agent to hold the material together, but in woody biomass naturally occurring lignin carries this out (Puig-Arnavat et al., 2016). Due to the high costs associated with pelleting biomass material, it has not been adopted on a widespread scale yet. Financial barriers are preventing the proliferation of the technology (Sansaniwal et al., 2017). Further gains in this area will bring down the costs associated with pelleting, leading to improvements in the handling, transport and storage of biomass (Puig-Arnavat et al., 2016).

2.2.4 Proximate & Ultimate Analysis

Due to the significant variations in biomass feedstocks, from their physical to chemical composition, it is important to carry out proximate and ultimate analysis on the materials before they are used as fuel (Gillespie et al., 2013). Such variety in composition can be down to any number of factors such as climate, soil characteristics or plant make-up. Fuel quality is significantly affected by these, which in turn affects the quality of producer gas created during the gasification process (Susastriawan et al., 2017). The fuel features which can be identified through this analysis includes moisture content, ash content, volatile matter, calorific value and elemental formation (Kozlov et al., 2015). This data can be gathered using relatively common lab equipment, and utilising the information the heating values of each biomass can be calculated theoretically, without the need for further expensive equipment (Demirbas, 1997). The higher heating value (HHV) is thought of as the most important factor when discussing the properties of biomass, as it can assist with the design and operation of biomass equipment and storage (Gillespie et al., 2013). Further importance is put on the ultimate analysis because of its use in modelling of the gasification process. Once the elemental composition is known, as well as the chemical reactions which occur during the process, modelling of the system can take place, to accurately predict products of the reactions (Ferreira et al., 2019).

2.2.5 Feedstock Selection

To ensure quality performance and sustainability of the project, the selection of feedstocks for gasification is a critical step. Common criteria that are usually the deciding factor for feedstock choice are abundance and availability (Vaezi et al., 2012). While these parameters are clearly very important for successful operation, they are only two factors amongst many which should be considered during the selection process. Sustainability, energy and moisture content are further parameters of importance. Biomass with moisture content below 30% are suitable for gasification, with those above this producing poor quality producer gas (Susastriawan et al., 2017). Feedstocks selected should be below this threshold, to avoid unnecessary energy being used on drying of material. Calorific value of the biomass should be investigated before selection, as it can be a gage for potential producer gas calorific value. The calorific value of solid biomass can be indicated by the carbon and hydrogen content of the material (Demirbas, 1997), which also has an influence on the potential calorific value of the producer gas. This data can be gathered from the simple proximate analysis and used to make informed decisions about which material will be able to generate significant energy.

With a focus on Northern Ireland, and potential biomass available here, the feedstocks of choice for this analysis have been selected as they each meet the sustainability, abundance and physical traits require for successful operation. These include various wastes, energy crops and potentially sustainable fuels, which can generate significant amounts of energy through the gasification process. Like many other countries, Northern Ireland has an economy that is heavily dependent on agriculture and associated works. This means that significant amounts of wastes from this industry should be available for energy production (Roy et al., 2013). These wastes which have been included for this project are poultry litter, arboricultural arisings, anaerobic digestion (AD) digestate and paper. Over 270,000 tonnes of poultry litter material was produced in 2016 across Northern Ireland, a figure which has increased in the meantime (Macauley, 2016). An average AD plant in Northern Ireland would produce 15,499 tonnes of digestate material per annum also (Cathcart et al., 2021). Some energy crops have also been included as they have great potential for proliferation, such as miscanthus and willow. Through the gasification as what would commonly be accepted as low quality biomass i.e. poultry litter and AD digestate, and introducing a blend of wood pellets, conversion efficiency and producer gas quality may be improved upon compared to poultry litter or AD digestate alone.

2.3 Downdraft Gasification

Biomass gasification is a thermo-chemical reaction that converts solid fuel into gaseous form (Kirsanovs et al., 2017). It is seen as an attractive alternative to more widespread energy production methods, such as combustion of fossil fuels or even more recent developments, for example solar and wind energy technologies. Many issues associated with fossil fuel combustion aren’t applicable to gasification technology such as; depleting resources, pollution emitted to atmosphere and climate change issues (Tańczuk et al., 2016). Comparing gasification to other renewable technologies, there are also numerous advantages. In comparison to wind or solar technologies, the advantages of gasification are its lack of weather dependency (Patra and Sheth, 2015). The operating conditions, as well as the type of gasifier, have a major impact on the quality of producer gas. These conditions include temperature, pressure, gasifying agent, catalysts, equivalence ratio (ER) and residence time to name but a few (Devi et al., 2002). Optimisation of each parameter is vital for high quality producer gas production.

2.3.1 Gasifier Selection

Many different styles of gasifier exist, and each can be classified depending the type of bed and the flow direction of feedstock and air. (Kumar et al., 2009). The gasifier bed can either be fixed, fluidized or entrained, with fixed bed capable of further division into updraft, downdraft and cross-draft gasifiers (Rakesh and Dasappa, 2018a). Updraft and downdraft fixed bed gasifiers have been the most extensively researched models (Asadullah, 2014a). In updraft gasifiers, the feedstock is introduced from the top and flows down, while the gasifying agent is introduced through the bottom. The producer gas exits the system at lower temperatures at the top of the apparatus, leading to high levels of tar (Kumar et al., 2009). In a downdraft gasification system, feedstock and gasifying agent travel downwards, as can be seen in Figure 2.1 Gasification in a Downdraft Gasifier. This leads to the producer gas having a lower tar content (Bunchan et al., 2017). This lower tar content makes the downdraft system more attractive when coupling the gasifier with further equipment, such as an ICE (Rakesh and Dasappa, 2018b). Comparison between the various gasifier types can be seen in Table 2.1 Gasifier Comparison (Briesemeister et al., 2017; Sansaniwal et al., 2017; Widjaya et al., 2018). Downdraft was chosen as the method of choice because it operates at the correct scale, producing the least amount of tar and in the best temperature range to avoid ash melting.

Table 2.1 Gasifier Comparison (Briesemeister et al., 2017; Sansaniwal et al., 2017; Widjaya et al., 2018)

	Fixed Bed		**Fluidised Bed**		**Entrained Flow**
	Downdraft	***Updraft***	***Bubbling Bed***	***Circulating Fluidised***	
Suitable Scale	Small - Medium	Small - Medium	Small - Large	Medium - Large	Medium - Large
Typical Tar Content (g/Nm^3)	0.1 – 1.2	20-100	0.9 - 15	0.9 – 15	0.2 - 1
Gasification Temperature (°C)	700 – 1200	700 - 900	<900	1450	1450
Feedstock Preparation	Critical	Important	Less Important	Less Important	Fines Only

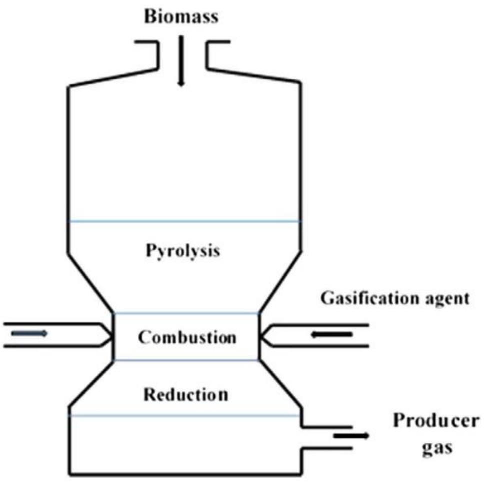


Figure 2.1 Gasification in a Downdraft Gasifier (Shayan et al., 2018)

2.3.2 Gasifying Agent

The choice of gasifying agent, sometimes known as gasifying medium, is an important decision as it can influence the overall efficiency of the process, and the producer gas composition (Prins et al., 2003). The main goal of the agent is to rapidly convert the biomass feedstock into a clean producer gas, using a variety of heterogenous reactions (Jangsawang et al., 2015). The most common choices of agent are air, oxygen, and steam, each with their own advantages and disadvantages (Baruah and Baruah, 2014). Depending on the planned end use of the producer gas, each will also have a different heating value as can be seen in Table 2.2 Heating Values for Product Gas Based on Gasifying Medium (Basu, 2018). Using air as the agent is the cheapest option, but dilutes the producer gas with nitrogen, lowering the calorific value (Puig-Arnavat et al., 2010). Oxygen as the agent will avoid the problem of nitrogen dilution but will lead to an overall more expensive set up, due to the cost associated with oxygen production (Widjaya et al., 2018). Steam will lead to an increase in hydrogen content of the producer gas, and higher heating value, but it will lower the overall thermal efficiency of the process due to the energy required for steam production (Asadullah, 2014a). Costs associated with the gasifying agent will increase when changed to steam or O_2, but no price has been indicated within the literature (Alauddin et al., 2010).

Table 2.2 Heating Values for Product Gas Based on Gasifying Medium (Basu, 2018)

Medium	**Heating Value (MJ/Nm^3)**
Air	4-7
Steam	10-18
Oxygen	12-28

2.3.3 Biomass & Air Flow Rate

Flow rates are critical in the fight against tar production. Near tar free gas can be produced with the optimal flow rate (Dasappa et al., 2004). Overfeeding of biomass into the system can cause issues such as blockages, which will impact on producer gas quality, similar to underfeeding of the system (Kumar et al., 2009). Therefore, optimisation of flow rates is critical. Biomass feeding rates in gasification are optimally between 30kg/h and 80kg/h Dry and Ash Free (DAF) depending on biomass types (Biagini et al., 2016). When talking about gasification, the flow rate of biomass is closely linked to the residence time, as it relates to the amount of time the biomass spends on the bed. For complete conversion of solid biomass into gaseous form, the material needs to have sufficient time on the gasifier bed (Sette et al., 2014). Failure to carry this out will mean that unconverted material will be present, in the form of excess char, leading to poor gas quality (Dai et al., 2015). As is true with other parameters, air flow rate also influences efficiency of the process. Increasing air flow leads to higher heating value producer gas, up to a flow rate of 5m^3/hr (Bunchan et al., 2017).

2.3.4 Equivalence Ratio

The equivalence ratio (ER) is the amount of air in a reaction, compared to the required amount for stoichiometric combustion (Prins et al., 2003). By regulating the ER, a thermochemical reaction can be classified as pyrolysis (ER =0), gasification (ER = 0.25 – 0.50) or combustion (ER ≥ 1). The ER is a measure of the air flowrate during the gasification process (Kumar et al., 2009). An optimum ER can be identified, where the fuel has gone through complete gasification with oxygen, but not so far as to begin producing solid carbon (Jangsawang et al., 2015). Biomass fuel choice also has an impact on the ER, as each biomass will require a different amount of oxygen to reach complete gasification (Asadullah, 2014a). The ER further influences the gasification process end products such as tar formation, gas make-up and calorific value of product gas (Sansaniwal et al., 2017). This parameter needs to be thoroughly investigated, as when temperature is altered the ER will also need to be changed. Therefore, optimizing the parameter is critical to successful gasification.

2.3.5 Gasification Temperature

The temperature at which gasification takes places is the final operating parameter which has a direct impact on producer gas composition and other properties such as tar content, reaction rates and ash formation (Emami Taba et al., 2012). Gasification usually takes place in the temperature range of 750 - 900°C, depending on the particular system set up (Cheng, 2010). Higher gasification temperatures can lead to better gas yields due to greater conversion efficiencies, and lower tar content, while lower temperatures lead to high tar content (Kumar et al., 2009). Increasing the temperature above 900°C to obtain a greater gas yield isn't advised, as it can lead to ash melting, which can cause damage and block internal piping (Asadullah, 2014a). Increasing the ER can lead to a temperature increase in the gasification process, as this will lead to improved combustion processes in the oxidation zone (Susastriawan et al., 2017). This improved combustion means a greater portion of H_2 and CO will be generated, leading to an increase in LHV (Asadullah, 2014a).

2.4 Producer Gas Cleaning

Once all feedstock preparation, process optimization and downdraft gasification has occurred, a producer gas of some quality will be generated. This producer gas will be contaminated with significant amounts of foreign material, such as particulates, unwanted chemicals and tar. The exact type and concentration of contaminants will vary with biomass feedstock (Asadullah, 2014a). This raw producer gas cannot be used for further downstream applications due to the severe threat of fouling and clogging (Devi et al., 2002). A variety of steps are available to assist with the removal of these impurities, to ensure a high quality producer gas for further downstream applications such as internal combustion (IC) engines or fuel cells (Rakesh and Dasappa, 2018a).

2.4.1 Particulate Removal

Particulates are a variety of solid impurities that have been picked up throughout the gasification process. They can include soot, char, fly ash and mixtures of organic and inorganic composites (Weiland et al., 2014). Depending on the use of the product gas, particulates level must be decreased. For example, particulate level must be below 50 mg/Nm^3 for use with gas engines and even lower for use with turbines, 15 mg/Nm^3 (Rezaiyan and Cheremisinoff, 2005). The most effective methods of particulate removal are wet scrubbers, barrier filters and cyclonic separators. The first step in most gas clean-up systems is that of the cyclone, due to its simple design. It is used to remove the larger particles from the gas (>20µm) (Cheng, 2010). Several cyclones can be used to increase effectiveness, and ensure better separation (Kumar et al., 2009). They operate through the use of centrifugal force, separating the solid portion from the gas, with little or no pressure drop across the system (Rezaiyan and Cheremisinoff, 2005). Barrier filters are another method through which particulates can be removed. They operate on the condition of capturing particulates through inertial impaction, interception and diffusion (Woolcock and Brown, 2013). These filters can remove smaller particles (<2.5 µm) but are dependent on temperature. Filters can be made from a variety of materials, such as sintered metal, ceramic or packed bed of materials. These filters each have their own optimum working conditions, depending on the material of interest and the operating temperatures (Cummer and Brown, 2002). The final common method of particulate removal from producer gas is by wet scrubbers. This set up uses a liquid spray, to trap contaminants in the gas stream. The most popular design of scrubber is a Venturi, where a pressure drop is used to allow for spray across the producer gas (Rezaiyan and Cheremisinoff, 2005). This lets a large proportion of particulates to be removed from the stream, but also has some issues related to it. Due to the mist form of the water, producer gas is cooled to below 100°C, leading to a loss of sensible heat (Kumar et al., 2009). Significant contaminated water is also produced from the scrubbing system, which creates as added cost as it must be treated before disposal (Abdoulmoumine et al., 2015).

2.4.2 Alkali, Nitrogen & Sulphur Removal

Alkali

Biomass traditionally has rich concentrations of alkali metals such as Calcium Oxide, Potassium Oxide, Phosphorus Pentoxide, and many more, present (Liu et al., 2018). They can range anywhere between 1 and several thousand ppm (Salo and Mojtahedi, 1998). At the elevated temperatures that occur during the gasification process, these compounds can vaporize, and when cooling occurs further downstream, will reform leading to clogging and blockages of internal pipes, reducing process efficiency as well as possible corrosion (Ruiz et al., 2013). The limit of alkali metals at which downstream application can operate is approximately 0.1ppm by weight (Salo and Mojtahedi, 1998). Other possible side effects of alkali metals in the gasification process is the inactivation of catalysts which have been added to crack tar. To remove these potentially harmful components, filters such as Teflon bags or packed beds of material are used (Laatikainen-Luntama and Kurkela, 2015).

Nitrogen

Nitrogen in the producer gas is introduced when air is utilised as the gasifying agent. While not taking part in the reaction, it significantly lowers the LHV due to dilution of the gas (Devi et al., 2002). The nitrogen contaminants present during the gasification process, typically comes from the proteins, amino acids and chlorophyll present in the biomass feedstock (Gambarotta et al., 2018). This nitrogen could potentially leave the system in the form of hydrogen cyanide, nitrogen oxide and ammonia. These are known to be precursors to NO_X, which is acknowledged to cause harmful air pollution (Broer and Brown, 2015). The method of removal of such nitrogen compounds depends on the end use of the gas. If hot gas is desired then catalysts such as iron or nickel-based catalysts can be utilised, otherwise wet scrubbers can remove all nitrogen components if cold gas is required (Hongrapipat et al., 2012).

Sulphur

Most biomass feedstocks contain only small amounts of sulphur, but if left untreated this can convert into Hydrogen Sulphide or Sulphur Dioxide during the gasification process. These chemicals can potentially inhibit any catalysts which have been added to the feedstock for syngas clean-up (Dutta et al., 2012). The release of these potentially harmful chemicals can be circumvented through the adjustment and optimization of various gasification parameters, such as the temperature of reactions and gasifying agent (Pinto et al., 2010). Other than adjusting the parameters, absorber columns can be utilised for the removal of sulphur. Here chemicals such as polyethylene glycol dimethyl ether or methanol remove the sulphur, to a level with which downstream applications can work, approximatively 1ppm (Kaufman Rechulski et al., 2014). Addition of catalysts may also assist with the reduction of sulphur, such as calcium-based sorbents. Limestone, dolomite and olivine are some of the most common to be used (Pinto et al., 2010).

2.4.3 Tar Removal

The formation of tar is one of the biggest problems facing the proliferation of biomass gasification technology (Abdoulmoumine et al., 2015; Ruiz et al., 2013). It is the most problematic impurity, which is formed by a number of organic components, mainly aromatic compounds with a molecular weight greater than benzene (Asadullah, 2014b). It is a sticky material, that can congeal in the lower temperature zones of the gasifier leading to blockages of narrow pipelines (Valderrama Rios et al., 2018). This can be detrimental to further downstream applications of the producer gas, such as CHP engines. It is therefore of vital importance to avoid excessive tar production through whatever means necessary. The downdraft gasification method is known to create the least amount of tar, and once the optimization of this setup has occurred further tar abatement strategies can be put in place (Bunchan et al., 2017). These abatement strategies can be divided into two separate categories: primary and secondary removal techniques (Devi et al., 2002).

2.4.3.1 Primary Removal Techniques

Primary removal techniques are those that occur during the gasification process, within the reactor, without the need for additional equipment. If effectively carried out, they will remove the need to carry out secondary removal techniques. There are three main methods in which primary removal techniques can be carried out. These are optimization of gasifier parameters, catalyst addition to feedstocks and modifications carried out on the gasifier (Devi et al., 2002). Once the correct gasifier has been selected, and parameters have been optimized, a solid platform has been built that the operator can work from, to ensure good quality producer gas has been generated.

Optimization of the operating conditions has been discussed in section 2.3, Downdraft Gasification.

The next step in the fight against tar production is the use of bed additives or catalysts. Catalysts of significance that have been studied previously include Ni – based, Dolomite and Alkali metal catalyst (Han and Kim, 2008). Nickel based catalysts have been seen to work well at tar removal, while simultaneously removing excess ammonia from the gas stream. Tar destruction of up to 99% using nickel catalysts have been reported, which also leads to an increase in hydrogen yield (Zhang et al., 2004). Nickel catalyst operate through tar cracking, which can occur at elevated temperatures where the tar compound is broken up into potentially useful gas products (Broer and Brown, 2015). Alkali metal-based catalysts are another method, known to successfully break up tar formed during the gasification process. Potassium Carbonate (K_2CO_3) has been used to break up tar generated from woody biomass such as cellulose, hemicellulose and lignin (Wang et al., 2010). This led to greater yield of gasification products, through the upgrade of secondary reactions and the lowering of temperatures required to obtain the product gases of interest. The final catalyst of interest are natural ores such as dolomite and olivine (Anis and Zainal, 2011). Dolomite, a calcium magnesium ore, has been highly effective as a catalyst when used for tar removal. It has been shown to reduce the amount of tar up to $1g/m^3$ (Han and Kim, 2008). Olivine can also be used, with some reports of reduction in tar of up to 46% when it was added to hot gas (Devi et al., 2005).

The final primary removal technique that can be employed is that of making modifications to the gasifier, to reduce the levels of tar produced. The most successful modifications that can be done are those that are simple, cost effective and impact on the levels of tar produced (Devi et al., 2002). Some of the most common modifications are secondary air injection, reduction zone extension and throat diameter alteration (Prasertcharoensuk et al., 2018). The benefit of injecting a secondary source of gasifying agent is that it increases the temperature at which the gasification reaction occurs leading to tar cracking and breaking down into further gaseous products. Identifying where is best to introduce the secondary air is important, as depending on throat size and length, greater tar reduction can be achieved by introducing the air in the optimal area (Han and Kim, 2008). The extension of the reduction zone leads to a much greater decomposition of the tars generated during the pyrolysis stage. This alteration allows for higher temperatures and reduces the amount of cooling occurring during the process (Pedroso et al., 2015). Throat diameter alteration can have a significant impact on producer gas composition. Increasing the throat to gasifier diameter ratio was seen to have a beneficial impact on the producer gas composition, to a ratio 0.40 (Prasertcharoensuk et al., 2018)(Devi et al., 2002).

2.4.3.2 Secondary Removal Techniques

Once all relative primary removal techniques have been undertaken, and the required levels of tar have still not been reached, it is time to adopt secondary or downstream cleaning methods. These methods can be split into hot and cold gas cleaning techniques. Hot gas techniques are simple filtration methods using heat resistant material, whereas cold gas techniques can be further split into dry or wet methods. Dry methods involve cyclones, various filters and absorbers. Wet methods include wet electrostatic precipitators (ESP), venturi scrubbers and wet scrubbers (Asadullah, 2014a).

Hot gas cleaning techniques are the simplest and most energy efficient methods of gas cleaning to carry out, as the producer gas doesn’t lose any of its sensible heat (Ptasinski et al., 2007). Most downstream applications require the producer gas to be a certain temperature, therefore cooling of the producer gas for cleaning only to heat again is wasteful. Two popular methods of hot gas cleaning include catalytic filter candles and activated carbon adsorption. Catalytic ceramic filters are suitable for gas cleaning as they allow hot gasses to pass through them, while completely removing of all particulates and tars, through their anisotropic porous filtering structure (Rapagnà et al., 2018). These filters can be further enhanced through the addition of various catalyst to them, for even greater tar and ammonia removal. Ni-based catalyst can be placed within the filter itself to carry this out (Rapagnà et al., 2018). Another hot gas cleaning technique is the use of activated carbon to act as an adsorbent, removing tars and other impurities. These have been found to work optimally at elevated temperatures, reaching complete removal efficiency at 850°C (Cammarota et al., 2016). Caution needs to be observed when using these techniques as blockage of filters with impurities can lead to pressure drops across the system, leading to poor quality gas production (Sansaniwal et al., 2017).

Cold gas cleaning techniques are common when the downstream application requires ambient temperature gas for operation (Asadullah, 2014b). Wet cleaning techniques for tar removal are popular as they are an effective methods of gas cleaning. Venturi and wet scrubbers allow the tar particulates in the producer gas to condense at lower temperatures, and to then be captured in water droplets. This is an effective method of tar removal, with results of tar concentrations of 20mg/Nm^3 achievable with this system (Rakesh and Dasappa, 2018a). Wet ESP's operate through water vapour air streams using induced electrostatic charge to remove particulates from the gas. They are effective at tar removal, but significantly more expensive (Kumar et al., 2009). A drawback to all wet systems is that a substantial amount of contaminated water is produced from the cleaning system which needs treatment before disposal (Arnif et al., 2018). To avoid additional water treatment costs dry methods can be employed using cyclones, rotating particle separators or charcoal and cotton fibre filters. Removing tar using cyclones and rotating particle separators operates using centrifugal and gravitational forces (Anis and Zainal, 2011). Hot gases enter the apparatus where tar and other particles are separated from the producer gas flow and settle at the bottom. Gas cooling occurs by ambient air temperature surrounding the apparatus. This technology is not without its own issues, which are due to the sticky nature of tar, the removal of it from the inside of the apparatus is extremely difficult leading to clogging (Kumar et al., 2009). As the gas is at cooler temperatures, more common filtration media can be used without the need for high heat resistant material (Sansaniwal et al., 2017). This allows for cheaper alternatives such as cotton, charcoal or simple saw dust filtration media to be used.

Experimental Catalyst Application

Literature in the field of catalyst application for tar removal includes the significant amount of experimental research that has been carried out. One of the most attractive methods of this is through the addition of calcium-based catalysts for increased H_2 content and significantly lower tar content. This has been carried out for multiple fixed bed reactors along with a variety of sustainable biomass materials. Examples include (Chiang et al., 2012; Hamad et al., 2016; Perondi et al., 2019; Taufiq-Yap et al., 2013). The information gained from this research will be applied to this experimental analysis and utilised to reduce producer gas tar content. Calcium based catalysts are readily available across Northern Ireland through their use to alter soil pH in agriculture

(DAERA, 2020). From previous literature the optimum catalyst loading rate for calcium catalysts was also identified. For a mixture of sustainable biomass and waste materials such as bamboo, poultry litter and agricultural residues the optimal ratio was between 5 – 40% by weight.

2.5 CHP & Producer Gas Application

The conversion of producer gas into heat and electricity occurs once all feedstock preparation, gasification and producer gas cleaning has taken place. This conversion can take place through gas-turbines, boilers or engines as is displayed in Figure 2.2 Flow Diagram of Power Generation from Biomass Gasification (Asadullah, 2014a). Gas engines and turbines are more prevalent conversion equipment as they can convert producer gas with approximately 50% efficiency, in comparison to steam boilers whose efficiency is in the region of 20%. (Sansaniwal et al., 2017). Conversion efficiencies as low as 6% for actual applications have been identified but a start must be made from somewhere (Zabaniotou et al., 2013). Tar concentrations should be below 100mg Nm^{-3} for successful engine operation, and to avoid fouling, clogging or corrosion of the equipment.

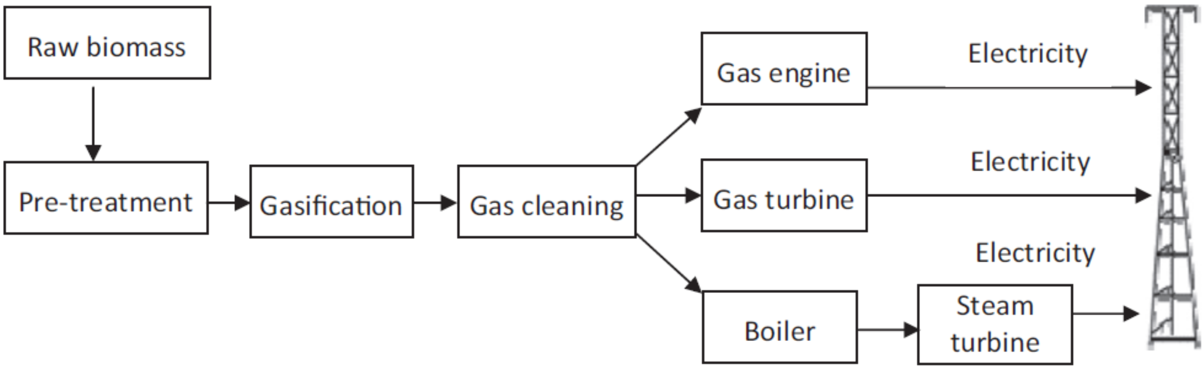


Figure 2.2 Flow Diagram of Power Generation from Biomass Gasification (Asadullah, 2014a)

There are significant advantages associated with creating heat and electricity through gasification over direct combustion. These are greater efficiencies achievable through gasification and gas production allows for the removal of contaminants that could potentially be harmful if combusted (NO_x, SO_x) (Whitty et al., 2008). Further advantages associated with gas engines include simple operation, low investment cost, low maintenance costs and robust set-up.

Limitations associated with the technology such as biomass procurement, heating value and cost of electricity have hindered the commercialization and proliferation of the technology. Cheaper, more reliable technologies are widely available for electricity generation. The only area where CHP can currently compete with existing technologies is in the rural electrification of developing countries. In areas such as Cambodia, where they are heavily reliant on fossil fuels such as diesel for electricity generation, gasification could successfully be can be utilised instead due to current high electricity costs and the amount of local biomass available for the process (Abe et al., 2007). To proliferate the use of such technology onto a global scale, effective cleaning of the producer gas needs to be able to consistently occur, with a decrease in initial capital cost and system flexibility to be able to operate with several biomass feedstocks (V. Siemons, 2001).

2.5.1 Factors Effecting Engine Output

When combining the producer gas with a gas engine for heat and electricity production, there are three critical factors which impact on the power output of the engine. These factors are the heating value of the gas, producer gas makeup and number of engine revolutions per minute (Roy et al., 2013). Producer gas heating value is liable to change regularly, according to the biomass feedstock of choice and operating parameters under which gasification is occurring. A consistent biomass fuel source could be identified for constant supply, but through the nature of biomass it varies by location and season. Gasification is seen as one of the most promising routes for energy production that can cope with the variability of biomass (Wu et al., 2012). This variability in conditions such as moisture or ash content, can impact on the LHV of the producer gas. Overall energy production is directly related to LHV (Roy et al., 2013). LHV is dictated by the combustible fraction of the producer gas, the methane, carbon monoxide and hydrogen content (Bhattacharya et al., 2001). Air as a gasifying agent can dilute these to reduce the overall LHV, so balancing the air intake to ensure enough for complete conversion, but not too much as to dilute the gas LHV is the aim.

The next factor of importance is the amount of this combustible fraction which enters the engine. Throughout the process the engine size remains constant, but what changes is the producer gas pressure (Asadullah, 2014a). Inlet gas pressure may change if there is a pressure change across the entire gasification system as producer gas is fed into the engine system after production, without an intermediary storage area. This could occur through blockages throughout the system which could be caused by tar, or changes in particle size which are very likely when using biomass (Rapagnà et al., 2018). This pressure drop equates to less gas being fed to the engine, which in turn will reduce the potential power output from the engine.

The final factor which has an influence on engine power output is the revolutions per minute (RPM) or speed of the engine. The combustion of producer gas with air in an engine isn't as high or as efficient as the standard petroleum air mixture. To reduce the power loss incurred by this the compression ratio of the engine can be amplified. This is to alter the volume of the engine chamber depending on the piston position (Raheman and Ghadge, 2008). This increased ratio can lead to engine damage if raised too high. This occurs through excessive vibrations, increased wear and tear of moving parts and an overall shorter life span for the engine. Utilisation of a gas turbine over a more common spark ignition engine will avoid these problems, but then issues surrounding levels of gas cleanliness will become problematic due to dust and other particulates damaging the internal components (Sansaniwal et al., 2017). Current efficiencies for ICE conversion of producer gas to heat and electricity are approximately 17-20% efficient, depending on the set up (Secco et al., 2016). Once ICE optimization such as improved heat recovery has occurred theoretically this figure could be increased to 50%, which should be the overall aim (Kinoshita et al., 2002).

2.6 Modelling

Due to the number of variable factors that can have an influence on producer gas makeup, LHV and tar content, mathematical modelling of the gasification process is seen as a cheaper and quicker way to predict outcomes than true experimental data (Patra and Sheth, 2015). Mathematical models can assist with visualisation of the gasification process. This is carried out by representing each operating parameter with a mathematical equation giving the user an insight into what impact parameters such as moisture content, ER, temperature and gasifying agent, have on process performance (Baruah and Baruah, 2014). Various types of gasification model have been developed, each with their own specific application (Yan et al., 2018). Some of the most complicated methods of modelling include fluid dynamics and chemical reactions, whereas simpler models consist of mass and energy balances, all with the aim of predicting producer gas make-up (Ferreira et al., 2019).

2.6.1 Equilibrium Models

The most common type of model in use is the thermodynamic equilibrium model, where modelling the process at its most stable takes place (Mutlu and Yucel, 2018). These models can be divided into two types: stoichiometric and non-stoichiometric equilibrium models. In the stoichiometric method, the equilibrium is calculated by using the equilibrium constant for certain reactions, whereas for the non-stoichiometric method it's about the minimization of Gibbs free energy (Ferreira et al., 2019). These models are used to predict the producer gas composition and LHV. They are an attractive modelling option, as they are quite simple, with the only input required being elemental composition, which can be obtained from the ultimate analysis (Puig-Arnavat et al., 2010). While carrying them out, some assumptions are also made such as chemical equilibrium has been met, pressure and temperature are uniform throughout the process, ash content is inert, and the producer gas consists of known elements (Yan et al., 2018).

2.6.2 Kinetic Modelling

Kinetic models are significantly more complex than their equilibrium counterparts. They are highly accurate, but also computationally more intense (Puig-Arnavat et al., 2010). Given that the model is more complex, further results can be collected from it. It can accurately predict producer gas makeup, temperature of reaction and process efficiency (Ferreira et al., 2019). To carry this out, the process is looked at after a specific period of time, while taking into account the precise configuration of the gasifier (Baruah and Baruah, 2014). Equilibrium modelling is completely separate from gasifier design and set up, which led to the creation of kinetic modelling to accurately imitate the gasifier behaviour (Patra and Sheth, 2015). This is carried out by including relevant reaction parameters such as reaction rate, residence time and reactor length (Gao et al., 2017). Accuracy and suitability of kinetic modelling is best at low temperatures, due to lengthy residence time for complete conversion (Baruah and Baruah, 2014).

2.6.3 Computational Fluid Dynamic Models

Advances in computational ability have allowed for further complex modelling to occur, in the form of Computational Fluid Dynamic (CFD) models (Eri et al., 2018). These models are used for exploring complex aspects of thermochemical conversion technologies such as mass transfer, fluid dynamics and chemical reactions (e.g. devolatilization and combustion (Wang and Yan, 2008). CFD models frequently include smaller sub-models within the main framework, which can focus on specific aspects of the process as can be seen in Figure 2.3 Modelling of Biomass Gasification using CFD (Patra and Sheth, 2015). These usually describe the vaporization or pyrolysis processes occurring (Ferreira et al., 2019). CFD is often used to simulate specific project set ups, utilising its complex capabilities to identify the optimal configuration of a gasification plant, dependent on the required project specifications (Patra and Sheth, 2015).

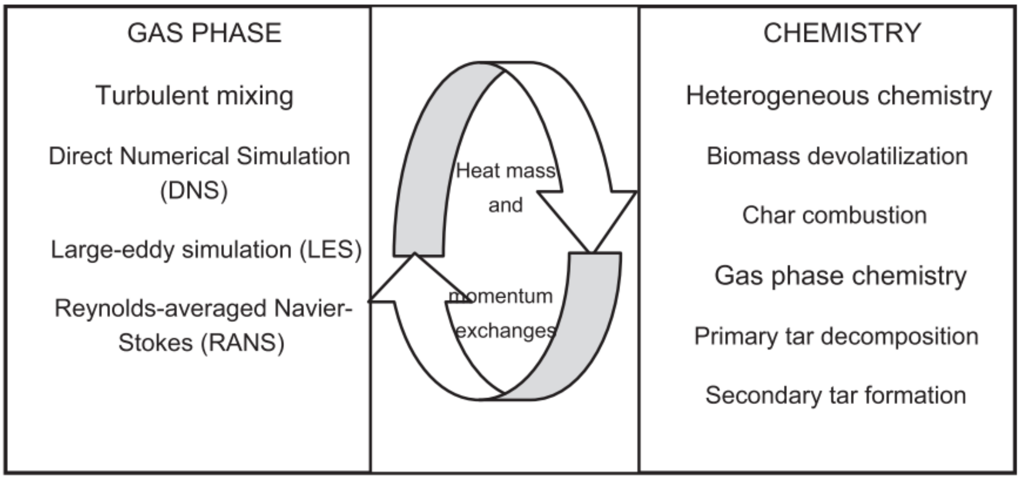


Figure 2.3 Modelling of Biomass Gasification using CFD (Patra and Sheth, 2015)

2.6.4 Artificial Neural Networks Models

Using artificial intelligence (AI) as a method to model parts of the gasification process has become possible. This is through the use of artificial neural networks (ANNs). These networks imitate the human brain in their decision making, using problem solving skills to recognize patterns, process signals, approximate functions and simulate processes (Puig-Arnavat et al., 2010). Due to the large data sets required for these networks to learn and recognise patters, their use in biomass gasification isn't widespread (Mutlu and Yucel, 2018). Successful application of the network requires large amounts of data and use of mathematical regression to successfully convert the inputs into accurate predictions of producer gas composition (George et al., 2018). It is a complex biomass map, using algebra as the medium of data transfer.

2.6.5 ASPEN Plus Models

A universal modelling software, that can be applied to numerous scenarios such as coal methanol synthesis, indirect coal liquefaction processes and biomass gasification is ASPEN Plus modelling (Nikoo and Mahinpey, 2008). The main components of the software are unit operation blocks, that are used to represent reactors, heaters and pumps associated with the process (Patra and Sheth, 2015). ASPEN Plus is often used for design and optimization of complex chemical processes, where simple modules can be picked from a database to represent complicated process components (Cheng et al., 2010). This simplification of the gasification process allows for the calculation and description of chemical, biological and physical reactions (Puig-Arnavat et al., 2010).

2.6.6 Model Validation

To ensure accuracy of the models that have been created, they need to be validated somehow. This can be carried out in two ways, either through data gathered from the literature, or with physical experimental data gathered first hand (Michailos and Zabaniotou, 2012). Variables such as ER, temperature or producer gas composition can be compared, from theoretical results to actual. When this is carried out, any discrepancies between the results produced from the model and true experimental data can be identified, and error correction can be introduced to guarantee greater accuracy (Barghi et al., 2013).

2.6.7 Model Parameters

Once the type of gasification model has been selected for application, it must be decided which parameters should be included and what impact they have on the model and reaction. There are many factors which can influence and control gasification performance such as reaction temperature, residence time, and oxygen content (Li and Ma, 2009). Any variation in these parameters can have an impact on gasifier operation and producer gas composition (Baruah and Baruah, 2014). Gasification temperature affects the thermochemical process greatly. Temperature can dictate the rate and products of the reaction, such as increases of O_2, N_2, and H_2

with increasing temperature, however this needs to be closely monitored because further increase could favour the conversion of this H_2 to CO and H_2O through water gas shift reactions (Kumar and Vivekanandan, 2016). Increasing the amount of O_2 in the reaction through the gasifying agent, will lead to an increased LHV, but further increases will lower overall LHV due to the increase in temperature that will occur, lowering overall process efficiency (Ghassemi and Shahsavan-Markadeh, 2014). Residence time will influence the reaction, impacting the gas yield. For complete conversion of material, it must have enough time to react. Shorter residence times will lead to unconverted material being wasted, and an inefficient process (Sette et al., 2014). Each of these parameters would be represented as a mathematical equation or constant, using a programme such as MATLAB.

2.7 Environmental

Before implementing any new renewable energy technology, the potential environmental impact of the technology should be assessed. The first step is to identify the conversion technology, ideally aiming for one with little or no release of harmful pollution to the atmosphere. The next step is to then identify the fuel of choice, preferably choosing a material which is available locally at low cost or for free. This can be achieved through partnering with local industry to accept their waste or by-products. Significant waste materials are available to produce heat and electricity across Northern Ireland such as agricultural residues, waste wood from factories or poultry litter from the poultry industry. These materials will allow for low cost energy production utilising the circular economy approach of thinking. This is to extract all value from materials before disposing of them for the final time (WRAP, 2019b). Gasification of these biomasses can be categorized as an environmentally friendly method of heat and electricity production, as there are very few pollutants released to the atmosphere during their exploitation. Traditional electricity and heat generation methods such as fossil fuel combustion are known for their release of large amounts of greenhouse gases (GHG) such as CO_2, which is contributing to climate change (Nguyen et al., 2013). Combustion of biomass also leads to the release of potentially harmful pollutants such as NO_x, SO_x and particulate matter to the atmosphere. Therefore, pairing the correct fuel with the correct technology is vital for efficient, environmentally sustainable heat and energy production.

Life Cycle Assessment

Carrying out a full life cycle assessment (LCA) on a material or a process will allow the user to study and interpret the total impact that a system has on the environment. The LCA can be used as a tool to follow a material or service from start to finish to assess the environmental impact it has. It can be carried out using software such as SimaPro (SimaPro, 2019). This cradle to grave analysis provides a holistic view of the possible pollution and resource requirements of a product or system (P. W. R. Adams and McManus, 2014). When utilising the LCA to interpret the gasification of biomass it would be appropriate to include a wide range of activities such as biomass sourcing, transport, pre-treatment, gasification, downstream processing and application of the producer gas to achieve the overall impact (Farzad et al., 2016). Previous research in the field was used as a benchmark for comparison (Guest et al., 2011; Kimming et al., 2011; Yang and Chen, 2014).

Pollution

Significant amounts of pollution can be generated during the conversion of solid fuel to usable energy. Globally, electricity generation has been the cause of significant environmental issues such as smog formation, acid rain, mercury pollution and climate change (Heller et al., 2004). Industry is known to be a major contributor of CO_2 to the atmosphere, largely from energy production for the national grid. These methods are having detrimental effects on the environment on a local, regional and global scale (P. W. R. Adams and McManus, 2014). The development of more sustainable and environmentally friendly methods of energy production are therefore an important target for many governments and agencies globally. The use of sustainable biomass for energy generation purposes has been identified to have many environmental benefits associated with it and has therefore been identified as a potential route for exploitation (Siegl et al., 2012).

Air

Significantly less emissions into the air are released from the combustion of biomass in comparison to that released from the combustion of conventional fossil fuels for energy production (Ahmad et al., 2016). These emissions include CO_2 and sulphur dioxide, the cause of acid rain. These lower air emissions can also be seen when comparing CHP systems. Diesel generators have GHG emissions in the range of 310

– 360g CO_2-e/kWh_e , where in studies utilising biomass gasification fed CHPs the results have been in the range of 5 – 163 CO_2-e/kWh_e, a significant drop (P. W. R. Adams and McManus, 2014). Lowering emissions from heat and electricity production is one of the key drivers associated with the push for bioenergy systems. Identifying potentially sustainable and environmentally friendly methods to replace harmful emission laden system is crucial (Adams et al., 2013).

Significant amounts of NO_x and So_x can still be generated during the gasification process if operating parameters are not adjusted. These can be removed through proper operation and effective cleaning systems. Dust from the gasification process can also be harmful to operators and the surrounding environment. This dust can be produced during a variety of steps such as fuel preparation, handling, storage and supply (Malik and Mohapatra, 2013). Measures such as protective clothing and extractor fans should be utilised to minimise harmful effects. Respiratory issues could be caused by dust or ash which has become airborne, so proper disposal and control is important for safe operation (Sansaniwal et al., 2017).

Water

The gas cleaning and tar removal steps carried out during the gasification process can lead to significant environmental damage if not properly controlled. There is a significant chance for water contamination to occur from discharge of process wastewater. This water will be contaminated with many different organic and inorganic compounds, which could potentially be harmful to aquatic life, and cause a serious threat to humans if found in drinking water. The types and concentration of contaminants found in the wastewater depends on the type of reactor used and process parameters (Muzyka et al., 2015) Contaminants include polycyclic aromatic hydrocarbons (PAH's), ammonia and small amounts of hydrogen sulphides and chlorides (Tripathi et al., 2013). Further treatment of this wastewater is required before disposal into the environment. Many methods exist with which water cleaning can take place, but most are energy intensive or require the addition of expensive catalysts (Muzyka et al., 2015). One of the most effective methods of wastewater cleaning can be done through filtration of the water with activated charcoal created as a by-product during the gasification process (Tripathi et al., 2013).

2.8 Gap Analysis

Through the detailed analysis of previously published literature in the field of downdraft gasification, a gap has been identified which this thesis aims to fill. This gap is the influence which various blends of biowaste and biomass materials have on producer gas composition, LHV, conversion efficiency and other relevant parameters identified through LCA and techno – economic analysis of the process. Previous research in the field of gasification of biomass blends has been carried out, as can be seen in Table 2.3. From further analysis carried out on this literature the gap was identified. Previous work in the field covered a variety of topics, such as blending multiple feedstocks together to find the impact it has or blending material with equal proportions for improvements. While similar to the work planned to be carried out in this research, they are not identical. Critical differences between this research and that previously carried out is that this research will use blends researched from the literature which has previously been identified as the best weight percentage blends, in a downdraft gasification set up, using both waste biomass feedstocks and bioenergy crops to understand the impact which they had. To further explore the gap, this research will include a full LCA analysis of the process, along with a techno – economic analysis to add further evidence to the impact of using blends of material past the influence on producer gas. The material of interest which has been previously researched in blends is poultry litter. Differences between this research and previous work is the downdraft gasifier selection, the use of multiple blends to investigate their influence and the blending material of choice. The focus of this research will be on blends of poultry litter, AD digestate, miscanthus and wood pellets. Improved gas quality (LHV) through lower tar production and improved producer gas makeup is one of the main benefits of blending feedstocks. This will make the gas easier to clean, through lower levels of tar and particulates present in the gas stream, and therefore a better-quality gas for downstream application. To further strengthen this research, a life cycle analysis of the blended feedstock producer gas will be compared to single streams along with a full techno-economic evaluation of the system.

Table 2.3 Comparison of Previous Gasification Blend Analysis

Article	**Gasifier**	**Material**	**Blend %**	**LHV (MJ/Nm3)**	**Yield Effect**
(Mallick et al., 2020)	Circulating Fluidized Bed Gasifier	Sawdust (SD)	Equal Weight Ratio	0.06 Increase	0.02 - 0.09 (Nm3/kg)
		Rice Husk (RH)		LHV = BD	0.04 - 0.1 (Nm3/kg)
		Bamboo Dust (BD)		0.09 Increase	0 - 0.04 (Nm3/kg)
(Jeya Singh and Sekhar, 2016)	Downdraft	Coconut Shell (CS)	100/0- 60/40 D0	8.5 to 7 with increasing RS	Conversion efficiency highest with more Coconut Shell
			90/10 D1		
		Rubber Seed Shell (RS)	70/30 D2		
			60/40 D3		
(Tańczuk et al., 2016)	Fluidized Bed	Chicken Manure (CM)	0, 25, 50 & 75 & 100 w.t.% of (CM)	4.5	26% Vol. CO
				4.45	24.8% Vol. CO
		Wood Pellet (WP)		3.7	22.5% Vol. CO
				2.9	18% Vol. CO
				2.6	17% Vol. CO
(AlNouss et al., 2020)	Downdraft	Date Pits	Manure/ Dates/Sludge	Up to 8.2 using steam	1.2 – 2.3 (kg product/kg feed)
		Manure			
		Dried Sewage Sludge			
(Tamili et al., 2018)	Downdraft	Corn Residues (CR)	Corn/Coconut	Energy related to CO & H_2	CO Increases with blend increase
		Coconut Shell (CS)			Increase CO, CH_4, H_2
(Dayananda et al., 2013)	Fluidized Bed	Chicken Litter	10RH/90CL to 50/50	4.48	Increased H_2, CO_2 & CH_4
		Rice Husk		4.5	
(Malatji et al., 2011)	Downdraft	Wood Chip	50/30/20 Wood/Grape/Chicken	From 5.7 to 6.8	17% Higher conversion efficiency
		Grape Skins			
		Chicken Litter			
(Augustine and Sekhar, 2019)	Downdraft	Rice Husk	100/0 FS1	5.31	N/A
			90/10 FS2	5.94	Inc. CO_2, CH_4, H_2
		Tea Waste	70/30 FS3	5.35	Inc. CO_2, CH_4, H_2
			60/40 FS4	5.55	Similar to FS3
(Inayat et al., 2017)	Downdraft	Wood	W20/CS80	Low air flow and high coconut for better quality	Highest H_2, CH_4
		Coconut Shell	W50/CS50		Highest CO
			W80/CS20		Lowest yield
(Ong et al., 2015)	Downdraft	Wood	0, 10, 20, and 33 wt %dried sewage sludge	4.7	17.1% CO, 17.3% H_2
				4.6	15.9% CO, 17.1% H_2
		Sewage Sludge		4.5	15.6% CO, 16.8% H_2
				3.6	Ash Agglomeration

2.9 Summary

The gasification of sustainable biomass coupled with an internal combustion engine has the potential to become a major part of renewable energy generation throughout rural parts of the globe (Kumar et al., 2009). Significant amounts of low value wastes and potential fuels are readily available for this process. This project will investigate the entire process, from optimal sustainable feedstocks to renewable heat and electricity generation, identifying and finding solutions for issues that could detract from the overall successful thermochemical conversion of biomass to energy.

What is evident from the literature is that feedstock preparation is a critically important step during the gasification process but is often overlooked (Arnsfeld et al., 2014). Drying, milling, or pelleting of materials, especially when dealing with non-uniform waste materials can be required to ensure a quality feedstock for gas production. These processes may be expensive so an alternative or cost-effective method of carrying them out must be identified.

Proper instrumentation set up is vital for successful renewable energy generation. This can be related to the gasifier itself or the engine for gas conversion. After appropriate gasifier selection, there are numerous operational parameters that need to be optimized. These include but are not limited to gasifying agent, temperatures, equivalence ratio and flow rates. These parameters play a significant role on producer gas quality, therefore optimization of each for high quality producer gas is critical (Ahmad et al., 2016). This is also true of the engine, which similarly requires fine tuning for converting the producer gas into renewable heat and electricity.

Gas cleaning is the final critical aspect of the work that has been identified. It is one of the most popular topics of discussion amongst the literature, but no consensus on best practise methods or technology have been identified (Hongrapipat et al., 2012; Mondal et al., 2011; Valderrama Rios et al., 2018). Contaminants found in the gas stream are known to damage and block engines internally, leading to lower efficiencies and costly repairs over time. Tars and particulates are the two main constituents that require further research into their removal, to ensure safe and sustainable conversion of producer gas into heat and electricity.

The current literature on biomass gasification and CHP application covers a large amount with nearly all aspects of the thermochemical conversion process investigated to some degree. While it is difficult to identify gaps amongst the literature, the information around the blending of feedstock for downdraft gasification application is limited. Previous research on this topic was limited to single feedstocks and did not include an investigating into the economic or environmental impact that the blends had on the process. Some agricultural residues had previously been investigated in the downdraft system for CHP application. These include rice husk and rubber seed shell (Jeya Singh and Sekhar, 2016; Susastriawan et al., 2020). This research will focus on other waste materials from agriculture in the forms of poultry litter and anaerobic digestate, along with miscanthus as a bioenergy crop for comparison, which are more prevalent and across the UK and Europe. Combining these blends of feedstocks, to the life cycle of the process from cradle to grave, and a techno-economic analysis of the impact has not been carried out, or a complete appraisal of the process from a UK/NI perspective.

Chapter 3 – Methodology: Feedstock Characterization and Energy Conversion

3.1 Methodology Overview

This chapter will discuss the research methods employed to reach the overall goal of the thesis. This is to analyse the influence that feedstock blending has on producer gas quality and gasification process efficiency. The methodology has been influenced by the findings of the literature review, by work previously carried out, as well as by international standards employed for material analysis. The chapter will cover the reasoning behind, and methods utilised for feedstock selection, characteristic analysis, experimental analysis and results interpretation. Modelling technique selection will also be discussed as to why the method was chosen. Included within this section are the results from the biomass proximate and ultimate analysis, as these results are required to feed into the ECLIPSE modelling database.

3.2 Introduction to Biomass Feedstocks

3.2.1 Feedstock Selection

The focus of this research is on underutilised sustainable biomass materials that have the potential to act as a reliable feedstock but are currently viewed as having little or no value. The biomass materials that have been chosen for investigation within this project are; poultry litter, anaerobic digestion (AD) digestate, miscanthus, willow chip and brash. These materials were selected due to their availability across the region of interest, their low cost or in some cases negative value and the environmental issues associated with them which can be rectified through gasification. Physical characteristics identified during the literature review have also been considered when choosing materials for downdraft gasification. These include but aren't limited to: moisture content, LHV, ash content and bulk density.

3.2.2 Poultry Litter

Growing global demand for food has meant the industrialisation of the farming sector. Across the UK approximately 20 million birds are produced weekly to supply this demand, meaning over 1 billion live birds annually. With a production value of £2.9 billion in 2019, sustainability is critical for further growth in an industry that employs

37,000 people across the UK (BPC, 2017). This large number of birds generate a substantial volume of poultry litter. Approximate estimations put this figure at 4.9 million tonnes of PL produced as a by-product across the UK annually, using the excretion rates proposed in Jeswani et al. (2019). PL can vary from farm to farm depending on bedding material, feed and ambient conditions (temperature, humidity, air flow). Bedding can consist of a number of materials such as woodchip, sawdust, straw or a mixture of each. Currently this material has two potential destinations. The first is to be utilised as a fertiliser and spread on neighbouring tillage lands, which successfully recycles important plant nutrients in the soil such as nitrogen (N), phosphorus (P) and potassium (K). The second potential route for the material is disposal through landfilling or similar waste removal methods where a cost per tonne of material would be required to be payed by the farmer. Estimates put the price of removal of poultry litter anywhere between £30 - £50/tonne, which over the course of a year can become thousands of pounds. Large quantities of the material had previously been sent from Northern Ireland to the Republic of Ireland for treatment due to the volumes being produced and lack of potential disposal routes available (Cunningham, 2016). Uncertainty surrounding the transport of wastes across international borders following Brexit has increased the need for alternative disposal methods to be identified. Therefore, there are multiple reasons why utilising poultry waste for onsite energy generation can benefit the farmer, the environment and the local community. Land spreading of poultry waste can have harmful effects on the local water quality. Excess application of nutrients to land can lead to pollution of waterways, with excess nitrates a direct cause of eutrophication. This can occur within areas of intensive agricultural practise, commonly found across Ireland and the UK. To mitigate these issues, the Northern Ireland Executive has introduced the Nutrient Action Programme (DAERA, 2019), where a limit on application of fertilisers to land has been designed. Alternative waste management is required to comply with this directive. Using the waste as an energy source ensures the protection of local waterways, offers financial incentives to the farm through lower utility bills, potential new revenue streams for the farms from renewable incentives and CO_2 savings compared to fossil fuel alternatives. Benefits to the local community include lower volumes of HGVs travelling the roads, increased air quality and a lower risk of spreading airborne diseases between farms such as botulism. Avoidance of these problems could ensure that this industry remains both financially and environmentally sustainable for the future. It is also a perfect example of a circular economy approach to the waste generated. To use all materials to their full potential before final disposal means that the energy from the material is extracted, instead of disposing of it. This will avoid the need to purchase energy from the grid or other fossil fuel powered sources to run the onsite farm processes such as heating, lighting, ventilation, feeding systems and other relevant uses. To carry out the experimental analysis, pre-pelleted poultry litter material was utilised. The brand name was “Westland Organic Chicken Manure Pellets“ and they were purchased from a local horticultural supplier. An example of the material can be seen in Figure 3.1.

Figure 3.1 Pelleted Poultry Litter for Experimental Analysis

3.2.3 AD Digestate

Anaerobic digestion has become a popular method of waste treatment across Europe for farms and industry alike. Slurries, plant wastes and industrial effluents can all be disposed by using this technology, with the added benefit of producing a methane gas for onsite energy use. The solid fraction leftover once the methane has been produced during the AD process is known as digestate. Across the UK approximately 2.5 million tonnes of this material are generated annually, from the 500 AD plants (NNFCC, 2019). This number will increase as well with further AD plants either in the construction or planning phase. Digestate material has similar disposal issues as PL, with land spreading for nutrient replacement the most common usage. To ensure industries and farms alike are operating within the scope of the NAP this digestate material could be utilised onsite for further energy production. Multiple uses for the heat and electricity generated through downdraft gasification of digestate are available. These include increasing AD efficiency through providing the heat required for mixing tanks, or providing the electricity required to run the plant and avoid the parasitic load. AD digestate was supplied pre-pelleted for experimental analysis from AFBI Hillsborough's AD plant in conjunction with another PhD project. This AD plant is mainly fed on a diet of grass silage. An example of the digestate material is displayed in Figure 3.2.

Figure 3.2 Pelleted Digestate Material for Experimental Analysis

3.2.4 Miscanthus

The choice of miscanthus for the research was because of its potential to grow on marginal land as an energy crop (Lewandowski et al., 2008). Once planted the crop requires very little attention from the farmer and can be harvested using existing machinery. Mature rhizomes require no fertilisers, which would assist with meeting NAP requirements. A perennial crop that can be harvested annually, it is also considered carbon neutral when converted thermochemically for heat or electricity production. The miscanthus represents all herbaceous energy crops and acts as a gauge for similar materials. Previous research has shown that a yield of 12 t ha $^{-1}$ of miscanthus is a viable possibility for most of the UK. This level of miscanthus growth could potentially generate between 0.09 and 0.034 EJ/year (Shepherd et al., 2020). This material can supplement the farms income through diversifying the production and make use of land previously thought of as unsuitable for crop rotation. Pelleted miscanthus was purchased from Agripellets based out of Warwickshire in England. A sample of the material is shown in Figure 3.3.

Figure 3.3 Pelleted Miscanthus for Experimental Analysis

3.2.5 Willow Chip

SRC willow is another example of a perennial biomass crop which can be grown for energy production. Cooler climates are well suited for willow growth, with an annual yield produced for up to between 15 and 20 years (The Scottish Agricultural College, 2008). Willow can have the added benefit of operating as a biofilter for process wastewater or sewage sludges. Yields vary on growing conditions but can fluctuate between 6 and 12 dry tonnes per hectare. Initial planting is more intricate than miscanthus and requires pest and weed control. Once the willow has been cut back through coppicing, the crop is encouraged to regrow and can produce a harvest every 3 years (Heller et al., 2004). While estimates of potential UK willow resources are difficult to find, with government incentives it could become the bioenergy crop of choice across the UK given the growing conditions are appropriate. Willow chip for analysis was supplied by AFBI Hillsborough. A sample of the willow material is displayed in Figure 3.4.

Figure 3.4 Willow Chip for Experimental Analysis

3.2.6 Arboricultural Arisings

Arboricultural arisings, or brash as it is more commonly known is the waste material left once forestry work such as logging, or tree trimming has occurred. It is made up of branches and leaves and any other leftover material. In some instances, this material is left within the forest to return nutrients to the forest floor or protect the ground from the heavy machinery operating above. Some of this material has been utilised as mulch on nature walks but the inherent carbon content of the material means it can be utilised as a fuel source. Accurate estimations on the potential resource of this material are difficult to estimate, as they can vary depending on the forestry technique used to harvest material or the grading system used to quantify material quality. Material from hedgerows qualifies as arboricultural arisings but generating a consistent quality and quantity to be supplied for energy production purposes is logistically challenging. These are important traits which require investigation when identifying a potential new biomass feedstock. From forestry alone sufficient arisings may be generated. As of March 2021, 1.41 million hectares of woodland are sustainably managed, representing 44% of total UK forestry (Ward, 2022). In 2020, 10.7 million tonnes of UK roundwood was delivered to primary wood processors. Arisings from this could have been utilised for energy generation purposes, but due to the technology available and machinery used a large portion was possibly left on the forest floor. Arboricultural Arisings were supplied from another project previously carried out in Ulster University. A representative sample of the material is displayed in Figure 3.5.

Figure 3.5 Arboricultural Arisings (Brash) for Experimental Analysis

3.2.7 Wood Pellets

For blending application, wood pellets were chosen as the blending material of choice due to their low-cost and availability (Balcas, 2021). Balcas brites wood pellets were chosen as they are sustainably produced. They are created from the process waste material such as sawdust and offcuts in a timber manufacturing factory. Energy for pellet production comes from an onsite CHP system, which used low quality bark and timber from the logs delivered to site as feedstock. This material represents waste wood, which could be utilised as an alternative energy source, utilising the circular economy approach. This material is generated from a number of different sources such as construction, manufacturing, demolition, wood processing or household such as that found as local council recycling centres. This material accumulated to at total 4.5 million tonnes across the UK in 2020 (Forestry Commission, 2021). This is a significant volume of material, ideal for energy exploitation. Wood pellets utilised are displayed in Figure 3.6.

Figure 3.6 Wood Pellets for Experimental Analysis

3.3 Material Characteristics

Before gasification experimental work proceeded, a full proximate and elemental analysis of the materials of interest was carried out. This provided a full breakdown of all relevant biomass characteristics. Results from this analysis can be seen in Table 3.1. Biomass Characteristics and are presented on a dry basis.

Table 3.1 Feedstock Proximate & Ultimate Analysis

	Arboricultural Arisings	***Digestate Pellets***	***Miscanthus Pellets***	***Poultry Litter Pellets***	***Willow Chip***	***Wood Pellets***
C	43.13	44.49	45.13	33.65	42.27	47.14
H	6.08	6.56	6.26	4.61	6.03	6.51
N	1.61	2.51	1.26	4.08	1.96	0.38
S	0.31	0.34	0.31	0.34	0.30	0.30
O	48.89	46.09	47.04	57.32	49.44	45.66
Moisture (%)	15.56	7.69	7.15	10.27	10.78	7.50
Ash (%)	2.24	11.18	2.51	12.93	0.79	0.30
Energy (kJ/kg) DAF	23.84	22.32	21.25	18.15	22.53	18.66
Ash Melting (°C)	1510	**1227**	1285	<1530	**<1530**	1350
Volatile Matter (%)	79.83	74.51	83.74	62.15	72.37	83.93
Fixed Carbon (%)	17.94	14.31	13.75	24.91	26.83	15.77
Bulk Density (kg/m3)	236	716	604	810	152	682

Ultimate

Ultimate analysis of the materials was carried out using a Perkin Elmer PE2400 CHNS elemental analysis. Oxygen was calculated by difference. Samples were sent to an external lab for this analysis as the equipment required was not available within the research centre. The external analysis was carried out by ASEP Analytical Services in Queens University Belfast. Results generated from the ultimate analysis were accurate to 0.3%.

Moisture, Ash & Volatile Matter

Moisture content of material was carried out utilising the oven dry method as described in BS EN ISO 18134 – 1- 2015 Solid Biofuels – Determination of moisture content – Oven Dry Method. A known weight of fresh biomass was set in a pre-weighed crucible and placed in a Carbolite AAF 1100 oven at 105°C until constant mass was achieved. Once complete, the sample is removed and weighed again so that the moisture can be calculated by difference.

Ash content was carried out using the same instruments, where a dried biomass sample would be heated at 250°C for 2 hours and 550°C for 1 hour as described within BS EN ISO 18122: 2015 Solid Biofuels – Determination of ash content. Remaining material can then be weighed, and ash content is calculated by difference.

Volatile matter and fixed carbon were identified using the same equipment and following BS EN ISO 18123:2015 – Determination of the content of volatile matter. A known weight of material is placed into an oven at 900°C for 7 minutes, mostly out of contact with air. Volatile matter percentage is calculated from the weight difference, while also considering the moisture content of the material. Fixed carbon was the material remaining once the analysis had been completed.

Energy

Energy content of the material was carried out utilising an IKA C200 bomb calorimeter. Following BS EN ISO 18125: 2017 – Solid Biofuels – Determination of calorific value, approximately 1.0g of a pellet generated from a hand die was placed into a glass crucible. A cotton string attached to the firing wire was put in direct contact with the pellet in the crucible. This was then placed in the vessel which had been pressurised with oxygen to 3MPa. The sample was then combusted in water and higher heating value (HHV) was provided by the instrument through calculations using the heat capacity of water. Analysis was repeated in triplicate to achieve an average, ensuring the validity of the results. Accuracy of instrument to 0.1% is listed in the manual.

Ash Melting

To identify the ash melting behaviour of the different biomass ashes, a Carbolite CAF Digital Ash Melting Oven was used and BS EN ISO 21404: 2020 – Solid Biofuels – Determination of Ash Melting Behaviour was followed. Ash is prepared for the analysis by following BS EN ISO 18122: 2015 Solid Biofuels – Determination of ash content. This material is mixed with a small amount of deionised water to create a paste. This paste was then inserted into a triangle mould to shape it, before removal and placing it on a ceramic tile. Tiles were loaded onto a sample holder and placed in the ash melting oven. In an inert N_2 atmosphere, temperature increases within the oven at a rate of 7°C/min. A camera attached to the front of the oven captures an image of the ash sample every 5°C to follow the different stages of ash melting from shrinkage, deformation, hemisphere and finally flow.

Bulk Density

To calculate the bulk density of the materials of interest BS EN ISO 17828:2015 – Solid Biofuels – Determination of Bulk Density was followed. This involves dropping a quantity of the biomass material from a known height into a standard container. Material densifies as it falls until a volume of 5 litres has been filled. The bulk density of the material is then calculated from the net weight per standard volume.

3.3.1 Characteristics Analysis

For carrying out any modelling or simulation of gasification reactions, the biomass composition must be known. When the individual makeup of the biomass is known, and the reactions taking place are known, an accurate estimation of reaction products and therefore producer gas composition can be identified. From the ultimate analysis carried out we can see that the carbon content of each material apart from poultry litter is relatively similar, with the greatest variation being 4.87% between wood pellet and willow chip at 47.14% and 42.27% respectively. Poultry litter has a significantly lower carbon content at 33.65%. This lower carbon content will negatively affect the gasification reaction. Less carbon in the material means less carbon available for conversion into CO and other desirable gas components. The similar carbon content of all other material is due to the fact that they are all composed of lignocellulosic biomass. These materials consist mainly of cellulose, hemicellulose and lignin which contain long chains of carbon. These chains make up the structure of most plant tissues such as cell walls (Wang et al., 2010). The digestate utilised for this research also consists of a high level of this substance as it was created through the anaerobic digestion of grass silage, another material with a high lignocellulosic content. Poultry litter on the other hand has a low carbon content, 33.65% due to it being a heterogenous mixture of materials such as poultry manure, feed, feathers and bedding amongst other things. This lower carbon content may negatively affect producer gas energy content.

For similar reasons all feedstocks have near identical hydrogen contents, again apart from poultry litter. We can see that there is a 0.53% difference in hydrogen content between the lignocellulosic feedstocks of digestate and willow chip. Poultry litter again has a significantly different hydrogen content of 4.61%, a total of 1.42% different than the next lowest. This lower hydrogen content will negatively affect the heating value of the feedstocks. This can be seen when looking at the energy content of each material. Poultry litter has the lowest hydrogen content of the feedstocks and also the lowest energy content at 18,153 J/g. This can be used as an early indicator for potential producer gas quality. Moisture content of material is important, as defined within Chapter 2 – A Review of Fuel Gas Production from Biomass and Biowaste. Optimum moisture for downdraft gasification is between 15 – 20%. Most materials utilised here have a lower M.C than that due to the pre-treatment steps they have gone through such as drying or densification. The highest is arboricultural arisings with 15.56%, while miscanthus pellet have the lowest at 7.15%. Too high a M.C and energy will be wasted during the drying stage of gasification to remove it. If moisture content is low, it will negatively affect the H_2 in the producer gas. This is because the H_2 in the gas stream is generated from the water gas shift reaction. Therefore a lower feedstock M.C will mean lower H_2 in the producer gas and an overall lower producer gas LHV (Raheem et al., 2019). Low M.C in the pelleted material is due to the fact that excess moisture would inhibit the materials from binding. Relatively dry material is required for pelleting (<20%), with further drying occurring through the pelleting process due to the heat generated by the pellet mill (Puig-Arnavat et al., 2016).

Ash content of the feedstocks is important, as having too high a percentage of ash will lead to issues such as low conversion efficiency, potential for agglomeration within the reactors in the form of sintering and clinker and lower overall heating value. Ash disposal may also become an issue once the system is scaled up to handle tonnes per annum (de Mena et al., 2017). Identifying clean, low ash content biomass has been important for biomass research and is one of the main issues faced when using wastes or by-products as the main feedstock of choice for thermochemical conversion. Of the material of interest wood pellet has the lowest ash content at 0.3%, as would be expected from materials which reach the international ENplus A1 standard (EPC, 2021b). The highest is poultry litter at 12.93% which is again probably related to the litter's makeup of various materials. Through blending of different materials, the overall amount of ash generated can be lowered through mixing a high ash content material with a lower ash content material. The ash melting temperature of materials is also important to consider for the feedstocks, as significant damage could be done by a build-up of ash clinker within the gasifier. Downdraft gasification reactions occur between 800 - 1000°C depending on material and system. It is therefore crucial to ensure that the ash won't go through transformation at these temperatures to avoid unnecessary equipment damage. Ash melting of these materials are all above 1200°C and therefore should avoid any potential issues. Images from the ash melting analysis are included here and can be seen in Figures 3.7 and 3.8. The four stages of ash melting are shrinkage, deformation hemisphere and flow. While each ash has its own characteristics, from Figures 3.7 and 3.8 we can see that deformation of poultry litter ash doesn't occur until 1530°C while miscanthus ash has already reached flow conditions at 1285°C. The remaining results from the ash melting analysis can be seen in the appendices in Table A.13.

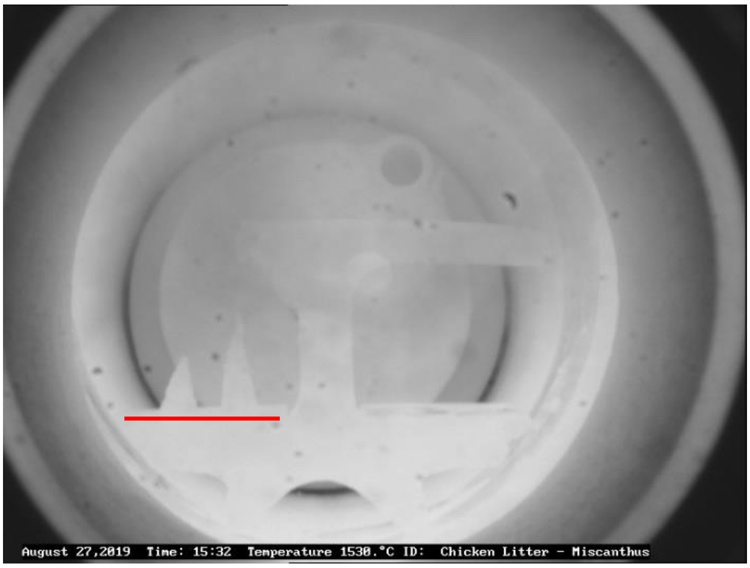


Figure 3.7 Ash Melting Image of Poultry Litter (on left). Deformation of sample at 1530°C

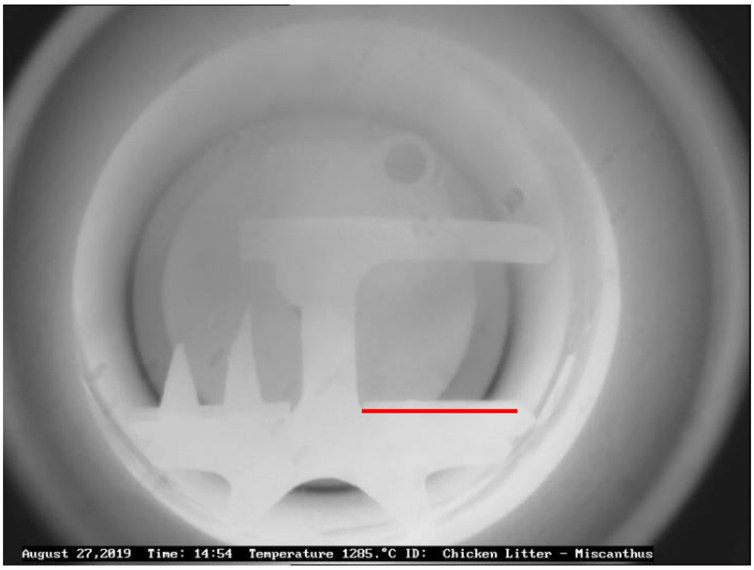


Figure 3.8 Ash Melting Image of Miscanthus (on right). Flow temperature of sample 1285°C

A further indication of the potential quality of a feedstock for gasification purposes which can be gathered from the results of the proximate analysis is how readily the material will break down into its constituent components. This can be seen from the volatile matter found in the material. The higher the volatile matter, the easier the material will convert to gas during the gasification process. Wood pellets are the best quality feedstock for this characteristic, with 83.83% volatile matter. The worst is poultry litter, with only 62.15% VM. The remaining material will act as a carbon sink in the form of fixed carbon, which could be utilised as a type of biochar if such material was desired. Biochar can have multiple applications with uses in a variety of application such as agriculture for soil nutrient content improvement, construction as a carbon sequestration method in concrete, and water treatment through the absorption or removal of contaminants such as heavy metals (Ng et al., 2017). Blending of various feedstocks could potentially increase the volatile matter of materials if necessary similar to the ash content, by selecting a high VM material with a low VM material.

The final characteristic of note within the proximate analysis was the bulk density of the feedstocks. Due to the design of the downdraft gasification system being used to carry out the experimental analysis, materials with a low density would cause issues for the biomass feeding. These issues could be throat blocking or bridging of the material over the grate (S.A. Sulaiman, M. Inayat, H. Basri, 2016). This caused unreliable system operation, with spikes in the pressure across the system leading to unreliable gas production and quality. This occurred when using materials with a bulk density below 500 kg/m^3. It was decided from the results of the bulk density analysis and trials of the gasification experimental analysis that only pelleted material was appropriate for the system being utilised to avoid these issues. This decision was made to ensure the Fluidyne gasifier system utilised during the experimental analysis functioned optimally. It is a specific design issue related to this system and may not be seen within other research. Experimental results from the gasification of willow chip and arboricultural arisings are therefore not included in the results from this research.

3.4 Parameters for Small Scale Gasification Models

Computational simulation of the small-scale downdraft gasification system is an integral part of the research being carried out. Being able to accurately predict producer gas composition, LHV and gas yield is critical for successful application of the data.

It is known from previous literature that the gasification reactions are divided into four stages: drying, pyrolysis, oxidation and reduction. Defining each reaction, as well as its products is vital to ensure accuracy of simulation results. The drying stage is the first to occur, where excess moisture is driven off the material. The pyrolysis stage then occurs where biomass is broken down into its separate components:

Biomass → $CO + H_2 + CO_2 + CH_4 + H_2O$ + Tar + Char (1)

The next step is the partial or complete oxidation reactions. These reactions produce combustion or partial combustion products. These are:

Char + $O_2 \rightarrow CO_2$ (*Char Oxidation*) (2)

$C + ½\, O_2 \rightarrow CO$ (*Partial Oxidation*) (3)

$H_2 + ½\, O_2 \rightarrow H_2O$ (*Hydrogen Oxidation*) (4)

The reduction step is then final stage of gasification. It is made up from six different reactions occurring. These reactions are a mixture of both heterogeneous and homogeneous reactions. They are:

$C + CO_2 \leftrightarrow 2CO$ (*Boudouard Reaction*) (5)

$C + H_2O \leftrightarrow CO + H_2$ (*Reforming of Char*) (6)

$CO + H_2O \leftrightarrow CO_2 + H_2$ (*Water Gas Shift Reaction*) (7)

$C + 2H_2 \leftrightarrow CH_4$ (*Methanation Reaction*) (8)

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ (*Steam Reforming of Methane*) (9)

$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ (*Dry Reforming of Methane*) (10)

To accurately predict the results of these reactions, the use of computational simulation is required. From the elemental analysis carried out, the precise chemical composition of the chosen biomass materials is known. Knowing the chemical composition, and the reactions occurring during the gasification process, we can through some computational simulations accurately predict the producer gas composition.

For this application the chosen simulation software was the ECLIPSE process simulation package. ECLIPSE is a personal computer-based package that was developed for the European Commission by the research centre of the University of Ulster. It contains all the necessary modules to successfully carry out step by step technical and environmental evaluation of the downdraft gasification process. The software carries out a significant amount of mass, energy and exergy balances to generate the accurate results. Further information on ECLIPSE simulation software will be discussed in Chapter 5 – Process Modelling and Simulation.

3.4.1 Biomass Molecular Weight

The ECLIPSE modelling software utilised for this research is defined within Chapter 5 – Process Modelling and Simulation. This process simulation software calculates reactions based off the assumption of 1 mole of material. For this calculation to take place, the molecular weight of the biomass materials of interest had to be calculated. This calculation was carried out using the data provided by the ultimate analysis, as displayed in Table 3.1 Feedstock Proximate & Ultimate Analysis.

To carry out the calculation, the individual biomass components (C, H, N, S, O) were divided by their molecular mass to find the individual molar mass of each element within 100g of the biomass sample. Dividing the moles of each individual element by the component with the overall lowest amount and multiplying the answer by 2 to will then allow for an estimation of the biomass chemical formula. From this formula an approximation of molecular weight can be calculated. This process of removing the lowest volume component from the calculation is repeated until an accurate estimate for the actual molecular weight is found. This process was repeated until the molecular weight for each biomass was found. Results for each molecular weight calculation are displayed in Table 3.2 – Calculated Biomass Molecular Weight. An example of the calculation in six steps is included in the appendices in Figure A.1.

Table 3.2 Calculated Biomass Molecular Weight

Biomass	Calculated Molecular Weight
Arboricultural Arisings	1113
Digestate Pellet	1130
Miscanthus Pellet	1156
Poultry Litter Pellet	1364
Willow Chip	1100
Wood Pellet	1193

3.4.2 Lower Heating Value

For accurate estimations of biomass LHV a further calculation must take place. This calculation estimated the latent heat lost during the transition phase between states. HHV was found earlier through experimental analysis as explained in Section 3 Material Characteristics. Using this figure, we can estimate the LHV, as it is also required for modelling through ECLIPSE. This calculation used the relative molar weight of the sample, which is calculated using the ultimate analysis compositional analysis found in Table 3.1 Feedstock Proximate & Ultimate Analysis. Heat losses are estimated using 2.3 MJ/kg as the standard unit of loss. The formula for the heat losses calculation is:

$$\frac{\frac{[H_2]}{2} * 18 * 2.3 \frac{MJ}{kg}}{Relative\ Molar\ Weight} \tag{11}$$

The results of this LHV calculation are displayed in Table 3.3 – Calculated Biomass LHV.

Table 3.3 Calculated Biomass Feedstock LHV

Biomass	LHV (MJ/kg)
Arboricultural Arisings	17.36
Digestate Pellet	20.96
Miscanthus Pellet	19.88
Poultry Litter Pellet	17.19
Willow Chip	21.28
Wood Pellet	17.27

The LHV of each of the producer gases generated through experimental analysis was also found through calculation rather than from direct measurement. Calculation of the parameter allowed for a truer representation of the value in comparison to the value displayed by the gas analyser. As experiments were ran multiple times for each feedstock and blend, to calculate LHV a time period where constant gas was produced was chosen from the results generated once displayed in excel. An average result for producer gas composition was then found using this chosen time period. Averaged results for each combustible component was then multiplied by its calorific value to obtain the total producer gas LHV. Values for each in MJ/Nm^3 were: CH_4 358, CO 226.36 and H_2 107.98 (Waldheim and Nilsson, 2001).

3.5 Experimental

The single stage downdraft reactor utilised for this research was a MicroLab Class gasifier prepared especially by Fluidyne Gasification of New Zealand, as can be seen in Figure 3.9 – MicroLab Class Fluidyne Downdraft Gasifier. The downdraft gasifier was developed by Fluidyne to analyse fuel samples and incorporates all features of their larger systems. The gasifier was also used for introductory training to gasification technology for students. The gasifier had previously been utilised for other sustainable biomass research within the university.

Figure 3.9 MicroLab Class Fluidyne Downdraft Gasifier

Modifications carried out to the original gasifier design for experimental analysis include changing of the feedstock intake port and addition of a tap to the exhaust stream for gas cleaning and analysis. A new feed intake port was designed and installed to reduce the volume of material required for analysis. Changing from a large fuel hopper to a metal plate reduced the volume of material required and made cleaning and analysis easier as can be seen in Figure 3.10. To simplify the addition of materials during the reaction a plumbing weld was installed on the metal plate. High temperature gasket material was sized for the lid. This ensured no leaking of producer gas and a tight seal to guarantee control over the air entering the reaction.

Figure 3.10 New Feedstock Intake Port

The gasifier hearth was designed for gas to be produced in a single stage. The component has an internal diameter of 155mm, 5mm wall thickness made from stainless steel and height 165mm. 6 air nozzles surround the hearth, which are made from ¼” steel pipe. These air nozzles introduce the gasifying agent to the hearth and are controlled from an external handle to increase or decrease the flow of air. The reduction tube in the centre of the hearth is 30mm in diameter and can be adjusted for biomass of different size by adding of removing spacer plates beneath the tube collar. The grate sits within the reduction tube, whose height can also be adjusted through a screw handle below the hearth module. A thermocouple is situated directly below the reduction tube within the hearth to accurately record gas production temperature. Firebrick has been placed below the reduction tube to ensure insulation of the hearth module. Once the gas has been produced it travels from the hearth through the blast tube where large particles and some tar drop out of the gas stream before the gas reaches the cyclones. Further temperature lowering occurs within the cyclone and the finer powder sized particulates drop out of the stream also. The two cyclones direct gas to either the condenser for engine application or towards the exhaust. Each component contains a clean out port consisting of a metal screw cap for tar and particulate removal. Manometers connected to feedstock intake and the blast tube display pressure across the system. Further thermocouples are connected to the blast tube and cyclones to record temperature evolution across the system. An air pressure fan in the base of the cabinet supplies air to the test flare assembly and to the air inlet nozzles within the hearth. A cooling fan is also turned on for all experimental analysis to prevent over heating of internal components.

Approximately 1kg of material was loaded into the hearth for each experimental analysis carried out. A heat gun was inserted through the plumbing weld to begin the reaction, steadily increasing feedstock temperature to approximately 130°C. Once combustion had begun, the gasifier was turned on. The opened plumping weld was closed, and air is supplied to the system. An initial heat up period would last between 10 – 20 minutes depending on feedstock, before temperatures would settle in the 700 - 900°C range. Thermocouples in the hearth, blast tube and cyclones were connected to a Grant Squirrel 2020 data logger for recording of temperatures. The air control handle is opened slightly until a consistent temperature is achieved within the hearth.

Gas is sampled from the exhaust stream through an ETG PSS 100. This is a scrubber where the gas is passed through three consecutive bottles of bubbling water for removal of any tar or particulates remaining in the system. The scrubber contained a condensation trap for moisture removal, but this was bypassed for a DRIERITE laboratory air and gas drying unit as can be seen in Figure 3.12. This desiccant material ensured complete moisture and tar removal before feeding to the analyser. DRIERITE material changes colour once exhausted and can be easily restored through regeneration. Clean, dry producer gas is then fed to the ETG MCA 100 Syng Biogas Multigas Analyzer. A schematic of the temperature and pressure probes across the system are displayed in Figure 3.11, where T1 – T4 are thermocouples and M1 – M2 are manometers.

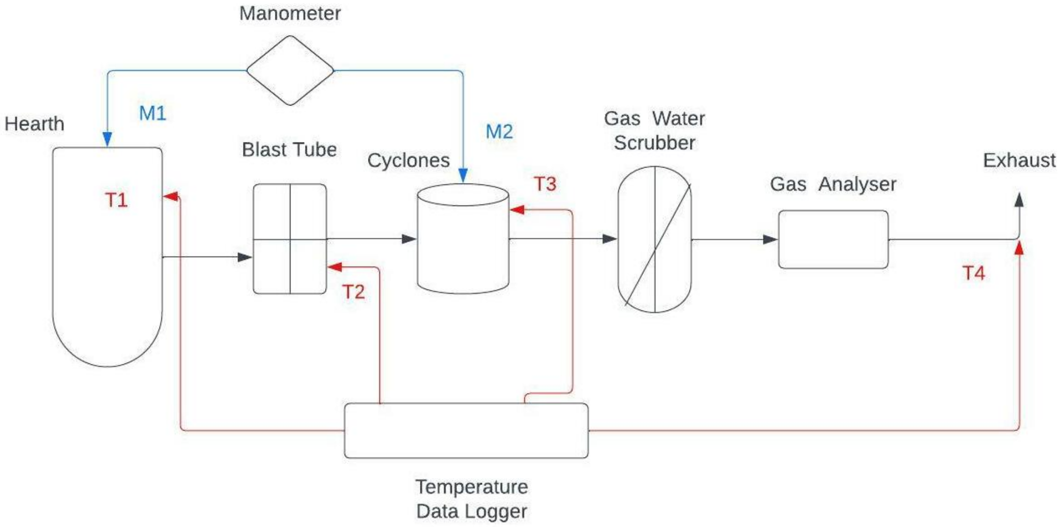


Figure 3.11 Schematic of Temperature and Pressure probe locations

Figure 3.12 Scrubber with moisture capturing DRIERITE material. Discolouration can be seen where material has absorbed moisture.

The gas analyser displays the volumetric percentage of the constituent gases that make up the producer gas. This is a mixture of CO, CO_2, CH_4, H_2 and N_2. The sensors operate on potential difference and are measured as output voltage. This data is displayed on a live graph, as well as stored on an internal memory card which can be downloaded through insertion of an external USB device. During each run of the experiment approximately 200g of additional biomass was added to supplement the reaction. Due to the relatively low reactor volume, experimental time was between 40 minutes to an hour before all feedstock was consumed and the reaction finished. This period could be identified through swift temperature spikes in the reactor. All materials analysed were ran in triplicate to ensure the validity of the results. Once the analysis was complete, the gasifier was turned off and allowed to cool down with the fan across the system remaining on to assist. When completed ash, tar and char were removed from the hearth, blast tube and cyclones and weighed. Water in the scrubber was changed after each analysis to ensure no contamination of the analyser. Composition data from the gas analyser and temperature data from the logger were downloaded and combined using Microsoft excel. Full experimental apparatus set up can be seen in Figure 3.13.

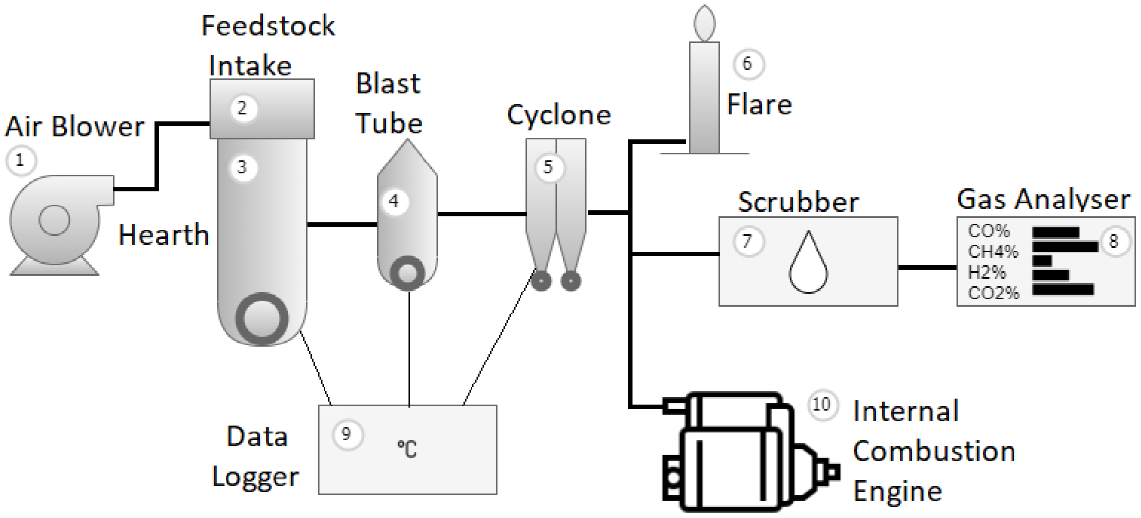


Figure 3.13 Experimental Apparatus Set Up (de Priall et al., 2021)

Engine application of the producer gas was not carried out due to time restraints within the project. To identify engine application results along with efficiencies, simulation of the process was carried out on a validated engine model from previous application research. For carrying out the experimental analysis containing blends, the same methodology was followed using this equipment, with the only difference being two feedstocks were weighed out. The main biomass material of choice i.e. poultry litter, digestate and miscanthus along with wood pellets. The optimum blend ratios for analysis were identified through the literature review and were measured by weight. Blends by weight percentage (wt.%) were 80/20, 60/40 and 40/60. Experiments were again carried out in triplicate to ensure the reliability of the results. Further experimental analysis of the blended feedstock carried out was utilising a catalyst to further increase producer gas LHV and conversion efficiency. This calcium carbonate ($CaCO_3$) catalyst was loaded using the optimum measurement found in the literature of 20 wt.% of the feedstock. This was done using the optimum blend of feedstock with an improved LHV compared to single feedstock, to further improve the LHV and reduce tar content.

Additional research was carried out on poultry litter feedstock with the aim of further reducing the tar content of the producer. Experiments carried out include preheating of the feedstock, adding a metal catalyst into the hearth of the reactor, addition of heated sand to the reactor and gasification of pyrolyzed material in the form of charcoal. Experiments are explained in detail within chapter 4. All results were collated and are displayed in Chapter 4 – Experimental Results for Model Validation.

3.6 Summary

This chapter discusses the methodology employed to carry out the both the simulation and experimental work during the course of the project. This involved identifying and acquiring appropriate sustainable biomass for experimental analysis, employing the correct equipment for carrying out the analysis, and use of the appropriate international standards to ensure reproducible results were generated. A number of suitable feedstocks had been identified as underutilised with an opportunity for further exploitation. After identifying potential material for exploitation, a gauge on the amount of the material available and how it would benefit the environment was carried out. Feedstock characteristics were used as indicators for a materials gasification potential. Following all appropriate standards to identify relevant material characteristics it was found that some of the feedstocks would not function through the gasification system of choice due to low bulk density. The materials that could be used in the system were put forward for further analysis. Developing the information found through the proximate and ultimate analysis of the feedstock's, accurate simulations of the downdraft gasification process and CHP application of the producer gas could be generated. These simulations could then be validated through practical small-scale experimental analysis carried out on the MicroLab Class Fluidyne Downdraft Gasifier. Through analysis of single feedstocks, blended feedstocks and catalyst doped feedstocks it was identified under what conditions the best quality producer gas was generated in terms of producer gas composition, LHV and gas quality.

Chapter 4 – Experimental Results for Model Validation

4.1 Introduction

This chapter will focus on the data generated from the variety of practical experiments carried out as well as some data which was calculated during the course of this research. These results include but are not limited to the characterisation of the biomass feedstocks of interest through proximate and ultimate analysis, the downdraft gasification of single feedstocks, gasification of blends of materials for increasing producer gas quality, and the use of a reaction catalyst on the optimum identified producer gas to further improve overall performance. Extra experimental analysis which was carried out to improve the overall gasification system performance will also be included within the chapter. All experiments listed below have been carried out at Ulster University's Jordanstown campus as described within the methodology chapter. Ultimate analysis was carried out externally through ASEP laboratories in Queens University Belfast.

4.2 Feedstock Characteristics

To carry out the relevant experimental analysis and identify the pertinent biomass characteristics the appropriate international standards were followed, as described within Chapter 3 – Methodology. Results have previously been displayed in Chapter 3 - Table 3.1. Ash melting for two of the materials, willow chip and digestate pellets, was unable to be carried out due to moving of equipment from one campus to another, so therefore estimations have been taken for these from relevant literature (Chen et al., 2019).

4.3 Single Feedstock

To carry out the downdraft gasification analysis of the biomass material each feedstock was gasified as a single feedstock multiple times to identify producer gas quality. Experiments were ran in triplicate to ensure a consistent average gas quality could be found. Following this, once average producer gas composition had been identified, gasification of blends of two feedstocks together would be carried out with the aim of improving the identified gas quality. For each feedstock of interest, multiple gasification experiments were carried out as described within the methodology to ensure reproducible and accurate results were found. The materials which were analysed under gasification conditions include:

- Poultry Litter
- Anaerobic Digestion Digestate
- Miscanthus
- Wood Pellet

An example of the gas composition data gathered from the ETG analyser and collated alongside temperature data from the Grant Squirrel logger is displayed in Figure 4.1. This result is from the experimental analysis of poultry litter as a single feedstock. Gas volumetric composition is on the Y-axis, time is on the X-axis and temperature is on the secondary Y-axis. From this approximately 10-minute sampling period despite consistent gas composition being produced, the temperature of the system is fluctuating significantly, between 750°C and 1025°C. All reactions carried out faced the same temperature variations.

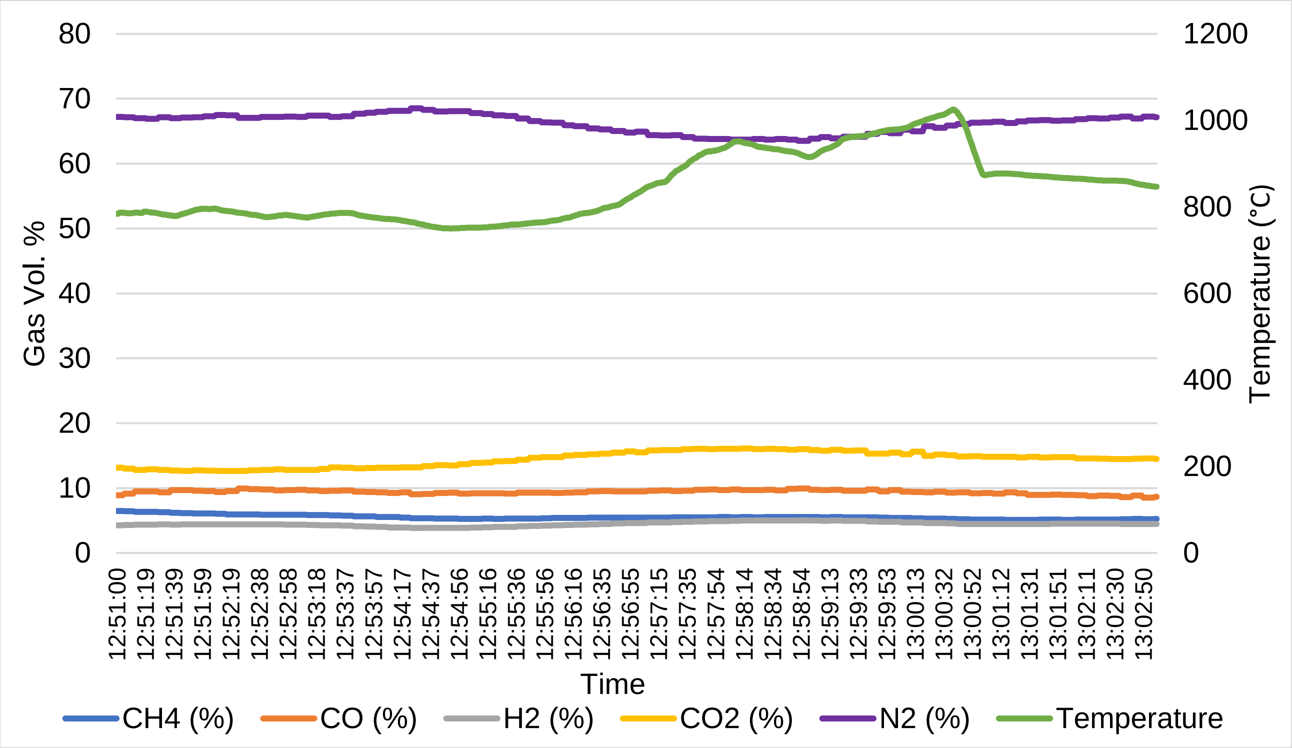


Figure 4.1 Single Feedstock Poultry Litter Experiment Result

The first results from the downdraft gasification experiments that were carried out are from experimental analysis of a single streams of feedstock. For each material analysed, at least 3 experiments were carried out until consistent results were obtained. More than 3 experiments were carried out if irregular results were found, or if the temperature range did not remain consistent. As each experiment lasted for approximately an hour, the optimum 5 minutes of gas production was used to gather the results from. These 3 optimum producer gas periods were then averaged to obtain the final result for producer gas composition. This averaged result is what has been utilised for visual representation of the producer gas, as displayed in Figure 4.1 Single Feedstock Producer Gas Comparison. The graph shows volumetric makeup of the gas on the Y – axis, and the different gas components that make up the producer gas on the X – axis. The components of interest within the producer gas are methane (CH_4), carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and nitrogen (N_2).

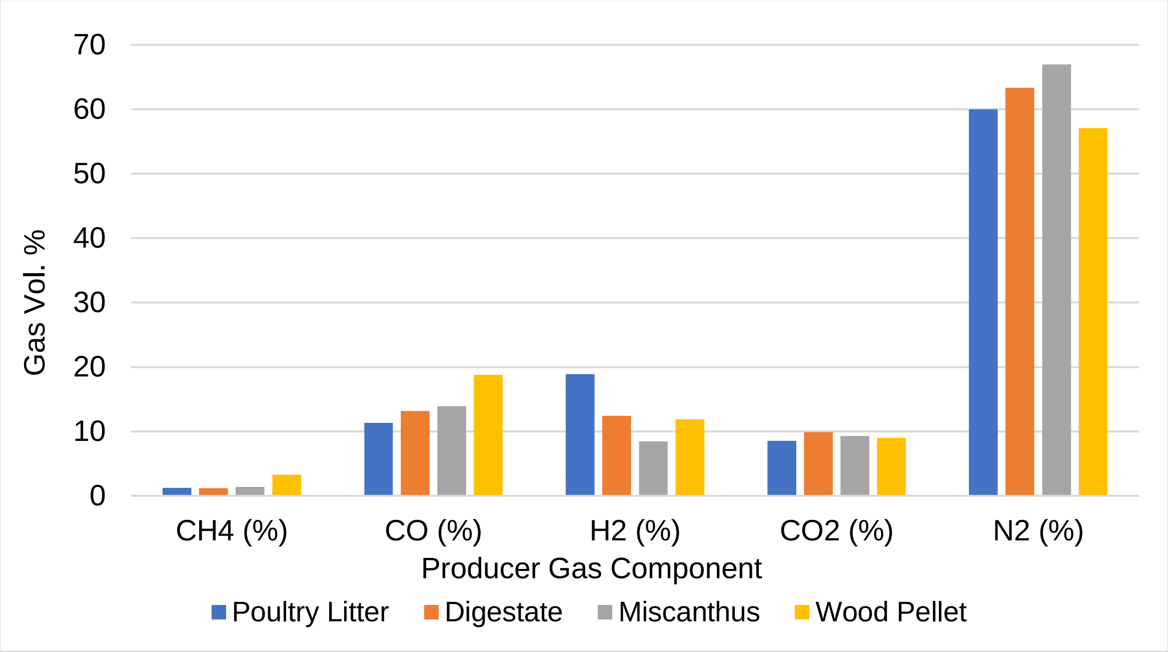


Figure 4.2 Single Feedstock Producer Gas Comparison

On first impressions, the most notable characteristic from the results presented in Figure 4.2 is the large amount of N_2 present in each producer gas. This is due to the fact that air is used as the reaction carrier gas. The gas generated during the gasification process is therefore diluted with atmospheric N_2 leading to a lower overall heating value (Iribarren et al., 2014). LHV for each gas generated is displayed in Table 4.1, along with detailed gas composition and average reaction temperature. A visual representation of the LHV of each producer gas is displayed in Figure 4.3. The gas with the greatest LHV is wood pellets, due to its high CH_4 content. With an average N_2 content of 60%, the LHV for the gases fall between 3 – 5 MJ/Nm^3, agreeing with the values found in literature for downdraft gasification of biomass material (Asadullah, 2014a). To achieve a higher LHV from the reaction, a different carrier gas could be introduced such as steam or oxygen. This would increase the LHV but could detract from both the economic and energetic aspect of the research. Miscanthus has the highest proportion of N_2 in the producer gas, with 66.95% of the gas composed of it. The next gas component that stands out is the volumetric percentage of H_2 in the feedstocks. From Figure 4.2 it can be seen that poultry litter generated the greatest amount of H_2, with 18.89%. The next highest is 12.43% in the digestate. The reason for this is that of the materials gasified, poultry litter contained the highest moisture content, at 10.27%, 2.58% more than the next material of digestate at 7.69%. This percentage difference has led to an 6.46% increase in producer gas H_2 content. Interesting to note that while poultry litter had the lowest fixed hydrogen content in the biomass, it generated the most H_2 gas, down to the influence of moisture within the feedstock.

Table 4.1 Single Feedstock Composition, LHV & Temperature

Feedstock	**CH_4 (%)**	**CO (%)**	**H_2 (%)**	**CO_2 (%)**	**N_2 (%)**	**LHV (MJ/Nm^3)**	**Temperature (°C)**
Poultry Litter	1.23	11.35	18.89	8.53	60.00	3.91	945.7
Digestate	1.19	13.19	12.43	9.88	63.31	3.44	831.5
Miscanthus	1.40	13.91	8.44	9.30	66.95	3.17	871.4
Wood Pellet	3.26	18.79	11.88	9.01	57.06	4.82	839.2

The amount of CO_2 produced during the gasification process remained consistent throughout all experiments, with only 1.35% difference between the lowest and highest amount. This is due to the reduction in CO_2 at temperatures above 500°C to CO, which has occurred in each reaction. Temperatures were above 830°C for each reaction, as can be seen in Table 4.1.

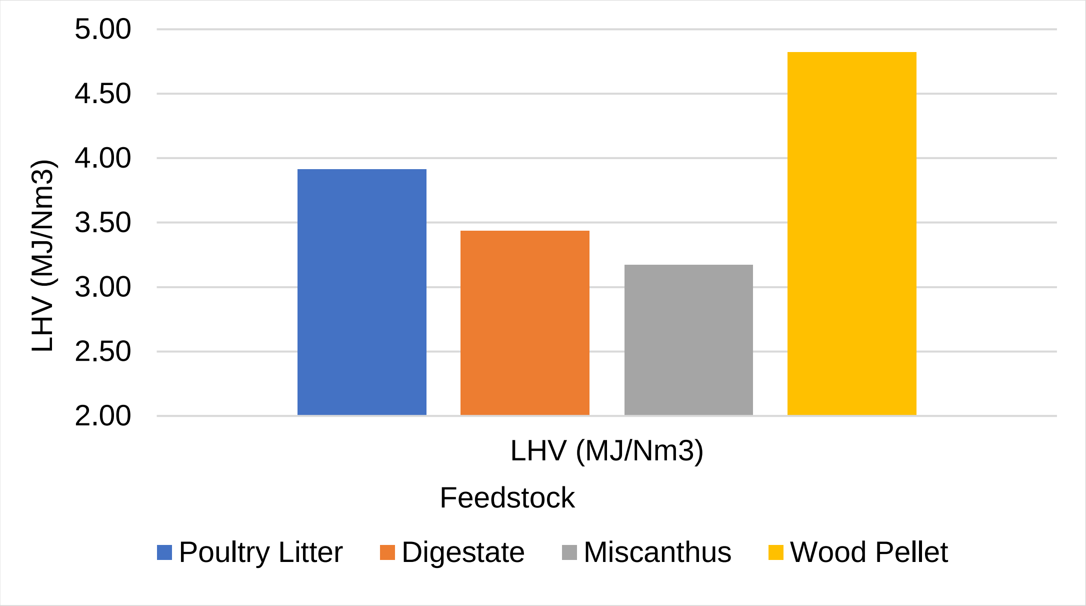


Figure 4.3 Single Feedstock Producer Gas LHV

The last two gaseous components generated during the reaction are CH_4 and CO. While digestate and miscanthus have a similar CO concentration in the final producer gas, poultry litter's CO concentration is slightly lower. This lower concentration is a consequence of the lower carbon content present in the poultry litter feedstock. Wood pellet producer gas has a much higher concentration of CO and CH_4 which can be attributed to the high carbon content, low ash content and high amount of volatile matter. This allows for nearly all the carbon present to be broken down into its constituent components and form these gaseous products. CH_4 content of the producer gases is low and consistent in each material between 1.19 – 1.40%, with wood pellets an outlier here at 3.26%. This is due to the tar produced during gasification of wood pellets, which is significantly higher than the other materials. This could be attributed to the lignin present within the wood pellet, which acts as binding agent during the pelleting process.

Conversion efficiency for each of the feedstocks of interest was calculated. This was done through a simple mass balance where the weight of feedstock fed into the reaction was measured, and the weight of the ash, tar and char removed from the reactor was recorded. This figure gave an indication of conversion efficiency.

$$\textit{Conversion Efficiency (\%)} = 100 - \frac{(\text{Ash} + \text{Tar} + \text{Char})}{\text{Feedstock In}} * 100 \qquad (16)$$

Results from this calculation for single feedstock streams are displayed in Table 4.2. As the reactor is a fixed bed, there is a significant amount of unconverted material. At this scale for experimental analysis, fixed bed is the most appropriate. We can see that almost every material has a near identical conversion efficiency, with digestate pellet 2% higher than the other feedstocks. A high volatile matter content (74.51%), along with a high bulk density (716 kg/m3) could attributed as a potential reason for this.

Table 4.2 Single Feedstock Conversion Efficiency (%)

Feedstock	Poultry Litter Pellet	Digestate Pellet	Miscanthus Pellet	Wood Pellet
Conversion Efficiency (%)	68.42	70.87	67.86	68.33

4.4 Blended Feedstock

Once the average composition for single feedstock producer gas had been identified, the optimization of the producer gas generated through downdraft gasification of blends of the sustainable biomasses with wood pellets were analysed. The appropriate blend ratios for experimental analysis were identified through the literature review. The ratios which were identified for use were:

- 80/20
- 60/40
- 40/60

These three ratios of biomass in the form “biomass/wood pellet” were acknowledged as the optimal choice from previous research and used for this experimental analysis. Increasing the weight percentage (w.t%) of wood pellets beyond 60% was not carried out due to economical reasoning. If a gasification system using wastes were to be set up, purchasing 60% or more of the feedstock while trying to remain environmentally and financially sustainable would be difficult to achieve given current subsidy levels available. The research was carried out to identify the best quality producer gas (LHV) and utilise that blend for further research such as for catalyst application. Displayed in Figure 4.4 is the experimental results collected for a ten-minute sampling period of the 60/40 blend of poultry litter and wood pellets. As was seen in the Figure 4.1, despite consistent gas production throughout the sampling period, the temperature fluctuates. Temperature varies between 784°C and 942°C.

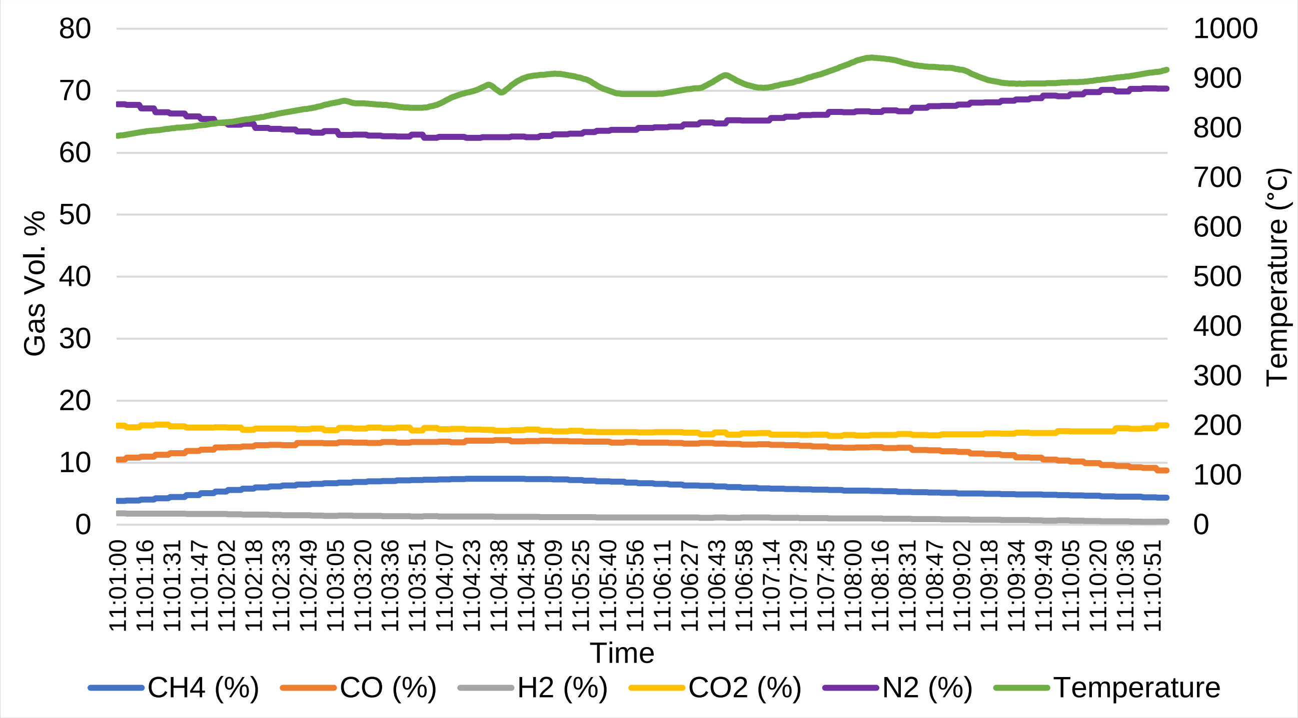


Figure 4.4 Poultry Litter/Wood Pellet 60/40 Blend Experiment Result

4.4.1 Mixing Poultry Litter with Wood Pellets

The blends of poultry litter and wood pellets was one of the most promising from a research point of view, as it has the greatest potential for real world applications in terms of providing energy to the numerous poultry farms in the UK. Results from this research are displayed in Figure 4.5, where the producer gas composition is compared between blends and the original gas composition.

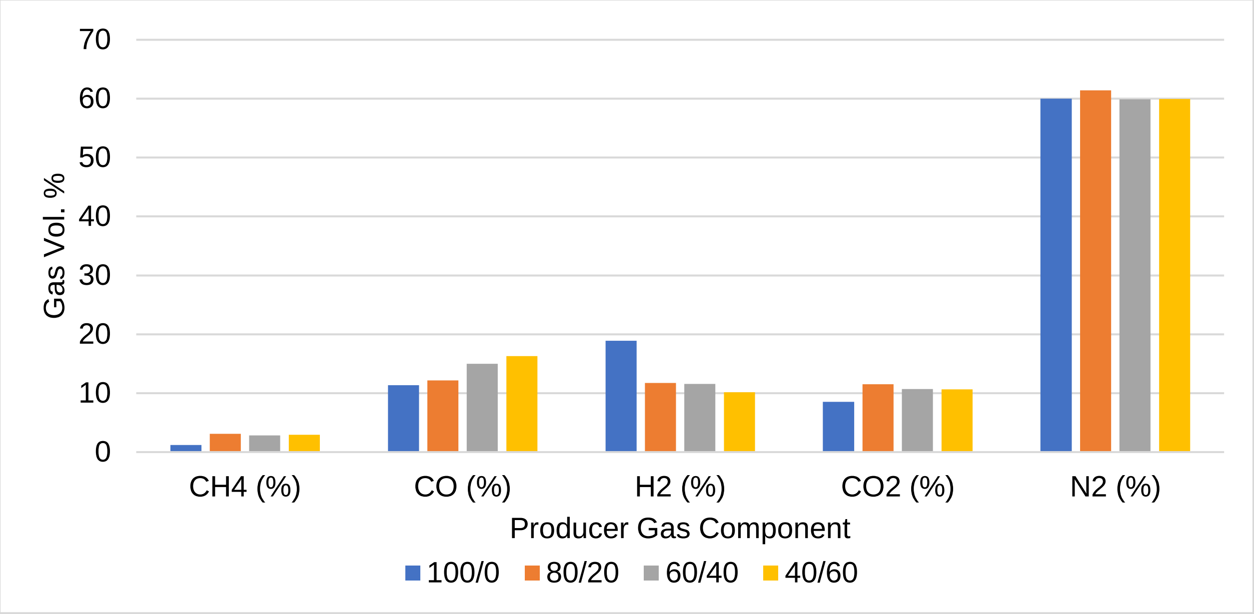


Figure 4.5 Poultry Litter Blend Comparison

The most notable trend identifiable from the blends of poultry litter and wood pellets, is the volumetric CO component increasing with increasing proportion of wood pellets in the blend. This may be down to the increased carbon content of the feedstock from the wood pellets. More carbon available, means that the underlying reaction which generates CO during the gasification process can take place. This is the Boudouard reaction, where carbon and CO_2 react to create CO (Olgun et al., 2011). The CO_2 concentration within the producer gas is controlled by this reaction, and it initially increases when blending occurs. Further increases of the wt.% make the CO_2 concentration decrease where it then remains consistent. While CO increases as the blend percentage increases, the H_2 concentration goes the opposite direction. The largest fraction of H_2 by a margin is in the 100% PL feedstock, and when blending occurs this value decreases significantly, from 18.89% to 11.55% and further decreases with higher proportion blends. The decrease must be due to the temperature at which the reactions are occurring. From Table 4.3 we can see that while the average reaction temperature for gasification of PL alone is 945.7°C, the blending experiments which were carried out under the exact same conditions in the exact same reactor set up occur at temperatures over 100°C less. The reaction temperature follows a rough trend of decreasing with increasing wt.% of wood pellets. This could be explained as less fixed oxygen within the biomass, meaning an overall lower temperature. PL has a high fixed oxygen content, at 57.32%. Wood pellets meanwhile is significantly lower, at 45.66%. The amount of fixed oxygen within the feedstock has an influence on overall temperature through the combustion reactions. Increasing oxygen will increase reaction temperature, and therefore decreasing oxygen will lead to a lower overall temperature. The water gas shift reaction, which is encouraged through higher reaction temperatures is then less likely to take place, leading to the lower H_2 content of the blended feedstock producer gas.

Table 4.3 Poultry Litter Blend Producer Gas, LHV & Temperature

Blend	CH_4 (%)	CO (%)	H_2 (%)	CO_2 (%)	N_2 (%)	LHV (MJ/Nm^3)	Temperature (°C)
100/0	1.23	11.35	18.89	8.53	60.00	3.91	945.7
80/20	3.13	12.16	11.76	11.55	61.40	3.93	812.9
60/40	2.83	14.98	11.60	10.70	59.89	4.16	820.0
40/60	2.97	16.29	10.19	10.63	59.92	4.22	795.7

While the H_2 content of the producer gas decreases, the overall LHV of the blended feedstock increases with increasing wt.% blend. This again can be seen from Table 4.3, where slight increases were calculated for each blend of feedstock. This increase was due to the increase in CO and CH_4 in the analysed producer gases. The increased carbon content of the feedstocks from the increasing proportion of wood pellets is the reason for this. While LHV was increasing, temperature was decreasing as mentioned. To further increase LHV, if temperature could remain consistent above 900°C, a better-quality producer gas could be generated. Finally, for PL, the concentration of N_2 within the producer gas remains virtually the same throughout all blends. At approximately 60% for each, the N_2 content doesn't change. This means if a different carrier gas was used, an almost 60% increase in LHV could be generated.

4.4.2 Mixing Digestate with Wood Pellets

The use of digestate as an alternative fuel for energy production from a waste or by-product is an attractive proposal, and while the energy requirements of where it may be applied may not be comparable to the poultry litter scenario, it may still be a viable option depending on individual farm requirements.

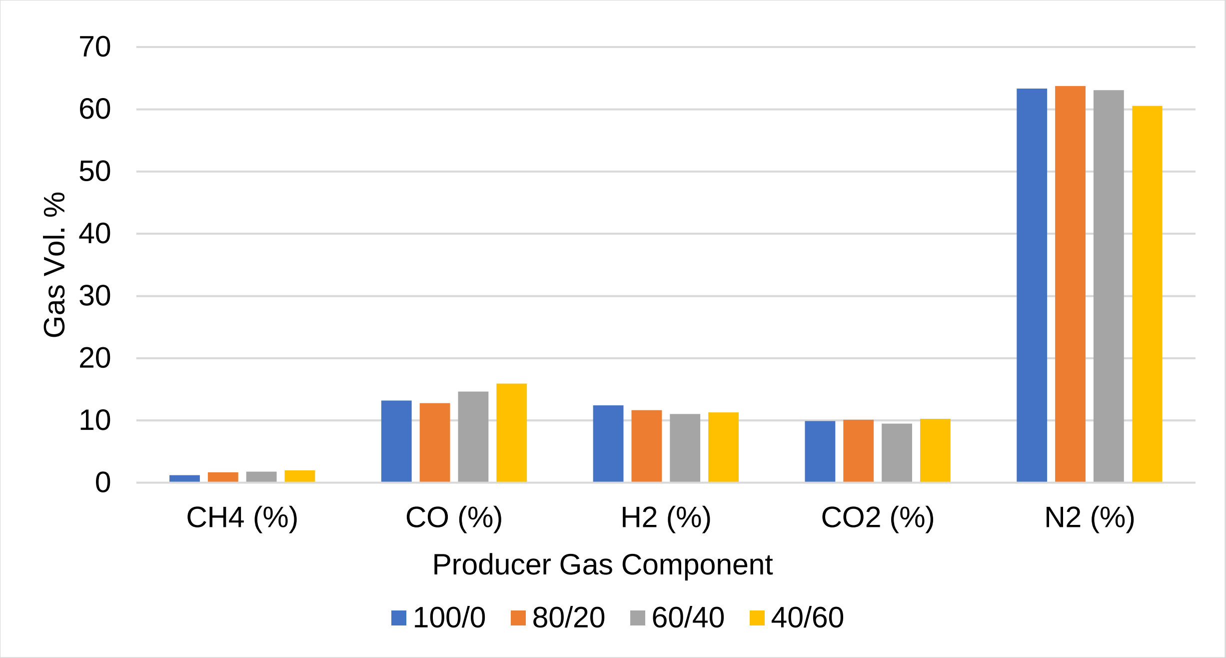


Figure 4.6 Digestate Blend Comparison

We can see from Figure 4.6 that the results for the blends of digestate and wood pellets follow similar trends to its poultry litter counterpart. With increasing proportion of wood pellets in the blend, the CH_4 and CO content of the producer gas increases. These increases are only slight, with 0.80% difference in CH_4 content of the producer gas between digestate as a single feedstock and the 40/60 blend. The CO content increased slightly higher throughout the blends, with a 2.73% increase noted from the original feedstock to the 40/60 blend. Again, this can be viewed as a result of the increasing carbon content in the feedstock from the wood pellets. The H_2 content of the producer gas has decreased with increasing blend proportion, with a 1.13% reduction. Slightly lower moisture content in the wood pellets compared to the digestate pellets, 7.50% and 7.69% respectively, may be the cause of this with less moisture available for conversion into H_2. The CO_2 concentration throughout the various blends remain consistent, while the N_2 component of the producer gas actually decreases with increasing blend proportion. The reduction in CO_2, specifically noticeable in the 40/60 blend that is 2.49% lower than the previous, could be caused by the reaction temperature. Unlike poultry litter, the digestate average reaction temperature increases with blend proportion. From Table 4.4 it can be seen that the original feedstock reaction temperature is 831.51 °C, while the 40/60 blend had an average temperature of 910.54°C. This higher reaction temperature promotes the generation of CO from CO_2 and lowers the overall N_2 content of the producer gas.

Table 4.4 Digestate Blend Producer Gas, LHV & Temperature

Blend	**CH_4 (%)**	**CO (%)**	**H_2 (%)**	**CO_2 (%)**	**N_2 (%)**	**LHV (MJ/Nm^3)**	**Temperature (°C)**
100/0	1.19	13.19	12.43	9.88	63.31	3.44	831.51
80/20	1.67	12.81	11.67	10.10	63.75	3.48	820.67
60/40	1.80	14.65	11.03	9.48	63.05	3.69	851.38
40/60	1.99	15.92	11.29	10.24	60.56	3.94	910.54

The LHV of the producer gases generated from digestate blend gasification follow the same trend as those identified with poultry litter, that the higher the blend proportion of wood pellets, the higher the LHV. PL had a 0.31 MJ/Nm^3 increase in LHV from lowest to highest, while digestate had a greater increase at 0.51 MJ/Nm^3 between lowest and highest producer gas energy content. Both the increased reaction temperature, and the greater carbon content of the feedstock may have influenced these higher LHV's.

4.4.3 Mixing Miscanthus with Wood Pellets

The final feedstock of interest with which the blending analysis was carried out was miscanthus pellets. While it may not be an industrial by-product or waste like poultry litter and anaerobic digestate, it does have some advantages in terms of its characteristics as a feedstock. Miscanthus' ash content of 2.51% is the lowest of the three materials by 8.67%. Blending of materials can occur to lower overall ash content, and miscanthus' low ash could make it a more attractive option under certain circumstances. Miscanthus also acts as a barometer for the gasification potential of other herbaceous energy crops such as willow, poplar and switchgrass.

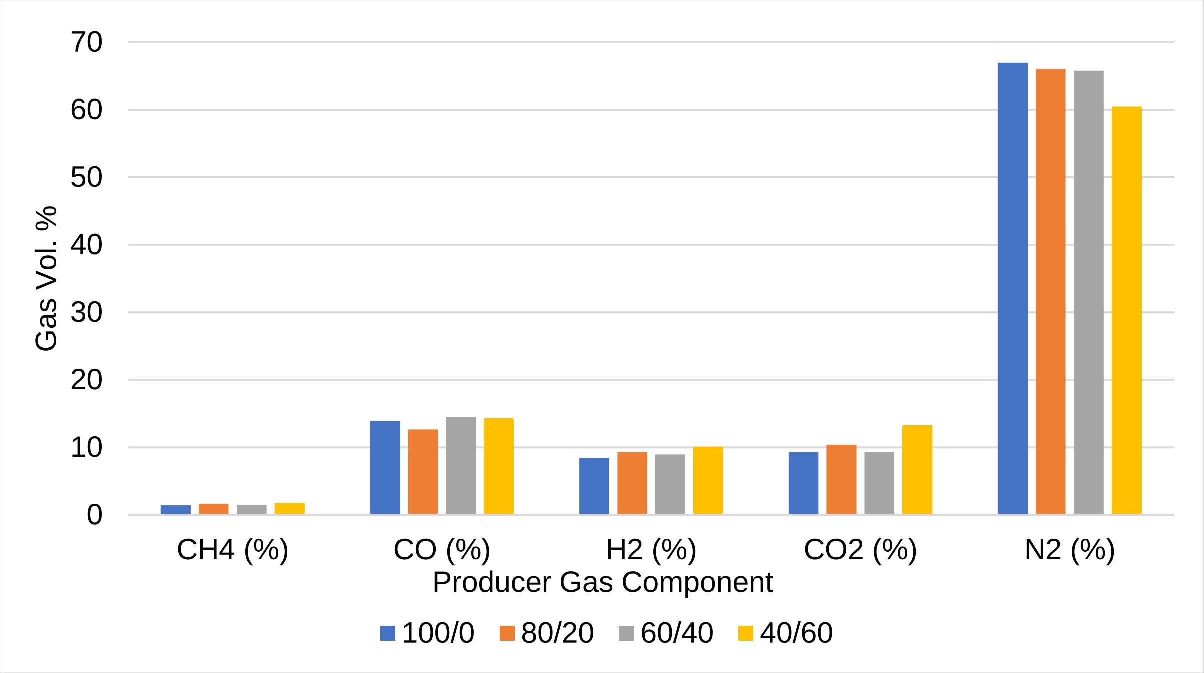


Figure 4.7 Miscanthus Blend Comparison

Results of the miscanthus feedstock blending gasification experiments can be seen in Figure 4.7. When compared to PL and digestates analysis, the results of the miscanthus analysis are much less stable. From the figure we can clearly see that CO concentration decreases when blended at 80/20, before increasing at a further blend of 60/40, and decreasing again with a blend of 40/60. This is in contrast to what was seen previously, where CO followed the trend of increasing with increasing proportion of wood pellets in the feedstock. This inconsistency within the results can be seen through the progression of H_2 and CO_2 also. H_2 content of the original producer gas is 8.44% before increasing to 9.28% when using the 80/20 blend. It then decreases to 8.94% for the 60/40 blend and increases again for the final 40/60 blend to 10.11%. The concentration of CO_2 also follows this inconsistent nature, which can be seen in Table 4.5. The final gas component, N_2, does not vary with the other constituents. It decreases with increasing wood pellet proportion, dropping 6.45% in this space. The LHV of the producer gases increases when the proportion of wood pellets in the blend increases, which is what was seen with both poultry litter and digestate before this. A 0.37 MJ/Nm^3 increase was identified between the single feedstock and the 40/60 blend.

Table 4.5 Miscanthus Blend Producer Gas, LHV & Temperature

Blend	CH_4 (%)	CO (%)	H_2 (%)	CO_2 (%)	N_2 (%)	LHV (MJ/Nm^3)	Temperature (°C)
100/0	1.40	13.91	8.44	9.30	66.95	3.17	871.35
80/20	1.65	12.67	9.28	10.36	66.05	3.19	987.09
60/40	1.45	14.49	8.94	9.35	65.77	3.32	912.68
40/60	1.77	14.34	10.11	13.28	60.50	3.54	838.72

One reason for this inconsistent producer gas makeup could be due to the effects that the reaction temperature is having. From Table 4.5 we can see that the reaction temperature is not very stable and fluctuates between experiments. The single feedstock reaction occurred at 871.35°C, the next at 987.09°C, followed by 912.68°C and 838.72°C. Miscanthus has a similar chemical composition as the digestate feedstock, with the only difference in characteristics between the two volatile matter, 74.51% for digestate while miscanthus has 83.74%. Therefore, the cause of this instability within the reaction temperature must be caused by external physical parameters related to the downdraft gasification system design such as air flow. While every effort was made to ensure consistent air volume was utilised for each reaction, poor air control and reactor design may have caused slight variations. This will be deliberated in further detail in Chapter 8 – Discussion.

4.4.4 Catalyst

Once the optimum blend of feedstocks had been identified through experimental analysis, a catalyst was added to the reaction to further enhance producer gas quality. While many catalysts exist for reducing tar content within the gasifier (Cheng et al., 2020; Perondi et al., 2019) and increasing producer gas LHV (Yang et al., 2016), the optimum choice for this research is a calcium-based catalyst due its availability across the UK agricultural sector as soil pH amendment product (DAERA, 2020). Therefore, catalyst experiments were carried out utilising a calcium carbonate ($CaCO_3$) powder. Through the addition of a CaO catalyst tar cracking can be carried out by promoting the absorption of tar molecules amongst some others on the CaO active sites (Li et al., 2022). These active sites promote tar cracking through dehydrogenation, dealkylation and ring opening of aromatic tar molecules. All these reactions involve carbon molecules breaking their bond to either hydrogen or other carbon molecules. This cracking can lead to other species forming such as CO, CO_2 or H_2. The increased H_2 or CO content will improve the overall LHV of the producer gas. From the literature, the optimum ratio of catalyst loading was identified to be 20 wt.% of the biomass feedstock. The blend ratio that was chosen to be used for analysis was 60/40. This was because the LHV of the gas produced was greater than the single feedstock, by 7.3%, but didn't include such a high proportion of wood pellets that the economical aspect of the application would be significantly detracted from.

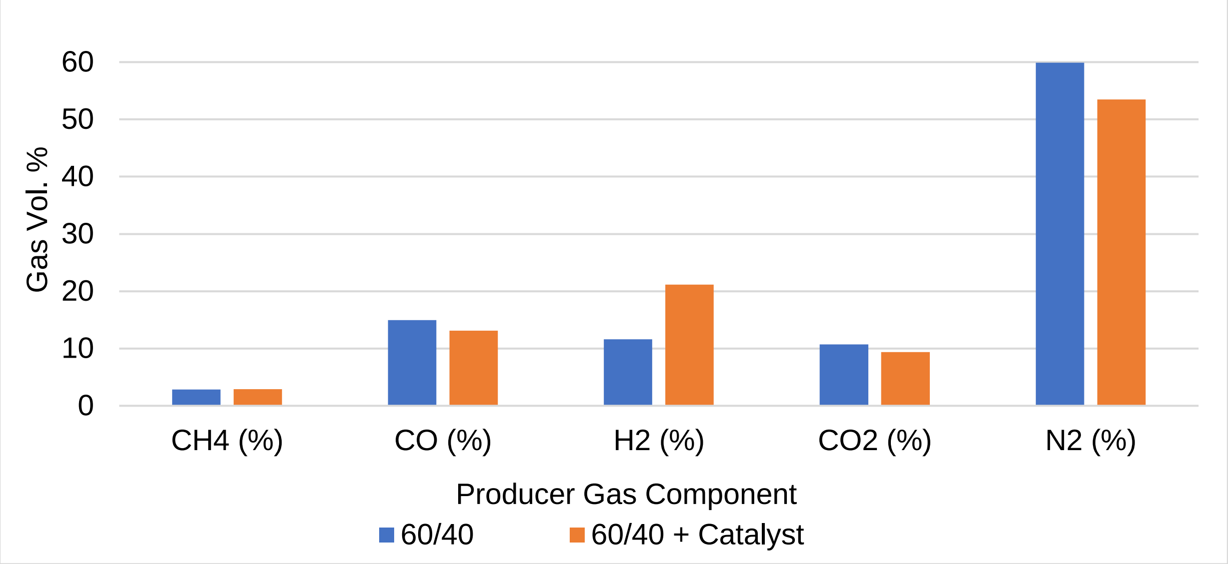


Figure 4.8 Poultry Litter Catalyst Comparison

In Figure 4.8 the difference between the gaseous components in the 60/40 blend producer gas and the 60/40 blend with 20% wt. catalyst is illustrated. The primary difference between the two is the almost 10% increase in H_2 content of the producer gas generated with the calcium catalyst. It is clear from the result that the catalyst had the desired effect, increasing the LHV of the producer gas by 16.45% or 0.82 MJ/Nm^3, from 4.16 to 4.98 MJ/Nm^3 as can be seen in Table 4.6. This increase occurred due to cracking of the tar generated, due to a reaction such as (17) being promoted:

$$C_nH_m(Heavy\ Tar) \rightarrow\ C_xH_y\ (Light\ Tar) + H_2 \tag{17}$$

The presence of the CaO in the gasification reaction promotes the cleaving of carbon bonds within the tar, and carbon – hydrogen bonds. This free hydrogen is then able to form new gas species in the shape of H_2. Breaking down the tar into a lighter form is the simplest method of handling the material. Despite the cracking which occurred, no visible difference in tar quantity was noted. The reaction occurs at temperatures lower than expected too, with gasification of poultry litter generally occurring above 900°C (de Priall et al., 2021). As can be seen in Table 4.6 the catalyst reaction occurred at temperatures almost 70°C below the reactions which took place without the catalyst. This could be related to the lack of control over the system which the user has.

Table 4.6 Poultry Litter Catalyst Comparison

Blend	**CH_4 (%)**	**CO (%)**	**H_2 (%)**	**CO_2 (%)**	**N_2 (%)**	**LHV (MJ/Nm^3)**	**Temperature (°C)**
60/40	2.83	14.98	11.60	10.70	59.89	4.16	820.0
60/40 + Catalyst	2.89	13.14	21.13	9.37	53.48	4.98	751.4

To ensure reliability of the results generated, the catalyst was applied to another feedstock blend for comparison. Similar results were seen when the catalyst was applied to the 60/40 blend of digestate. The same catalyst loading of 20% wt. was used to ensure comparable application. While the H_2 content of the gas increased by only 2.71% in this case, the overall LHV of the producer gas increased 15.53% or 0.67 MJ/Nm^3, from 3.69 to 4.36 MJ/Nm^3. For the digestate blend, CO_2 concentration increased in the reaction with the catalyst illustrated in Figure 4.9, unlike the poultry litter test. This increase in CO_2 could be related to another reaction taking place, such as steam dealkylation (18):

$$C_nH_m + H_2O \rightarrow C_xH_y + H_2 + CO_2 \tag{18}$$

$$C_nH_m + H_2 \rightarrow C_xH_y + CH_4 \tag{19}$$

From the results we can assume that the catalyst was functional for the reaction but due to some other reactions taking place, it did not increase H_2 content as much as previously seen with poultry litter. This reaction taking place could be the hydro dealkylation reaction (19), where a portion of the excess H_2 could be used increasing the CH_4 content, which was seen for digestate as can be seen in Table 4.7. A reason for this could be the increased temperature at which the digestate catalyst reaction takes place. Digestate catalyst reaction occurred 11°C higher than the original at 862°C. This is a total of 111°C higher than the poultry litter equivalent reaction and could have influenced the hydro dealkylation to take place.

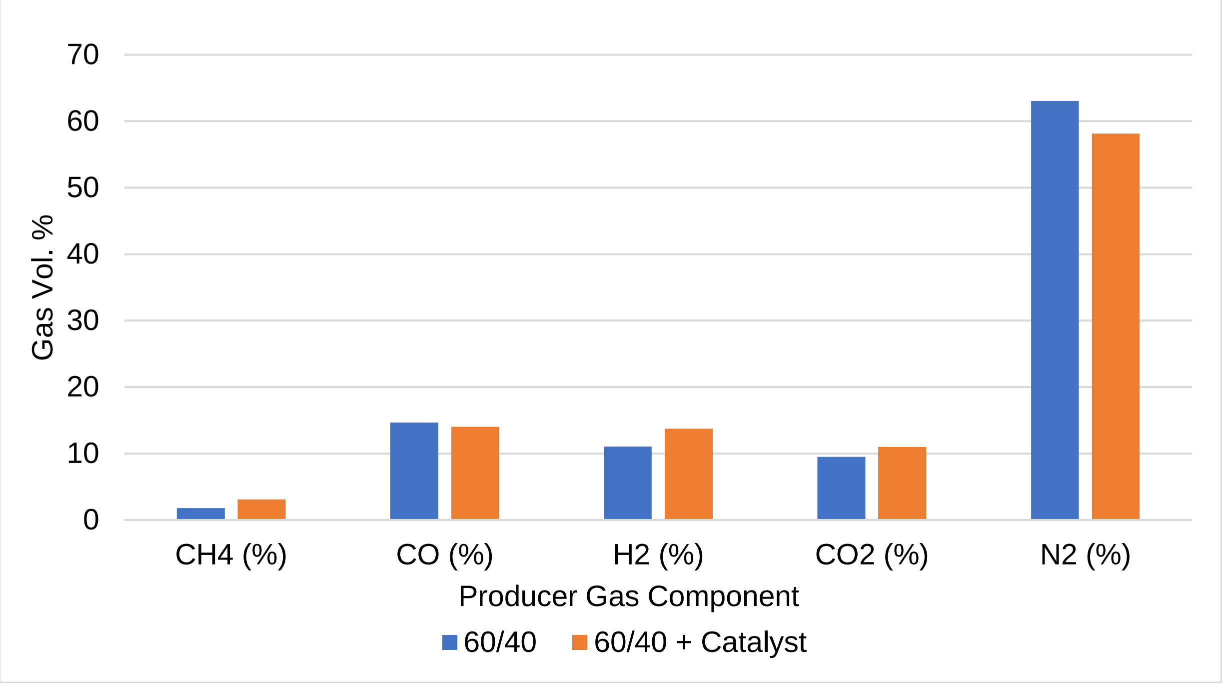


Figure 4.9 Digestate Catalyst Comparison

While slight increases in CH_4 and H_2 were noted from the catalyst loaded reaction, the increase in LHV may have also been influenced by a reduction of the N_2 concentration in the final producer gas composition. An almost 5% reduction in N_2 was seen from 63.05 to 58.14%, which meant less N_2 to dilute the energy containing components of the producer gas with.

Table 4.7 Digestate Catalyst Comparison

Blend	**CH_4 (%)**	**CO (%)**	**H_2 (%)**	**CO_2 (%)**	**N_2 (%)**	**LHV (MJ/Nm^3)**	**Temperature (°C)**
60/40	1.80	14.65	11.03	9.48	63.05	3.69	851.38
60/40 + Catalyst	3.09	14.04	13.74	10.99	58.14	4.36	862.21

4.5 Additional Experimental Analysis

While increasing the performance of the DGS through the use of blends of sustainable biomass and waste material was the main aim of the research, further improving the gasification performance using different methods were also investigated. The additional analysis that was carried out using the DGS is included in this section. These experimental analyses were carried out to try further improving the overall system performance such as lower tar content, increased LHV and greater conversion efficiency. Methods through which this could be carried out were identified in literature and applied to the downdraft gasification system at the focus of this research.

4.5.1 Pre-Heated Feedstock

The first piece of extra gasification analysis that was carried out was the pre-heating of the biomass feedstock before the gasification reaction takes place. The feedstock of choice was poultry litter, as this had exhibited some of the most promising results from the analysis previously carried out. The preheating of a biomass feedstock for thermochemical conversion has been carried out by multiple researchers before. Microwave assisted preheating has been a prevalent method employed to uniformly increase temperature feedstock. Results from this analysis has shown to generally increase production from the biomass feedstock during thermochemical conversion (Y. F. Huang et al., 2013; Ke et al., 2019). During microwave heating, microwave energy penetrates the biomass particles and immediately transforms to thermal energy. This analysis was carried out with the rational that a preheated feedstock is better prepared for gasification than material at ambient temperature. While microwave assisted pre-heating couldn’t be accomplished for this research, an alternative method was carried out. This was to heat the within the system reactor before closing it to the atmosphere. The heat gun used for ignition purposes was used to gently heat the feedstock while continuously mixing it to ensure an even and equal temperature rise throughout. By gently mixing the material at the same time as heating, combustion was avoided.

Results of the analysis displayed in Table 4.8 show improvement in CO concentration generated from the preheating of the feedstock. An increase in CO of 6.99% was noted when compared to the original analysis. While CO concentration had increased significantly, the H_2 concentration of the producer gas has had the opposite response to the preheating step. From 18.89% in the original single feedstock analysis, this has decreased significantly to 8.67% after preheating. This equates to a 54% reduction in producer gas H_2 concentration. This decrease in H_2 could be caused by pre-pyrolysis of the feedstock leading to losses in the volatile matter content. This is caused by the direct application of heat to the feedstock, and not indirectly as was carried out by previous research.

Through increasing the temperature within the gasification reactor, an increase in enthalpies of the air occurs. This will lead to higher temperatures found in the pyrolysis, oxidation and reduction zones of the gasifier (Ependi et al., 2019). This greater temperature can lead to increased formation of combustible gas components, such as CO (Trninić et al., 2020). While indirect heating can be beneficial, direct heating has the opposite effect of detracting from the producer gas LHV through lowering the combustible H_2 of the gas. Feedstock moisture content was 10.27%. Direct heating of the feedstock would lower this through drying. This would result in the hydrogen and oxygen present in the moisture being unable to react to produce gas components in the producer gas generated (Widjaya et al., 2018). From the single feedstock analysis conversion efficiency was 68.42% for the poultry litter. After the preheating analysis was carried out, conversion efficiency reduced to 64.17%. This 4.25% reduction in efficiency could be due to the breaking of heavier tars generated into additional lighter components (Kostyniuk et al., 2019), with an example of the tar produced during the gasification reactions visible in Figure 4.10.

Table 4.8 Poultry Litter Preheating Comparison

Feedstock	**CH_4 (%)**	**CO (%)**	**H_2 (%)**	**CO_2 (%)**	**N_2 (%)**	**LHV (MJ/Nm^3)**	**Temperature (°C)**
100/0	1.23	11.35	18.89	8.53	60.00	3.91	945.7
PL Pre-Heated	1.27	18.33	8.67	8.72	63.01	3.71	908.7

Figure 4.10 Image of tar captured from the downdraft gasification system

LHV decreased from 3.91 to 3.71 MJ/Nm^3. This equates to a 5.49% decrease in LHV or 0.20 MJ/Nm^3. Repeating the analysis with a microwave for more accurate replication of what was carried out in the literature could improve performance of the pre-heating step.

4.5.2 Steel Wool

The next piece of analysis which was carried out with the aim of improving system performance was the addition of steel wool to the reactor. Within the hearth of the downdraft gasifier, 12 pieces of steel wool as seen in Figure 4.11 were placed while the system was at ambient temperature. This meant that any gas produced would have to pass through the steel wool before reaching the blast tube and continuing on its journey through the system. Steel wool is comprised of groups of ferrous alloys that prevent the iron from rusting. With its large surface area, the stainless steel can assist with the catalytic reforming of biomass tars, at temperatures between 600 – 800°C (Guo et al., 2019; Yu et al., 2021). The material should trap any tar or other particulates before they move further down the system, encouraging them to convert into gaseous species, increasing gas yield and LHV. These metals are attractive due to their high activity and low costs (Kostyniuk et al., 2019). While individual tar species and yield was not identified when collected during the research, it was an issue that required cleaning after each experiment. Tar and char were removed from the clean out ports together along with some unconverted materials, meaning distinguishing between the various components was not possible.

Figure 4.11 Steel Wool Pieces before the reaction

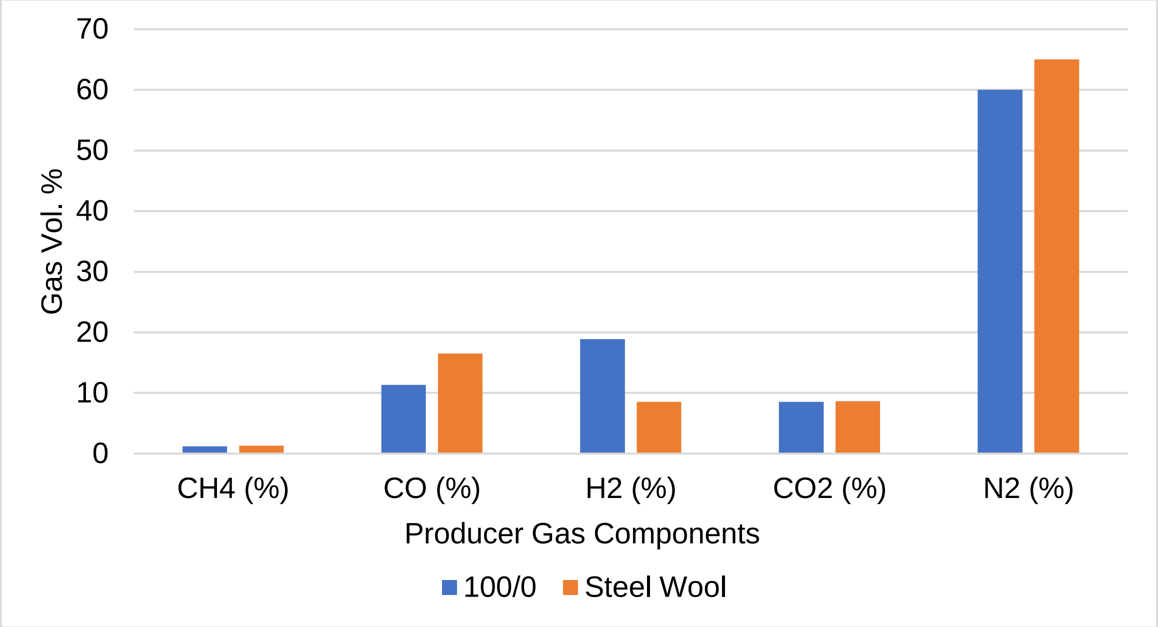


Figure 4.12 Steel Wool Reaction Comparison

Results illustrated for this analysis in Figure 4.12 show us that CO content of the producer gas generated with steel wool is significantly higher than that without, showing an increase of 5.15% from 11.35% to 16.49%. Concurrently the H_2 content of the producer gas is considerably lower. H_2 content decreased by over 10% when compared than the original single feedstock analysis. This led to a great reduction in LHV from 3.91 to 3.47 MJ/Nm^3 or a 11.3% reduction as can be seen in Table 4.9. Conversion efficiency for the system also decreased from the original analysis by 6.75% to 61.67%. While in theory the addition of the steel wool to increase performance is an attractive proposal, in the small-scale downdraft gasifier utilised for experimental analysis, no increase in LHV was identified. While thermal cracking (20) of the tar took place to generate increased CO content within the gas, hydro dealkylation took place concurrently, utilising H_2 from the gas stream for promotion of the tar cleavage (Guo et al., 2019; Li et al., 2022). This led to an overall decrease in gas LHV.

$$C_nH_m \rightarrow C + C_xH_y + gas \tag{20}$$

Table 4.9 Poultry Litter Steel Wool Comparison

Feedstock	CH_4 (%)	CO (%)	H_2 (%)	CO_2 (%)	N_2 (%)	LHV (MJ/Nm^3)	Temperature (°C)
100/0	1.23	11.35	18.89	8.53	60.00	3.91	945.7
Steel Wool	1.29	16.49	8.55	8.64	65.02	3.47	1110.2

Two further experiments for investigating gasification potential which were investigated but for reasons beyond operator control could not be carried out will be discussed next.

4.5.3 Charcoal

Gasification of charcoal to experimentally investigate the products of the reaction was explored. Through this experiment it was hoped that a much lower tar content generated from the gasification process would be found when compared to what was generated from some of the sustainable biomass feedstocks. This was due to the fact that a significant amount of the volatiles associated with the biomass would have been removed during the pyrolysis stage when the charcoal material was being generated. While every effort was made to carry out the experiment using the Fluidyne system in Ulster University, due to the high temperatures required for charcoal gasification, and the lack of control that the operator has on air flow rate within the system, gasification could not take place. When experimental analysis of the charcoal was carried in the fixed bed downdraft system the main products of the reaction were high temperature combustion products such as CO_2 and a small amount of CO. It is therefore agreed that gasification did not take place. This experiment should be repeated when the user has greater control over the carrier gas flow rate. This will be discussed in Chapter 8 during section 6 – Changes.

4.5.4 Sand

A final experiment which was investigated for its potential to have a beneficial influence of the gasification reaction was the addition of heated sand to the reaction. Sand that had been preheated was added to the biomass feedstock to increase the ignition temperature of the material improving reaction kinetics. Sand was heated in a metal dish with the aforementioned heat gun for approximately 10 minutes, to ensure an even and equal temperature across the material. Using a temperature probe to identify when the material had been heated to a reasonable level it was then added to the biomass feedstock in the gasifier reactor to increase ignition temperature with the impression that it could improve overall system performance such as conversion efficiency, increased gas production or simply lower the time period required for the start-up process. Due to the simple downdraft gasifier design and lack of agitation of material within the grate, once the sand was added instead of acting as an additional heat source it quenched the reaction through minimising the spaces available for airflow between the biomass particles. The downdraft system operated through air from the nozzles within the hearth passing down the reactor through the feedstock and into the vessels below. When the fine sand particles were placed within the reactor, they covered any gaps through which the air may travel, stopping the reaction from taking place. Changing the particle size of the feedstock may assist with allowing this experiment to take place.

4.6 Summary

The experimental work carried out within this project was undertaken with the aim to evaluate the influence that blends of sustainable biomass material have on the downdraft gasification process and particularly on the producer gas generated through the process. Summarised in Figure 4.13 are the LHV's of the various producer gases generated throughout the analysis. From this figure the obvious trend we can see is that with increasing proportion of wood pellets in the blend, the LHV of the gas increases. This rise in LHV could be due to the increased carbon content of the feedstock from the introduction of wood pellets. This would allow for more carbon to be converted into the desirable combustible gas products such as CO, CH_4 and H_2 from an increase in the rate at which the Boudouard reaction takes place.

The optimum blend identified from the results was the 60/40 blend. This offered an increase in LHV of between 4.39 – 6.78% depending on the feedstock of interest. While further increases, up to 12.88% can be found at the 40/60 blend for digestate, the 60/40 offers the best potential due to the economics and sustainability of the process when purchasing a feedstock to act as a co-firing material.

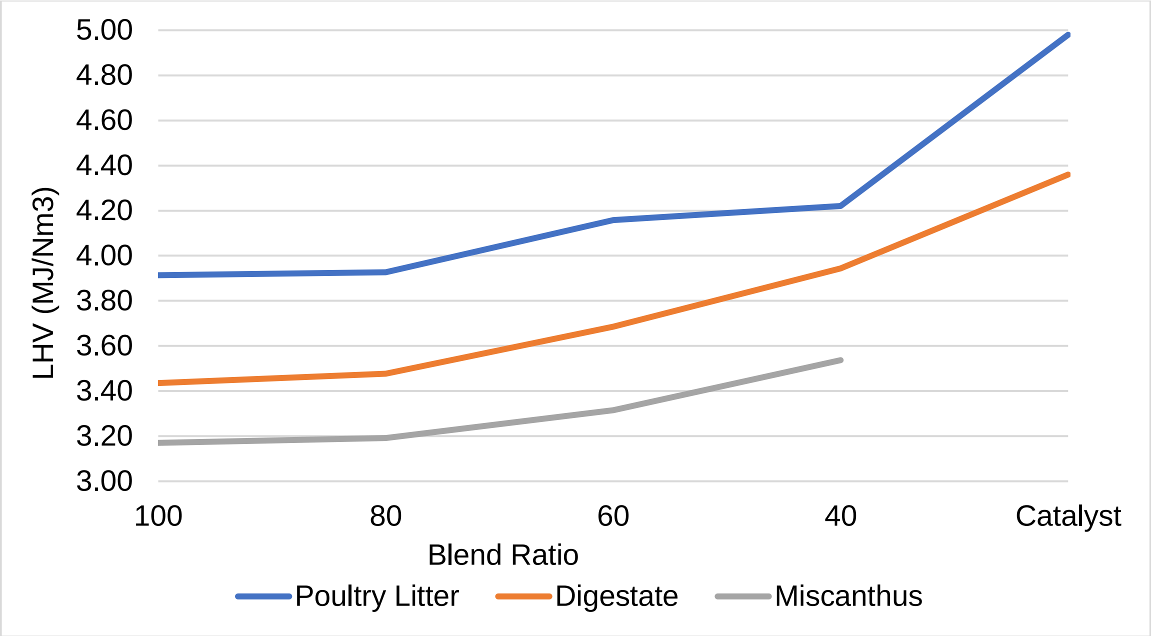


Figure 4.13 LHV Comparison of different feedstocks and blends

The addition of a catalyst to the reaction further increased the performance significantly. From Figure 4.13 we can see that when the $CaCO_3$ catalyst was applied to the 60/40 blend at a concentration of 20% wt. an increase in the LHV of the producer gas by 16.45% for PL and 15.53% for digestate was found. This was due to the influence of the catalyst on the cracking of tar generated during the process. This induced lighter tar being produced alongside additional generation of H_2 during the gasification process. To further promote H_2 production a material with a higher moisture content could be utilised, allowing for even greater LHV increase. Pelleted material was chosen for the research for the ease of biomass handling and to avoid issues within the grate due to system design. While the feedstock with approximately 7% moisture content could still generate a producer gas with near 5 MJ/Nm3, a material with a moisture content at the upper end of acceptable for gasification, closer to 15% could potentially increase this LHV even further.

Table 4.10 Conversion Efficiency of Experiments

	Conversion Efficiency (%)			
	100/0	***80/20***	***60/40***	***40/60***
Poultry Litter	68.4	63.9	66.4	65.0
Digestate	70.9	66.1	63.3	65.8
Miscanthus	67.9	62.2	66.9	62.5

While some of the extra analysis carried out to further improve the quality of the gas generated did not work as expected, with greater system control and the ability to agitate the material within the grate this could be rectified. Conversion efficiency for the fixed bed gasifier remained consistent across materials at between 62 - 70% as can be seen in Table 4.10. Increasing this performance would require some fluidisation or agitation of the bed. Further breakdown and research into the impact of the results will take place in Chapter 8 – Discussion.

Chapter 5 – Process Modelling and Simulation

5.1 Introduction & Background to Eclipse

To successfully carry out multiple chemical reaction simulations an applicable simulation software must be employed. ECLIPSE was chosen as the simulation package of choice as it was developed to accurately investigate the technical and economic performance of chemical reaction processes, with specific emphasis placed on the investigation of gasification-based power plants. It is an effective process simulation package for PC that has been successfully employed for numerous previous research projects at Ulster University (Huang et al., 2020, 2011, 2000; Y. Huang et al., 2013). ECLIPSE is comprised of multiple programmes, which offer a step by step analysis of a process, from feedstock conversion to economic analysis of a system. These programmes have been utilised for this research to accurately simulate the downdraft gasification process, along with engine application of the producer gas and carrying out the economic analysis aspect of the project. A schematic of the process flow has been included, as can be seen in Figure 5.1. This chart shows how each ECLIPSE package relates data. Each module represents a different component of the downdraft gasification system such as tanks, pumps, fans and heat exchangers. To properly estimate the thermodynamic properties of the various components within the system, such as modules and streams, standard chemical equations and formulae are utilised by ECLIPSE. This information is supplied through what is defined within the databases.

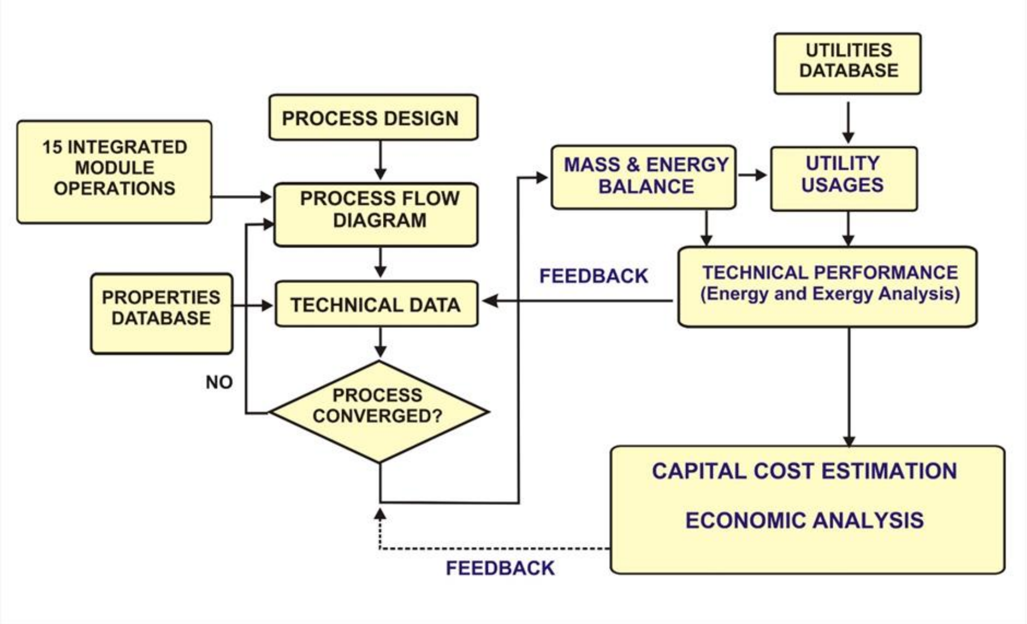


Figure 5.1 ECLIPSE Process Flow Chart

The objective of this chapter is to explain the modelling process as it was carried out, how the different programmes were implemented, what results were gathered from the analysis and how these results were then used throughout the project. The objectives were carried out to generate an accurate simulation of the downdraft gasification process, predicting producer gas composition, assessing various CHP applications of the producer gas and the emission products of that reaction. This is carried out to optimise the operation of the downdraft gasification system along with any associated equipment. To begin with we will define some of the key words within ECLIPSE.

Process – any chemical process which can be defined within ECLIPSES engineering units' operations.

Module – a chemical engineering unit that can be joined together with other *modules* by *streams* to generate a *process*.

Stream – A flow between *modules* connecting them together to create a *process*.

Utility – a flow, which is not included as part of the *Process*, but either gives or takes energy away from the *Process*.

Compound – any chemical that has been defined in the compound database. Can be a solid, liquid or gas.

To put these terms into use then, the *process* which in this instance is a downdraft gasification system connected to a combined heat and power unit, is defined in terms of various *modules* that are connected to each other by numerous *streams*. These *streams* are formed by a number of *compounds*. These *compounds* and their standard form are defined within the *compound database*.

The *utilities* can either be defined separately from the process, or within the *process* depending on preference. *Utilities* include but are not limited to steam, cooling air, fuel gas or thermal fluid. When not included in the *process* itself, *utilities* can be defined within the *utility database*. For use of the capital cost estimation function of ECLIPSE, all operating costs and factors are defined within *cost database*.

From the start to the finish, the simulation of a process using ECLIPSE can be divided out into 7 separate stages. Four stages are designated for the technical calculation of the process, with the final three stages for the economic evaluation.

Step 1	-	Design and preparation of process flow diagram
Step 2	-	Addition of technical information to the process
Step 3	-	Mass and energy balance calculations
Step 4	-	Utility usage calculations
Step 5	-	Process and utilities capital cost estimation
Step 6	-	Operating costs calculation
Step 7	-	Economic evaluation of the process performance

5.2 Gasification Reaction Simulation

5.2.1 Feedstock Composition

From the methodology chapter, the various biomass feedstock proximate and ultimate analysis results can be seen. These results will act as the inputs for the simulation and modelling being carried out. A copy of these results is presented in Table 5.1. Within ECLIPSE, the various biomass characteristics are defined within the database. The information supplied in Table 5.1 is that which has been added to the database to ensure accurate representation of the various feedstocks of choice. ECLIPSE functions on a DAF basis, and this is how the results are presented.

Table 5.1 Feedstock Properties for ECLIPSE Simulations

		Digestate Pellets	***Miscanthus Pellets***	***Poultry Litter Pellets***	***Wood Pellets***
Elemental Analysis (%)	**C**	44.49	45.13	33.65	47.14
	H	6.56	6.26	4.61	6.51
	N	2.51	1.26	4.08	0.38
	S	0.34	0.31	0.34	0.30
	O	46.09	47.04	57.32	45.66
Moisture (%)		7.69	7.15	10.27	7.50
Ash (%)		11.18	2.51	12.93	0.30
Energy (kJ/kg) DAF		22.32	21.25	18.15	18.66
Ash Melting (°C)		**1227**	1285	<1530	1350
Volatile Matter (%)		74.51	83.74	62.15	83.93
Fixed Carbon (%)		14.31	13.75	24.91	15.77
Bulk Density (kg/m3)		716	604	810	682

5.2.2 Downdraft Gasification System Setup

For the relevant scale and application that this research is focused on, downdraft had been chosen as the method of choice due to its ability to handle a variety of biomass materials and generate less tar than other reactor design systems. The ability to handle multiple feedstocks is important for small scale testing of various feedstocks. Low tar content is beneficial for downstream application of the producer gas where tar content could lead to clogging or spoiling of the equipment. The simulation set up is shown as a simplified diagram in Figure 5.2.

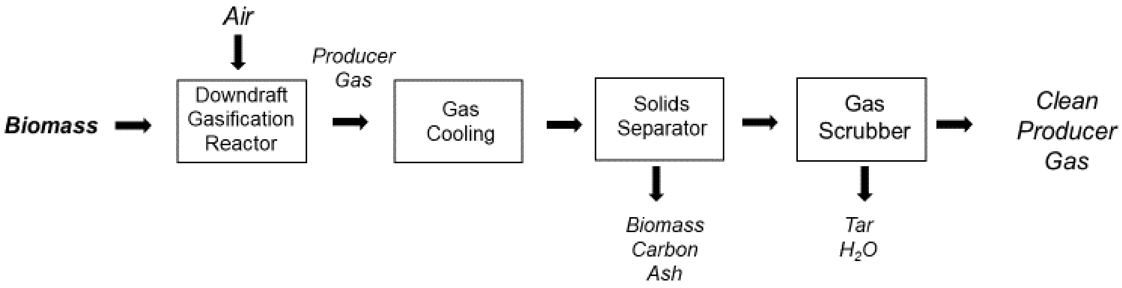


Figure 5.2 Biomass Downdraft Gasification System

The downdraft gasification system being modelled functions as follows:

- Downdraft Gasification Reactor: The biomass feedstock of interest is fed into the gasifier reactor where it is broken down into its gaseous components within the hearth of the reactor. The gasifying agent used to carry the reaction was air, as the cheapest and most abundantly available option. Gas travels along the system from the reactor to go through a variety of upgrading steps to improve its quality. The chemical reactions which take place during this stage are defined in Table 5.3.
- Gas Cooling: The producer gas will be generated at temperatures in excess of 800°C. This gas will then require cooling before gas cleaning through the water scrubber or application in downstream equipment can take place. Gas cooling will increase the energy density of the producer gas, making it more suitable for further use. Gas cooling can be carried out through many methods with the most common being passing the gas through cyclones and heat exchangers removing excess heat, to cool it to the desired level.
- Solid Separator: While solid biomass is converted to gas during the reactions, some unconverted solids remain within the producer gas in the form of tars, ash, unconverted biomass or particulates. Passing the gas through cyclones and filters ensures the removal of this material during this stage and creates a cleaner gas for application.
- Gas Scrubber: A producer gas containing low amounts of solids or impurities is then passed through the gas scrubber for one final cleaning and removal of unwanted components. During this stage moisture and any remaining tars are removed from the gas stream. A clean producer gas is the output from this module and can then be applied to further downstream equipment depending on the requirements.

5.2.3 Gasification Simulation Characteristics

During the reaction simulations, the system operates utilising a small number of assumptions for carrying out the process. These assumptions cover some of the basic characteristics of the reaction such the rate of feedstock input, the inlet temperature for the feedstock and gasifying agent, the pressure at which both inlets operate, as well as the equivalence ratio at which the reaction takes place. All assumptions for the reactions are summarised in Table 5.2.

Table 5.2 Gasification Assumptions

	Poultry Litter Pellet	**Digestate Pellet**	**Miscanthus Pellet**
Input Rate (kg/h)	229	207	218
Inlet Temperature (°C)	15	15	15
Inlet Pressure (bar)	1.013	1.013	1.013
Gasifying Agent Inlet Temperature (°C)	15	15	15
Gasifying Agent Inlet Pressure (bar)	1.013	1.013	1.013
Equivalence Ratio	0.35	0.35	0.35

The input rate varies between feedstocks as it is based on a dry and ash free (DAF) basis. Material with a higher ash and moisture content will therefore require a higher input feed rate to ensure equivalent biomass is being introduced to the reaction as a material with less. Temperature and pressure at the inlet for both the feedstock and gasifying agent are based off ambient air temperature and ambient pressure. The pressure of 1.013 bar is equivalent to 1 atm. The equivalence ratio (ER) at which the reactions were carried out was 0.35. This was found through literature to be the optimum ER at which to carry out downdraft gasification of poultry litter, and was utilised for the other materials of interest to ensure comparability across feedstocks (Olgun et al., 2011; Salem and Paul, 2018).

5.2.4 Chemical Reactions

For the downdraft simulation, the biomass feedstock of choice is fed into the gasification system. In ECLIPSE, the gasification reactor is divided into 4 distinct zones, as displayed within Figure 5.3. Within each zone, specific reactions take place as part of the gasification process. These reactions are listed in Table 5.3.

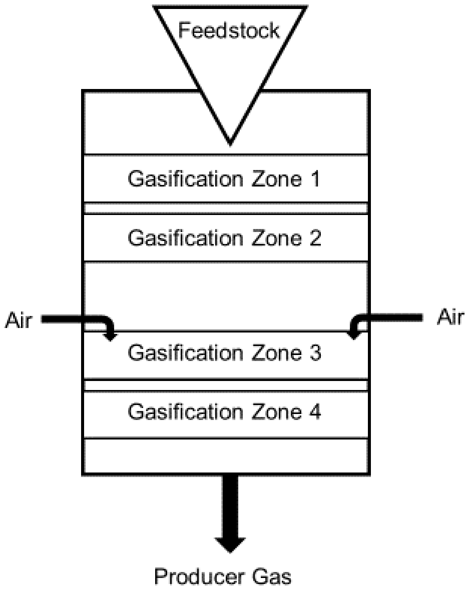


Figure 5.3 Diagram of the zones in the gasification system

A total of 13 reactions occurs within the 4 gasification zones during the conversion of the solid biomass feedstock into a producer gas. These reactions are defined within Table 5.3. In zone 1, decomposition of the biomass feedstock into its individual elements occurs. This includes C, H, N, S, O and what little chlorine (Cl) is present. The final step in zone 1 is these individual elements converting to their gaseous form in the shape of H_2, N_2, O_2, COS, HCl and C. In zone 2, the reaction products from zone 1 are further converted to produce CO, CO_2 and CH_4. The next stage of the reaction occurs within zone 3, where the gasifying agent is introduced. For all reactions of interest, the gasifying agent is air at an ER of 0.35. In zone 3 the O_2, H_2 and C undergo further reaction which leads to the generation of CO, CH_4 and CO_2. Any remaining C, H_2 and O_2 at this point undergoes further transformation in zone 4, to generate extra CO, CO_2, H_2O and CH_4. Each of these reactions is defined within Table 5.3 and are named equation (1) – (13).

Table 5.3 ECLIPSE Gasification Zone Reactions

Reaction	Equation Number
Gasification Zone 1	
Biomass → Tar	*Eq (1)*
Biomass → Breaks into Elements	*Eq (2)*
C → C; CL → HCl; H → H_2: N → N_2; S → COS; O → O_2	
Gasification Zone 2	
$O_2 + 2\ C \rightarrow 2\ CO$	*Eq (3)*
$O_2 + 1\ C \rightarrow 1\ CO_2$	*Eq (4)*
$H_2 + 0.5\ C \rightarrow 0.5\ CH_4$	*Eq (5)*
Gasification Zone 3	
$O_2 + 2\ C \rightarrow 2\ CO$	*Eq (6)*
$O_2 + 1\ C \rightarrow 1\ CO_2$	*Eq (7)*
$C + 2\ H_2 \rightarrow 1\ CH_4$	*Eq (8)*
Gasification Zone 4	
$O_2 + H_2 \rightarrow 2\ H_2O$	*Eq (9)*
$O_2 + 2\ C \rightarrow 2\ CO$	*Eq (10)*
$O_2 + 1\ C \rightarrow 1\ CO_2$	*Eq (11)*
$O_2 + 2\ H_2 \rightarrow 2\ H_2O$	*Eq (12)*
$H_2 + 0.5\ O_2 \rightarrow 2\ CH_4$	*Eq (13)*

5.2.5 Solid & Scrubber Separator

For the operation of both the solids separator, and the scrubber for water and tar removal, some further assumptions must be made about their operating conditions. For the removal of solids such as ash, particulates and unconverted biomass material, the most common techniques are filters (Valderrama Rios et al., 2018). For the simulation of the process, it is assumed that 90% of each of these materials is removed from the gas stream. Once the solids have been removed, the producer gas is fed to a scrubber separator for one final cleaning stage. This separator removes any remaining water or tar remaining in the gas stream. It is assumed that this separator also operates to remove 90% of these components. The scrubber separator method of choice would be a venturi scrubber, due to its high efficiency and relatively low-cost (Hasler and Nussbaumer, 1999). Both separators like the gasification system function at 1.013 bar, or 1 atm. Parameters related to the separator are listed in Table 5.4. A layout of the ECLIPSE gasification system is displayed in Figure 5.4.

Table 5.4 Separators Defined Parameters

	Assumption
Solid Separator	
Biomass Removed	90%
Carbon Removed	90%
Ash Removed	90%
Scrubber Separator	
Water Removed	90%
Tar Removed	90%
Operating Pressure for Solid & Scrubber Separator (bar)	1.013

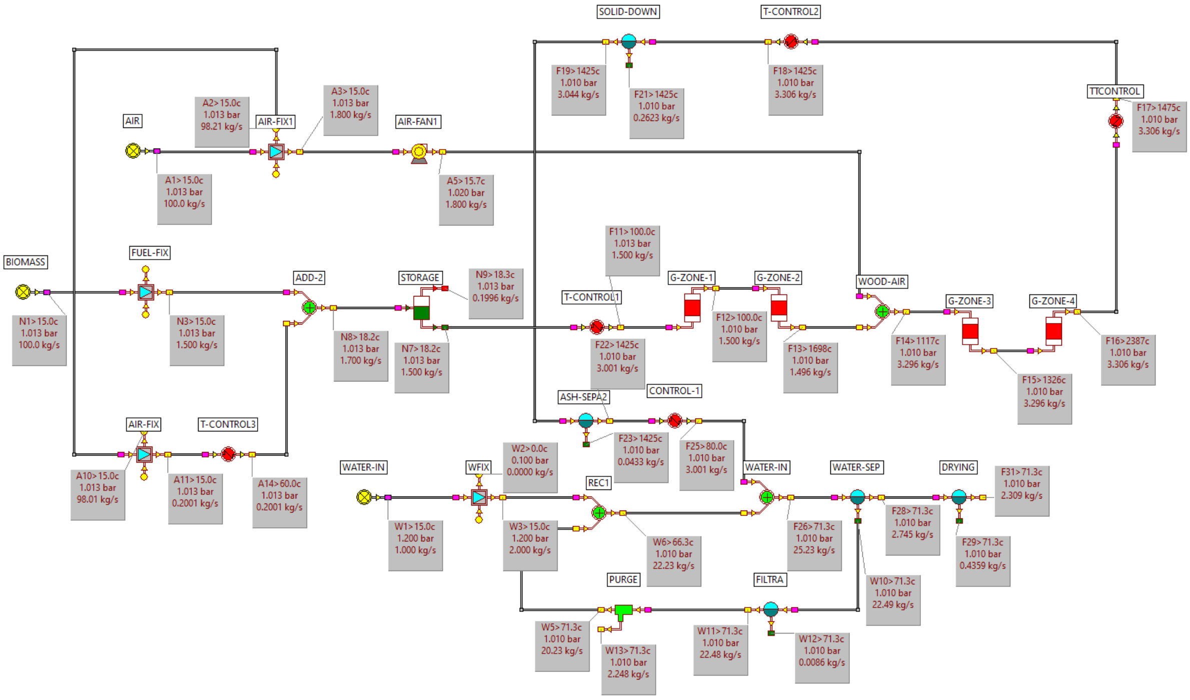


Figure 5.4 ECLIPSE Gasifier Simulation Setup

5.2.6 Gasification Simulation Results

Once all relevant process components had been defined and set up, the simulation of the downdraft gasification reactions took place. Results for the volumetric composition of the various producer gases are given in Table 5.5. Results are presented in kg/s from the mass balance of the simulation. LHV of the producer gases was calculated using the MJ/Nm^3 values for energy content found in Waldheim and Nilsson (2001).

Table 5.5 Simulation Producer Gas Composition

	Poultry Litter Pellet		**Digestate Pellet**		**Miscanthus Pellet**	
	kg/s	*k mole/s*	*kg/s*	*k mole/s*	*kg/s*	*k mole/s*
CH_4	0.0333	0.0021	0.0549	0.0034	0.0525	0.0033
CO	0.2817	0.0101	0.2966	0.0106	0.541	0.0193
H_2	0.0095	0.0048	0.0235	0.0118	0.0154	0.0077
CO_2	0.5266	0.0120	0.5618	0.0128	0.5339	0.0121
N_2	1.3967	0.0499	1.9434	0.0694	2.4181	0.0864
LHV (MJ/Nm^3)		3.31		3.70		3.54

5.2.7 Comparison

For the comparison of results, we will compare the simulation results generated to those found through experimental analysis which was spoken about in greater detail in Chapter 4 – Experimental Results for Model Validation. Results are expressed as volumetric percentage for easy comparison between the two and are displayed in Table 5.6.

Table 5.6 Comparison of Simulation & Experimental Results

	Simulation Results			**Experimental Results**		
	Poultry Litter	*Digestate*	*Miscanthus*	*Poultry Litter*	*Digestate*	*Miscanthus*
CH_4	2.6%	3.2%	2.5%	1.2%	1.2%	1.4%
CO	12.8%	9.8%	15.0%	11.4%	13.2%	13.9%
H_2	6.0%	10.9%	6.0%	18.8%	12.4%	8.4%
CO_2	15.2%	11.8%	9.4%	8.5%	9.8%	9.3%
N_2	63.4%	64.3%	67.1%	60.1%	63.4%	66.9%
LHV (MJ/Nm^3)	3.31	3.70	3.54	3.91	3.44	3.17

Results show good agreement between those generated from the ECLIPSE simulation and those found through experimental analysis. While most components in the simulation are within a single percentage of those found experimentally, the difference between poultry litter H_2 content from simulation to experiment is 12% different. The simulation underestimated the H_2 content significantly. Importantly the LHV of the producer gas was still reasonably accurate, allowing the results to be utilised for further downstream application. Further analysis on why this may be will take place in the discussion chapter.

Comparison of the results was then carried out with those found in published literature to ensure the validity of the results from the simulations and experiments. In Table 5.7 a representative producer gas composition from each feedstock of choice is shown for comparison with simulation results. Good comparability between simulations and literature can be seen, where despite differing biomass compositions, gas composition is similar for poultry litter, digestate and miscanthus to what was predicted by the ECLIPSE simulation (Freda et al., 2019; Pandey et al., 2016; Samson et al., 2018).

Table 5.7 Experimental Results from Literature

	Poultry Litter Pellet	**Digestate Pellet**	**Miscanthus Pellet**
	Pandey et al. (2016) (v/v%)	*Freda et al. (2019) (v/v%)*	*Samson et al. (2018) (v/v%)*
CH_4	2.55	3.3	3.1
CO	8.52	9.9	16.7
H_2	11.6	9.4	9.7
CO_2	13.22	14.0	16.6
N_2	58.53	62.5	53.9

5.2.8 Blend Analysis

As the reasoning behind the research is to compare the effect that utilising a blend of biomasses has on the gasification process, ECLIPSE was employed to carry out the relevant blend analysis using the simulation packages. To best represent the selected blend for analysis, two feedstocks where chosen within the software as the input feedstock, along with an averaged ash content and LHV. The blend of choice selected for the analysis was the 60/40 blend by weight of Poultry Litter and Wood Pellets. This particular blend showed good promise from the experimental analysis carried out on the small-scale fixed bed gasifier and was selected as a representative blend for further analysis. Further blends were unable to be analysed due to time constraints of the project. Through the simulation software, accurate producer gas composition for the blend was generated, as well as application to downstream equipment for heat and electricity generation. CHP emissions from the blend were used as the basis for the LCA analysis carried out in Chapter 6.

5.3 Producer Gas Application Simulation

Once a finalised producer gas composition had been identified using the ECLIPSE simulation software, the resulting gas can then be applied to the next software suite of ECLIPSE, the utility package for downstream application. The proposed internal combustion engine CHP system is displayed in Figure 5.5. Through compression, combustion and expansion of the producer gas heat and electricity are generated from the system. Heat recovery also takes place within the system to ensure best possible efficiency is achieved.

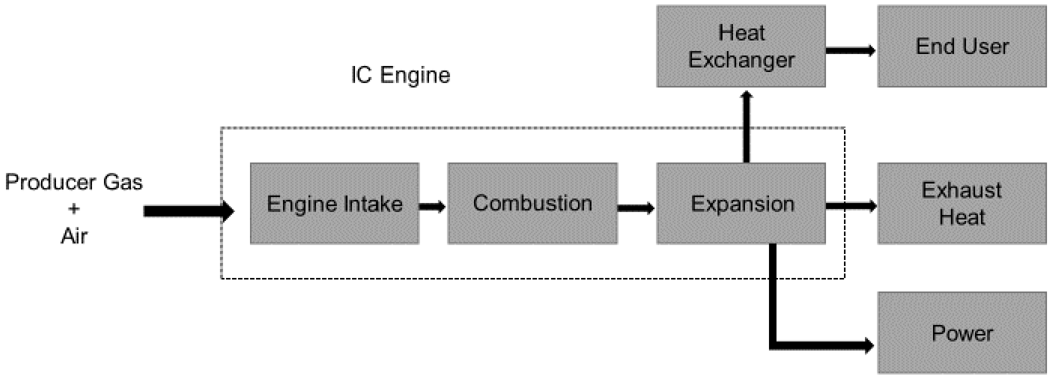


Figure 5.5 ECLIPSE CHP Block Diagram

The conversion process being simulated by ECLIPSE is based off the following assumptions:

- The producer gas generated from the simulation of the downdraft gasification process is used as the input fuel for the CHP system.
- Input producer gas, along with air is fed to the system where it initially undergoes compression to increase fuel density. Any relevant assumptions required for this process are listed in Table 5.8.
- Fuel gas then undergoes combustion within the reactor in the presence of air. Combustion reactions which are simulated at this stage are further described in Table 5.9.

- The high temperature and pressure gases generated in the combustion reactor move to the next stage of the process for expansion where the chemical energy of the system is converted to useful energy to produce electricity. Detailed assumptions of this stage are covered in Table 5.10.
- The final step is heat recovery from the engine where a large proportion of the exhaust gases are recovered for recycling and used for drying, heating and supplying hot water. Heat exchangers within the engine are used as cooling systems, where water is utilised as the cooling agent for heat recovery purposes. Heat exchanger assumptions are detailed in Table 5.11.

5.3.1 Application Assumptions

As the output from the gasification simulation is used as the input for the CHP simulation, ensuring the accuracy of the results through validation with experimental results is imperative. Input fuels for this application are those listed in Gasification Simulation Results. The IC engine is modelled using an equivalence ratio for the air consumed of 1.8. Similar to the gasification simulation, the IC engine simulation is carried out at ambient temperature and pressure. The optimum equivalence ratio was found through the literature review, where Singh et al. (2015) found that 1.8 worked best for the combustion of producer gas. This coefficient was therefore used for the simulation of the combustion of all producer gases generated.

Table 5.8 Producer Gas Conversion Assumptions

	Parameter	**Assumption**
Air	Combustion Excess Air Coefficient	1.8
	Input Air Temperature (°C)	15
	Input Air Pressure (bar)	1.013
Compression	Gas Inlet Temperature (°C)	25
	Compression Pressure (bar)	22
	Compression Polytropic Efficiency (%)	91

To model the compression stage, producer gas and air are compressed after passing through the cooler to ensure that the gas energy density is suitable for application. Gas temperature at the input is maintained at 25°C. Compressions pressure of 23 bar is utilised with an efficiency of 91%. Following compression, the producer gas which remains pressurised to 23 bars is fed into the combustion reactor, where reactions take place generating CO_2, H_2O, NO_2 and SO_2. The combustion reactions which take place to produce these components at this stage are defined within Table 5.9.

Table 5.9 Combustion Reactions Simulated

Reaction	**Equation**
$CO + 0.5\ O_2 \rightarrow 1\ CO_2$	*Eq (14)*
$H_2 + 0.5\ O_2 \rightarrow 1\ H_2O$	*Eq (15)*
$CH_4 + 2\ O_2 \rightarrow 2\ H_2O$	*Eq (16)*
$O_2 + 0.5\ N_2 \rightarrow 1\ NO_2$	*Eq (17)*
$COS + 2\ O_2 \rightarrow 1\ CO_2 + 1\ SO_2$	*Eq (18)*

Expansion simulation follows on from the combustion stage. This is where hot gases from the combustion reaction are converted to energy through expansion of pressurised gases into useful products, in this case electricity. The two assumptions which were made for this stage were related to engine back pressure and engine polytropic efficiency, which can be seen in Table 5.10.

Table 5.10 Expansion Simulation Assumptions

Expansion	**Parameter**	**Assumption**
	Engine Back Pressure (bar)	1.08
	Engine Polytropic Efficiency (%)	91

The attached cooling system is the final step to be defined before simulation can take place. This system is based off two heat exchangers recovering heat from the process. The heat exchangers use water as a coolant for the system. Both heat exchangers are calibrated to operate with a 10°C temperature difference. Heat exchanger data is displayed in Table 5.11. A layout of the ECLIPSE CHP process diagram is displayed in Figure 5.6.

Table 5.11 Simulation Heat Exchanger Assumptions

	Heat Exchanger 1	***Heat Exchanger 2***
Parameter	**Assumption**	
Water Inlet Flow Rate (kg/s)	0.1	1
Inlet Cooling Water Temperature (°C)	15	15
Pump Volumetric Efficiency (%)	85	85
Hot Stream Outlet Temperature (°C)	550	80
Cold Stream Outlet Temperature (°C)	90	70
Minimum Approach Temperature (°C)	30	5
Heat Loss Percentage (%)	0.2	1
Hot Side Pressure Drop (bar)	*N/A*	0.25
Cold Side Pressure Drop (bar)	*N/A*	0.9

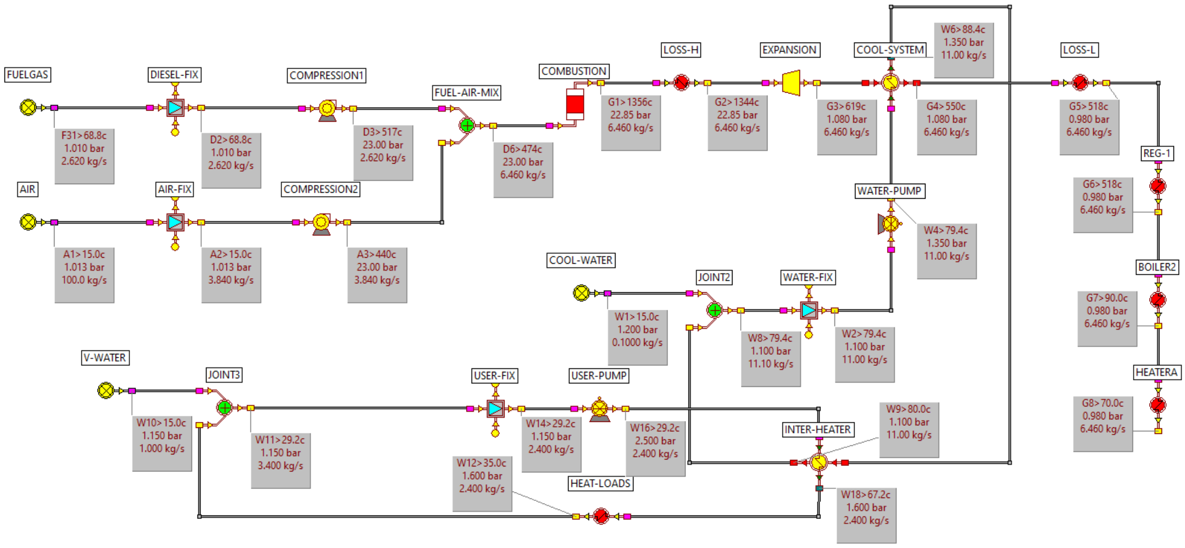


Figure 5.6 ECLIPSE CHP Process Diagram

5.3.2 Results

Once all relevant parameters had been defined, the CHP simulation of the various biomass generated producer gas was carried out. This simulation was carried out to identify the power generated, both electrical and thermal, alongside the system efficiency for each individual producer gas. Finalised results are displayed in Table 5.12.

Table 5.12 Technical Results from CHP Simulations

	Results		
Parameter	*Poultry Litter Pellet*	*Digestate Pellet*	*Miscanthus Pellet*
Biomass Input (kg/h)	183.5	165.4	173.5
Total Thermal Input (kWth)	763.4	1025.5	1023.7
CHP Heat Output (kWth)	275.0	274.2	277.5
Power Output (kWe)	200.0	200.0	200.0
Net CHP Output	475.0	474.2	477.5
Overall CHP Efficiency (%)	54.18	49.25	49.66
Electric Power Efficiency (%)	22.82	20.77	20.80

From the results we can see that the feedstock with the greatest efficiency is the poultry litter producer gas. The overall CHP efficiency for the poultry litter stream is 54.18%, almost 5% greater than the next stream of miscanthus at 49.66% efficiency. The net output from each stream is similar, with 3.3 kW difference between the lowest and highest output. Similar efficiencies were found for another small-scale biomass gasification CHP system through the literature review. Patuzzi et al. (2016) found electrical efficiency of 23% and thermal efficiency of 52% for the conversion of wood chips. Similar conversion efficiencies were also found in Francois et al. (2013) and Huang et al. (2013), and therefore some belief that the simulation was accurate as the values are similar to those found in published literature. Results from the CHP application of the blended feedstock are displayed in Chapter 8 – Discussion. Comparison between single feedstock and blended are shown along with analysis and discussion on what the outcomes of the results are.

5.4 Economic Analysis

Through the successful application of ECLIPSE's economic analysis package, a complete understanding of the project's finances can be generated. This takes place using classic capital budgeting indexes through the analysis of the systems NPV, the BESP for each MWh of electricity generated from the proposed producer gas application systems along with a discounted payback period (PBP) (in years) for the initial capital investment required for the complete installation of the systems equipment and ancillary components. NPV allows the user to identify under what conditions the system will generate a positive return on investment. This allows for the assessment of the economic feasibility of the project over the lifetime of the equipment utilised, with the initial capital cost and any applicable cash flow generated by the system (Wood and Rowley, 2011). It is a measure of the systems potential profitability, used to measure the net cash benefit created by a system (Li et al., 2012). It will be used to evaluate the potential profitability of the proposed CHP systems. NPV is a common financial indicator used across biomass CHP research, with examples of its use in (Cardoso et al., 2019; Elsner et al., 2017; Kempegowda et al., 2012; Ng et al., 2017). The NPV scenarios generated to assess potential return on investment will be based off a cumulative cash flow, where each cash stream generated is added to the previous for a total value. Calculation of the NPV is through using the following equation:

$$NPV = \sum_{n=1}^{t} \frac{CF_n}{(1+r)^n} - C_c \tag{12}$$

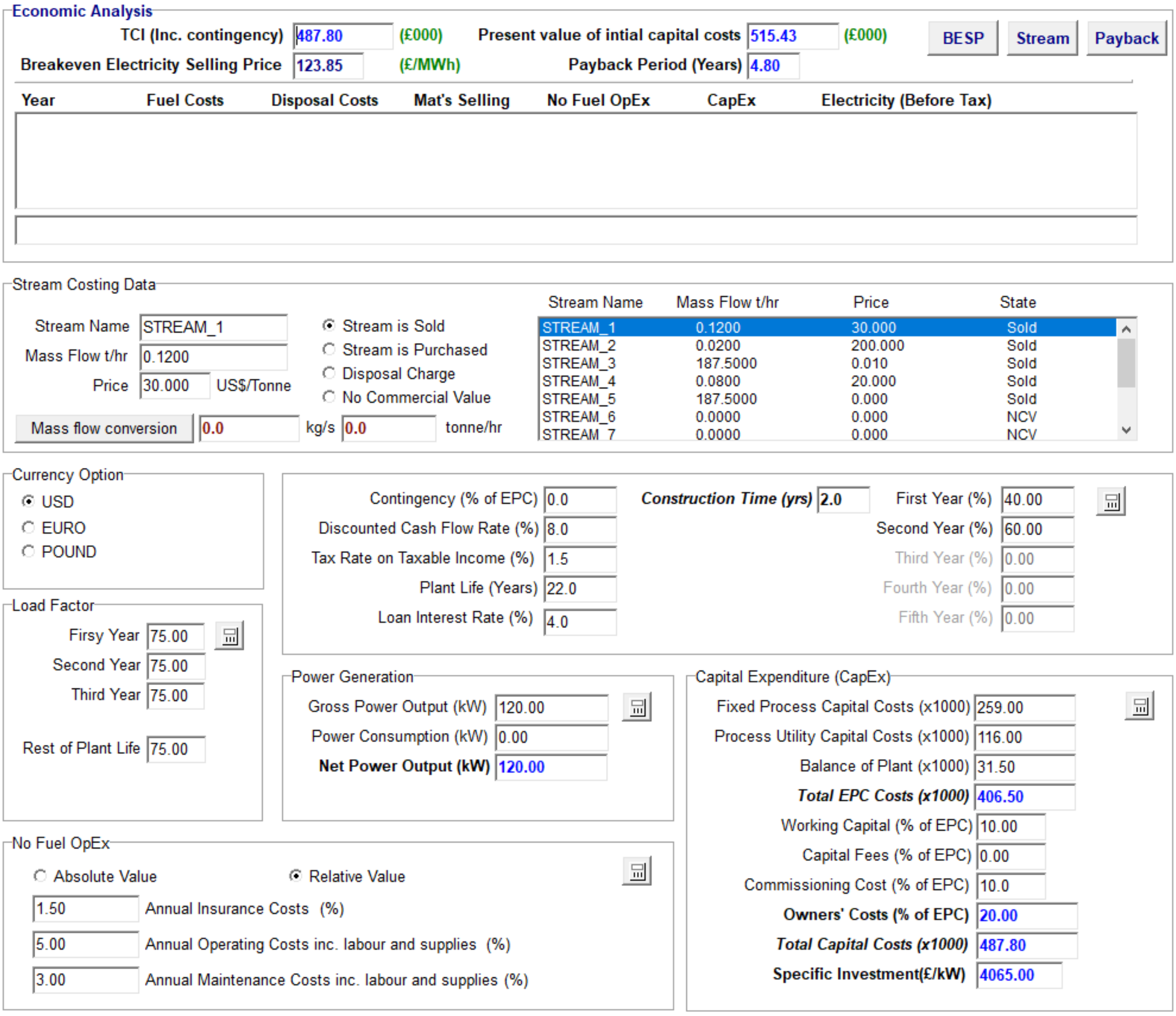
where CF_n is the annual total cash flow, which is the difference between revenues and expenditures, r is the discount rate, C_c is the total capital costs of the system and t is the lifetime of the equipment (22 years)(Safarian et al., 2020). Another financial indicator utilised for this analysis is the BESP of the electricity from the CHP generation systems being proposed. The BESP is the minimum price that each MWh of electricity produced by the system has to be sold for if the initial investment costs are to be recovered (Jeswani et al., 2019). Like NPV it has been used many times throughout CHP application research such as (Al Moussawi et al., 2017; Hany et al., 2019; Shackley et al., 2011). BESP is in other words the total cost associated with producing each MWh of electricity generated from the proposed systems. This would be the same as the NPV of the system being equal to zero over the course of the equipment's lifetime. The formula for calculating the BESP is:

$$BESP = \frac{\sum_{i=1}^{N} \frac{(I_i + O_i + M_i + F_i)}{(1+DCF)^i}}{\sum_{i=1}^{N} \frac{E_i}{(1+DCF)^i}} \tag{13}$$

where I_i is investment expenditures in the year i, O_i and M_i are operation and maintenance costs in the year i, DCF is the discounted cash flow rate, F_i is the fuel cost, and E_i is the electricity produced in the year i, N is the expected lifetime of the system. The use of BESP alongside NPV and the discounted PBP will give a detailed analysis of the financial performance of the proposed energy generation systems. Discounted payback period is calculated as follows:

$$DPP = \frac{LN\left(\frac{1}{1-\frac{C_c \times r}{CF}}\right)}{LN(1+r)} \tag{14}$$

Exact system components and results from the economic analysis are discussed in detail in Chapter 7 – Techno – Economic Analysis of the Downdraft Gasifier based CHP System. In this section we will discuss the simulation package utilised for this research, define the components within the simulation package and what is required to successfully carry out the analysis. An example of the software interface is displayed in Figure 5.7. To generate the total capital costs of the systems, values from literature were developed. From relevant downdraft gasification literature, costs associated with feedstock preparation, gasification systems, power generation process and all other relevant components were collected. Values were adjusted to the applicable sized unit through the use of a factor and converted to £ sterling using the applicable conversion ratio (Copa et al., 2020; Elsner et al., 2017; Jeswani et al., 2019). A full breakdown of the capital cost for each system is available in the appendices.



Economic Analysis

TCI (Inc. contingency) 487.80 (£000)
Present value of intial capital costs 515.43 (£000)
Breakeven Electricity Selling Price 123.85 (£/MWh)
Payback Period (Years) 4.80

Year	Fuel Costs	Disposal Costs	Mat's Selling	No Fuel OpEx	CapEx	Electricity (Before Tax)

Stream Costing Data

Stream Name STREAM_1
Mass Flow t/hr 0.1200
Price 30.000 US$/Tonne
● Stream is Sold
○ Stream is Purchased
○ Disposal Charge
○ No Commercial Value
Mass flow conversion 0.0 kg/s 0.0 tonne/hr

Stream Name	Mass Flow t/hr	Price	State
STREAM_1	0.1200	30.000	Sold
STREAM_2	0.0200	200.000	Sold
STREAM_3	187.5000	0.010	Sold
STREAM_4	0.0800	20.000	Sold
STREAM_5	187.5000	0.000	Sold
STREAM_6	0.0000	0.000	NCV
STREAM_7	0.0000	0.000	NCV

Currency Option
● USD
○ EURO
○ POUND

Contingency (% of EPC) 0.0
Discounted Cash Flow Rate (%) 8.0
Tax Rate on Taxable Income (%) 1.5
Plant Life (Years) 22.0
Loan Interest Rate (%) 4.0
Construction Time (yrs) 2.0
First Year (%) 40.00
Second Year (%) 60.00
Third Year (%) 0.00
Fourth Year (%) 0.00
Fifth Year (%) 0.00

Load Factor
Firsy Year 75.00
Second Year 75.00
Third Year 75.00
Rest of Plant Life 75.00

Power Generation
Gross Power Output (kW) 120.00
Power Consumption (kW) 0.00
Net Power Output (kW) 120.00

Capital Expenditure (CapEx)
Fixed Process Capital Costs (x1000) 259.00
Process Utility Capital Costs (x1000) 116.00
Balance of Plant (x1000) 31.50
Total EPC Costs (x1000) 406.50
Working Capital (% of EPC) 10.00
Capital Fees (% of EPC) 0.00
Commissioning Cost (% of EPC) 10.0
Owners' Costs (% of EPC) 20.00
Total Capital Costs (x1000) 487.80
Specific Investment(£/kW) 4065.00

No Fuel OpEx
○ Absolute Value
● Relative Value
1.50 Annual Insurance Costs (%)
5.00 Annual Operating Costs inc. labour and supplies (%)
3.00 Annual Maintenance Costs inc. labour and supplies (%)

Figure 5.7 ECLIPSE Economic Package

We can see that within the ECLIPSE economic analysis package, there are 7 units which require some level of definition. These are:

1 Stream Costing Data: The first component which requires definition is the stream costing. Within here the streams of the system components can be defined, along with their flow rate and associated costs. These costs can either be positive or negative in relation to the system, depending on set up. For example, an energy source being replaced could be listed, with the price in p/kWh. This could also be a tariff payed, such as the cost associated with purchasing a feedstock. Streams can be defined as being sold, purchased, defined as a disposal charge or be listed as having no commercial value. Many options are covered within the software to ensure all possible set up variations can be modelled.

2 The currency option is the next to require definition and is the straightest forward. Using recent exchange rates, the software allows the user to carry out the analysis in different currencies depending on preference: euro (€) or pound sterling (£).

3 The load factor allows for the user to represent at what capacity the power generation system will operate during the course of its lifetime. The systems first year will be disrupted by installation and commissioning requirements and therefore may only operate in the region of 30% capacity in its first year. This will then increase with passing time as the system comes online and becomes operational. This will increase up to approximately 80% taking into account the downtime that will be required for annual servicing and maintenance of components.

4 The centre section of the page is where further economic factors and indices are listed, with each requiring definition for the particular energy generation system of interest. These include the construction time (in years), the plant life (in years), the contingency required (% of total Engineering, Procurement and Construction costs (EPC)), discounted cash flow rate (DCFR), tax rate and loan interest rate (all %). For construction time the build can be defined by how much will take place each year. Contingency is the money required to cover the unforeseen costs which may be incurred during the construction phase. The DCFR is the rate at which you discount cash flow in the future, giving a value to your cash at a set point in the future.

5 The power generation is the net electrical power output from the system. This is listed as kW and considers the parasitic load that the equipment may use. Parasitic load is the portion of the electricity generated used by the equipment.

6 No Fuel OpEx: These are the values associated with insurance, operation and maintenance costs. They can be an absolute or relative value. Values are taken from similar research carried out on gasification technology (Huang et al., 2020, 2015). Insurance and operation costs are generally lower than 1.5% and 5% of the total capital expenditure, but due to the relatively low level of investment that these systems represent, these values have been chosen to better represent the system of choice.

7 The final component is the capital expenditure. This includes a breakdown of the fixed capital costs; the utility capital costs and commissioning costs amongst

others. Using both ECLIPSE and relevant references, the accurate total capital expenditure can be calculated. Once completed, NPV, BESP and payback period can be derived.

5.5 Summary

Using an appropriate simulation software, the downdraft gasification of biomass feedstocks and producer gas application can be accurately estimated. ECLIPSE was chosen as the method of choice due to its robust yet simple design, and applicability for the technologies of interest. Definition of the biomass composition and characteristics, along with defining the layout of the conversion systems of interest is required for accurate representation of the system being researched. Through the various computational packages that make up the process simulation software, accurate producer gas composition, LHV and yield were generated. This producer gas was then applied to the appropriate downstream equipment using the next package of ECLIPSE software for CHP application through internal combustion engine (ICE) and Organic Rankine cycle (ORC) representation. Once completed, the final stage of the software could be completed, which covered the economic analysis of the proposed energy generation methods. This included financial indicators such NPV, BESP and a PBP for the initial capital investment.

Accurate producer gas composition was found using a combination of mass, energy and exergy balances. Once the gas composition had been found, the results were compared to those found through experimental analysis and literature. The subsequent findings were adjusted where necessary to ensure the accuracy of the results. Once reliable results were identified from this analysis, they could then be used for multiple applications throughout the research such as CHP application estimations, economic analysis of the project and for accurate emissions analysis for use in the LCA carried out in Chapter 6. All of this work was carried out with the aim of comparing the influence that blends of biomass feedstocks have on the downdraft gasification and producer gas application process. Through accurate simulation of the 60:40 blend of poultry litter and wood pellets, the comparison of all relevant gasification, application and economic parameters was carried out through the use of the ECLIPSE simulation package.

Chapter 6 – Life Cycle Assessment of Small – Scale Biomass Gasification CHP

6.1 Introduction

Dwindling reserves of fossil fuels and the threat caused by climate change has led to an international push for an increased uptake in renewable energy technology. To achieve this, improve energy market sustainability and guarantee energy security into the future we must ensure that sufficient renewable energy technology is brought online not only in the UK and Europe, but globally too. If a portion of current fossil fuel energy generation could be substituted for waste to energy technology, multiple societal issues could be solved at once. One such technology that could potentially assist in this capacity is downdraft gasification coupled with downstream energy producing equipment.

Currently there is much debate surrounding the environmental impact of many new renewable energy technologies, and whether they are as sustainable as they claim. The most common bioenergy types currently in use are biofuels (Yang and Chen, 2014). Examples of these are biodiesel or bioethanol from vegetable oils or sugars respectively. These are known as 1st generation biofuels and are lacking the level of support other renewables receive due to their impact on food resources, competition with other crops or potential negative biodiversity effects (Yang and Chen, 2014). To avoid these issues the use of 2nd generation biofuels has become more attractive, with residues and wastes from industry a reliable source. To fully understand the environmental impact of any product, system or process, a technique has been devised. This is through what is commonly known as Life Cycle Assessment (LCA). LCA is a decision support tool that provides evidence based evaluations of the different energy generation pathways (Pérez-Camacho et al., 2018). It can be defined as a method for evaluating the environmental performance of products, processes or technological system (Prestipino et al., 2021). LCA does this through quantifying the entire material and energy input and output of a product or process over its entire life cycle, or from cradle to grave (Shie et al., 2014). This method for evaluating the environmental performance of an energy system has been used by many researchers previously. Examples include crop residue gasification (Yang and Chen, 2014), biogas production (Natividad Pérez-Camacho et al., 2019), sewage sludge and woody biomass co-gasification (Ramachandran et al., 2017) and a comparison of different thermochemical conversion technologies (Patel et al., 2016). Results of these analysis can vary depending on the boundary conditions of what is included, but through the use of applicable software, a recognisable functional unit and a broad boundary, an accurate representation of the environmental performance of the system may be generated.

LCA has many potential functions and can assist with recognising opportunities to increase the environmental performance of a system or product, can inform policy or strategy when used by industry, government or other organisations, assisting with the selection of appropriate indicators of environmental performance and support environmental marketing through an evidence based approach (British Standards, 2020).

A successful LCA study should consist of four main parts:

1. The goal and scope definition phase
2. The inventory analysis phase
3. The impact assessment phase
4. The interpretation phase

The goal and scope phase are where the system boundaries are set, to identify all relevant parameters for inclusion. The level of detail included within the work depends on the subject, the intended audience and use of the work. Complexity of the LCA can vary between studies depending on the overall goal.

The 2nd phase necessary to carry out the LCA is the life cycle inventory (LCI) phase. It's in this stage that an account of all relevant input and output materials are collected for the system of interest. All relevant data is collected as required to achieve the goals of the study.

The impact assessment phase is necessary to provide extra information to interpret the results of the LCI phase. This is carried out to better understand the environmental significance of the results generated.

The final phase is life cycle interpretation. In this the results are summarised and discussed. Any conclusions, recommendations or decisions are made from these results within the goal and scope of the assessment (British Standards, 2020). How these phases are connected, and how they are reliant on each other can be seen in Figure 6.1 Phases of an LCA.

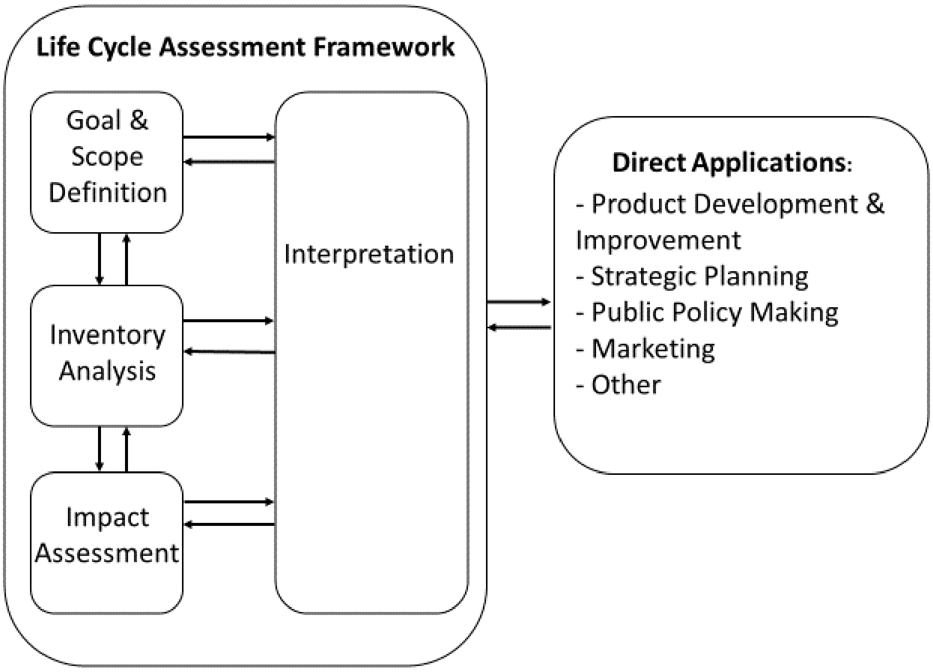


Figure 6.1 Phases of an LCA

6.2 Materials & Method

This section of the research utilises LCA to evaluate the cradle to grave environmental impact that the proposed downdraft gasification combined with a CHP system for heat and electricity generation would have if it were operational, with Northern Ireland used as the test area. The LCA analysis was carried out following the appropriate ISO standard, BS EN ISO 14040:2006+A1:2020. SimaPro software package, version 9.2.0.2, along with Ecoinvent database 3.5 was used to carry out the life cycle assessment study. SimaPro was selected as the LCA software of choice as it allows for the examination of data collected for the inventory to be interpreted in line with the principles of LCA ISO standards. SimaPro is also the software of choice for a number of peer reviewed articles, which have been used to assist with this research, due to the detailed databases it contains (P. W. R. R. Adams and McManus, 2014; Arteconi et al., 2013; Pérez-Camacho et al., 2018; Rolfe et al., 2018).

6.2.1 Goal & Scope

The goal of this study was to evaluate and compare the environmental performance of electricity and heat generated through different methods. This will be done through a cradle to grave approach, where all materials and energies in the systems are included within the scope as is displayed in Figure 6.3 Boundary Conditions of LCA analysis. A comparison will be carried out between the different electricity and heat generation scenarios. Small scale downdraft gasification coupled with a CHP is the energy conversion method of choice for this comparison. Heat and electricity generated through the proposed system will be compared to grid electric and traditional heat generation methods in terms of its environmental impact through the ReCiPe 2016 Midpoint (H) and ReCiPe 2016 Endpoint (H) impact assessment methods. ReCiPe is the method of choice for many LCA reports carried out, with multiple authors utilising it for their research (P. W. R. R. Adams and McManus, 2014; Pérez-Camacho et al., 2018). The midpoint method evaluates the environmental performance of a system in 18 distinct categories. These are; global warming potential, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. Endpoint summarises the results into 3 easily understandable impact categories; human health, ecosystems and resources. From Figure 6.2 the relationship between midpoint impact categories and endpoint is displayed. If a system impacts particulate matter or ionizing radiation, it could add to damage of the human health. Similarly, freshwater ecotoxicity and eutrophication are examples of damage to the ecosystem. Through comparing each individual energy generation system against both methods and all associated environmental impact categories, it will be possible to identify which method performs better in terms of environmental impact.

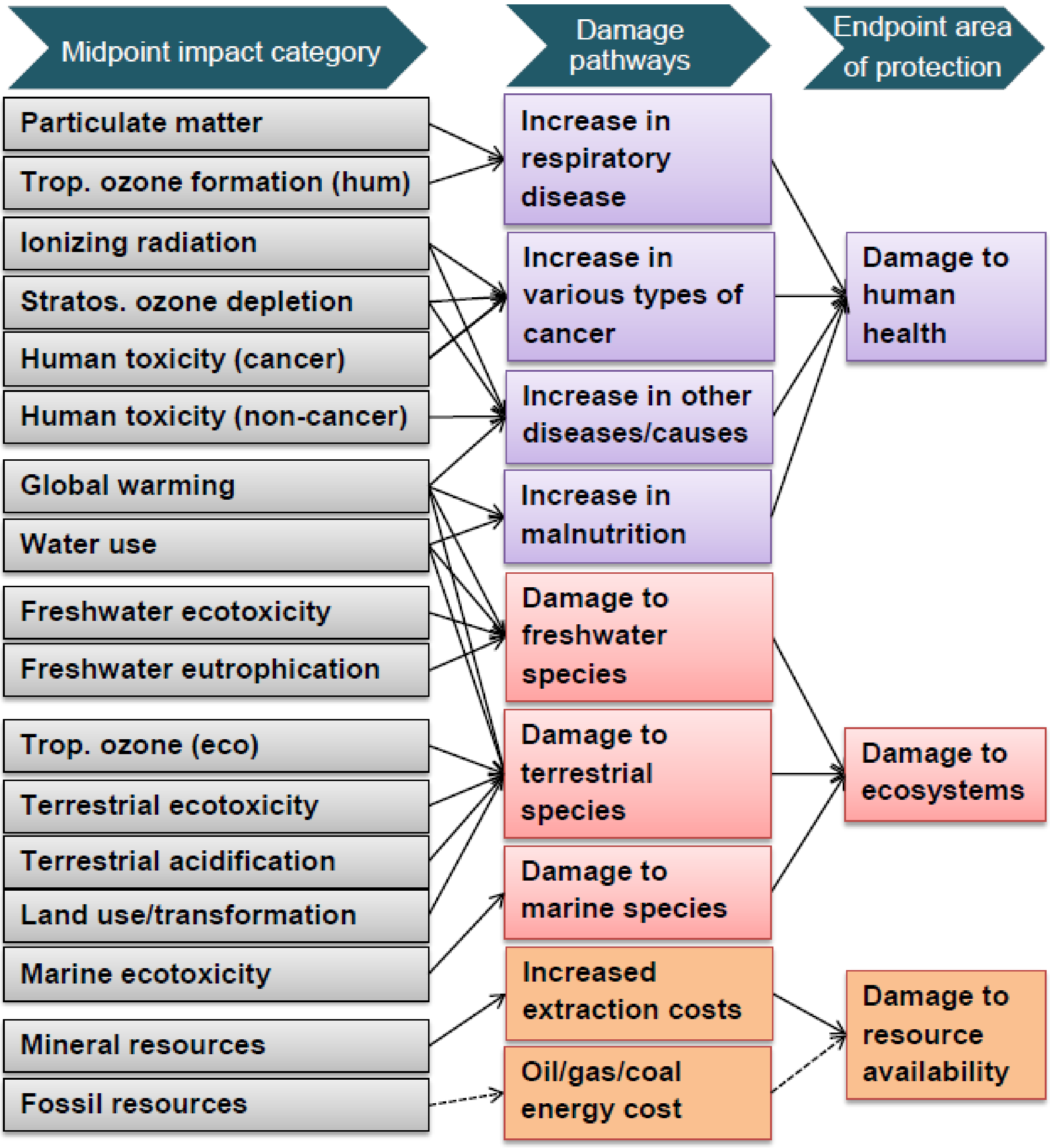


Figure 6.2 Overview of ReCiPe 2016 Impact Categories (Huijbregts et al., 2016)

A number of distinct scenarios involving the proposed system will be investigated, where the producer gas generated will be applied to a CHP engine for electricity and heat production. To ensure a thorough investigation and a complete understanding of the environmental impact of the proposed system 4 distinct assessments will be carried out to cover all aspects of potential impacts. These assessments are:

1. Comparison of electric from the national grid to electricity produced through downdraft gasification of single biomass feedstocks connected to a CHP system
2. Comparison of heat from traditional sources such as natural gas or liquid petroleum gas (LPG) combustion to heat from single feedstocks in the downdraft CHP system
3. Comparison of electric from the national grid to electricity produced through downdraft gasification of the best quality (LHV) blend of feedstocks
4. Comparison of heat from traditional sources such as natural gas or liquid petroleum gas (LPG) combustion to heat from the best quality (LHV) blend of feedstocks applied to the CHP system

These scenarios have been chosen to compare current electricity generation and its environmental impact to the proposed system, identifying the advantages and disadvantages associated with each in terms of their environmental impact. The single feedstock generation method will be utilised as a benchmark for comparison of the blended electricity generation. This research could benefit those who make policy as well as potential users of the technology, such as those who generate biomass as a by-product from an industrial process.

6.2.2 Modelling

LCA is a functional tool that has been utilised to assess the environmental performance of the energy production scenarios. These scenarios are the generation of electricity from the downdraft gasification of biomass and the application of the producer gas to downstream equipment for heat and electricity production. The biomass materials of interest are:

- Poultry Litter
- Anaerobic Digestion Digestate
- Miscanthus
- Wood Pellet

The study has been carried out using SimaPro version 9.2.0.2 along with the Ecoinvent database 3.5. Emission results from the individual biomass energy generation methods, as well as the blended feedstocks, have been produced from the validated ECLIPSE modelling which took place earlier. Reaction by-products such as tar and ash have been included from the ECLIPSE results as well.

6.2.3 Functional Unit & System Boundaries

The functional unit (FU) of the LCA is a critical component for comparison between different systems. It is defined within the ISO standard as a quantified performance of a product system to be used as a reference unit (British Standards, 2020). Within this study two FU's are utilised for comparison of different energies. When comparing electricity, the FU of choice is 1 kWh of net electric delivered to the grid, and when comparing heat, the FU of choice is 1MJ of thermal energy produced. This was identified as the most appropriate functional unit choice, so that the environmental performance of the energy production through the downdraft gasification system can be compared to current UK grid electric and traditional heat generation methods. This functional unit was chosen in agreement with other research covering similar topics such as Adams and McManus (2014).

System boundaries have been set to include all pertinent energy and material flows as can be seen in Figure 6.3 Boundary Conditions of LCA analysis. For the scenarios of interest this includes the planting, harvesting and transport of miscanthus from field to farm. Poultry litter and AD digestate's boundary begins with collection from poultry sheds between crops for the litter and collection from the AD process for the digestate. Each material requires drying, commuting and pelleting. Wood Pellets as the blend material is adjudged to be derived from factory waste wood. Once the materials have been applied to the gasification process, relevant process wastes include tars, ash and emissions to both air and water. Application of the producer gas to an engine for heat and electricity production will generate further emissions such as low levels of particulates and some CO_2 amongst other things.

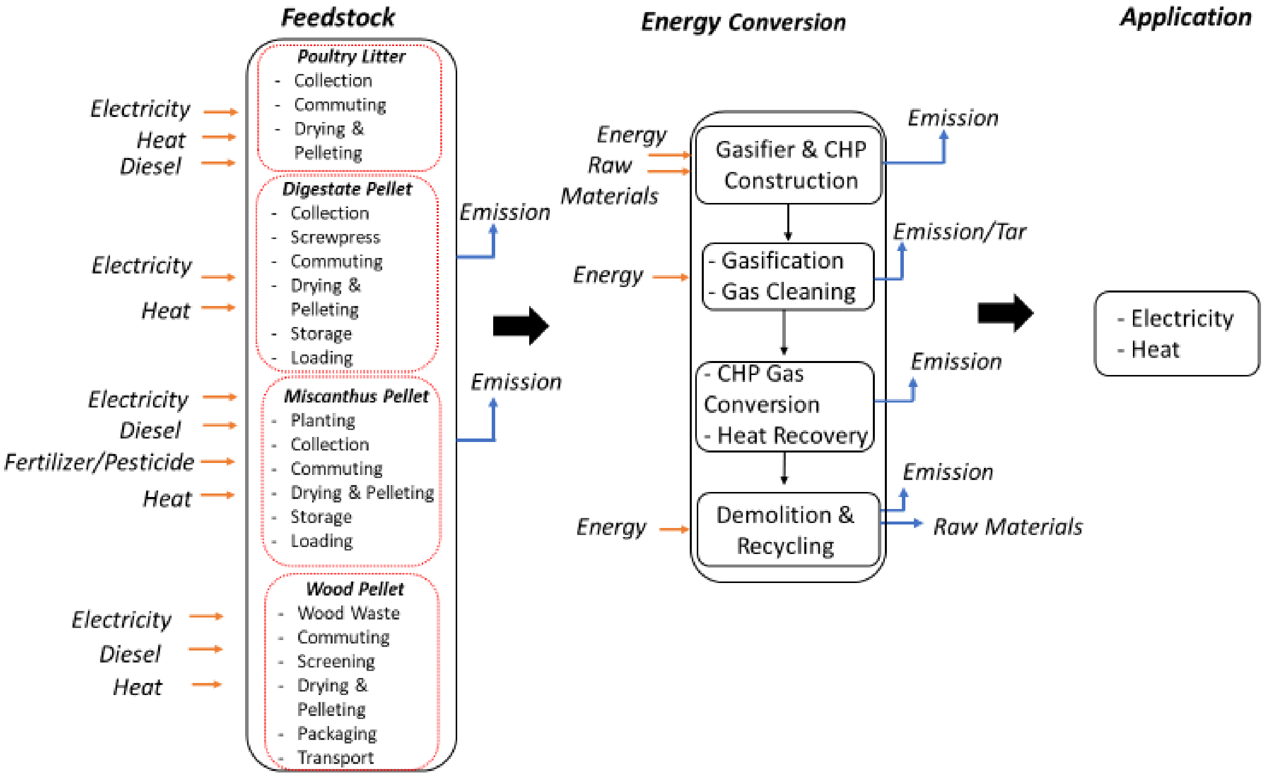


Figure 6.3 Boundary Conditions of LCA analysis

6.2.4 Alternative Generation Methods

To ensure the validity of the comparison being carried out, the alternative energy generation methods were chosen to represent the standard methods through which a rural farm in Northern Ireland would receive their power or self-generate if required. The most common source of electricity for most agricultural or industrial application is through the use of grid electric. This has previously been utilised for research carried out by Natividad Pérez-Camacho et al. (2019) for comparing CHP application of AD produced biogas for electricity generation to that of the grid. Across the UK, the most common method for rural heat generation is through the combustion of fossil fuels such as natural gas or LPG. In research carried out by Jeswani et al.(2019), they compared heat and electricity from poultry litter gasification and CHP application to grid electric and natural gas CHP combustion. This research will therefore follow a similar approach and include LPG derived heat to ensure older installations are covered within the scope of the research. In Northern Ireland alone there are 15,000 LPG users in both the industrial and domestic settings (DfE, 2022).

6.3 Inventory

To ensure the accuracy and validity of the LCA work being carried out, an inventory of material and energy flows for the entire system must first be produced. This is the most crucial step during the course of the assessment, as correctly quantifying the flows between techno sphere and the product will guarantee the strength of the results produced from the assessment. A significant portion of the LCA analysis is therefore gathering the relevant data for this inventory. The following are the results of the data gathering inventory. Results are also summarised in Table 6.1 along with assumed electrical and thermal efficiencies for the system.

The account of what is required for each biomass material to be converted into energy is dependent on the feedstock, but similarities are present between streams also. For poultry litter gasification, for the generation of 1 MJ of heat through CHP application of the producer gas generated, 755kg of fresh poultry litter material is required. This material will also generate 734kWh of electrical energy from the CHP process. Processing energy required for collection, commuting or drying of the material will be approximately 244kWh/tonne of material utilised. This comes from analysis carried out by the European Pellet Council (EPC, 2021a). For the 755kg of PL this equates to 184.3kWh of energy. Tar and ash content from the process is calculated from the proximate analysis of the feedstock, which identified the ash content at 12.9%. For each MJ of heat generated 97.7kg of ash are generated. Tar content is slightly lower at 25.6 kg per MJ of heat. Final emissions from the system are those to air which include carbon dioxide (CO_2), sulphur dioxide (SO_2), oxygen (O_2), nitrogen (N_2), argon (Ar) and carbon monoxide (CO). Each MJ of heat from the system will generate 1097kg CO_2, 6.2kg SO_2, 98.7kg O_2, 2937kg N_2, 49kg Ar and 3.9kg CO.

For digestate gasification, the generation of 1MJ of heat through CHP application of the producer gas will require 562kg of digestate being fed into the system. 748kWh of electric will also be generated alongside the heat from the CHP process. Utilising the same reference from the pellet council, 137kWh of electric will be required for the pre-processing of the material for every MJ of heat generated. Ash content of the feedstock is 11.18%, therefore 62.79kg of ash will be generated from the process along with 59.9kg of tar. Emissions to air from the process are slightly lower than those from PL with 845kg CO_2, 3.6kg SO_2, 81.9kg O_2, 2393kg N_2, 40.6kg Ar and 3kg CO per MJ of heat generated.

Miscanthus gasification again follows a similar trend to the two previous feedstocks, with 533kg of miscanthus required to generate 1MJ of thermal energy. This will also generate 745kWh of electrical energy from the CHP process. Required for pre-processing of the miscanthus material will be 135kWh of electrical energy. Low ash content of miscanthus (2.51%) means only 13.88kg of the material is generated, alongside 47.07kg of tar. Emissions to air from miscanthus gasification include 772kg CO_2, 3.2kg SO_2, 1812kg N_2, 30.8kg Ar and 2.6kg CO.

The final stream requiring definition in terms of inputs and outputs is the optimised blend of biomasses which has been identified through experimental analysis. This is the Poultry Litter/Wood Pellet blend with a ratio of 60/40 by weight. With this stream of feedstock for the generation of 1MJ of thermal energy, the inputs required are 400kg of PL and 267kg waste wood. The electrical load generated as part of the CHP process for this feedstock is 730kWh. Pre-processing of the material will require 162.7kWh for drying, commuting or similar. As clean wood waste will have a very low ash content (0.3%), the overall ash generated will be 52.5kg per MJ heat, which is significantly lower than the single stream PL technique at 97.7kg. Tar content of the material is 25.65kg. The final emissions to air from this system are 650kg CO_2, 4.2kg SO_2, 228.7kg O_2, 2854.8kg N_2, 48.4kg Ar and 1.6kg CO.

Table 6.1 Inventory for LCA Analysis

	Poultry Litter Pellet	Digestate Pellet	Miscanthus Pellet	Blended Feedstock (60/40 PL/WP)
Input (t/h)	0.76	0.56	0.55	0.67
Gas Production (m3/h)	1529.24	1307.08	1468.84	1602.28
Heat Output (MW)	1.001	1.000	1.000	1.000
Electrical Output (MWh)	0.73	0.75	0.75	0.73
Electrical Efficiency (%)	20.34	22.89	24.3	22.85
Thermal Efficiency (%)	48.06	53.47	56.94	54.16
CO_2 Emissions (tonne/h)	1.10	0.85	0.77	0.65
SO_2 Emissions (kg/h)	6.16	3.60	3.22	4.28
Ash (kg)	97.67	62.79	13.88	52.54
Tar	25.65	59.97	47.07	25.65

6.4 Results & Discussion

Once the goal, scope, functional unit, system boundaries and inventory have all been defined the results of the LCA analysis can be generated. The results are displayed in graphical form for each, with an adjoined table to further describe the results generated from the analysis. All results are displayed in percentage (%) of damage to the environment, known as characterisation of the results. When comparing the different systems environmental impact across the 18 midpoint categories along with the 3 endpoint categories, the greater the negative percentage impact, the more beneficial to the environment the result is in that impact category. Conversely the larger the positive impact, the more harm caused to the environment in that category.

6.4.1 Single Stream Electric vs Grid

The first comparison carried out as part of the LCA was the comparison of electricity sources, comparing the environmental impact of 1kWh of electricity from 4 different sources. Downdraft gasification of poultry litter, digestate and miscanthus and applying the producer gas to a CHP system for electricity generation are the first 3 scenarios. The 4th source of electricity is obtaining the equivalent 1kWh of electricity from the Northern Ireland grid.

Midpoint Analysis

Midpoint analysis to quantify the environmental impacts of the process is carried out to identify the emissions from the system and associate them with their original source. It is widely used for its holistic set of impact categories which offer a broad overview of the systems emissions (Guest et al., 2011).

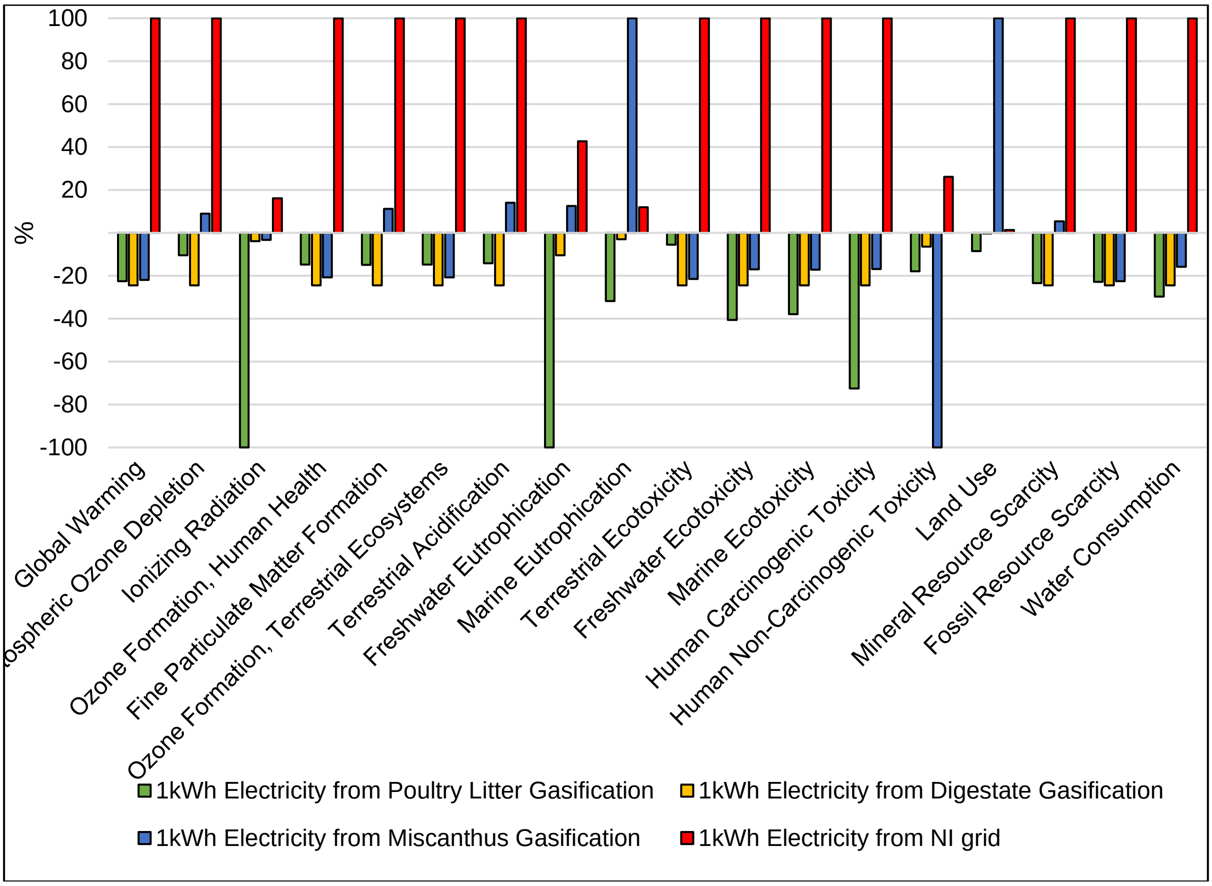


Figure 6.4 Midpoint Comparison of Environmental Impact of 1kWh of Electricity from 4 Sources

In Figure 6.4 we can see that as a general trend, the electricity generated from the downdraft gasification of biomass and applied to a CHP system has a lower environmental impact than electricity from the Northern Ireland grid. This is shown through the blue, orange and green bars representing the various biomass being below 0, and into negative impacts, where the red bar representing grid electric is above the 0 mark with a harmful positive impact in nearly all categories. The figures associated with each category are displayed in Table 6.2 Midpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from 4 Sources. In all 18 of the categories of interest, electricity from PL and digestate has a negative impact when compared to electricity from the grid. Electricity from miscanthus gasification outperforms NI grid electric in 16 out of the 18 categories of interest. Only in marine eutrophication and land use does it fare worse, due to the emissions from the planting, growing and harvesting processes as well as using land for growing that could be used for other purposes such as food. To put the figure into some context, for the year ending in June 2021, 54.6% of the electricity generated across Northern Ireland came from non-renewable resources (NISRA, 2021). This works out to be an average of approximately 339g CO_2/kWh_e generated. To avoid some of these therefore unnecessary CO_2 emissions, the switch to the proposed downdraft gasification of waste system would be beneficial. Future introduction of further renewable technologies to the grid will lower the average CO_2/kWh_e and therefore impact on the results generated here. Of the 4 electricity generation scenarios compared, PL gasification and CHP application is the best performing in terms of environmental impact.

Table 6.2 Midpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from 4 Sources

Label	Poultry Litter (%)	Digestate (%)	Miscanthus (%)	NI Grid (%)
Global Warming	-22	-25	-22	100
Stratospheric Ozone Depletion	-10	-25	8.9207	100
Ionizing Radiation	-100	-4	-3	16.0954
Ozone Formation, Human health	-15	-25	-21	100
Fine Particulate Matter Formation	-15	-25	11.1647	100
Ozone Formation, Terrestrial Ecosystems	-15	-25	-21	100
Terrestrial Acidification	-14	-25	14.0681	100
Freshwater Eutrophication	-100	-10	12.5507	42.722
Marine Eutrophication	-32	-3	100	11.8908
Terrestrial Ecotoxicity	-6	-25	-21	100
Freshwater Ecotoxicity	-41	-25	-17	100
Marine Ecotoxicity	-38	-25	-17	100
Human Carcinogenic Toxicity	-73	-25	-17	100
Human Non-Carcinogenic Toxicity	-18	-6	-100	26.0537
Land Use	-8	0	100	1.3873
Mineral Resource Scarcity	-23	-25	5.39	100
Fossil Resource Scarcity	-23	-25	-23	100
Water Consumption	-30	-25	-16	100

Endpoint Analysis

Endpoint analysis was carried out to identify final damages which are caused by the proposed energy generation systems. Unlike the broad range found through midpoint analysis, endpoint summaries the results into 3 easily understandable categories for final impact assessment.

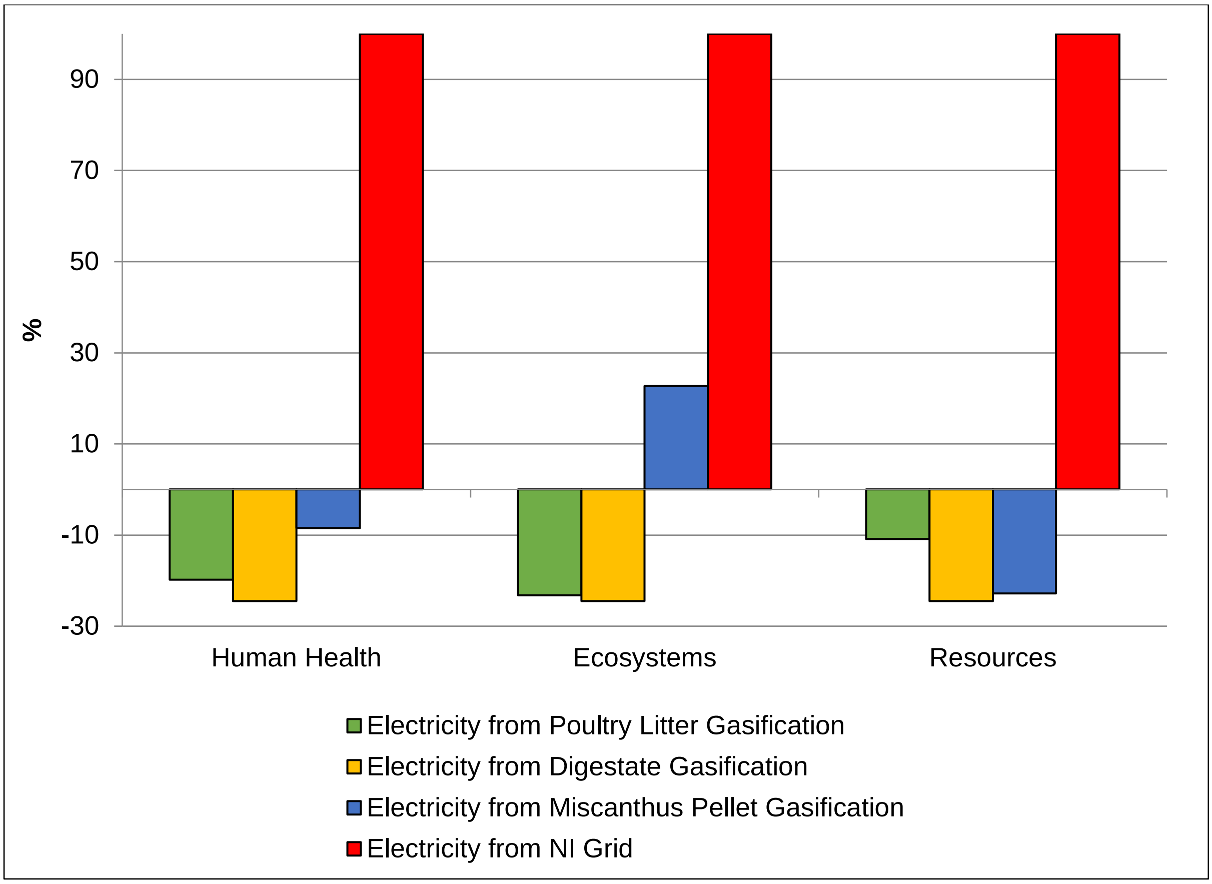


Figure 6.5 Endpoint comparison of 1kWh of Electricity from 4 Sources

From Figure 6.5 we can see that the producer gas generated 1kWh of electric has much less of an impact on the 3 categories than the grid equivalent. Under these conditions, the best performing in terms of environmental impact is the digestate generated electricity, which consistently shows the lowest impact across all impact categories. Compared to grid electric, the proposed system has a large benefit in terms of human health, resources and ecosystems. Miscanthus produced electric shows slightly less favourable than poultry litter and digestate through the 22.7% impact on ecosystems. This can again be associated with the use of land and machinery for planting and harvesting of the material. Table 6.3 shows the breakdown of these results, with all biomass generated electricity outperforming grid electric in each impact category.

Table 6.3 Endpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from 4 Sources

Label	Electricity from Poultry Litter Gasification	Electricity from Digestate Gasification	Electricity from Miscanthus Pellet Gasification	Electricity from NI Grid
Human Health	-20	-25	-8	100
Ecosystems	-23	-25	22.7607	100
Resources	-11	-25	-23	100

6.4.2 Single Stream Heat vs Traditional Methods

The second comparison which is carried out as part of the LCA, is similar to the first but compares heat generated from the proposed system in place of electricity. 1 MJ of heat generated from the application of the producer gas from the 3 biomass feedstocks, poultry litter, digestate and miscanthus, to a CHP system is compared the equivalent 1MJ of heat generated through two traditional methods. The traditional methods are combustion of natural gas or LPG in a simple boiler system. Midpoint and endpoint analysis have again been utilised to ensure a clear understanding of the overall environmental impact each system has. Midpoint results are displayed in both Figure 6.6 Midpoint Comparison of Environmental Impact of 1 MJ of Heat from 5 Sources and Table 6.4 Midpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from 5 Sources, while endpoint results are in Figure 6.7 Endpoint comparison of 1MJ of Heat from 5 Sources and Table 6.5 Endpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from 5 Sources.

Midpoint Analysis

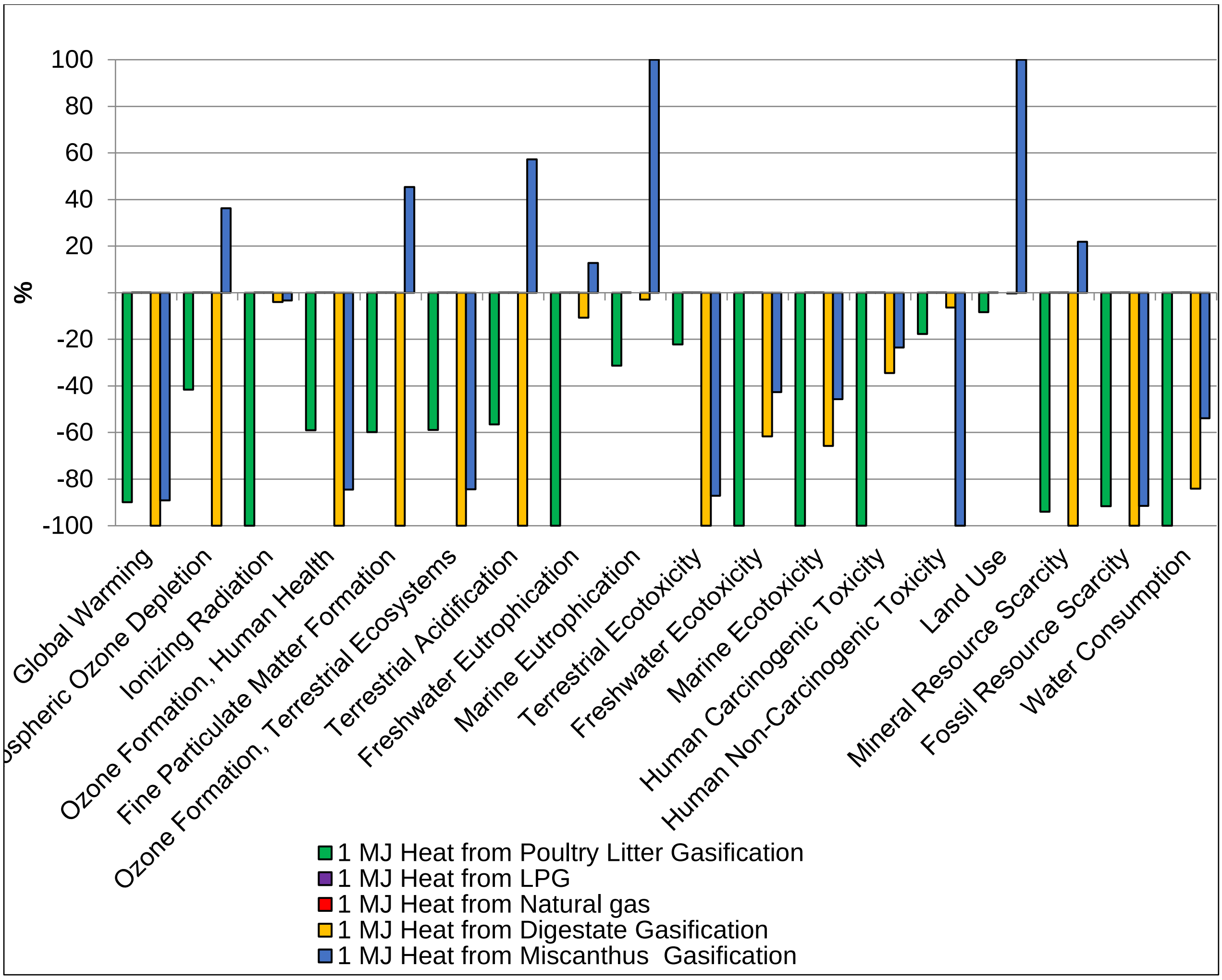


Figure 6.6 Midpoint Comparison of Environmental Impact of 1 MJ of Heat from 5 Sources

In Figure 6.6, like the midpoint comparison of 1 kWh of electric, the midpoint comparison of 1 MJ of heat shows similar results. This is that all heat generated from the CHP application of producer gas is more environmentally friendly than the traditional heat generation methods found in Northern Ireland. This can be seen through the large drops into the negative percentages visible in Figure 6.6 for the green, orange and blue columns representing poultry litter, digestate and miscanthus generated heat. Heat from the miscanthus system is better for the environment in 11 of 18 impact categories but is also more harmful in the other 7 categories. Through growing of a separate crop for energy production new issues are being raised, in comparison to energy harnessed from a waste resource. Results for heat from LPG and natural gas are difficult to view on the graph, as they are small positive numbers. This can be verified by reading the results listed in Table 6.4 Midpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from 5 Sources, where despite their small size, the environmental impact from the heat for both is a positive number. This means that the environmental impact of LPG and NG generated heat is more damaging in their impact categories than the heat generated from the 3 downdraft biomass feedstock systems of interest. This is promising for the downdraft gasifier coupled with CHP technology, as so far both electricity and heat generated from the system is significantly more environmentally friendly than the traditionally used energy sources.

Table 6.4 Midpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from 5 Sources

Label	**Poultry Litter**	**Digestate**	**Miscanthus**	**LPG**	**Natural Gas**
Global Warming	-90	-100	-89	0.0127	0.0084
Stratospheric Ozone Depletion	-42	-100	36.2529	0.0164	0.0032
Ionizing Radiation	-100	-4	-3	0.0019	0.0001
Ozone Formation, Human health	-59	-100	-84	0.0101	0.0017
Fine Particulate Matter Formation	-60	-100	45.3734	0.0131	0.0005
Ozone Formation, Terrestrial Ecosystems	-59	-100	-84	0.0106	0.0017
Terrestrial Acidification	-57	-100	57.1733	0.012	0.0004
Freshwater Eutrophication	-100	-11	12.7388	0.004	0.0001
Marine Eutrophication	-31	-3	100	0.0017	3.85E-05
Terrestrial Ecotoxicity	-22	-100	-87	0.0058	0.0002
Freshwater Ecotoxicity	-100	-62	-43	0.0049	0.0003
Marine Ecotoxicity	-100	-66	-46	0.006	0.0014
Human Carcinogenic Toxicity	-100	-34	-24	0.0059	0.0006
Human Non-Carcinogenic Toxicity	-18	-6	-100	0.0013	9.02E-05
Land Use	-8		100	0.0002	4.31E-06
Mineral Resource Scarcity	-94	-100	21.9044	0.0173	0.0028
Fossil Resource Scarcity	-92	-100	-91	0.0624	0.0121
Water Consumption	-100	-84	-54	0.0279	0.0043

Endpoint Analysis

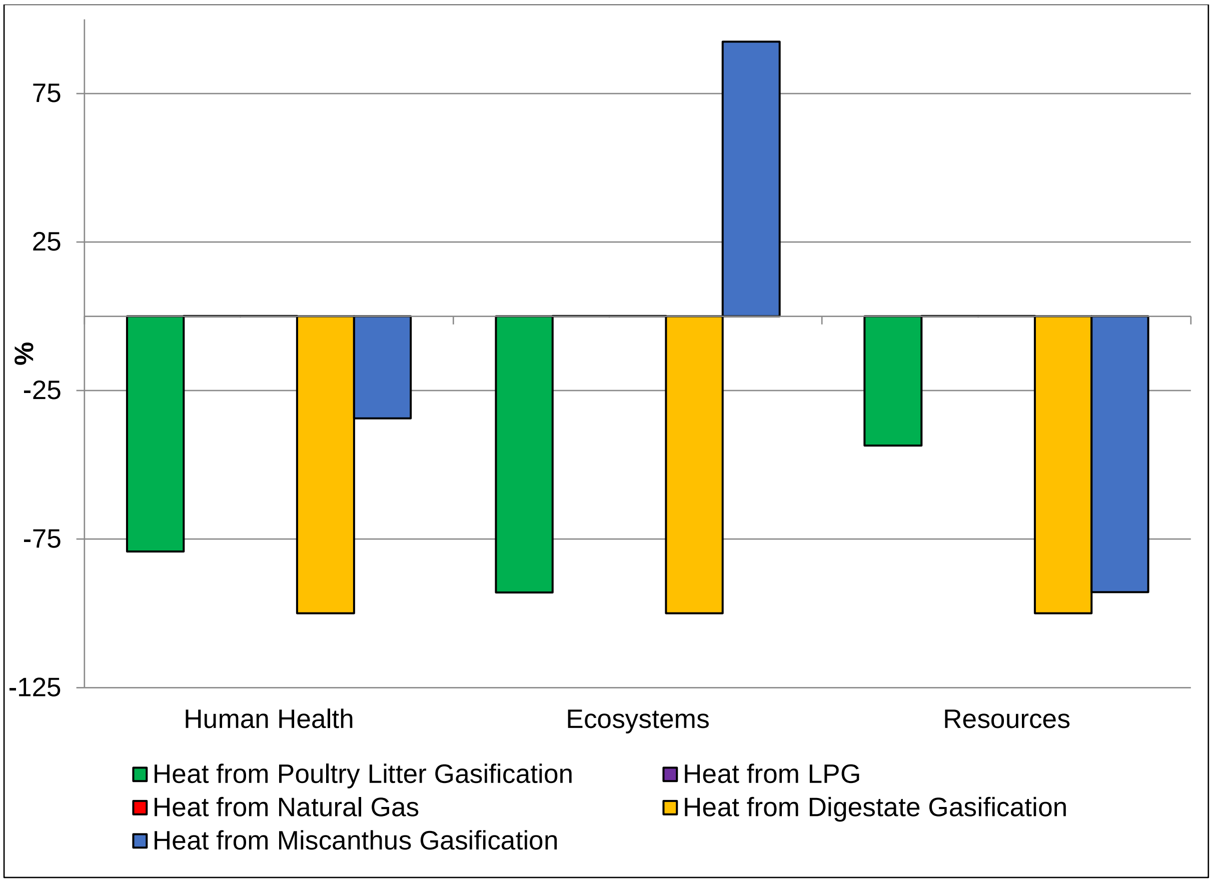


Figure 6.7 Endpoint comparison of 1MJ of Heat from 5 Sources

Further details on the impact of heat from the proposed energy generation system compared to traditional heat generation methods can be harnessed from Figure 6.7 Endpoint comparison of 1 MJ of heat from 5 sources. All 3 biomass sources of heat provide a much more sustainable and environmentally friendly impact than the traditional heat sources, similar to the results seen for the electric comparison. Both fossil fuel sources show slightly positive results as can be seen in Table 6.5. Miscanthus again shows a bad environmental performance for the ecosystems impact category when compared to all other heat sources, through its need for planting, harvesting and potentially using fertilizers to assist with growing.

Table 6.5 Endpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from 5 Sources

Label	**Heat from Poultry Litter Gasification**	**Heat from LPG**	**Heat from Natural Gas**	**Heat from Digestate Gasification**	**Heat from Miscanthus Gasification**
Human Health	-79	0.0132	0.0037	-100	-34
Ecosystems	-93	0.0127	0.0053	-100	92.4996
Resources	-43	0.062	0.0098	-100	-93

6.4.3 Blend Electric vs Grid Electric

The next relevant comparison carried out was to compare the environmental impact that 1kWh of electricity generated from the Poultry Litter/Wood Pellet blend has compared to 1kWh of grid electricity in Northern Ireland. The blend used was 60/40 PL/WP by weight. This blend was identified through experimental analysis as being a promising mixture for producer gas generation. With comparisons previously showing the benefit of utilising electricity and heat from the proposed waste to energy system, the trend is expected to continue here when using midpoint and endpoint environmental impact categories.

Like the previous section, results for midpoint analysis are displayed in Figure 6.8 Midpoint Comparison of Environmental Impact of 1 kWh of Electric from Blended System vs NI Grid and Table 6.6 Midpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from Blended System & NI Grid. Endpoint results are displayed in Figure 6.9 Endpoint comparison of 1kWh of Electricity from Blend vs Grid and Table 6.7 Endpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from Blend vs. Grid.

Midpoint Analysis

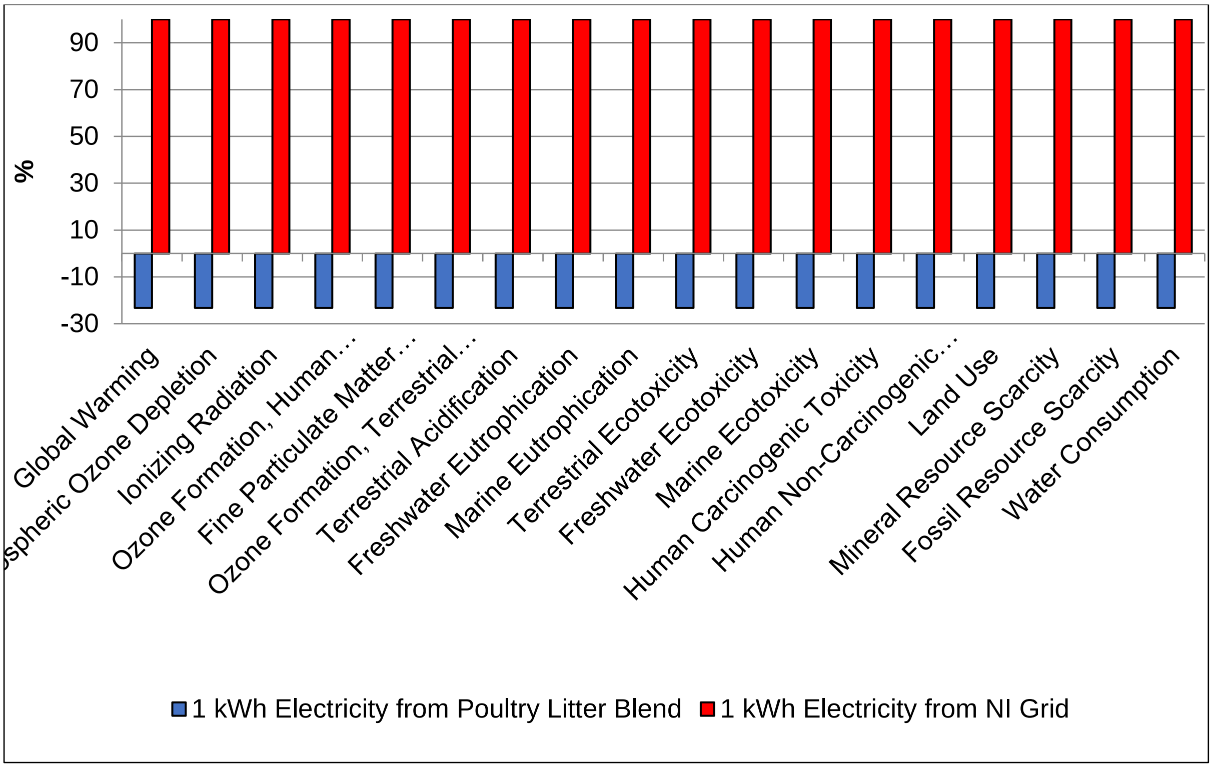


Figure 6.8 Midpoint Comparison of Environmental Impact of 1 kWh of Electric from Blended System vs NI Grid

We can see in Figure 6.8, that the 1 kWh of electricity generated from the downdraft gasification of the poultry litter and wood pellet blend has substantial environmental benefits when the midpoint comparison to 1kWh electricity from the Northern Ireland grid is carried out. In each environmental impact category of interest, the impact from the blended system is significantly more environmentally friendly than that of its NI grid counterpart. The results indicate a consistent performance across each category, with 123% difference in the environmental impact of the category between systems. This performance follows the earlier trend associated with energy from the proposed downdraft gasification system, where both heat and electricity are more sustainable when generated through them than the national grid or traditional heat sources.

Table 6.6 Midpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from Blended System & NI Grid

Label	1 kWh Electricity from Poultry Litter Blend	1 kWh Electricity from NI Grid
Global Warming	-23	100
Stratospheric Ozone Depletion	-23	100
Ionizing Radiation	-23	100
Ozone Formation, Human Health	-23	100
Fine Particulate Matter Formation	-23	100
Ozone Formation, Terrestrial Ecosystems	-23	100
Terrestrial Acidification	-23	100
Freshwater Eutrophication	-23	100
Marine Eutrophication	-23	100
Terrestrial Ecotoxicity	-23	100
Freshwater Ecotoxicity	-23	100
Marine Ecotoxicity	-23	100
Human Carcinogenic Toxicity	-23	100
Human Non-Carcinogenic Toxicity	-23	100
Land Use	-23	100
Mineral Resource Scarcity	-23	100
Fossil Resource Scarcity	-23	100
Water Consumption	-23	100

Endpoint Analysis

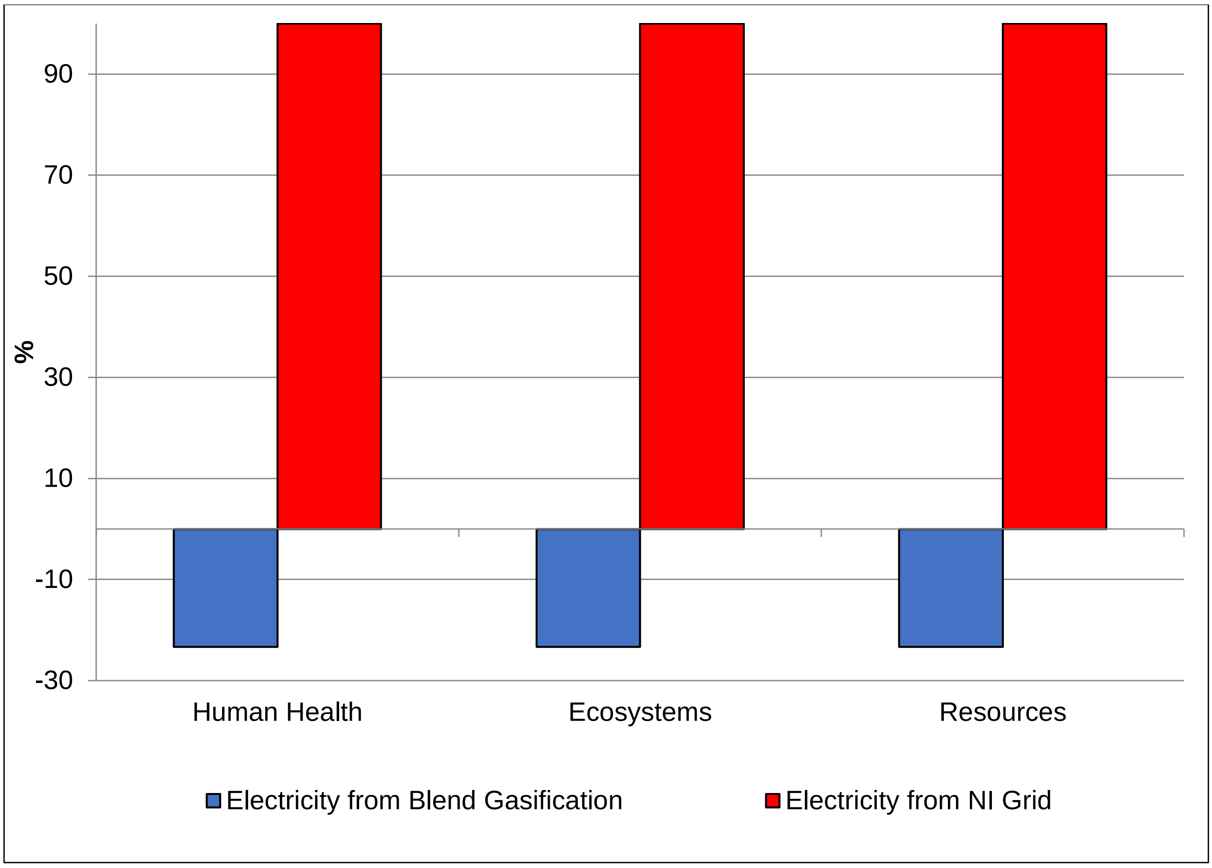


Figure 6.9 Endpoint comparison of 1kWh of Electricity from Blend vs Grid

The trend identified from earlier analysis continue with the endpoint investigation of 1kWh of electricity generated from the blended feedstock, as it outperforms electricity from the NI grid in every impact category associated with this particular analysis. Human health is less impacted by the electricity generated from the blend of poultry litter and wood pellets, as are ecosystems and resources compared to its grid electric counterpart. The further research carried out on the environmental impact of producing energy through the proposed system, the more evidence generated to support its introduction.

Table 6.7 Endpoint Percentage Results from Comparison of Environmental Impact of 1kWh of Electricity from Blend vs. Grid

Label	Electricity from Blend Gasification	Electricity from NI Grid
Human Health	-23	100
Ecosystems	-23	100
Resources	-23	100

6.4.4 Blend Heat vs. Traditional Heat

The final environmental comparison carried out was between 1MJ of heat generated from the blend of PL and WP, compared to 1MJ heat generated from traditional sources. The final performance analysis across the 18 environmental impact categories associated with the midpoint analysis are displayed in Figure 6.10 Midpoint Comparison of Environmental Impact of 1MJ of Heat from Blended System vs Traditional Sources and Table 6.8 Midpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from Blended System & Traditional Sources. Endpoint results are displayed in Figure 6.11 Endpoint comparison of 1MJ of Heat from Blend vs Traditional Sources and Table 6.9 Endpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from Blend vs. Traditional Sources.

Midpoint Analysis

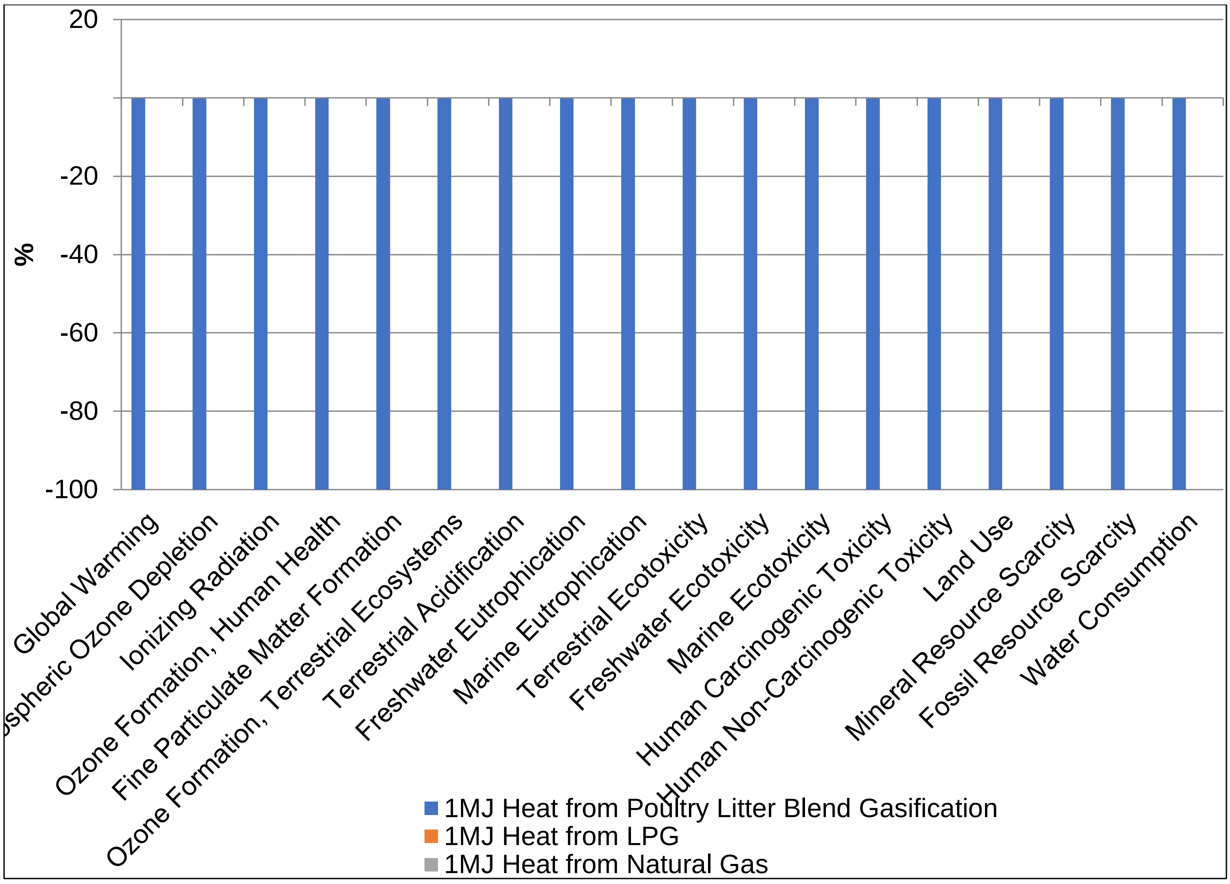


Figure 6.10 Midpoint Comparison of Environmental Impact of 1MJ of Heat from Blended System vs Traditional Sources

We can see in Figure 6.10 that the results of the heat comparison again follow the same trend as the electric comparison in Figure 6.8. This is that across all impact categories of interest, the heat generated from the blended feedstock system generates energy in a much more environmentally sustainable way than the traditional heat sources found on a poultry farm. While both heat from LPG and NG have slightly positive impacts, as can be seen in Table 6.8, the heat from the poultry litter blended system is consistently 100 times less damaging to the environment across all 18 impact categories when compared. From this analysis we can therefore promote the downdraft gasification of waste materials along with the utilisation of blends as an environmentally sustainable method through which energy can be generated for small scale applications.

Table 6.8 Midpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from Blended System & Traditional Sources

Label	**1MJ Heat from Poultry Litter Blend**	**1MJ Heat from LPG**	**1MJ Heat from Natural Gas**
Global Warming	-100	0.0137	0.0353
Stratospheric Ozone Depletion	-100	0.0177	0.0096
Ionizing Radiation	-100	0.0506	0.0377
Ozone Formation, Human Health	-100	0.0109	0.006
Fine Particulate Matter Formation	-100	0.0142	0.0044
Ozone Formation, Terrestrial Ecosystems	-100	0.0115	0.0064
Terrestrial Acidification	-100	0.0129	0.0041
Freshwater Eutrophication	-100	0.0407	0.0396
Marine Eutrophication	-100	0.0636	0.0516
Terrestrial Ecotoxicity	-100	0.0062	0.0023
Freshwater Ecotoxicity	-100	0.0085	0.0137
Marine Ecotoxicity	-100	0.0098	0.013
Human Carcinogenic Toxicity	-100	0.0185	0.021
Human Non-Carcinogenic Toxicity	-100	0.0212	0.023
Land Use	-100	0.0476	0.0226
Mineral Resource Scarcity	-100	0.0186	0.0211
Fossil Resource Scarcity	-100	0.0672	0.0418
Water Consumption	-100	0.0357	0.0069

Endpoint Analysis

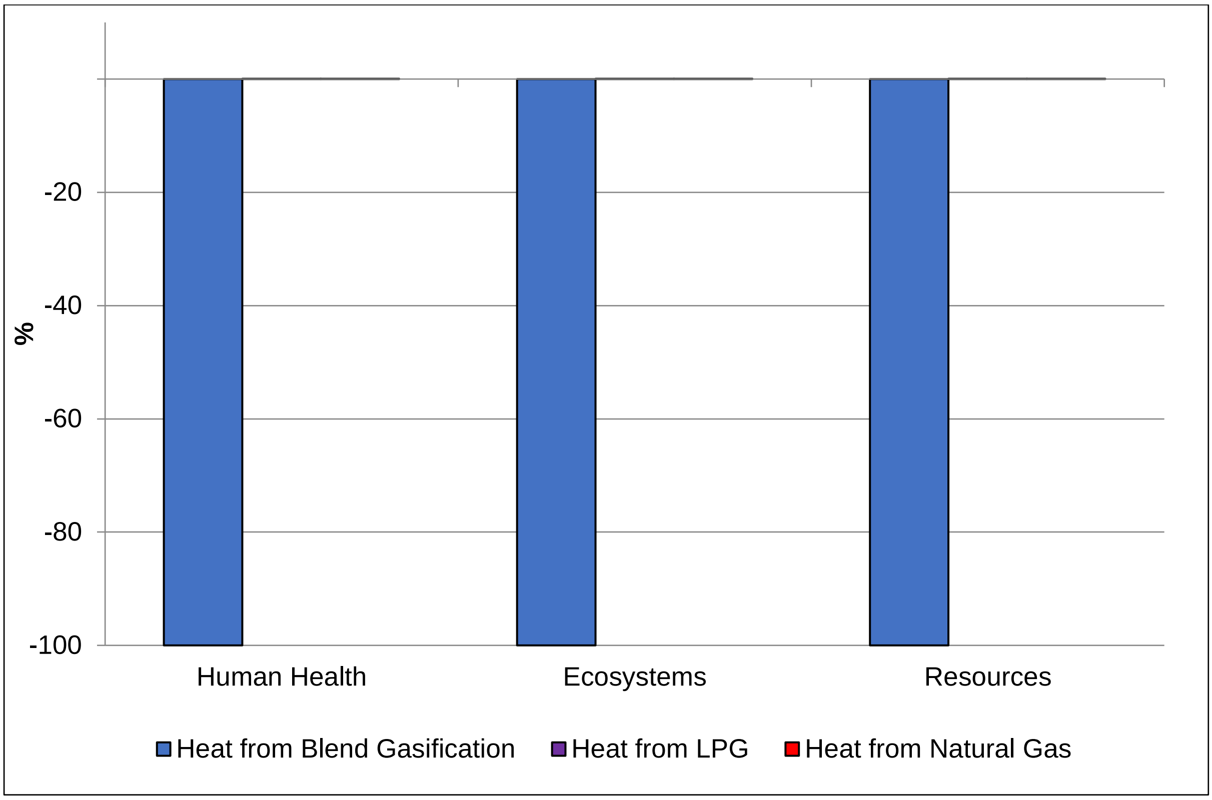


Figure 6.11 Endpoint comparison of 1MJ of Heat from Blend vs Traditional Sources

The final piece of analysis for this LCA is the endpoint comparison of 1MJ of heat from the blend system compared to traditional sources. The prevailing trend identified earlier that energy from the downdraft gasification of biomass and application of producer gas is seen here again. When looking at the impact on human health, ecosystems and resources, heat from the blend gasification system is one hundred times more sustainable than heat from LPG or natural gas sources. These have slightly positive results as can be seen in Table 6.9, but from Figure 6.11 it is obvious that within each endpoint category heat from the blend system is the optimum choice.

Table 6.9 Endpoint Percentage Results from Comparison of Environmental Impact of 1MJ of Heat from Blend vs. Traditional Sources

Label	Heat from Blend Gasification	Heat from LPG	Heat from Natural Gas
Human Health	-100	0.0142	0.0173
Ecosystems	-100	0.0137	0.023
Resources	-100	0.0668	0.0333

6.5 Summary

With increasing levels of industrial waste being produced to sustain current global food and population demands, new waste treatment solutions are required. The argument for reliable renewable energy and decarbonising industries has led many people to trying to solve these societal issues with new technologies, or in the case of gasification an old technology that has recently become an attractive method to deal with industrial waste materials. This LCA work was carried out with the aim of understanding the environmental impact of the proposed downdraft gasification system where the producer gas is applied to a CHP unit for heat and electricity generation. A full life cycle assessment has been carried out where both the thermal and electrical energy generated from the proposed system is compared to traditional energy generation methods found on farms in Northern Ireland such as grid electric or heat from the combustion of LPG or natural gas. Following the methods proposed by BS EN ISO 14040:2006+A1:2020 the goal and scope of the research was identified; an appropriate software and method was used along with a relevant functional unit and system boundaries. 1MJ of heat was used as the functional until when comparing heat, and 1kWh of electric was used when comparing electricity. Both midpoint analysis, with 18 unique environmental impact categories, and endpoint analysis with its 3 impact categories were used to ensure a clear understanding of the potential impact that the different methods of energy generation may have.

Results from the analysis show that both heat and electricity generated from the proposed downdraft gasification coupled to a CHP unit system are more environmentally friendly and sustainable than traditional sources of these energies for farms in Northern Ireland. While poultry litter and anaerobic digestate as a source of heat and electricity outperform traditional sources such as grid electric or LPG and natural gas combustion, miscanthus does not. Miscanthus performs badly throughout the LCA as it requires land, energy and potentially even fertilisers for its production. Compared to the other two feedstocks which are generated as a waste or by-product from an existing process, miscanthus performs negatively in terms of the impact on land use and ecosystems. The positive results from the analysis show that both poultry litter and digestate as single biomass feedstocks, and the blend of poultry litter and wood can be a sustainable source of heat and electricity for farms in Northern Ireland.

While the results from this LCA alone are promising for the technology, it is when we compare them to what has previously been found in literature that we get a better understanding of the current status of gasification of wastes as an energy source. Research into the use of agri – residues or wastes as an energy source for the agricultural sector have always shown promise when compared to fossil fuel equivalents. Kimming et al. (2011) displayed the possibility of displacing fossil fuels with a biogas or through the gasification of willow chips. Jeswani et al. (2019) found that in 14 of 16 impact categories that poultry litter gasification performed fossil fuels as a source of energy. Prestipino et al. (2021) showed the benefits of agri-residues through utilising citrus peel as a source of energy when compared to electricity purchased through the national grid. Rafaschieri et al. (1999) compared energy from poplar crops to conventional fossil fuels and found that the only drawbacks to the system are the use of chemical fertilisers for growth of the plants. These results from literature all agree with what has been found through this LCA work, giving increased credibility to the analysis and results.

Chapter 7 – Techno – Economic Analysis of the Downdraft Gasifier Based CHP System

7.1 Introduction

When researching the potential for any renewable technology, the main driving forces for change is government policy, which often influence market forces. This is through subsidisation to make it economically viable (Kempegowda et al., 2012). To understand the market potential of downdraft gasification coupled to a CHP system for energy generation, an understanding of the initial investment required, the costs and savings associated with the project and a potential payback period for the system is required. A complete financial and economic analysis associated with the proposed downdraft energy generation system will be carried out. This will be done through economical modelling of the various proposed scenarios, comparing different economic indicators and the influence that a blend of biomass may have on these indicators. ECLIPSE economic analysis package has been utilised for this research, to ensure the validity and reproducibility of the results, as discussed in Chapter 5 – Process Modelling and Simulation. Previously published research utilising this software includes but is not limited to (Huang et al., 2020, 2015, 2011).

This chapter is therefore dedicated to the financial impacts that introducing the proposed system may have on a rural farm in Northern Ireland. If it can be proven that the proposed system can offer a swift return on investment, it will be further justification for the introduction of such technology to the market. The chapter will begin with a detailed explanation of what exactly is covered within the downdraft gasification system (DGS). This will include the various processing stages associated with the biomass conversion such as collection and storage methods, pre-treatment required such as drying, commuting or pelleting, the downdraft gasification of the feedstock, and finishing with cleaning and application of the generated producer gas. A discussion will then take place around the potential costs associated with the proposed system, as well as any savings which may occur through avoidance of disposal expenses or fuel purchasing costs. The final factor which needs to be taken into account to ensure a valid calculation is that of potential subsidies available to the system user. Across the UK a variety of renewable heat and electricity tariffs are available depending on technology, scale and application. These will be evaluated, and the correct rate will be applied to the calculation set up. To carry out the economical modelling ECLIPSE simulations financial package will be utilised to accurately estimate the net-present value (NPV) of the investment, the break-even selling price (BESP) for the electricity generated from the system and a payback period (PBP) for the initial capital cost outlay of the equipment.

This economic evaluation will consist of three CHP scenarios which are explained in greater detail below. The aim will be to compare how each feedstock of poultry litter, digestate and miscanthus performs in terms of economic indicators within the system. The results of these single feedstocks will then be compared to the blends of interest for this research to understand the potential economic impact of blended feedstocks.

7.1 System Set Up

An overview of the proposed downdraft gasification and engine application system set up, and how it would operate can be seen in Figure 7.1 – System Components. The system comprises of six stages. These are a method of material collection, a container for material storage, a pre-treatment system for feedstock preparation, a downdraft gasifier for conversion of solid biomass to gas, a gas cleaning method for impurities removal, and an engine for heat and electricity conversion. Biomass material of interest is poultry litter, anaerobic digestion digestate and miscanthus. Wood pellets are the blend material.

Figure 7.1 System Components

A comparison of three different energy generation set ups have been carried out to assess the potential benefits of utilising the proposed system. These are:

1. To use all the poultry waste available in an internal combustion engine (ICE) for heat and electricity production (120kW), which generates an excess amount of electricity for selling back to the grid
2. To use an Organic Rankine Cycle CHP system to meet the thermal demand of the farm while limiting the amount of electricity generated that requires selling to the grid (36kW)
3. To use a 21kW ICE to meet the electrical demand of the site along with a gas boiler (150kW) that uses excess producer gas to meet the thermal demand of the site not achieved by the ICE

7.1.1 Collection

For feedstock material collection the simplest method would be using a “skid steer” engine powered machine. This would be appropriate for the collection of both poultry litter and digestate. Poultry litter will be collected between crops from the bird houses. With 8 crops per year, once every 40 days the skid steer is brought into the shed to transfer the litter material when all birds have been removed. Litter is physically pushed out of the doors of the shed and into a storage area. Previously this material would be further transported, either to fields for spreading or offsite processing but this would not be required. Digestate material once removed from the AD tank is sent through a separator, where liquid is removed from the remaining solid fraction. This solid material is stacked in the shed and could also be moved using the skid steer. The machine can either be rented for these uses or purchased if it could be used to complete other tasks on the site such as lifting and moving other heavy goods (bedding material, feed, fertilisers etc.). An estimate of costs for moving of this material would be approximately £4/tonne, which is included in the ECLIPSE labour operation costs.

For collection of miscanthus material, much more equipment is required. A harvester along with tractor and trailer is needed for removal of the material from the field and brought to the site for use. Certain farms may already own such equipment, but not all will. Alternatively, harvesting contractors could be brought in to carry out the work on behalf of the owner. This would be another cost for the owner to manage, and at £92/hectare it could become a significant outlay (NAAC, 2020).

7.1.2 Storage

Material storage will be similar for all materials. This will be a three-sided shed with a roof. If orientated the correct way it could protect the material from the worst effects of the weather along with enabling easy access for removing and adding materials. Material stored in the open is liable to begin decomposition due to the moisture content, or leech potentially harmful chemicals into the local watercourse (López-Mosquera et al., 2008). Construction of a building will be a significant outlay that will need to be calculated and included in the overall quote for the capital cost of the system. It is critical that the shed is sized appropriately for the volume of material that it will be required to store. Once constructed the shed can be used annually without further modifications or costs.

7.1.3 Pre – Treatment

Pre-treatment of biomass feedstock may be one of many different processes, such as drying, commuting or densification, or a combination of each. Drying of material may need to occur depending on the as received moisture content (M.C%) of the biomass feedstock. Ideal M.C% of feedstock for effective downdraft gasification is between 15-20% (Susastriawan et al., 2017). Reducing the as received M.C% of poultry litter (approximately 60%), digestate (up to 90%) (Cathcart et al., 2021) and miscanthus (70%) (Lewandowski et al., 2008) is therefore imperative for the entire system to operate efficiently. The drying method of choice would be through a belt dryer system. This will use recycled exhaust gas and heat from the engine application of the producer gas to dry the feedstock. Commuting of material may be required to ensure equal and even particle size throughout. Poultry litter consists of a heterogenous mixture of material such as feathers, feed and manure. Digestate similarly is not of equal particle size, consisting of the leftover material from the AD process. Miscanthus will require commuting if it has not occurred during the harvesting process. While commuting can be an energy intensive process, an even particle size will ensure higher quality gasification. This can be carried out by a shredder or similar equipment. The final pre-treatment step that may be required depending on system set up and gasifier design is densification of the material. In biomass terms this could mean briquetting, baling or pelleting. For this research we will assume material requires pelleting to avoid bridging or throat blocking issues within the grate of the gasifier. Pelleting is another energy intensive process that requires consistent material in terms of moisture and particle size. Excess electricity from the engine application can be utilised for pelleting of material. Pelleting will also lower the feedstock M.C% further due to the heat produced during the pelleting process. This can be beneficial to the system for removal of unwanted water from the feedstock but could also be detrimental in lowering moisture too much and removing a source of H_2 from the producer gas. A balance between the two will need to be found or producer gas LHV will be negatively affected.

7.1.4 Gasification

The most important component in the system for successful operation is the downdraft gasifier. This gasifier will be a small-scale system capable of accepting feedstock at a rate of up to 120kg/hr while in operation. The system will be rated for a capacity of 500kW. Ancillary equipment will be required to introduce feedstock to the gasifier on a continuous basis, as well as removing ash and biochar as required. A feed in auger or rotary valve and an ash removal auger would be an ideal solution. These would be best suited for the operation as they can provide a consistent flow of material into the system, while avoiding the addition of undesirable air. This will ensure a consistent pressure across the system and assist with avoiding bridging issues around the grate. The successful installation and commissioning of the equipment will require a bespoke designed system, which will depend on parameters specific to the site such as scale and location. Each of these elements will add to the cost of the system.

7.1.5 Gas Cleaning

Many methods of gas cleaning exist as described within Chapter 2 – A Review of Fuel Gas Production from Biomass and Biowaste. These cleaning methods are vital for the downstream application of the producer gas, as clogging and fouling of equipment is a serious threat. Significant amounts of tar or particulates may need to be removed depending on biomass feedstock quality. Once primary removal techniques have been carried out, there is a possibility of further tars and particulates remaining in the gas stream. To ensure their removal and avoid fouling of equipment a secondary technique should be employed. The recommended method of choice for this system is a gas scrubber. The scrubber works by passing the producer gas through a water vapour cloud. Tars and particulates are trapped by the water droplets, while the producer gas passes through. The waste tar and particulates can then be removed from the scrubber and fed back to the gasifier to increase conversion efficiency. Clean gas is then available for the engine application. While the technology for this system is simple, it will add a further cost to the system which needs to be considered.

7.1.6 Application

The final step in the process is that of applying the cleaned producer gas to some downstream equipment for heat and electricity production. This equipment could take many forms, depending on site specific requirements but the most likely options are that of an ICE system, an ORC system or gas boiler. An ICE system would be better suited to a site with a high electric demand. A site that required more heat and had little demand for electric could install an ORC system. The ORC system also wouldn’t require the gas cleaning system. Sites with a lack of access to the national grid may also favour this method. Sites with no electric demand at all may install a gas boiler for heat generation. A combination of technologies could be used to generate heat and electricity as required.

7.2 Costs & Economic Considerations

This system is being proposed with multiple goals in sight. These are to significantly reduce the on-site energy costs, to reduce waste disposal costs, and to increase the overall sustainability of the site. To fully understand the potential scope of the savings that may be available, we must first understand the costs that potential users are currently liable for. To remain consistent with the costs across the system the proposed site will be for a mid-Ulster farm in Northern Ireland. Where costs specific to this region cannot be used, a UK average cost will be availed of.

7.2.1 Fuel to be Replaced

Fuel and energy purchasing price can vary depending on a multitude of factors. These factors include but are not limited to system size, localised demand, storage capacity, delivery costs and climate change levy. Current fuel costs for the potential site are found from the Department for Business, Energy and Industrial Strategy (BEIS) Non-Domestic Energy Prices. Industrial electricity prices across the UK are dependent on annual consumption, with price per kWh decreasing the greater the consumption is. The proposed system will be in the “small” size band, covering consumption between 20 – 499 MWh. This band prices electricity at 15.83 pence per kWh (p/kWh) including the local climate change levy (CCL). The CCL came into effect in April 2001 and as of April 2021 stands at 0.775p/kWh for electricity. Depending on their circumstances, many different types of fuels may be used on the site before installation of the DGS. We assume that the DGS will replace a previously installed fossil fuel combustion system such as LPG or natural gas. Due to the remote nature of most industries that would be interested in the installation of the DGS, it is unlikely that they are receiving natural gas from the national grid. To cover all aspects of the argument, if they were, they would also be classified in the “small” size band for annual consumption, which covers between 278 – 2,777 MWh annual consumption. Gas at that rate is priced at 2.47 p/kWh including the CCL. CCL for gas in April 2021 was 0.465p/kWh. The other option for previously installed systems is an LPG boiler system. Current UK LPG costs are approximately 0.66 £/L (mylpg.eu, 2021). As LPG has a calorific value of 46.1 MJ/kg and a density of 0.51kg/L, we estimate that LPG will have a cost of 7.0 p/kWh. All fuel costs have been included in Table 7.1 for ease of reading.

7.2.2 Feedstock

While every effort should be taken to ensure a waste or by-product can be utilised as the feedstock for energy generation, under certain conditions or to increase overall system efficiencies, a feedstock may need to be purchased to supplement what material is already available. The potential supplementary feedstock that will be utilised for this research is wood pellets. These can be generated as a by-product from a wood processing facility and therefore would not decrease the sustainability of the overall process. Prices for wood pellets are roughly 4 – 5 p/kWh (Balcas, 2021). Other feedstocks for this system include poultry litter, AD digestate and miscanthus. As poultry litter and digestate are a by-product or waste from a process already taking place on the site, there is no cost associated with their purchase. Miscanthus is a perennial energy crop that grows well on marginal land. It's cost after planting, growing and harvesting will be approximately 40 £ per oven-dried tonne (£ odt^{-1}) (Wang et al., 2012). For comparability with the other feedstocks this is approximately 24 p/kWh.

Table 7.1 Fuels Costs Used for Economic Analysis

Fuel	Cost	Unit	Reference
Electricity (Grid)	15.83	*p/kWh*	(BEIS, 2021)
LPG	7.0	*p/kWh*	(mylpg.eu, 2021)
Natural Gas	2.47	*p/kWh*	(BEIS, 2021)
Wood Pellet	4.5	*p/kWh*	(Balcas, 2021)
Miscanthus	24	*p/kWh*	(Wang et al., 2012)

7.2.3 Waste Disposal

While some expense may occur due to the purchasing of feedstock or other relevant materials for the DGS, a significant amount of money can be saved from avoiding disposal of wastes or by-products under certain circumstances. Using a poultry farm as an example, the most common method for disposal of poultry litter is through land spreading of the material for fertilisation. This is carried out to return nutrients to the soils such as N, P and K. There are several reasons why land spreading of the material may not always be possible. These include the, the volume of litter produced per farm, the number of farms near each other within Northern Ireland, and a lack of land available for spreading the material. Recently introduced legislation, the Nutrient Action Programme (NAP) has also limited the amount of fertiliser which can be spread on land due to the overapplication of nutrients from an intensive farming industry across the region (DAERA, 2019). To circumvent this issue materials was previously sent across the border to the Republic of Ireland or to mainland Great Britain for land spreading or waste treatment. Recent changes in the geopolitical landscape caused by Brexit may impact on the potential for this to continue. This change in circumstances may yet prove beneficial to poultry farmers across the region as up until this point they may have been paying a high cost per tonne for disposal of this material. Estimates of this cost are difficult to obtain but previous government discussion put the figure at £30/tonne, which could easily have increased in the intervening period to somewhere in the region of £50/tonne (Assembly, 2012). The NAP may also impact on digestates ability to be spread on land. Digestate will not have the same disposal cost as poultry litter due to its consisting of a much higher percentage of moisture (60% vs. 94%). This means that digestate can be spread in the same fashion as slurry's, with contractor pricing found in (NAAC, 2020). To have an alternative disposal method which may also lower site running costs would be attractive to some sites.

7.3 Subsidies

To successfully estimate the potential payback period for this equipment, along with costs incurred by the system, we must also estimate the potential revenue that it could generate. This revenue is through applicable renewable incentive tariffs that are available to the system owner. These are government backed subsidies payable per kWh of renewable heat or electricity generated for close to the lifetime of the equipment. Many governments globally offer incentives to industry to switch to low carbon technology (DCCAE, 2017; Ofgem, 2021b). This is all part of the drive to reduce our reliance on fossil fuel energy sources and utilise resources that are closer to the end user.

7.3.1 Non – Domestic Renewable Heat Incentive

The non-domestic renewable heat incentive (RHI) is a government funded environmental scheme. Its aim is to increase the uptake of renewable heat generation across the UK through providing financial incentives. If an installation is deemed eligible, it will receive quarterly payments for the heat generated by the system. In England, Scotland and Wales the scheme is managed by OFGEM, while in Northern Ireland it's the Department for Enterprise, Trade and Investment (DETI) who are responsible for overseeing it. To ensure high standards are kept, all plant installations must be carried out by a registered installer. To remain compliant to the scheme strict maintenance, calibration and meter reading records need to be kept so that accurate payments can be made to the user. Fuel sustainability is another important criterion for the scheme. Comprehensive fuel records are required for compliance, with purchase receipts, harvesting records and storage methods all part of the process.

The tariffs payable by the scheme are dependent on multiple factors. An applicable tariff will be assigned to the plant considering the technology type (solar, biomass, heat pump etc) and capacity or size. Payments are calculated based off the submitted meter readings, where an accredited user will receive an amount per kilowatt hour (kWh_{th}).

$$\text{Payment} = \text{Tariff level} \times \text{Heat generated by RHI installation} \qquad (15)$$

The proposed DGS would fit into the Medium Biomass category, for installations 200kWth and above but less than 1MWth. Tariff payments are made on a two-tiered basis. The installation receives the initial tier 1 tariff for the first 35% of the year or 3,066 hours. For any heat generated beyond this point, the tariff is payed at the tier 2 amount. This resets back to the tier 1 tariff at the beginning of the next 12-month period. For the applicable technology tier 1 is 3.17 p/kWh while tier 2 is 2.22 p/kWh. Installations which gain accreditation to the system are guaranteed a 20-year contract, where they will receive quarterly payments on submission of their meter readings. This subsidy is currently closed for new applications in Northern Ireland due to previous mismanagement. Legacy installations of the NI scheme are still receiving payments. The NI RHI scheme was included in the calculation to cover all possible routes of payback across Great Britain and Northern Ireland, to understand under what conditions the systems would be feasible. A weighted average of 2.55p/kWh was used to best represent the RHI tariff within the ECLIPSE simulation software.

7.3.2 Smart Export Guarantee

The Smart Export Guarantee (SEG) is another government funded environmental scheme that contracts electricity suppliers to pay local small-scale electricity generators for any low carbon electric that they export to the grid. As with the RHI, there are many sustainability and eligibility criteria that need to be met. SEG began in 2020, following on from the Feed in Tariff (FIT) that closed to new applicants in March 2019. It is open to all low carbon electricity generators such as AD, hydro, onshore wind and solar PV. Micro CHP is supported up to 50kW. Unlike the RHI scheme, there is no single tariff rate for any technology or scale. It is at the discretion of the licensee to agree upon an applicable tariff rate and contract length. To become an accredited generator, the generator must provide evidence of certification to verify that the equipment is appropriate for the scheme. This could consist of an installation certificate or microgeneration certification scheme (MCS) certificate, or another if the

SEG licensee believes it appropriate. Ongoing obligations which the generators must comply with include ensuring reliable meter readings are provided to the licensee when required and completing sustainability reports as requested by the licensee also. Generators must ensure they are not in receipt of both FIT and SEG payments as this may constitute fraud. Like the RHI, this tariff is currently unavailable in Northern Ireland. It has also been included to cover all potential revenue streams with a possibility for it to be introduced in the near future.

7.3.3 Energy Crop Scheme

The energy crop scheme (ECS) was a one-off establishment payment made to farms to encourage them to plant a significant amount of approved bioenergy crops (DEFRA, 2003). It covered the planting or short rotation coppice (SRC) willow and poplar, or miscanthus. Like the other schemes there were of a number of rules which had to be obeyed to ensure compliance. There was the level of planting required (at least 3 hectares), the types of crop planted, and the end use for the material. A focus on CHP or power generation is the encouraged end use for the scheme. Previously the scheme was only available to farms in England, with no supports offered to farms in Northern Ireland. The payments available for the planting of miscanthus is a one-off payment of £920 per hectare. To ensure ongoing compliance with the scheme once planting has taken place, the farmer must allow for periodic environmental checks by the applicable regulator. A 5-year agreement must also be in place, meaning that the selected bioenergy crop will be allowed to grow for a period of at least 5 years. Multiple harvests can be carried out during this time. This scheme was funded by the EU, and with Brexit occurring it in unclear whether the British government will revive the scheme under their own control.

7.4 Payback Calculation

Once all the relevant components and parameters have been considered, and input into the ECLIPSE software the NPV, BESP and PBP for the system are all calculated. The systems have been sized to meet the energy demands of a poultry farm based on the island of Ireland. A standard sized poultry shed is approximately 73m x 18m and can hold 27,000 birds at any time. This shed requires 35MWh$_e$ and 240MWh$_{th}$ annually (Caslin, 2016). A farm containing 4 of these sheds would therefore require 960MWh$_{th}$ and 140MWh$_e$ annually. For ease of comparison, the digestate and miscanthus feedstock will also utilise the same sized systems for heat and electricity production.

To assess the potential cost-effectiveness of the energy generation methods which are being planned the NPV of the CHP conversion systems are calculated (Cardoso et al., 2019). This is carried out using the economic analysis package of ECLIPSE. To project the potential NPV of the system over time and how costs, subsidies and payments may influence it, 6 scenarios were generated. In each scenario after the base case additional income or expenditure could be generated by the system through avoided or incurred costs, subsidies payable to the system or selling of by-products generated. The various scenarios are defined within Table 7.2. The selling price of biochar is estimated at £200 per tonne using Shackley et al. (2011). To carry out the analysis, the cases were added together with a cumulative reasoning, with the income sources increasing as the cases rise.

Table 7.2 Scenarios Defined for CHP System

Base Case	Basic configuration without any incomes/incentives from outside the farm
Case 1	Disposal of poultry litter & digestate material at £30/tonne or miscanthus production costs of £40/tonne
Case 2	Selling of biochar generated from process, approximately 20% of input feedstock. £200/tonne
Case 3	Displacement of LPG fuel required for heating purposes 7p/kWh
Case 4	Carbon Tax on CO_2 emissions, £20/tonne
Case 5	RHI subsidy payable at 2.55p/kWh_{th}
Case 6	ECS subsidy payable at £76.67/tonne

Further economic factors and indices which required definition for the ECLIPSE software to carry out the analysis are defined within Table 7.3.

Table 7.3 Economic Factors and Indices

Project Life (Years)	22
Discounted Cash Flow Rate (DCFR) (%)	8.0
Owners Cost (% EPC)	10.0
Project Contingencies (% TCI)	10.0
Plant Occupancy (%)	75.0
Operating Cost (%TCI)	5.0
Maintenance Cost (% TCI)	3.0
Insurance Cost (% TCI)	1.5

7.4.1 Poultry Litter Scenario

Poultry litter will be gasified in a downdraft gasification unit and applied to a CHP system for heat and electricity production. The generated heat and electricity will be used to meet the daily energy requirements of the onsite poultry houses as well as for removal of excess moisture from the feedstock. A full account of the technical parameters that were considered for calculation of the payback period are displayed in Table 7.4 Poultry Scenario Technical Parameters. The total installed costs for the systems generated through ECLIPSE are £487,835 for the 120kW system, £375,331 for the 36kW system and £231,431 for the 21kW system. A full breakdown of the costs associated with each of these set ups is displayed in Table A.1 in the appendices.

Table 7.4 Poultry Litter Scenario Technical Parameters

	120kW	**36kW**	**21kW**
CV (kWh/kg)		4.16	
Input (kg/h)	120.00	84.50	78.00
Thermal Input (kW_{th}/h)	499.08	351.44	324.40
Gasification Efficiency (%)	***68.0%***	***68.0%***	***68.0%***
Producer Gas Energy (kWh/h)	339.37	238.98	220.59
To CHP System (%)	***100.0%***	***100.0%***	***32.3%***
Total CHP Energy Input (kWh/h)	*339.37*	*238.98*	*71.25*
Heat Recovery Efficiency (%)	***85.0%***	***85.0%***	***85.0%***
Thermal Energy Output (kWh_{th}/h)	187.5	172.7	42.4
Electrical Efficiency (%)	***35.0%***	***15.0%***	***30.0%***
Electrical Power (kWh_{e}/h)	118.78	35.85	21.38
Drying Heat Consumption (kWh/h)	24.80	17.47	16.12
Electric Consumption (kWh_{e}/year)	140,000	140,000	140,000
Heat Used (kWh_{th}/year)	1,122,962	1,074,753	1,065,925
Heat Difference (kWh/year)	108,941	59,625	46,607
Electric for Export (kWh/year)	640,391	95,511	437
Producer Gas Energy Diverted to Boiler	**-**	**-**	**67.7%**
Boiler Thermal Energy (kW_{th})	-	-	149.34
Boiler Efficiency (%)	**-**	**-**	**85.0%**
Thermal Energy from Boiler (kWh_{th}/year)	-	-	833,999
Sent to the grid (kWh/h)	97.5	14.5	-
On-Site Consumption (kWh/h)	21	21	21

Results from the BESP of the three distinct CHP set ups that are using poultry litter as the feedstock are displayed in Figure 7.2. In this figure we can see how the 120kW system has the lowest BESP for electricity, through generating the highest quantity. The 36kW and 21kW systems both require much higher BESP’s as they generate a lower amount. All 3 systems BESP lowers with increasing case number, due to the increase in monies available to the system.

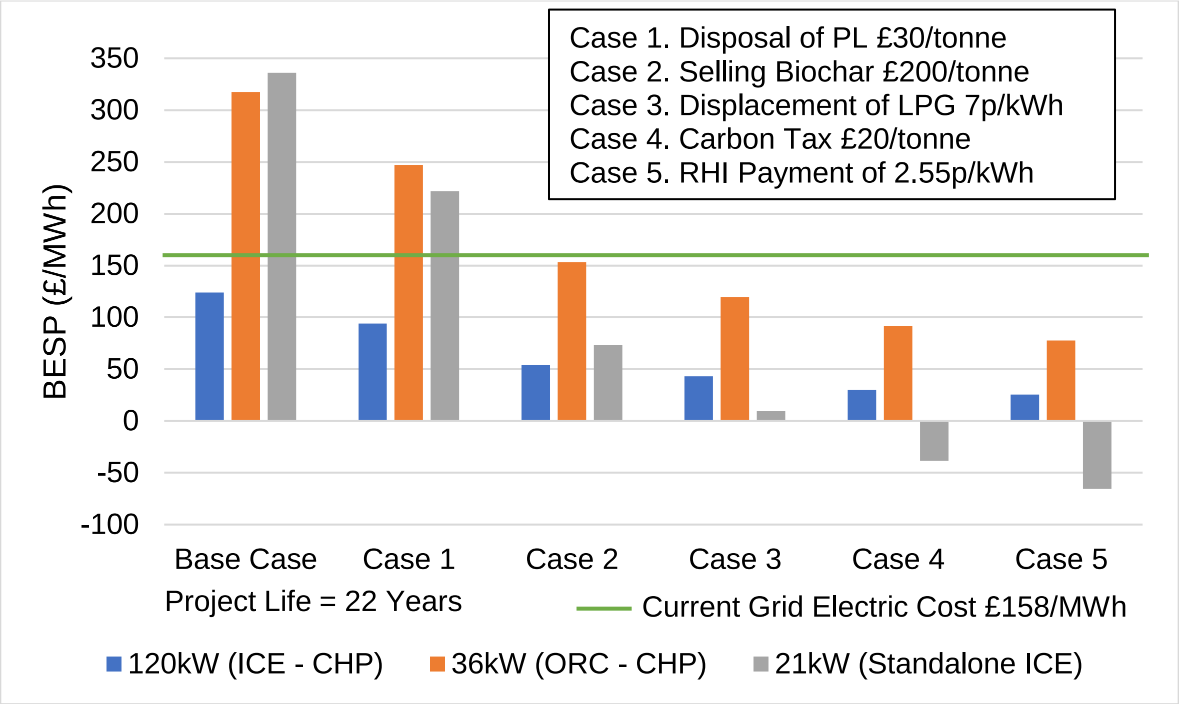


Figure 7.2 BESP for Electricity from Poultry Litter Gasification based CHP Systems

When we compare the current grid electricity costs that the user would be liable for, in all but four of the proposed cases, electricity produced through the proposed system is cheaper than the grid. Electricity generated through the 120kW ICE system is cheaper than the grid under all scenarios. If any of the three CHP systems avoided the disposal costs which they are liable for and sold the biochar by-product from the system, they would produce electricity cheaper than the current grid price. A breakdown of the BESP for each single feedstock scenario is given in Table A.2 in the appendices.

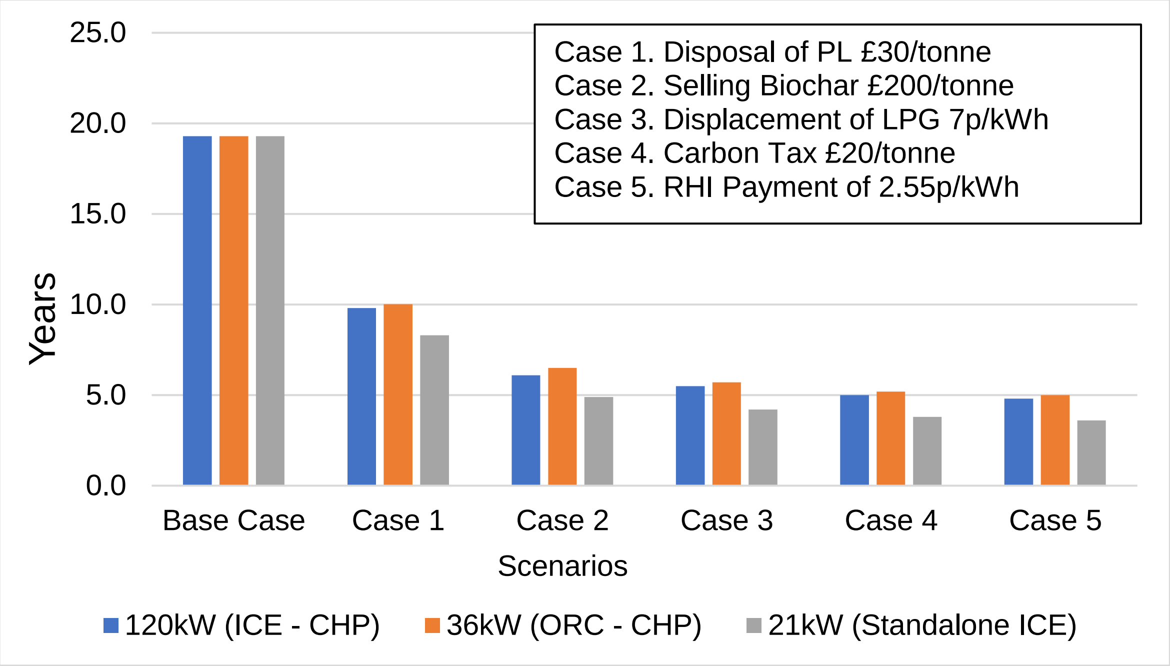


Figure 7.3 Payback in Years of Downdraft Gasification of Poultry Litter & CHP Systems

Comparing the three CHP systems we can see that the payback period for the initial capital cost decreases with increasing case number, due to the increased revenue streams available to the system. This is displayed in Figure 7.3. The payback period for each system begins at 19.3 years and decreases significantly depending on the case of interest. For case 1, each CHP systems payback period is below 10 years. These values continue to decrease up to case 5, where payback is below 5 years for each system. The NPV of each CHP system is covered in Figure 7.4, where the cumulative value of the system at the end of its 22-year lifetime is displayed. This value varies from between £515,470 to £1,205,450 for the 120kW ICE-CHP, £396,610 to £967,070 for the 36kW ORC-CHP and between £244,710 and £801,700 for the 21kW standalone ICE. Depending on the avoided expenses and subsidies available, in comparison to the initial investment the NPV can be doubled under certain scenarios.

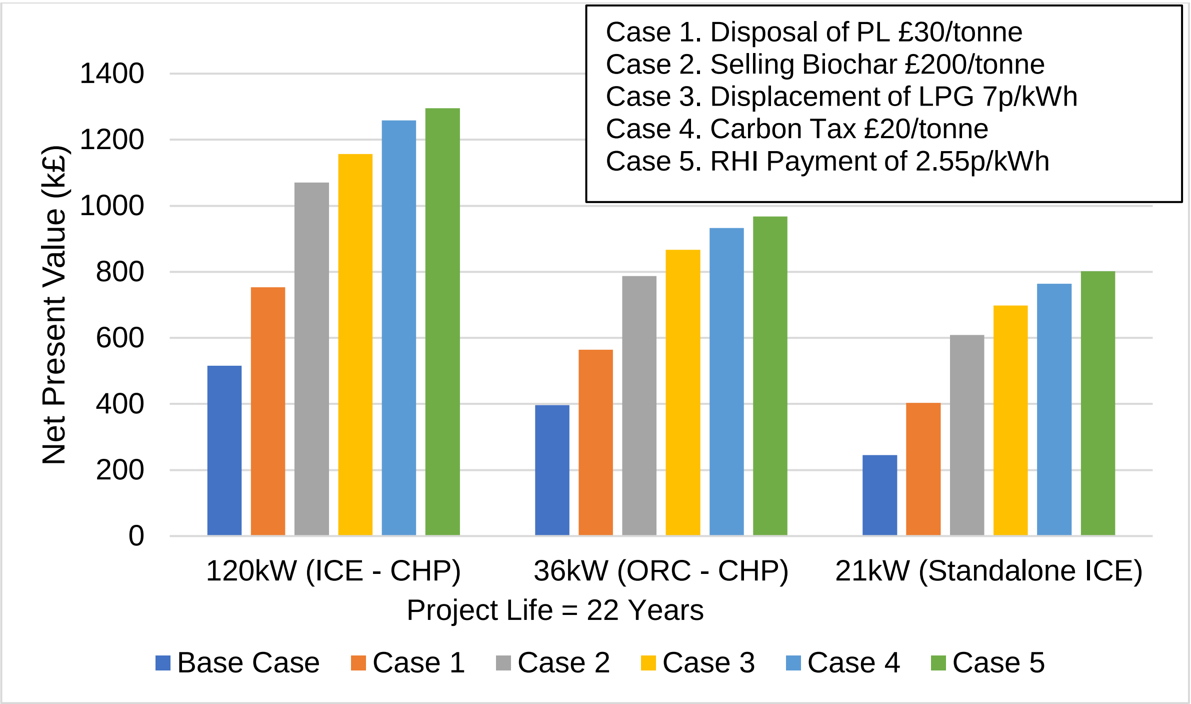


Figure 7.4 NPV for the proposed Poultry Litter CHP systems

7.4.2 Anaerobic Digestate Scenario

The proposed scenario where anaerobic digestate is utilised as the biomass feedstock will be set up in a similar manner to that of poultry litter. The downstream application will be for heat and electricity production on a farm in Northern Ireland. For comparison reasons, we assume the electric and heat demand are the same as that of the previously mentioned poultry farm, 140MWh$_e$ and 1,012MWh$_{th}$. The technical parameters associated with this feedstock are displayed in Table 7.5. A notable difference to the poultry litter scenario is the higher calorific value of the feedstock leading to a lower throughput of biomass. This lower feedstock feeding rate has an influence on the preparation costs, and therefore on the total installed costs which are £479,036 for the 120kW system, £372,247 for the 36kW system and £226,647 for the 21kW system. A breakdown of the system components costs can be seen in Table A.3 of the appendices.

Table 7.5 Digestate Scenario Technical Parameters

	120kW	**36kW**	**21kW**
CV (kWh/kg)	6.20		
Input (kg/h)	80.00	58.00	53.00
Thermal Input (kW_{th}/h)	496.00	359.60	328.60
Gasification Efficiency (%)	***68.0%***	***68.0%***	***68.0%***
Producer Gas Energy (kWh/h)	337.28	244.53	223.45
To CHP System (%)	***100.0%***	***100.0%***	***32.3%***
Total CHP Energy Input (kWh/h)	*337.28*	*244.53*	*72.17*
Heat Recovery Efficiency (%)	***85.0%***	***85.0%***	***85.0%***
Thermal Energy Output (kWh_{th}/h)	186.3	176.7	42.9
Electrical Efficiency (%)	***35.0%***	***15.0%***	***30.0%***
Electrical Power (kWh_{e}/h)	118.05	36.68	21.65
Drying Heat Consumption (kWh/h)	16.54	11.99	10.96
Electric Consumption (kWh_{e}/year)	140,000	140,000	140,000
Heat Used (kWh_{th}/year)	1,068,642	1,038,765	1,031,975
Heat Difference (kWh/year)	155,660	121,967	94,954
Electric for Export (kWh/year)	635,575	100,982	2,254
Producer Gas Energy Diverted to Boiler	**-**	**-**	**67.7%**
Boiler Thermal Energy (kW_{th})	-	-	151.27
Boiler Efficiency (%)	**-**	**-**	**85.0%**
Thermal Energy from Boiler (kWh_{th}/year)	-	-	844,791
Sent to the grid (kWh/h)	96.7	15.4	-
On-Site Consumption (kWh/h)	21	21	21

Results from the BESP analysis of the proposed CHP systems can be viewed in Figure 7.5. For the capital cost of the three CHP systems to be recovered by selling the electricity generated over the course of the equipment’s lifetime, like the poultry litter set up, the 120kW system works out cheaper than grid electric under every case. Unlike the previous scenario, in 6 cases the BESP of electricity generated costs more than current grid electric prices. This is due to lower throughput of material meaning lower disposal costs avoided, along with lower biochar production from the system. The largest difference is between case 2 of the 36kW system, where the BESP for digestate is £202.5/MWh whereas for poultry litter it was £153.2/MWh.

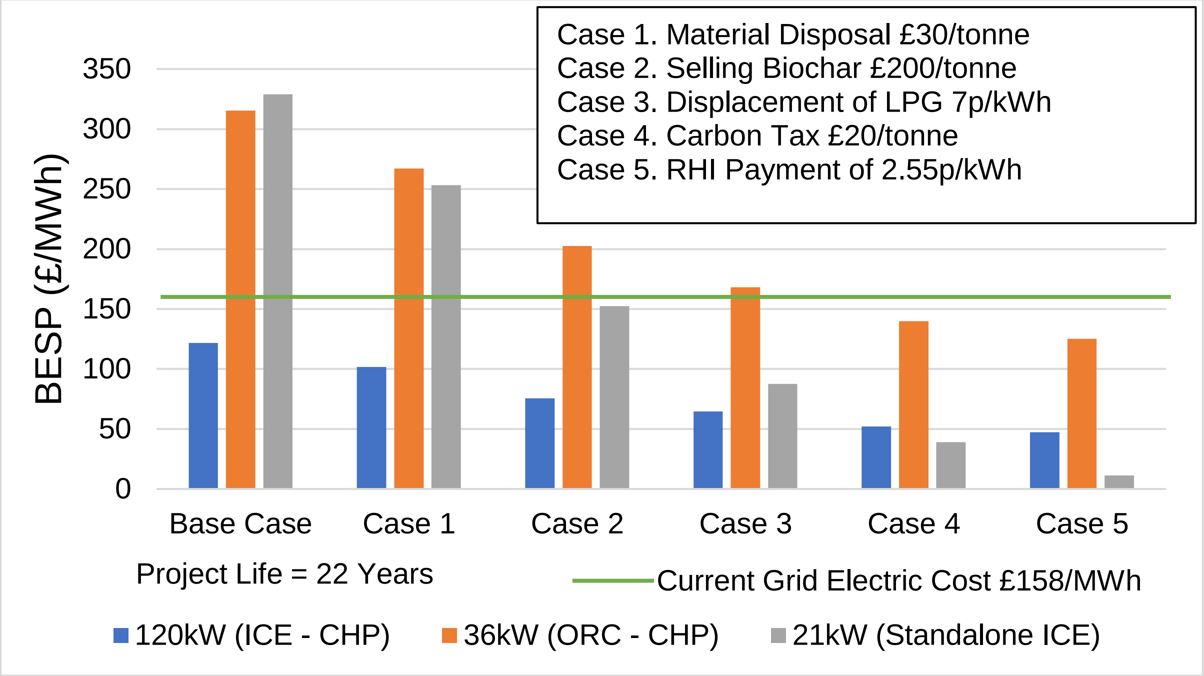


Figure 7.5 BESP for Electricity from Digestate Gasification based CHP Systems

The payback period for the digestate fed CHP systems are displayed in Figure 7.6. Payback period begins at 19.3 years for each system as it did for the poultry litter scenarios. As the case numbers rise, the payback period decreases, but again due to the lower feedstock throughput of the digestate material the payback period is longer than that which was seen previously. Case 1 sees all systems requiring between 10.1 and 11.9 years for payback, whereas previously seen results were for between 8.3 and 10.0 years for poultry litter under the same conditions.

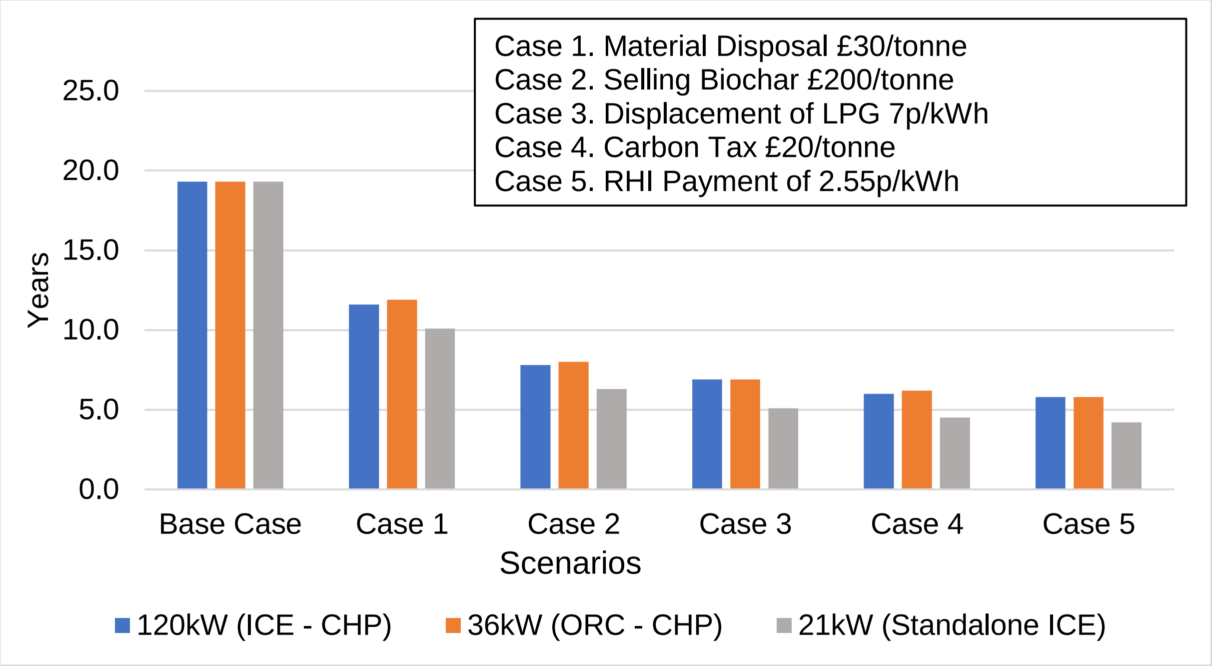


Figure 7.6 Payback in Years of Downdraft Gasification of Digestate & CHP Systems

The final parameter of interest for the digestate scenario is the NPV of the CHP systems over the course of their 22-year lifetime. This is displayed in Figure 7.7, where we can see that with increasing cases the cumulative NPV increases. Under certain circumstances the initial value could be doubled by the end of the equipment's lifetime, where it able to access all relevant subsidies and cost savings.

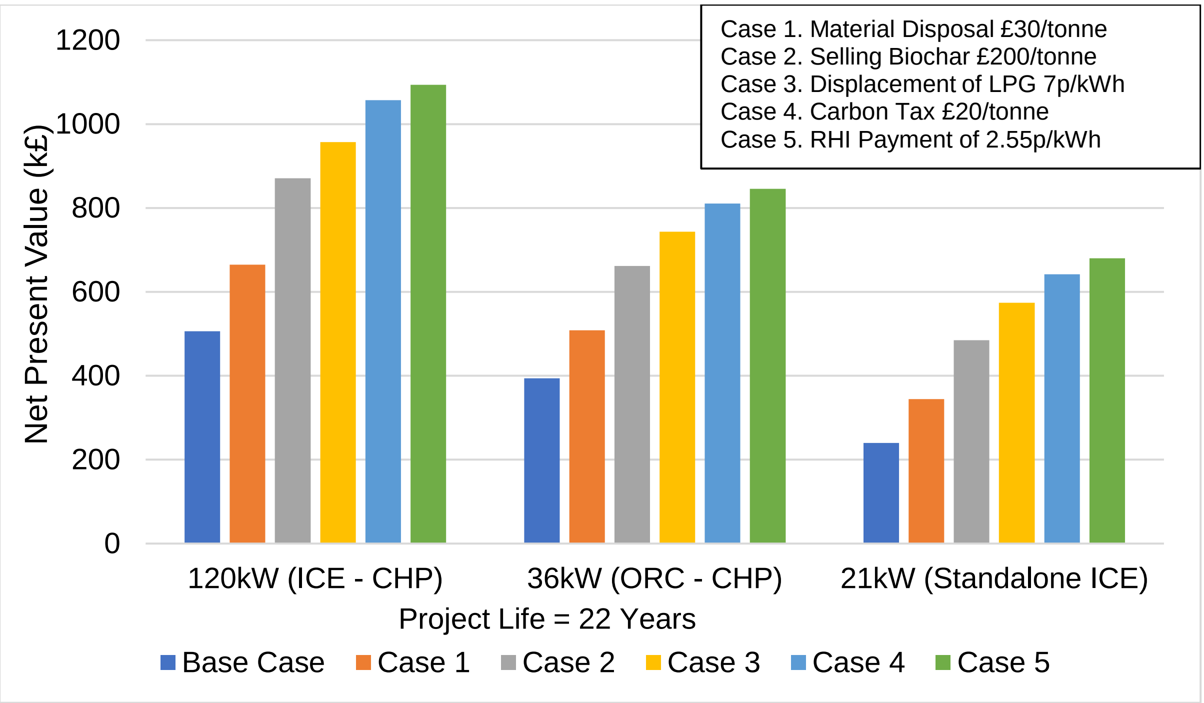


Figure 7.7 NPV for the proposed Digestate CHP systems

7.4.3 Miscanthus Scenario

The final scenario for comparison of a single biomass feedstock is miscanthus as defined within Table 7.6. The methodology is the same as the previous two scenarios where BESP, payback period and NPV of the 3 proposed CHP systems is calculated. The main difference with miscanthus as a feedstock is that instead of saving £30/tonne on disposal costs, as a perennial energy crop miscanthus' production costs are £40/tonne of material. While the ECS doesn't exist within Northern Ireland, a subsidy at the same rate of it has been included in case 6 to understand the impact it may have on the systems finances. The subsidy is £76.67/tonne. This is using £920/hectare and a yield of 12 tonnes/hectare. This feedstock cost will negatively influence all economic factors of interest. Heat and electricity demand are assumed to be the same as previous scenarios. Total installed costs for the systems are £482,925 for the 120kW system, £370,462 for the 36kW system and £227,877 for the 21kW system. A full breakdown of these costs is displayed in Table A.4 in the appendices.

Table 7.6 Miscanthus Scenario Technical Parameters

	120kW	36kW	21kW
CV (kWh/kg)		5.90	
Input (kg/h)	86.00	60.00	56.00
Thermal Input (kW_{th}/h)	507.40	354.00	330.40
Gasification Efficiency (%)	***68.0%***	***68.0%***	***68.0%***
Producer Gas Energy (kWh/h)	345.03	240.72	224.67
To CHP System (%)	***100.0%***	***100.0%***	***32.3%***
Total CHP Energy Input (kWh/h)	*345.03*	*240.72*	*72.57*
Heat Recovery Efficiency (%)	***85.0%***	***85.0%***	***85.0%***
Thermal Energy Output (kWh_{th}/h)	190.6	173.9	43.2
Electrical Efficiency (%)	***35.0%***	***15.0%***	***30.0%***
Electrical Power (kWh_e/h)	120.76	36.11	21.77
Drying Heat Consumption (kWh/h)	17.78	12.40	11.58
Electric Consumption (kWh_e/year)	140,000	140,000	140,000
Heat Used (kWh_{th}/year)	1,076,790	1,041,481	1,036,049
Heat Difference (kWh/year)	175,651	101,175	97,053
Electric for Export (kWh/year)	653,401	97,230	3,034
Producer Gas Energy Diverted to Boiler	**-**	**-**	**67.7%**
Boiler Thermal Energy (kW_{th})	-	-	152.10
Boiler Efficiency (%)	**-**	**-**	**85.0%**
Thermal Energy from Boiler (kWh_{th}/year)	-	-	849,419
Sent to the grid (kWh/h)	99.5	14.8	-
On-Site Consumption (kWh/h)	21	21	21

Results of the BESP for the miscanthus fed CHP systems are displayed in Figure 7.8. As was seen in both the poultry litter and digestate systems, all electricity generated through the 120kW system can be sold for below the grid purchasing price and still offer payback on the initial capital cost. Due to the increased costs associated with miscanthus production the BESP of electricity from 12 of the scenarios is above that of the grid cost. When the RHI payment is made to the system per kWh_{th} generated, the electricity for both the 36kW and 21kW systems is still above grid prices. Only when the additional ECS payment is made does the system become cheaper than grid electric.

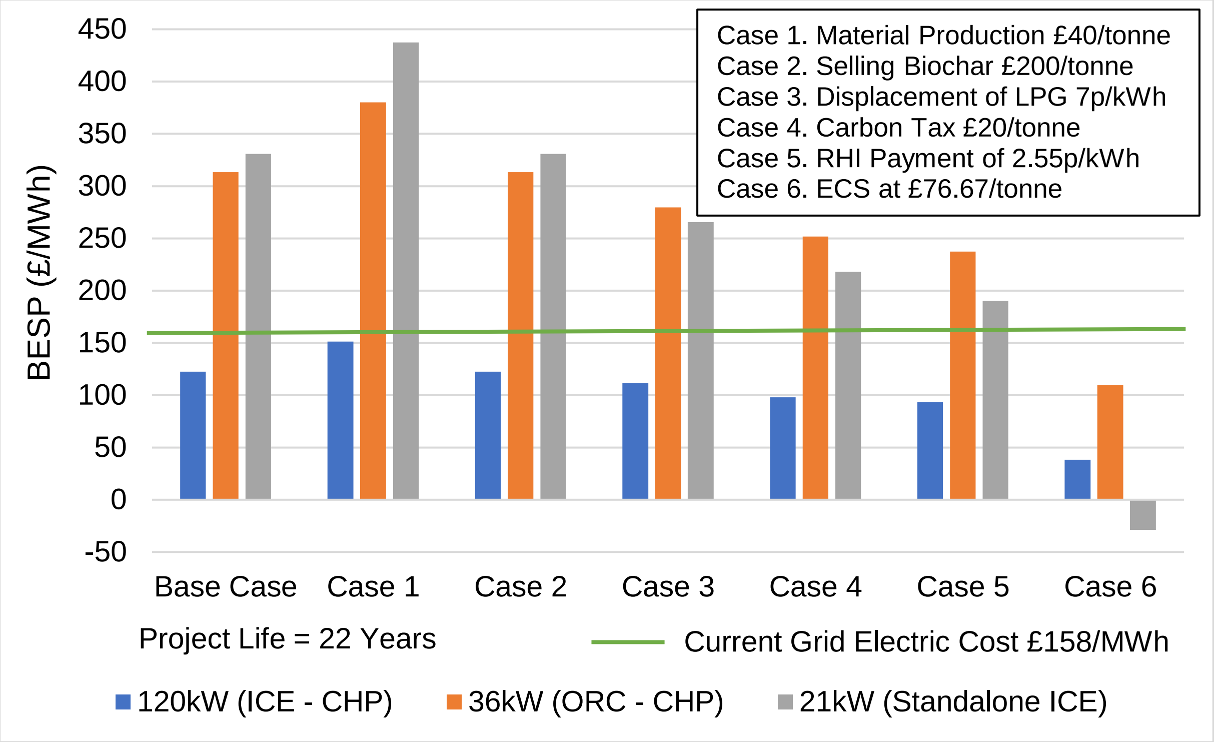


Figure 7.8 BESP for Electricity from Miscanthus Gasification based CHP Systems

The next financial indicator for the system is the payback period, which is displayed in Figure 7.9. Here we can see that like the previous two scenarios, the payback begins at 19.3 years, but unlike the previous, the payback period increases from the base case to case 1. This is because the base case only considers the initial capital cost, where in case 1 the miscanthus feedstock cost of £40/tonne is also included. For all CHP systems the payback period increases to 22 years, the lifetime of the equipment. Payback period then decreases with increasing case number, as further savings and subsidies become available.

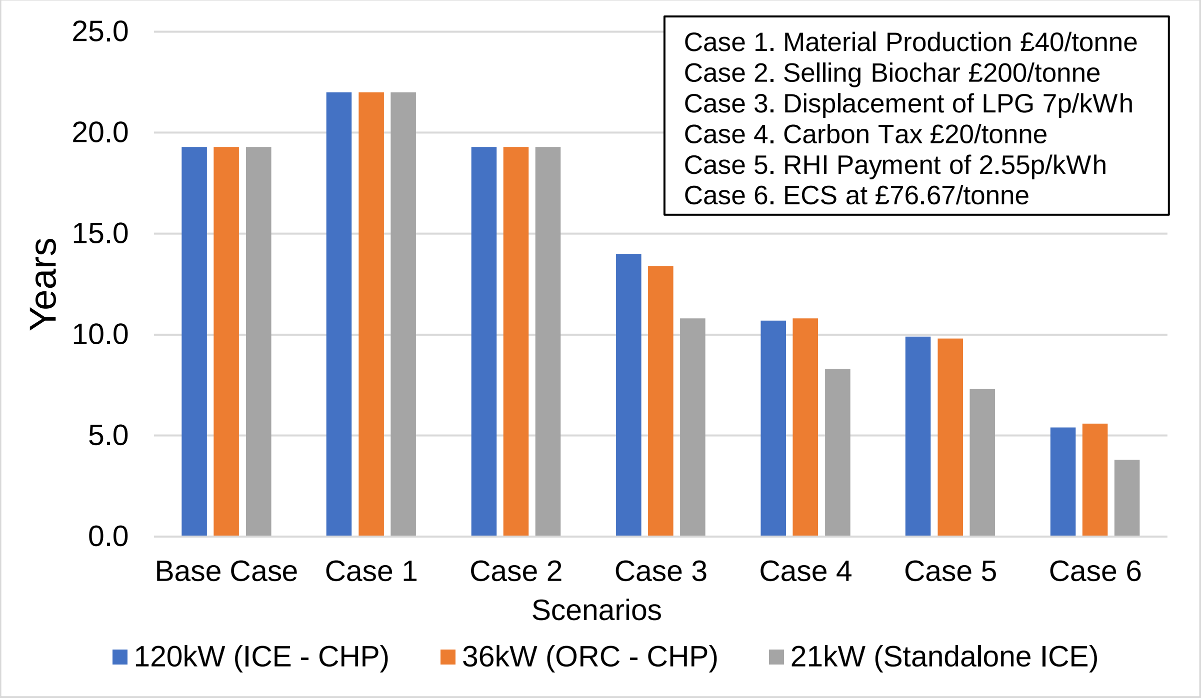


Figure 7.9 Payback in Years of Downdraft Gasification of Miscanthus & CHP Systems

Finally, for the miscanthus production, we can see the NPV of the proposed CHP systems over the course of the equipment's lifetime in Figure 7.10. The most noticeable difference to previous feedstocks is the much lower NPV for each case that has been examined. While poultry litter and digestate systems could double their value over the equipment's lifetime, under most scenarios the value has only slight increased. Costs associated with miscanthus production make this system less attractive when comparing the potential payback to the two previous feedstocks. A large NPV is only identified for case 6, where the ECS subsidy is payed.

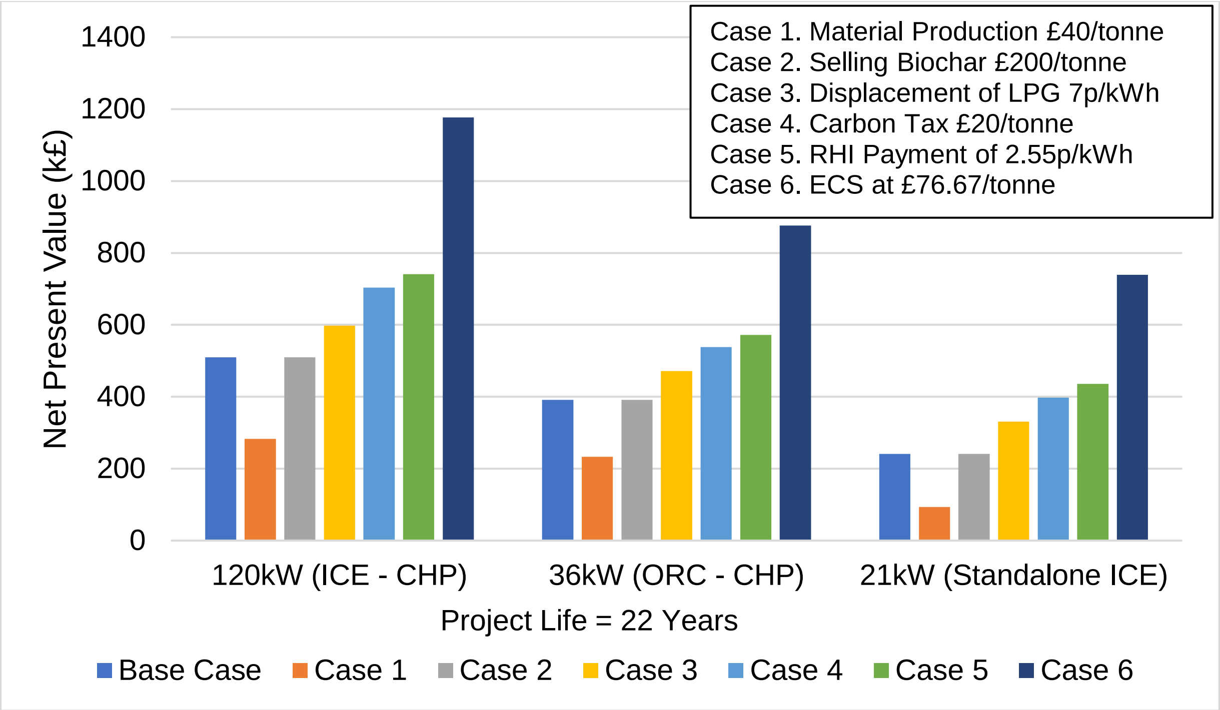


Figure 7.10 NPV for the proposed Miscanthus CHP systems

7.5 Impact of Blend

From the analysis carried out we can see the best performing feedstock in terms of NPV, BESP of electricity and PBP. As mentioned previously, the gap this research aims to fill is the impact that blends of biomass materials have on the gasification process. This is in terms of producer gas quality, environmental impact and project finances. Here we will discuss the potential economic impact of utilising blends of the selected feedstock with wood pellets for improved gasification performance.

Three blends will be focused on for the analysis carried out, which will follow the same methodology as the single feedstocks. Therefore BESP, PBP and NPV for each will be identified. The blends measured by weight are:

- Poultry Litter 80% / Wood Pellets 20%
- Poultry Litter 60% / Wood Pellets 40%
- Poultry Litter 40% / Wood Pellets 60%

7.5.1 Blend Ratio 80/20

For the first blend of poultry litter and wood pellets, the technical set up is based on a weighted average for the calorific value of 4.36kWh/kg. Full technical details are available in Table A.5 of the appendices. This changes the feedstock input rate and therefore the capital cost of some equipment as can be seen in Table A.6 of the appendices. Total installed costs are now £488,710 for the 120kW system, £375,076 for the 36kW system and £231,542 for the 21kW system. Along with changes in capital cost, the calculation must also consider the impact that purchasing 20% of the feedstock by weight will have. Changes to the BESP from the increased feedstock cost are displayed in Figure 7.11. Electricity is required to be sold for above current grid prices in 8 cases, compared to just 4 cases for the single feedstock stream. The 120kW system recorded an average BESP increase of £32.90/MWh whereas for the 36kW system it was a £76.65/MWh increase and £123.25/MWh increase for the 21kW system. The BESP for blended feedstock scenarios is displayed in Table A.7 in the appendices.

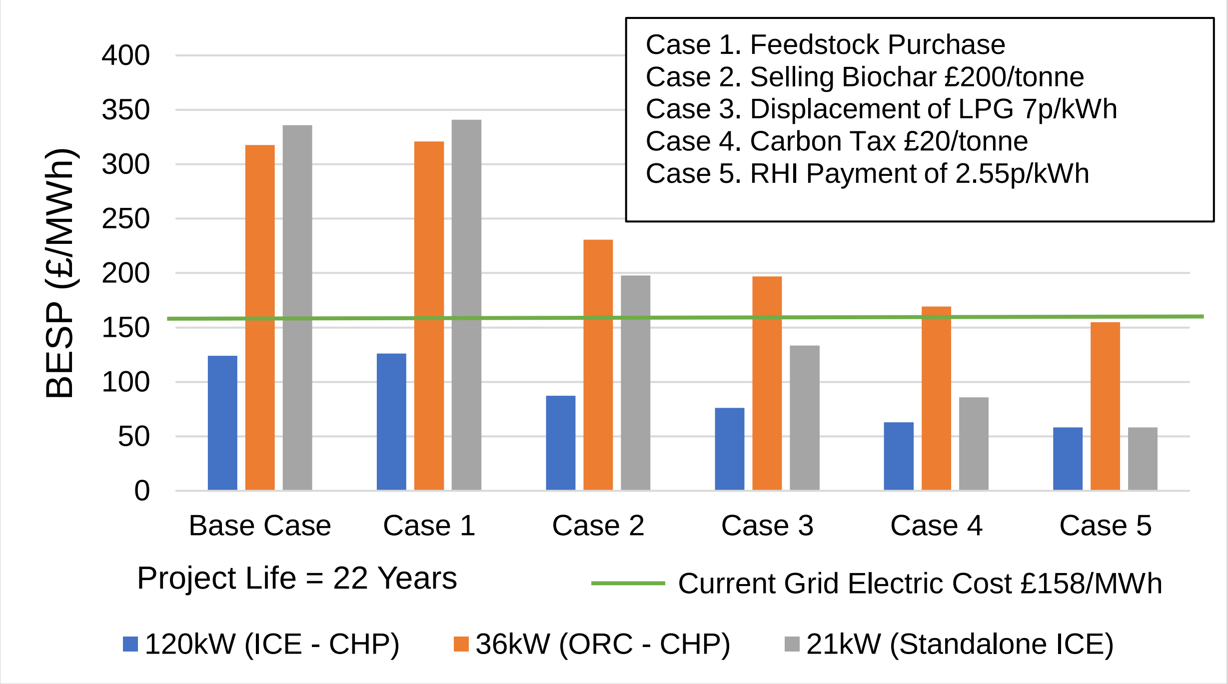


Figure 7.11 BESP for Electricity from 80/20 Blend

The NPV of the 80/20 blend system is displayed in Figure 7.12. The value of the systems is negatively impacted by the need to purchase 20% wood pellets at a cost of £209/tonne. The 120kW system had an average reduction in value of £258,744 for each case when comparing single feedstock to the 80/20 blend. Similar reductions in value are seen across all cases for the 36kW system. It sees reduction in each case of approximately £182,118, while the 21kW systems reduction is closer to £170,830. The largest single difference is in case 1 where a 55% difference in value is noted from the need to purchase a portion of the feedstock. This can also be seen through the payback period in Table A.8 of the appendices. Similar percentage increases can be seen for the payback period and the NPV of each case.

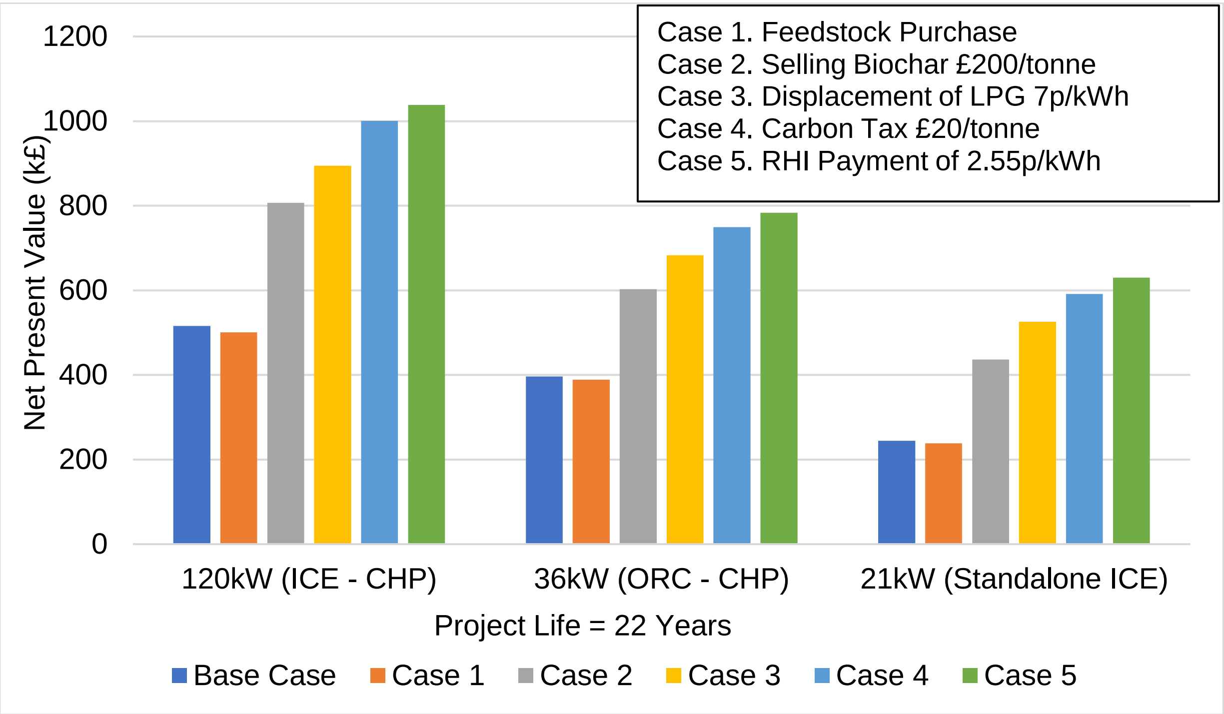


Figure 7.12 NPV for the proposed 80/20 Blend CHP systems

7.5.2 Blend Ratio 60/40

The next blend to be analysed is the 60/40 blend of poultry litter and wood pellets as can be seen in Figure 7.13. Technical details related to this blend are displayed in Table A.9 of the appendices, where the CV for the blended feedstock is 4.57kWh/kg. Total installed costs are £486,732 for the 120kW system, £373,757 for the 36kW system and £229,867 for the 21kW system. A full breakdown can be seen in Table A.10 of the appendices. As was seen for the previous blend, the BESP for each case is higher than what was identified for the single stream. 9 cases identified require a BESP higher than grid electric costs. The BESP of the 120kW system increased by an average of £38.73/MWh when compared to single feedstock. The 36kW system increased by £83.31/MWh and the 21kW system by £137.84/MWh. The percentage increase in BESP for each case is similar to what was found for the 80/20 blend. A 30% increase was identified for case 1, along with a 48% increase identified for case 2. This trend continues for each case number.

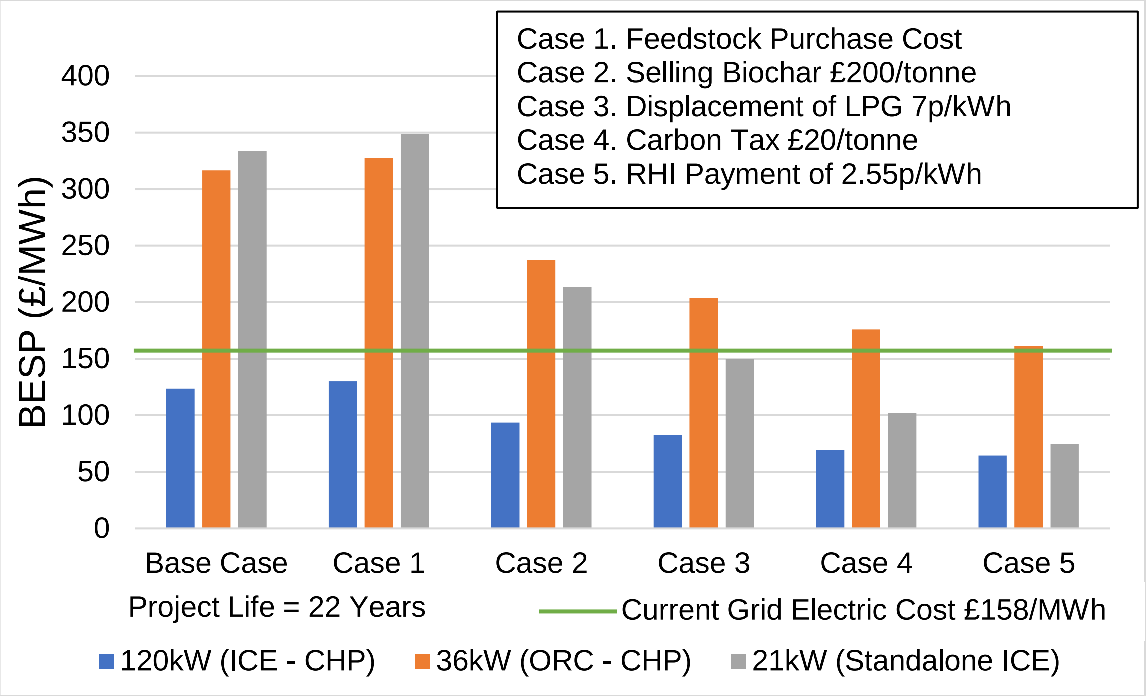


Figure 7.13 BESP for Electricity from 60/40 Blend

When looking at the NPV of the various systems as can be seen in Figure 7.14, the increase in wood pellet proportion of the blend again negatively influences it. On average the value of each case for the 120kW system is £310,000 less, for the 36kW system it is £201,000 less and £196,000 less for the 21kW system. As would be expected, this increase in the proportion of wood pellets from 20% to 40% has decreased the value of each system significantly. Case 1 across all systems is an average of 66% lower in value compared to single feedstock. The lowest change is case 5 with an average 31% reduction in present value across the three systems. These reductions in values are reflected in the payback period of the systems which can be seen in Table A.8 of the appendices.

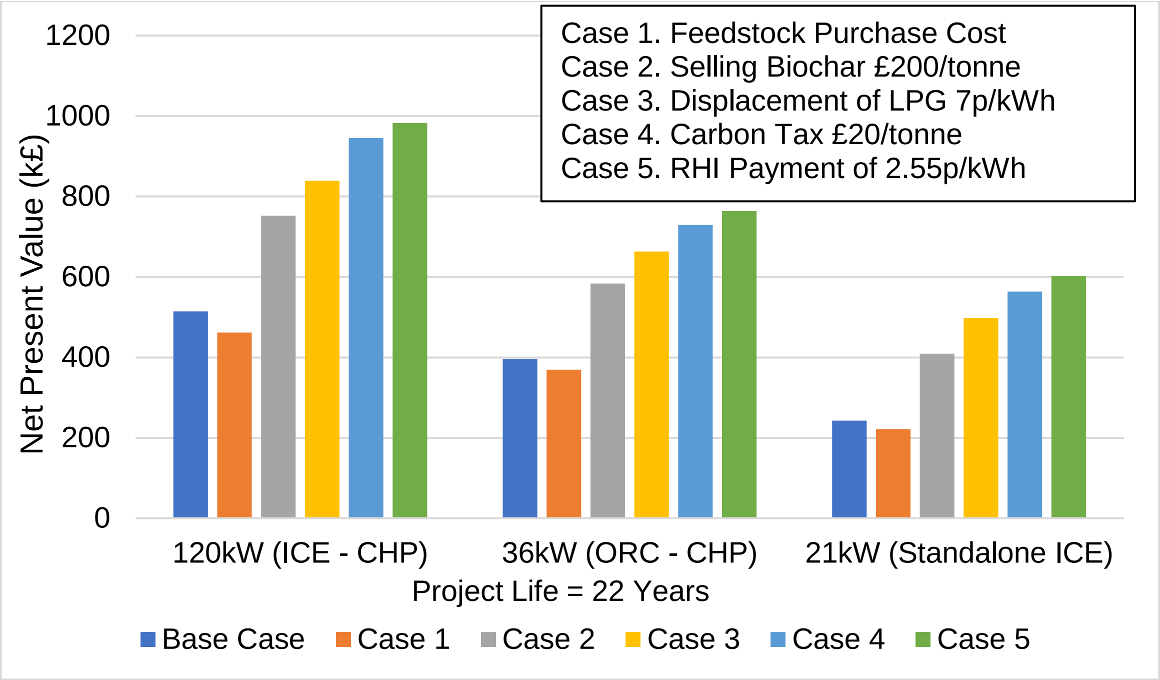


Figure 7.14 NPV for the proposed 60/40 Blend CHP systems

7.5.3 Blend Ratio 40/60

The final blend ratio of interest for analysis is the 40/60 blend. This case is interesting as it is the only one where the purchased feedstock outweighs the poultry litter by-product. Calorific value has increased again to 4.77kWh/kg with full technical details available in Table A.11 of the appendices. Total installed costs are £486,687 for the 120kW system, £373,450 for the 36kW system and £229,201 for the 21kW system with full breakdown available in Table A.12 of the appendices. Results are displayed in Figure 7.15 and as expected further increases in BESP are identified, with 10 separate cases requiring a BESP higher than the current grid electric costs of £158/MWh. Not including the base case, for the 120kW system the average increase was £43.90, for the 36kW system it was £95.40 and for the 21kW system it was £151.30. These are significant increases which seriously detract from the appeal of the system.

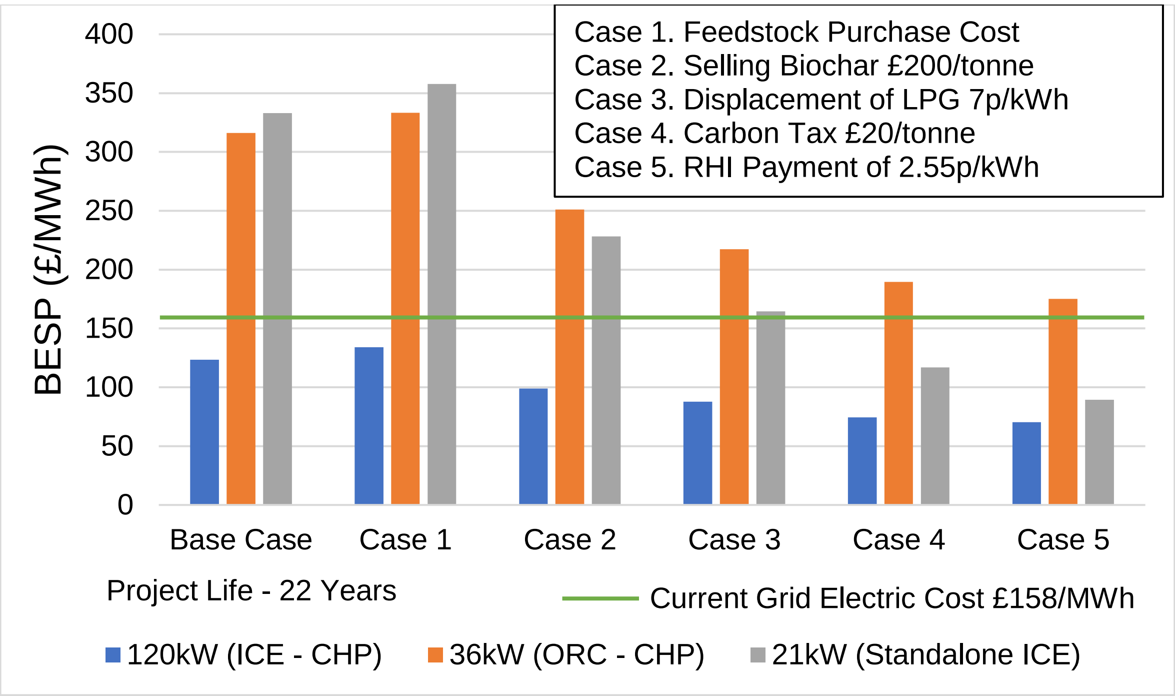


Figure 7.15 BESP for Electricity from 40/60 Blend

The final analysis carried out was on the NPV of the 40/60 blend with results displayed in Figure 7.16. The large feedstock volume which requires purchasing along with lower amount being saved from poultry litter disposal means that the NPV of each CHP system has a large drop in comparison to the single feedstock scenario. The average reduction in value for the 120kW system is £349,772. For the 36kW system it is a reduction of £232,252 and £216,382 for the 21kW system. These are substantial drops in value for each system, but as can be seen from Table A.8 in the appendices, payback period above case 1 remain positive, with most systems still returning the initial investment within 10 years.

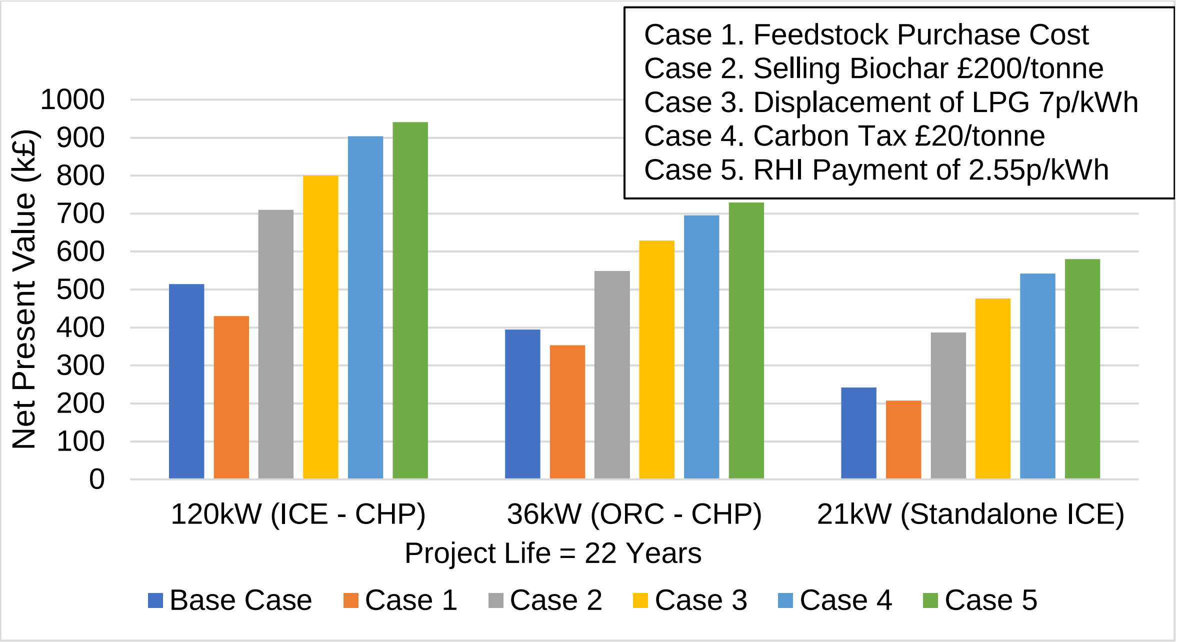


Figure 7.16 NPV for the proposed 40/60 Blend CHP systems

7.6 Summary

The introduction of any new equipment is driven by necessity. While equipment does have a lifetime and will require changing once this has been met, the choice of what to replace it with can be daunting. If an energy generation system will offer significant return on investment the end user will see it as a much more attractive option. The main aim of the chapter was to assess the potential of using blends of biomass for downdraft gasification application and what influence these blends may have on the economic indicators being investigated; BESP, NPV and PBP.

From the analysis carried out in this chapter, on the three proposed CHP systems, each has their own merits and benefits. The 120kW system is suited to a farm which has access to the national grid for exporting excess electricity, the 36kW system is better suited to a farm which would rather increase their thermal load and the 21kW system is one where they want to manage their own power usage or could even store producer gas for use at another time.

From the analysis, it was found the poultry litter systems can payback their initial capital investment within 10 years under most conditions, with the scenarios defined in Table 7.2. The BESP of electricity generated through the system was also lower than grid electric costs in 14 out of 18 cases investigated. NPV of the system could also be doubled by the various subsidies and savings available to the system under certain conditions. Using the single feedstock streams as a basis for comparison, the blended feedstock did not perform as well due to the purchase cost of £209/tonne of the wood pellets used to blend the poultry litter with. Best performing was the 80/20 blend due to it containing the least proportion of pellets, and it could only produce electric below the cost of grid electric in 10 of the same 18 cases. The 60/40 blend produced electricity cheaper than grid costs in 9 out of 18 cases and 40/60 was 8 of 18. Payback of below 10 years was available to the blend systems but required increased case numbers to achieve it. The NPV of the blends was reduced significantly by the introduction of blending, with the 80/20 blend reducing the NPV of the 120kW system by an average of £258,744. These reductions in value increased as the blend proportion increased due to the increased cost of wood pellet feedstock required.

Chapter 8 - Discussion

8.1 Introduction

In this chapter a detailed discussion will take place on all the research which has been carried out as part of this project. This will include the results generated from both the modelling and experimental work carried out on the blends of feedstocks, comparing them to what has previously been published in literature and discussing what impact they may have. An examination of the parameters associated with gasification and the influence they had on the results will take place such as but not limited to feedstock, temperature and ER. We will look at the results of the LCA in more detail, comparing it to other work in the field and interpret what the outcomes could mean for the various energy generation methods covered. A discussion on some of the social impacts of the system will take place, as well as recent policy from a national and international level which influences, or hinders, the proposed system. Changes which should take place if the work was repeated or if the research was to continue will be discussed, as many minor issues with the experimental set up have been identified throughout the project timeline. Examples include increased insulation for temperature control, better carrier gas control and adjustments to the feeding mechanism to streamline the process. Finally, we will discuss the opportunities to continue the research and what would the next step in the process be.

A large data set has been generated during this research. These include full proximate and ultimate analysis of the biomass materials of interest, single feedstock producer gas composition carried out in triplicate, blended feedstock producer gas composition in triplicate, a number of additional system improvement experiments such as catalyst and additional feedstock preparation steps, LCA of the system from cradle to grave, techno-economic analysis of the process from feedstock procurement to application and more.

8.2 Influence of Blends on Experimental Results

The overall goal of this research is to investigate the influence that blends of sustainable biomass have on downdraft gasification. Through the literature review in Chapter 2 optimal blends and the gap in the analysis was identified (Augustine and Sekhar, 2019; Inayat et al., 2016; Jeya Singh and Sekhar, 2016; Tamili et al., 2018).

The primary aim for this was to increase system performance. Gasification performance was measured using producer gas calorific value, conversion efficiency and tar yield as indicators. Further performance indicators can be gathered from the LCA and techno – economic analysis. In the LCA, results from the blended analysis were compared to single feedstocks and traditional energy generation methods, with performance indicators being the numerous environmental impact categories. Within the techno – economic analysis financial indices were used to compare the influence blends have, in terms of NPV, BESP and PBP.

8.2.1 Producer Gas

The effect that blending had on producer gas composition was apparent throughout the three feedstocks of interest; poultry litter, anaerobic digestate and miscanthus. When the proportion of wood pellets in the feedstock was increased, the LHV of the producer gas also increased. For the 3 feedstocks, similar percentage increases in LHV were identified for almost each blended producer gas when compared to the single material producer gas. The 80/20 blend showed no increase in poultry litter LHV, a 1% increase in digestate LHV and a 1% increase in miscanthus LHV. When the blend was increased to the 60/40 mix, the LHV increase was 6% for poultry litter, 7% for digestate and 5% for miscanthus, again a very similar percentage increase. For the 40/60 mix the LHV increased by 8% for the poultry litter, 15% for the digestate and 12% for the miscanthus. While there is a greater variation for the 40/60 blend, the trend of increasing LHV with increasing blend proportion remains consistent.

Table 8.1 Producer Gas LHV increases with blends

	Poultry Litter	**Digestate**	**Miscanthus**
Blend	**LHV (MJ/Nm3)**		
100/0	3.91	3.44	3.17
80/20	3.93	3.48	3.19
60/40	4.16	3.69	3.32
40/60	4.22	3.94	3.54

The LHV increase when compared to the single feedstock producer gas is obvious across all blends for each biomass material of interest, as can be seen from Table 8.1. These increases are apparent despite the various changes in producer gas composition identified throughout the experimental analysis. Percentage changes in poultry litter producer gas composition when compared to single feedstock can be seen in Figure 8.1. The energy content of the various components which make up the producer gas are CH_4 358 MJ/Nm3, CO 126.36 MJ/Nm3 and H_2 107.98 MJ/Nm3. Therefore, the component with the greatest influence on producer gas energy is CH_4. Large increases in CH_4 in the gas were noted compared to the single feedstock, while CO increased steadily. Coinciding with this, large reductions in H_2 concentration were identified. The reactions which influenced these alterations in producer gas composition are the water gas shift reaction, methanation and Boudouard reactions.

$CO + H_2O \leftrightarrow CO_2 + H_2$ (*Water Gas Shift Reaction*) (7)

$C + CO_2 \leftrightarrow 2CO$ (*Boudouard Reaction*) (5)

$C + 2H_2 \leftrightarrow CH_4$ (*Methanation Reaction*) (8)

In Figure 8.1 the percentage change in producer gas composition compared to the single feedstock poultry litter is displayed. Material which shows the greatest change in concentration is CH_4 with between 130 – 155% increase in concentration depending on the blend. H_2 showed the greatest reduction, with between 38 – 46% reduction when compared to the single feedstock. CO shows a steady increase when the proportion of wood pellets in the blend increases. The increases are between 7 – 44%. Final components of interest are the non-combustible fraction of CO_2 and N_2. CO_2 increases by 35% with the 80/20 blend before reducing to a 25% increase compared to single stream. All N_2 components stay close to the original concentration, with only 80/20 blend showing a 2% increase.

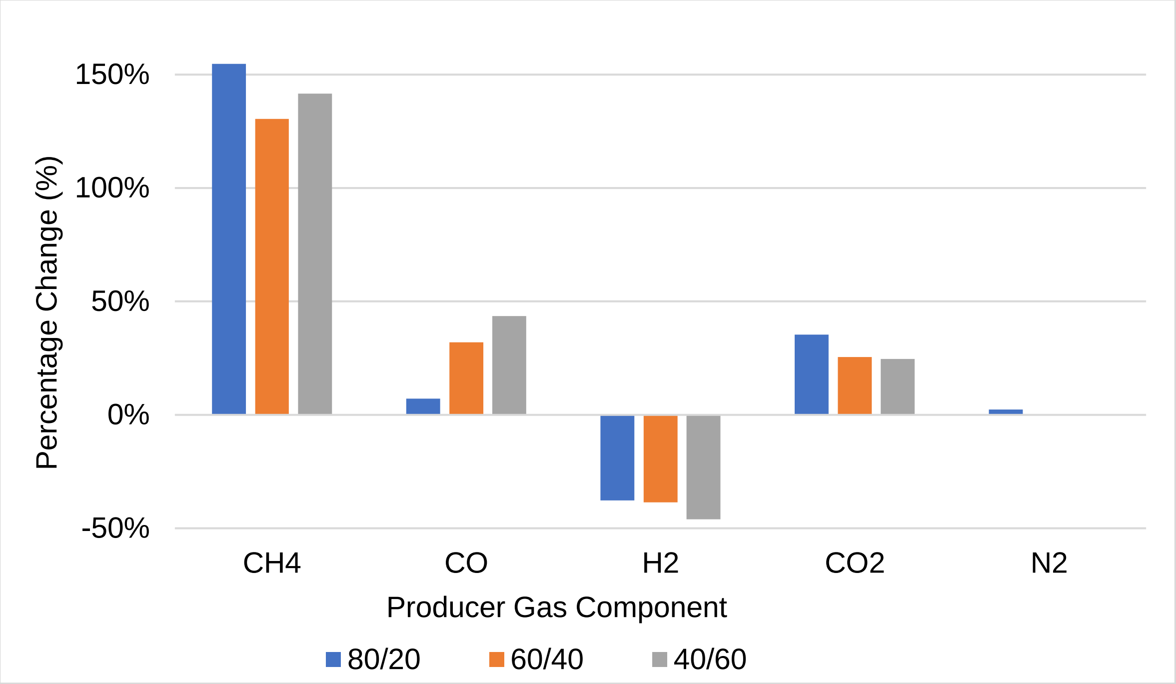


Figure 8.1 Poultry Litter percentage change in component composition

When we move on to the digestate material and look at the impact that the blends had on its producer gas composition similar trends as identified in the poultry litter can be seen in Figure 8.2. CH_4 concentration increases with increasing blend proportion and CO increases alongside this. Again, similarly to what was seen in poultry litter, the H_2 concentration decreases with increasing blend. The reactions causing these changes are the same reactions as before, the water gas shift reaction, methanation and Boudouard reactions. Changes in producer gas composition compared to single feedstock aren't as large for digestate as those identified for poultry litter. The largest increase in CH_4 was 67% for the 40/60 blend which also showed the largest change in CO of 21%. The largest changes for poultry litter were 155% increase in CH_4 and 44% CO. Understanding what is influencing the difference in producer gas composition changes is important for understanding the gasification process. The only two factors which could influence this are the temperature of reaction and the original feedstock composition.

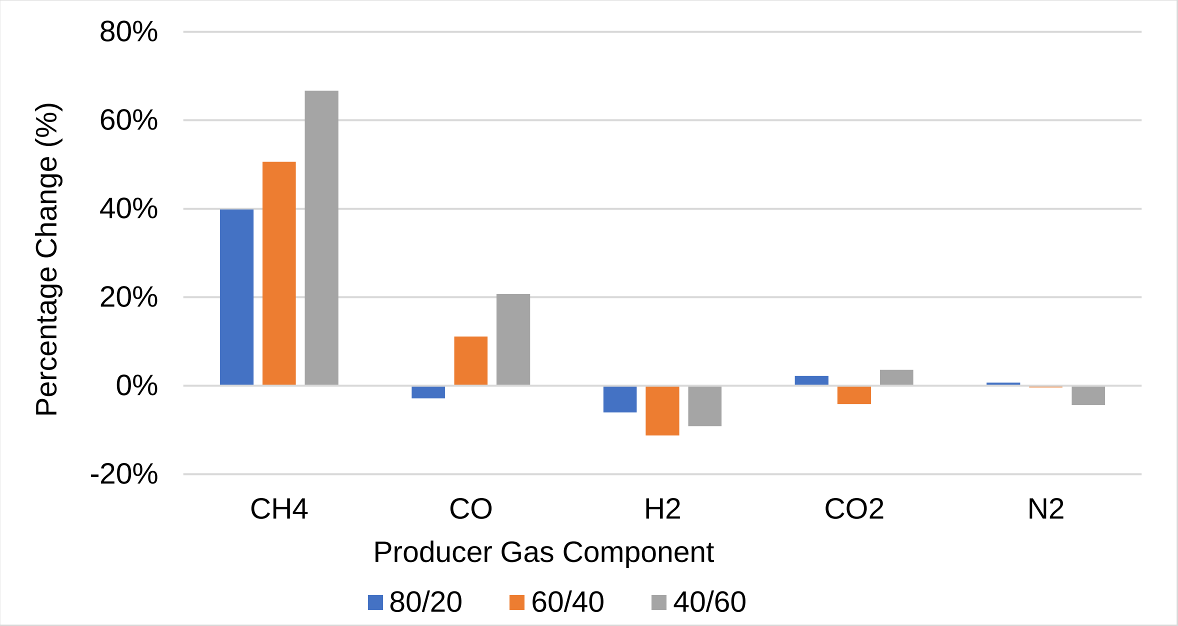


Figure 8.2 Anaerobic Digestate percentage change in component composition

Finally, for digestate while CH_4 and CO both showed increases with increasing blend when compared to single feedstock composition, the same cannot be said of the H_2, CO_2 and N_2 within the gas. H_2 concentration for each blend is up to 11% lower than the single feedstock experiment, CO_2 varies between 4% less for the 60/40 and 4% higher for the 40/60 blend. N_2 shows similar results, with a 4% decrease for the 40/60 blend.

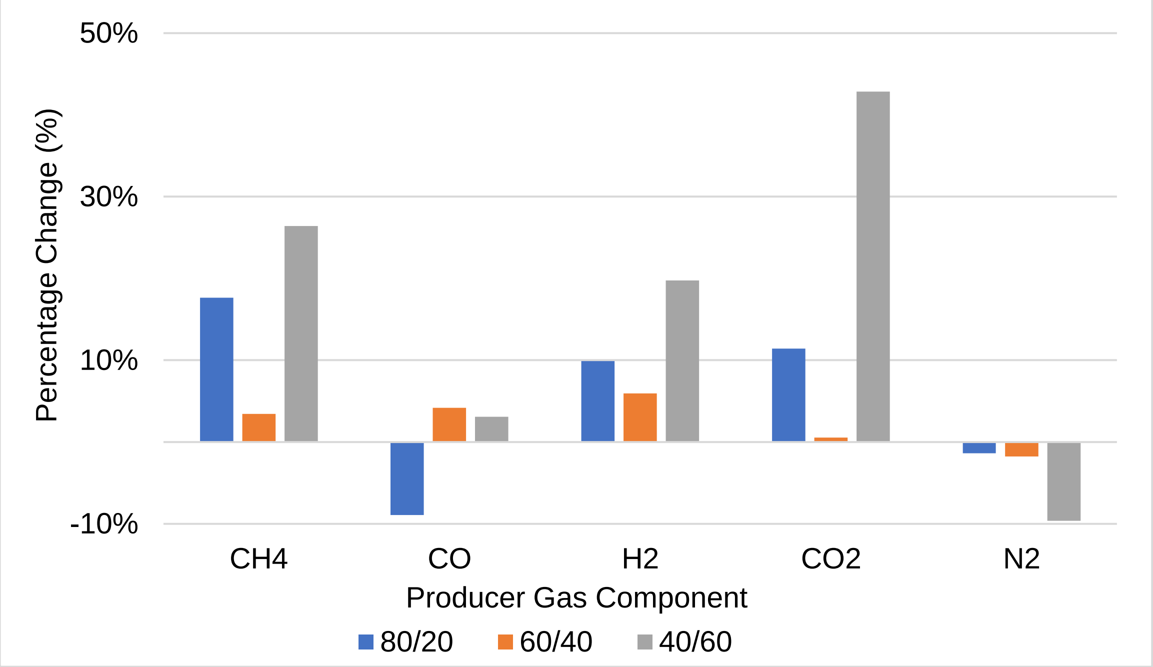


Figure 8.3 Miscanthus percentage change in component composition

The final producer gas for analysis is miscanthus generated gas. While trends were identifiable for the previous materials, within miscanthus the results are much less consistent as can be seen in Figure 8.3. The only definitive trend is the reduction in N_2 with increasing proportion of wood pellets. A total of a 10% reduction in N_2 can be seen between single feedstock and the 40/60 blend. Significant increases in CH_4 (up to 26% increase) and H_2 (up to 20% increase) are also found, with CO decreasing initially by 9% before increasing by 3% compared to single feedstock producer gas. The gasification reactions taking place which are the cause of these changes are again the water gas shift reaction, reducing the CO generated in place of CO_2 and H_2, and the methanation reaction using the H_2 generated for the production of further CH_4.

8.2.2 Feedstock

While we have evidence of producer gas compositional changes when feedstocks are blended, and an understanding of the reactions taking place that creates these changes, the question as to why must still be answered. From the results it can be seen that producer gas compositional changes did not happen even and equally for each feedstock. Poultry litter producer gas changed significantly more than either digestate or miscanthus. One reason why this could be is down to the chemical composition of the individual biomass feedstocks. While both miscanthus and digestate both have very similar chemical composition, as can be seen from Table 3.1 in Chapter 3 – Methodology, poultry litters composition differs greatly. Digestate and miscanthus both contained approximately 45% carbon and 6% hydrogen. Poultry litter contained 34% carbon and 4% hydrogen. Through the introduction of wood pellets, we are increasing the carbon content of the feedstock significantly as wood pellets contained 47% carbon and 6% hydrogen. This leads to an increase in CH_4, CO and CO_2 production through the water gas shift reaction, methanation reaction and Boudouard reaction by having more carbon available for conversion. The H_2 content of the producer gas could be explained using similar reasoning. While there are multiple mechanisms through which H_2 can be generated through gasification, the water gas shift reaction is the one which occurs at the beginning (Chiang et al., 2012). For poultry litter producer gas H_2 content, the introduction of wood pellets lowers the volumetric percentage due to it being a drier feedstock than the poultry litter, 10.3% moisture vs 7.5%. Less H_2O in the feedstock means less available for initial conversion into H_2.

Similar results to those being observed in these experiments can be seen in (Gautam et al., 2011; Malatji et al., 2011; Vera et al., 2013) where the downdraft gasification of feedstocks with higher carbon contents generate producer gases with higher CH_4, CO and CO_2 contents. Therefore, through the blending of a low carbon content feedstock, with a high carbon content feedstock, gasification performance can be improved significantly.

8.2.3 Temperature

Another factor which may have had an influence on the producer gas composition is the temperature. As is known from the literature review, temperature has an influence on the gasification reactions (Susastriawan et al., 2017). Higher temperatures promote reactions to take place, supporting the production of particular gaseous products. While an increase in temperature is seen as a positive for gasification, above a certain point it can detract from the system efficiency and promote the melting of ash within the system leading to pipe blocking issues. While every effort was made to ensure a consistent temperature profile throughout the experiments, due to the system design and function, temperature was not an easy parameter to control.

Throughout the experiments, as producer gas composition was being recorded by the gas analyser, the temperature across the system was simultaneously recorded by a data logger. This allowed for best quality gas to be produced, through aiming to keep reactions at the optimum gasification temperature of approximately 850°C (Hamad et al., 2016). Results for poultry litter show that the temperature of gas production lowers with increasing blend proportion as can be seen in Figure 8.4. From the single stream poultry litter experiment occurring at 946°C, the 80/20 blend occurring at 813°C, the 60/40 blend at 820°C and the 40/60 blend at 796°C. Except for the 60/40 blend, temperature is decreasing with higher wood pellet proportion. When we compare this to the results identified for the digestate and miscanthus feedstocks, no discernible trend can be identified. With increasing blend proportion for digestate temperature fluctuates, and similar can be said of the miscanthus material. Digestate reaction temperatures begin at 831°C for the single feedstock, before decreasing to 821°C for the 80/20 blend. Temperature increases to 851°C for the 60/40 blend before further increases to 910°C for the 40/60 blend. Miscanthus begins at 871°C for the single feedstock, 987°C for the 80/20, 913°C for the 60/40 blend and 839°C for the 40/60.

Temperature along with ER of the system was difficult to control due to system design. These variations in temperature could be a side effect of the lack of control over the gasification reaction which the user has with the Fluidyne system.

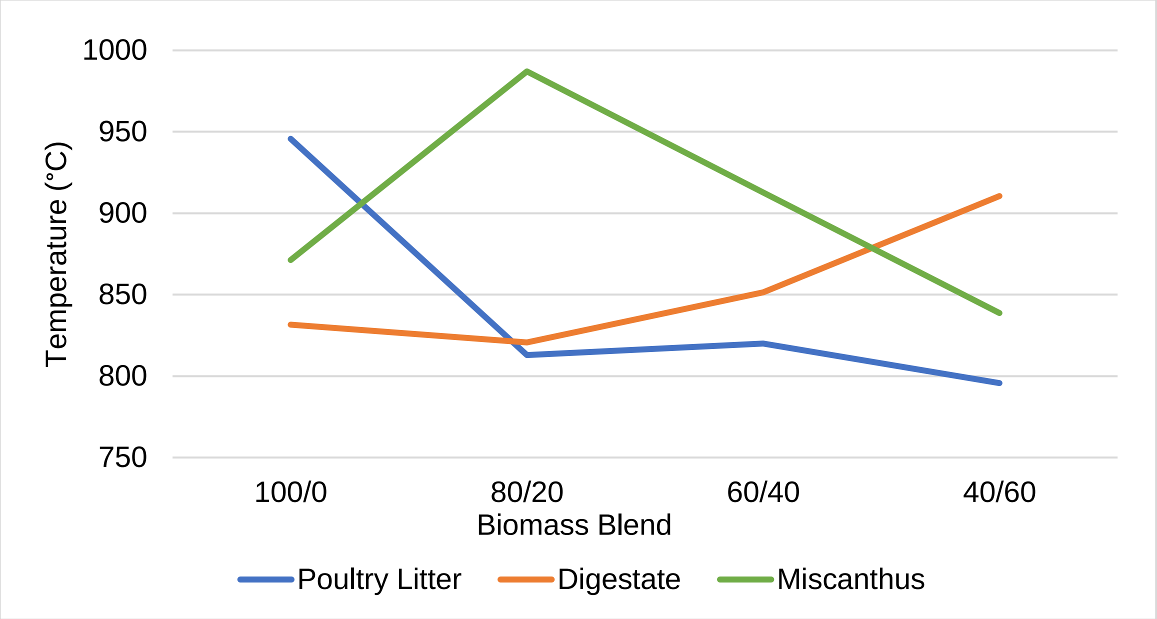


Figure 8.4 Changes in Temperature of Reactions

Downdraft gasification of poultry litter, digestate and miscanthus have all previously been carried out with results available in literature. Poultry litter was done at temperatures of between 800 - 900°C by (Ng et al., 2017) which is the same range which these reactions take place. Digestate under similar conditions was carried out by (Chen et al., 2017) with temperatures around 800°C. Previous miscanthus experiments found in literature show a range of temperatures for downdraft gasification, between 700 - 985°C (Kamble et al., 2019). Through comparison with previously published research, we can confirm that even with less control over the temperature than optimal, gasification of the various feedstocks took place in the correct temperature ranges.

8.2.4 Equivalence Ratio

The ER is defined as the amount of air in a reaction, compared to the amount required for stoichiometric combustion (Prins et al., 2003). Gasification requires an ER of between 0.25 – 0.50 to be carried out. This is accomplished through the reaction taking place in a controlled chamber, where the oxygen allowed into the system is regulated. From the modelling work carried out in Chapter 5, the ER of the gasification reactions was identified as being 0.35. This value falls between the suggested values from literature. Using this ER, producer gas composition generated from the simulation work was found to be very similar to the composition identified through experimental analysis of the feedstocks (Freda et al., 2019; Pandey et al., 2016; Samson et al., 2018). While significant effort was made to ensure consistent ER for each experiment carried out, due to the gasifier design and lack of air flow metering equipment this could not always be guaranteed. ER was therefore never experimentally found, and the suggested value of 0.35 is a best estimate. We will discuss this is greater detail in Section 5 where suggested changes to the system for future work will be carried out. While accurate changes to the ER could not be carried out, if we take the ER of 0.35 to be true and using the producer gas composition and temperature to be indicative of this, the results seen elsewhere in literature agree with the findings of this research.

8.2.5 Conversion Efficiency

To measure conversion efficiency a simple mass balance was carried out for the experimental analysis, comparing the weight of material fed into the system to the weight of material extracted. From the multiple experiments carried out on each material, an average value was calculated. Displayed in Figure 8.5 along with Table 8.2 we can see the results of this calculation, along with any trends that blend proportions had on the conversion efficiency of the downdraft gasification process.

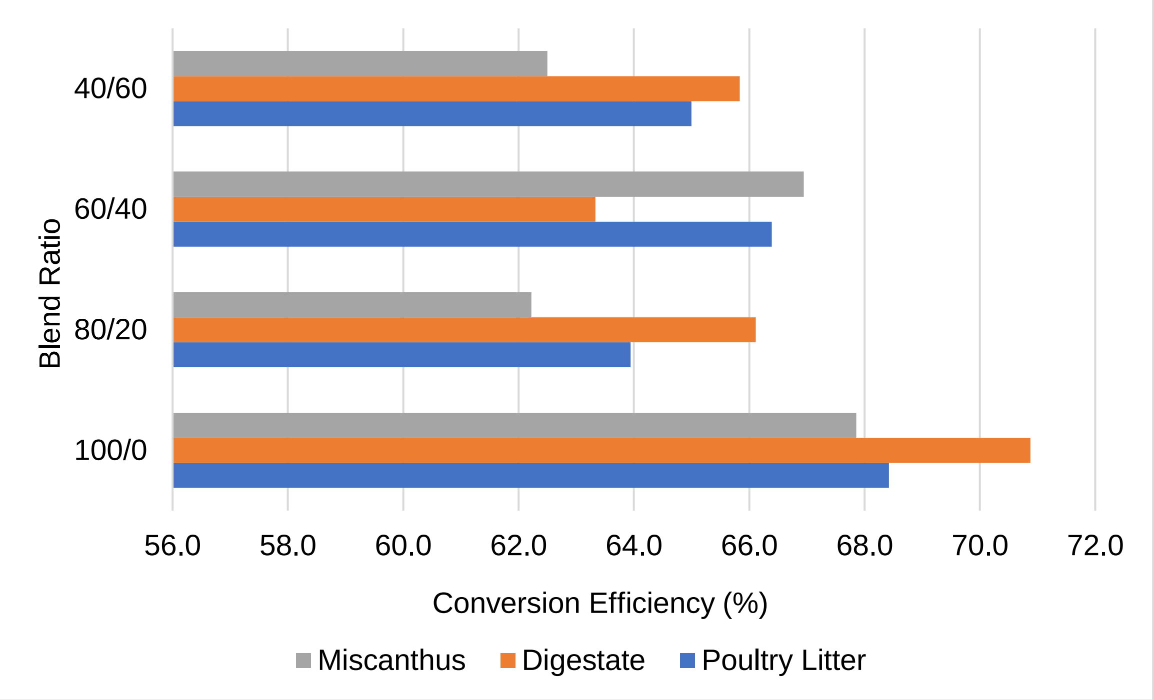


Figure 8.5 Conversion efficiency of material in downdraft gasification setup

Table 8.2 Blend Comparison of Conversion Efficiency

	Conversion Efficiency (%)			
	100/0	***80/20***	***60/40***	***40/60***
Poultry Litter	68.4	63.9	66.4	65.0
Digestate	70.9	66.1	63.3	65.8
Miscanthus	67.9	62.2	66.9	62.5

While blend proportion increased, no identifiable trend can be seen for changes in conversion efficiency. Fixed bed downdraft gasification was chosen as the conversion method of choice for this research due to the scale of operation, the wide variety of material acceptable for conversion, and the low amount of tar generated during the process. Fixed bed due its nature, will have a higher proportion of unconverted material in comparison to other technologies such as fluidised bed or entrained flow. Previously published literature has shown that the conversion efficiency found for various biomass feedstock in the downdraft set up can vary from 50.4% to 79.5%, a range which all of the experimental results generated fall into (Sarker and Nielsen, 2015).

8.2.6 Catalyst

Once complete analysis of the various feedstocks had been carried out, and individual producer gas compositions and LHV’s had been identified, the addition of a catalyst to the reaction was carried out to further improve producer gas quality. The catalyst of choice was a calcium carbonate ($CaCO_3$) powder. Through further literature review the optimum loading rate of the material was found to be 20% by weight of the total feedstock (Chiang et al., 2012; Raheem et al., 2019; Taufiq-Yap et al., 2013). This catalyst promoted tar cracking, breaking the heavy tar components into lighter tars along with further gas products. The most noticeable changes in the catalyst added reaction are a 45% increase in volumetric H_2 content, from 11.6% to 21.1%, and a 14% decrease in CO_2 content, from 10.7% to 9.4%. Further action of the catalyst allowed for gas production from the downdraft gasifier at lower temperatures than previously possible. When producer gas temperature is compared between the catalyst loaded reaction and without, there is a 69°C difference in production temperature. The addition of the $CaCO_3$ catalyst has increased H_2 production, lowered CO_2 content and carried this out at lower temperatures than were previously possible. Similar increases in H_2 content and lower reaction temperatures through the use of the catalyst have been identified in literature (Maneerung et al., 2015; Murakami et al., 2015). The catalyst has been shown to further increase the performance of a fluidised bed system through the stopping of agglomeration and sintering of the feedstock within the gasifier (Horvat et al., 2019).

Through the addition of the catalyst to the reaction an increase in LHV was found. This increase was 16.5%, from 4.16MJ/Nm^3 to 4.98 MJ/Nm^3. This is a significant improvement in system performance but will come with an additional cost of catalyst purchasing price. The cost associated with purchasing the calcium material is dependent on many factors such as quarry type, processing and transport but after conversation with industry, a price of £15/tonne for the calcium carbonate material is used as an estimated cost (Hill, 2021). Using the 20 wt.% feedstock loading factor, this would equate to just above £2,300 per annum in purchasing costs. This is a significant outlay that is not unequivocally required as adequate energy is generated by the proposed systems. The poultry industry would avoid this cost if waste eggshells were utilised as the catalyst source. The drying and pulverising of eggshells produces CaCO3, which could then be added to the gasification reaction for performance improvement at no extra cost (Yang et al., 2016). This could only work for breeder farms where the birds produce eggs, unlike a broiler farm which raise birds for meat consumption.

8.3 Modelling & Simulation

Using ECLIPSE simulation software, a full simulation of the downdraft gasification and producer gas application process, along with economic analysis could be carried out. Using the multiple software packages that ECLIPSE consists of, accurate data describing complex processes, emissions and financial characteristics have been generated for improved gasification awareness.

8.3.1 ECLIPSE Process Modelling

Results from the process modelling component of the research were validated against the practical experimental data generated and other research found in peer reviewed work. Using the data generated through the modelling software, further information could be generated than previously possible. This includes accurate producer gas composition, yield and LHV supplied for CHP application of the gas, data provided for the LCA analysis of the heat and electricity generation methods, and the economic assessment of the proposed CHP systems including NPV, BESP and PBP. Poultry litter producer gas composition differed from the experimental results. H_2 content had been underestimated by 12%, a significant amount when considering the LHV impact of tripling the H_2 content. Under and over estimation of reaction products can occur to equilibrium models, depending on the operating conditions of the gasifier (Aydin et al., 2017). While H_2 content was different, the LHV remained accurate for downstream applications.

8.3.2 Producer Gas Application

Application of the producer gas generated during the experimental analysis to an ICE for heat and electricity production was planned. Due to unforeseen time constraints within the PhD, this could not be carried out. Simulation of the process using validated results from ECLIPSE modelling of the system was carried out instead. Results from this simulation can be seen in Table 8.3. These results are all based off a DAF feedstock, in a 120kW ICE system. The 60/40 blend chosen for analysis was the poultry litter and wood pellet blend.

Table 8.3 Producer Gas Application Comparison

	Poultry Litter Pellet	**Digestate Pellet**	**Miscanthus Pellet**	**60/40 Blend**
Input (kg/h)	123.8	90.3	89.3	109.8
Gas Production (m3/h)	250.6	210.2	237.3	263.7
Gas LHV (MJ/Nm3)	3.91	3.44	3.17	4.16
Heat Output (kW)	164.0	160.8	161.6	164.6
Electrical Output (kWh)	120.3	120.4	120.3	120.1
Electrical Efficiency (%)	20.3	22.9	24.3	22.8
CHP Efficiency (%)	48.1	53.5	56.9	54.2

From the results of the process simulation, the two values which offer the greatest insight into the system performance are the electrical and CHP efficiencies (%). Using these values, the proposed systems can be compared to other relevant biomass CHP systems. When looking at electrical efficiency, the miscanthus pellet shows the greatest performance with 24.3%. Lowest electrical efficiency is poultry litter with 20.3% efficiency. Thermal efficiency, or CHP efficiency for poultry litter is also the lowest of the feedstock of interest at 48.1%, while again miscanthus shows the best result at 56.9% CHP efficiency. In terms of performance, using efficiency as the measure poultry litter is the worst, with miscanthus the best performing and digestate in the middle. Results are promising though, as the efficiencies found are the same as those in literature where downdraft gasification of biomass has occurred (Michailos and Zabaniotou, 2012; Moradi et al., 2020; Patuzzi et al., 2016). Poultry litter shows the worst efficiencies due to its high ash content, 12.9% and lower calorific value of 18.1MJ/kg. The system therefore requires 33.5kg more material than the equivalent digestate system to produce the same electrical load.

To combat these deficits in the poultry litter gasification system, the material was blended with wood pellets to improve producer gas LHV, conversion efficiency and CHP application. For comparison reasons, along with time restraints, the 60/40 blend of poultry litter and wood pellets was used. From Table 8.3 we can see that through the introduction of the portion of wood pellets to the feedstock, efficiencies have increased for both electrical and thermal. Electrical efficiency increased 2.5% to 22.8% and thermal efficiency increased 6.1% to 54.2%. These are significant improvements in system performance, with a 14kg decrease in feedstock required. This improvement is down to the increased LHV of the producer gas from the increased carbon content of the feedstock.

The implication of these results is significant, when we look at the total poultry litter resources available across the United Kingdom. With estimates putting that figure at 4.9 million tonnes per annum, through downdraft gasification and CHP application this could be enough material to run approximately 5,648 of the 120kW CHP systems across the UK (Jeswani et al., 2019). This would generate 4.76 TWh_e per annum, or approximately 1.4% of the total electricity consumed across the UK in 2020 (Martin, 2021). If the blended option were to be taken, the number of 120kW systems which could be operational increases by 11.5% to 6,370 systems producing a total of 5.36TWh's of electricity, or 1.6% of the total UK electric consumption in 2020.

8.3.3 Economic Modelling

Results from the economic modelling of using sustainable biomass blends for energy production showed good promise for potential users. Financial indices such as NPV, BESP and PBP were all used to compare the 3 proposed energy generation systems, along with comparisons between feedstocks and blend ratios.

The NPV of the proposed systems was dependent on the cumulative case number. For the 120kW ICE system, NPV could vary from £515,470 for the base case up to £1,295,450 for case 5, where all applicable tariffs and payments are made. Although NPV is very dependent on factors unique to the proposed system such as initial capital outlay, income payable, and avoided costs, we can compare the results to other downdraft gasification systems found in literature to see can any influencing factors be identified. While recent NPV analysis of downdraft gasification and producer gas application systems are few, for one identified similar values to those in this research were found. Safarian et al. (2020) calculated the NPV for their downdraft system of 100kW to be £1,242,800, which given the conditions under which it operates is close to case 4 and 5 for the poultry litter system of £1,258,320 and £1,295,450 respectively. For the gasification of waste in a similar system, Indrawan et al. (2020) found a NPV of £62,567 for a 60kW system. This is significantly different to the values found in this research, mainly due to the lower feed rate of 40 kg/h compared to 120 kg/h, with large portions of the value within this system coming from the avoidance of disposal costs. Other positive NPV’s for downdraft systems were identified in (Chockalingam et al., 2021; Feisal and Surjosatyo, 2021). While NPV remained positive for each blend of interest, with increasing proportion of wood pellets in the blend the total value decreased due to feedstock purchasing costs. A balance between increased energy content and increasing costs must be decided upon by the user. A comparison of the NPV for the 120kW ICE system is displayed in Figure 8.6. From this graph the decrease in value is apparent with increasing proportion of wood pellets in the blend. Maximum value for poultry litter is £1,258,320 for case 4, for digestate it was £1,057,070 and miscanthus was £703,380. Miscanthus is the only one who shows negative values under and scenarios, due to production costs.

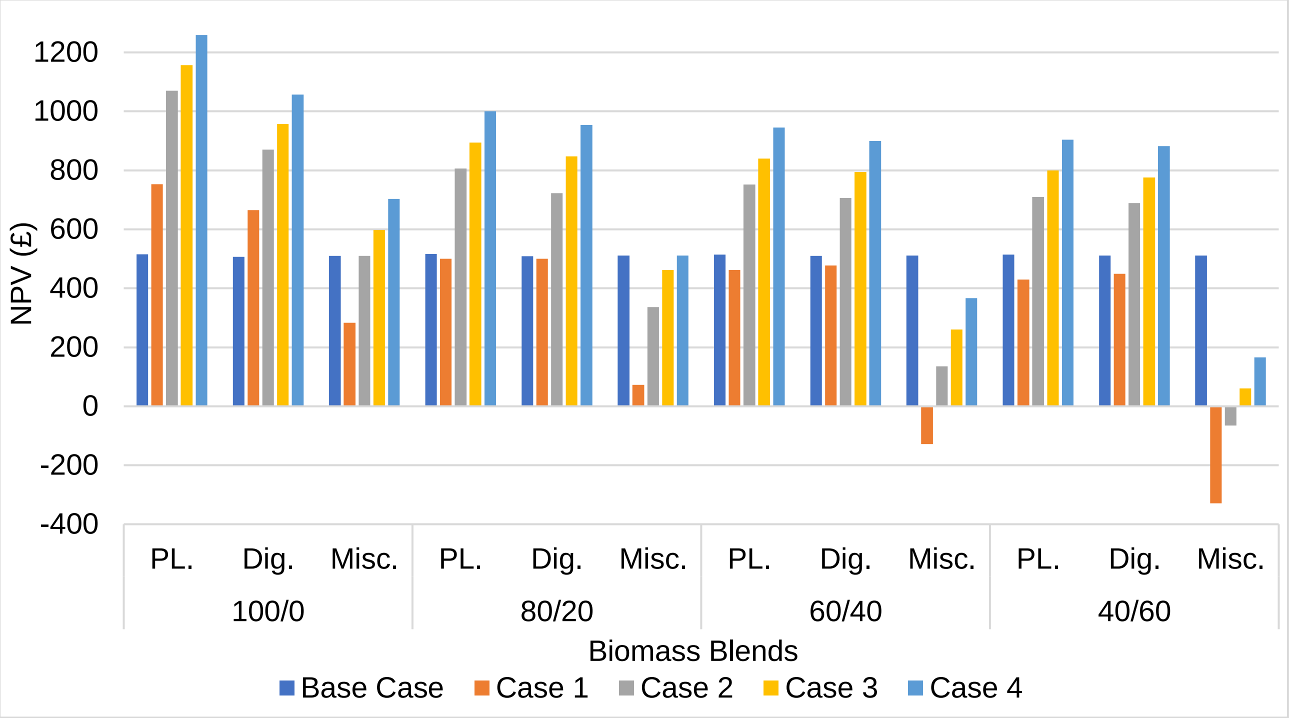


Figure 8.6 NPV Changes with Blend for 120kW ICE

Another financial indicator which can be compared to other systems in literature is the PBP. This may offer greater insight into the finances of the project, as PBP will be relevant to the locality such as electricity purchasing, transport and disposal costs. For a 15kWe downdraft gasifier system identified by Copa et al. (2020) a PBP of between 8.7 to 12.6 years was found. This agrees with the timeframe identified for payback within this research of between 5 and 10 years for the three poultry scenarios suggested between case 1 and case 4, or between case 2 and 5 for the blended feedstock. Depending on scale and initial capital costs, PBP can be as low as 2 years for a downdraft system using waste as the feedstock (Manara and Zabaniotou, 2014). PBP for blended feedstocks remain approximately 10 years or below when considering case 2 and above, but generally show a 2-year increase when compared to single feedstock. BESP is the final indicator, with the most relevant comparison being the current grid electric costs of £158/MWh (BEIS, 2021). In 22 of 57 cases, or 38.6%, electricity produced is more expensive than grid electric costs for single feedstock systems. For blended feedstock this increases to 27 of 54 cases, or 50%. In Figure 8.7, a comparison of the BESP for blends of poultry litter and miscanthus, using the 120kW ICE system is displayed. An obvious difference between poultry litter and miscanthus can be seen due to miscanthus production costs of £40/odt. BESP for poultry litter generated electricity remains below grid prices under all conditions, while for miscanthus it is above grid electric prices in 7 of 15 cases.

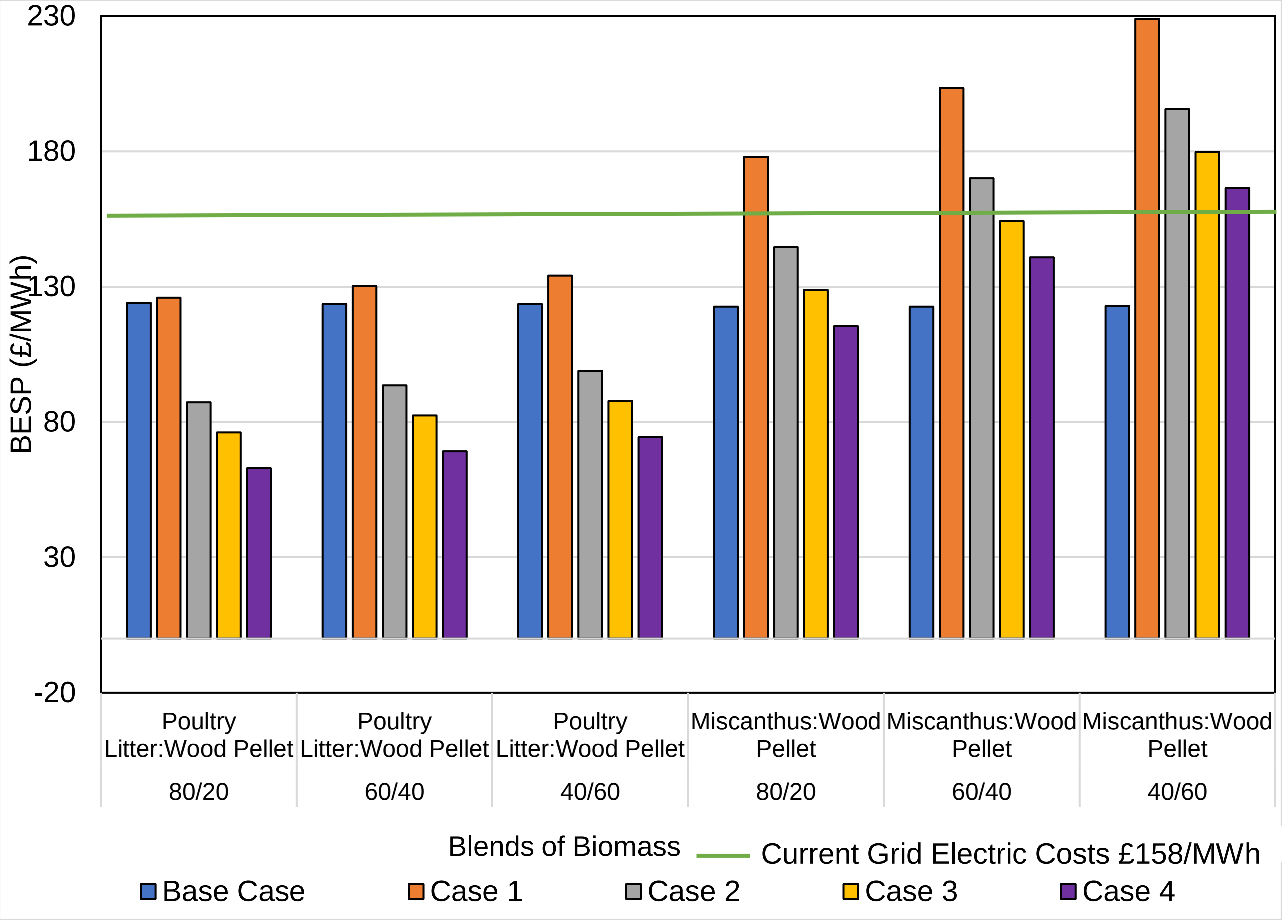


Figure 8.7 BESP for 120kW System Using Blends of Poultry Litter and Miscanthus

While 6 scenarios were defined within Chapter 7 for potential income routes for the CHP systems, not all will be available. Currently in Northern Ireland no new applications are being accepted on the RHI scheme due to previous mismanagement. Case 5, at 2.55p/kWh is therefore unobtainable for every system and was only included to show the potential if the tariff was available. Similarly, for the miscanthus feedstock in case 6 where a payment of £76.67/tonne was made, based off the hectares of miscanthus planted. This was not available outside of England and was included to show the potential a tariff of this kind would have.

8.4 Life Cycle Assessment

The LCA report generated as part of the research was carried out with the aim of comparing the environmental impact of producing heat and electricity through downdraft gasification to traditional heat and power generation methods found on rural farms. Within Northern Ireland these are grid electric, and heat from LPG or natural gas combustion systems. Once all relevant parameters had been calculated and included within the scope of the LCA, results showed that significant improvements in terms of environmental impact were found when using downdraft gasification for heat and electricity production.

To ensure a complete comparison of the technologies and effective use of the SimaPro software, both midpoint and endpoint analysis were employed to gather a comprehensive understanding of the potential impact that changing from one generation method to another may have. Consistent results in terms of the impacts were found for both poultry litter and digestate as a feedstock for heat and electricity production. Single stream poultry litter and digestate produced heat with lower impacts in all 18 of the midpoint categories of interest when compared to the fossil fuel alternatives. Both feedstocks also produced electricity with lower impacts than their grid counterpart in all 18 impact categories. Miscanthus did not perform as promising as these feedstocks, with negative environmental impacts seen for both heat and electricity production using the material. This is in marine eutrophication and land use, due to the fertilizers and land required for crop growth.

For an understanding of what impact changing from one system to another will have, the results of the endpoint analysis are used. Results are grouped together to represent 3 distinct categories; human health, ecosystems and resources. Here we can see that digestate has the biggest impact and will improve human health, ecosystems and resources the most compared to the traditional methods. This is true for both heat and electricity generation, with poultry litter closely following. Miscanthus has a negative effect on ecosystems for both. As the most important part of the LCA analysis was to compare the effect that blends of biomass had on the environment, the 60/40 blend of poultry litter and wood pellets was then compared to traditional heat and electricity generation methods. Small improvements in system performance can be identified when the single stream poultry litter is compared to the blended feedstock in terms of the endpoint impacts. Looking at the electric comparison first, the ecosystems impact is consistent at 23% decrease in effects, human health shows 3% improvement from -20 to -23% impact. This improvement can be attributed to the lower emissions released from the gasification system. Resources show the greatest improvement, where -11% for single stream is increased to -23% for the blend. This improvement of 12% can be attributed to the use of waste wood as the blended material, utilising the circular economy approach of extracting every use out of a material before final disposal and therefore improving resource uses. When comparing the single stream feedstock and blended for heat production, an improvement in each endpoint category can be seen. Human health improves 21% from 79 to 100%, ecosystems improve 7% from 93 to 100% and resources improve a total of 57% from 43 to 100%.

From the results of the LCA analysis, it can be said that the introduction of a blended feedstock has improved the environmental performance of the downdraft gasification system where the producer gas is applied for heat and electricity generation when compared to single feedstock. A 13% improvement in human health impacts and a 52% improvement in resource use for electricity generation are significant improvements and could entice the proliferation of the technology. Heat production shows improvements of 21%, 7% and 57% when comparing single and blended feedstocks for human health, ecosystems and resources respectively.

While the results of the LCA analysis are promising, the research does contain some limitations. These include the number of blends compared and the technologies of choice chosen for comparison. As with all research carried out, time is a limiting factor when trying cover everything of relevance. Due to unforeseen circumstances surrounding the PhD timeline, it was decided to compare the best performing blend of feedstocks identified through the experimental and economic analysis for the LCA. For greater rigour within the research, further LCA comparison of various blends of feedstocks should be carried out. This would increase the validity of the claims that feedstock blending is suitable choice for downdraft gasification. The comparison of the proposed new system to old technology such as LPG combustion could be seen as carrying out the comparison with outdated technology. While this may be true, the comparison stands as valid as these outdated technologies are the ones causing the most environmental damage and should be replaced sooner, rather than newly installed equipment which would have improved environmental performance. LPG is still widely used across Northern Ireland as a heating fuel, and only when the combustions systems are replaced will environmental benefits be seen (DfE, 2022).

8.5 Social & Policy

8.5.1 Social

Though many benefits from the introduction of renewable energy technology exists, and the benefits that the downdraft gasification CHP system will have include environmental and financial benefits, the social impacts that renewable technology have are as important for acceptance in wider society (IRENA, 2017). The introduction of the downdraft gasification systems in Northern Ireland and the rest of the UK could have multiple societal benefits, from minimising the volume of traffic on rural roads through disposal abatement to increased local economic value if the systems were constructed there.

The first benefit of note is to human health in a locality, which may notice improvements after the new systems introduction, if it were to replace older technology. This is down to the reduced $PM_{2.5}$ emissions from the gasification process compared to combustion (Watson et al., 2018). This is particularly related to the lower NO_x emissions which gasification produces. This will improve local air quality significantly. Further benefits to air quality come from the lower amount of large trucks required for material disposal. One farm consisting of 4 sheds would generate 907 tonnes of material, requiring 22 40-tonne articulated trailers for its removal. The avoidance of this would lead to less emissions and cleaner air for each locality where the system is found.

This lower volume of traffic is due to the societal benefit of improved waste management techniques that the system offers, with improved methods for handling the industry by-products generated. This circular economy approach to resources is a sustainable approach which should be adopted by more industries to ensure that the resources available to us are not exhausted. Avoiding transport of the material will also minimise the risk of diseases such as botulism being spread between farms, increasing local biosecurity (Cassidy et al., 2019).

As this is a technology which could proliferate across the entire of the UK, there is significant employment opportunities arising from it. Design, fabrication, installation and servicing are all potential jobs that require a skilled workforce. This would assist with improving rural employment, as most of the applicable applications will be found in rural areas. Not only do new jobs sustain the livelihoods of people, they also encourage growth in gross domestic product (GDP), they create value in the local economy and promote health and education (IRENA, 2017). These are just some of the benefits that the introduction of such technology could have. This will lead to an overall sustainable industry, through supporting the 3 pillars of sustainability, environment, society and economy as seen in Figure 8.8 (Manara and Zabaniotou, 2014).

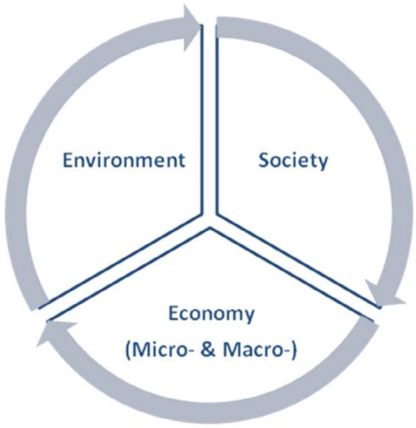


Figure 8.8 Three Pillars of Sustainability (Manara and Zabaniotou, 2014)

8.5.2 Policy

The research carried out to prove the capability of blending two biomass feedstocks to increase the LHV of the producer gas is significant, as validation of renewable energy technologies and their potential is critical to successfully tackle the climate crisis that we are currently experiencing. In 2014 the European Commission (EU) introduced regulation no. 592, which paved the way for the use of animal by products on site for energy production (European Commission, 2014). Little progress in terms of using this material has been made since. While proving a technology is capable of producing low carbon or carbon negative energy is important, without the support of government policy, it is unlikely that significant changes would be carried out. Within Northern Ireland the recent publication of The Path to Net Zero Strategy has provided impetus to those people who are working in the development of renewable energy technologies. This is because it is the first time that the government has published a plan for how they will achieve the goal of net zero emissions by 2050. This strategy will be driven by two main targets; increasing energy efficiency across buildings and industry by 25% by the year 2030 and generating 70% of electricity consumed through renewables by 2030 also (DfE, 2021a). With these two goals laid out and annual reviews to judge the progress being made, there is significant potential for new technologies to proliferate under this strategy. Changes to the current system of energy generation will be carried out using the framework to grow the green economy in Northern Ireland. This includes replacing high carbon content fossil fuels with renewable alternatives, developing renewable infrastructure across the jurisdiction and promoting the use of decentralized solutions to carry this out. This policy framework therefore supports the introduction of the proposed downdraft gasification system as it fits the scope of what is trying to be achieved. All gasification systems would be based on the use of waste or underutilised biomass for energy generation, replacing existing fossil fuel systems. Each would be located in a decentralized rural setting, close to where the end user is located to minimise transmission losses. The policy framework also mentions to do more with less, which fits with the reasoning of waste from energy that the system is based off. While significant emphasis is put on the hydrogen economy within the report, the amount of evidence gathered within this research will give support to gasification technology.

While there are very few operational gasification installations across the UK, the publishing of the Pathway to Net Zero strategy should give encouragement to those interested. Further evidence of the possibility for using this technology comes from Advanced Gasification Technologies (AGT) – Review and Benchmarking (AECOM, 2021). Within this report generated by consulting engineers for the UK government, the future role of AGTs are discussed, the limiting factors influencing the technology today as well as opportunities and barriers it faces. Further factors which require research before final recommendation of the technology are suggested, with financial support mechanisms a major factor requiring government intervention. As can be seen from Chapter 7, with subsidies available from government the technology becomes much more financially viable while the technology is in its infancy.

8.6 Changes

During the experimental research that was carried out, multiple issues with the Fluidyne downdraft gasifier were identified. These issues were mechanical or design flaws which during experimental analysis caused delays and in future could be improved upon. They include but are not limited to insulation of the reactors, the biomass feeding system and the carrier gas control system. In this section a discussion on changes to equipment or instrumentation to improve the quality of the gasification results will take place. Some design alterations could be carried out to ensure system improvements.

8.6.1 Insulation

Reaction temperature is critically important to produce the appropriate gaseous components within gasification. Typical temperatures for the generation of desired components in the form of CO and H_2 are above 800°C for downdraft gasification (Molino et al., 2018). While the ignition of the feedstock will bring the reaction temperature above the required 800°C, remaining at that levels becomes difficult for the gasifier due to the lack of insulation surrounding the system reactors which are used for this analysis. An example of the variations in temperature experienced for the analysis of miscanthus and its blends is displayed in Figure 8.9. In this figure we can see no discernible trend related to temperature changes. The temperature losses across the system contribute to lower conversion efficiency, high tar content and consequently a lower producer gas LHV. A drop in thermal efficiency can also be identified when using cold air for gasification which is why commercial gasifier preheat their air (Samson et al., 2018). To combat these problems, high temperature insulation material should be introduced. This material will ensure minimal thermal losses across the system, meaning a much greater conversion efficiency and lower potential for tar blocking the systems pipes and reactors. Previous research in the field of gasification have included high temperature insulation for these reasons (Pham et al., 2018; Rollinson and Williams, 2016; Zhang et al., 2004).

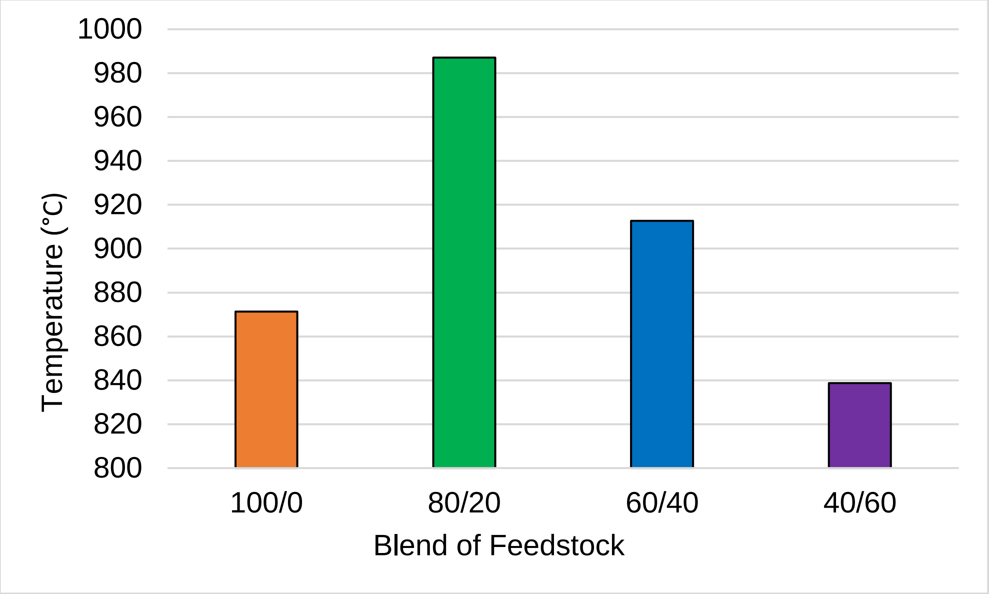


Figure 8.9 Temperature Changes for Miscanthus Experiments

8.6.2 Hearth Module

To ensure control over the amount of air being introduced to the system and therefore guarantee the gasification reaction was taking place and not combustion, the reaction must take place within a closed reactor. On the Fluidyne gasifier this is the hearth module. Due to the scale of the system of interest, there is no feedstock intake system on the gasifier. This means that it is required to operate on a semi-batch basis. Approximately 1.2kg of biomass is used to start the reaction and additional biomass can be introduced to the system once the reaction has begun. The addition of extra feedstock requires opening the hearth module to the atmosphere allowing excess air in and causing a large reduction in operating temperature. The impact that this has on the producer gas quality is negative, diluting it with excess N_2 from the air and lowering temperature by up to 300°C. To avoid these issues, a method of adding biomass feedstock without opening the system to the air must be introduced. This could be achieved through the installation of a new method to introduce biomass, such as a feedstock storage vessel above the ignition port that could be attached once the reaction had begun. Using such a device, approximately 2 – 3 kg of biomass could be added to the reaction without opening the system to the atmosphere. Reaction time could therefore be increased from 40 minutes to close to two hours, meaning greater data collection and a more stable producer gas generated.

As the gasifier is a fixed bed design, conversion efficiency of material is low in comparison to what a fluidised bed reactor could achieve (Ruiz et al., 2013). To increase conversion efficiency without significant alterations to the reactor design, a stirrer device could be installed in the system. This would agitate the biomass material within the hearth and increase conversion efficiency through the mixing action. Similar proposals have been carried out by Wolff et al. (2013) to prevent material bridging and increase performance.

8.6.3 Air Control

One of the most frustrating aspects of the downdraft gasifier used for experimental analysis was the amount of control that the user has on the reaction once it had begun. With only one handle on the side of the gasifier to either increase or decrease the air supply to the reaction, very little can be done to control the reaction. Through increasing air supply temperature would increase, due to the increased proportion of O_2 available to the reaction and decreasing the air supply would have the opposite effect. To try increase the reliability and reproducibility of the results generated, a laminated protractor wheel was attached to the handle where the angle of opening could be marked and accurately reproduced through multiple experiments as is displayed in Figure 8.10.

Figure 8.10 Carrier Gas Control Handle

To increase control and data collection potential of the system a gas flow meter should be installed in the gasifier. The addition of this one simple piece of equipment would allow for the precise control of the gasification reaction, the calculation of the ER and the production of better-quality producer gas. Once this installation has taken place, research into the influence of different carrier gases could also take place. If a flow meter was installed, changing of the carrier gas could be carried out too. Changing the system from an air ran gasifier to one that could use CO_2, O_2 or other would allow for a broader range of potential research opportunities.

8.6.4 Other

Further changes which could take place to improve the functionality of the gasifier are a removable hearth, increased temperature probes and optimization of their placement, and removal of tar blocking areas. If fitted with a basket type solution, the hearth of the gasifier could become much more functional. To date biomass is loaded into the gasifier using a hand shovel and unconverted material along with the ash is removed using spoons. If the hearth contained an inner – liner that could be removed, its loading and clearing out would become much more user friendly, reducing the time spent cleaning the system after an experiment and making it much easier to calculate conversion efficiency. Temperature probes on the gasifier were installed by previous users to this project. Only 1 probe is placed beneath the hearth in the reduction zone. To improve data collection further probes should be installed in the hearth module to ensure optimum temperature is being recorded. The final suggested change for the gasifier would be to change the pipe which gas travels along from the cyclone to the flare. This is currently a horizontal pipe with internal diameter of approximately 1”. During the research, multiple times this pipe became blocked with tar. If the angle of the pipe was changed slightly, so that it no longer sat horizontally but instead gently inclined downwards as it travels to the flare, tar would naturally move along the pipe to a catchment area which could be used to remove the unwanted by-product.

8.7 Continue Research

If this research were to continue, the next step would be to introduce some of the changes which have been listed above and repeat the analysis to investigate if the producer gas generated displays any changes. Increased thermal efficiency, better biomass feedstock handling and greater control over the gasifying agent as well as changing it would all potentially further increase producer gas quality.

Additional research which could be done to continue this work would include biomass mapping, tar identification and increased LCA. Mapping would be for the locations of poultry houses, AD plants and other sustainable biomass sources using GIS software. Once these sources of underutilised biomass had been mapped, they could be paired with a local energy user for environmentally sustainable heat and electricity production. This promotes the circular economy approach, utilising waste resources for energy production, avoiding unnecessary fossil fuel combustion. Fuel poverty is an issue across Northern Ireland. This is where a household is required to spend over 10% of their income on energy. In Northern Ireland the rate of fuel poverty is 22% (NiDirect, 2021). To combat this, we can pair the areas which experience high rates of fuel poverty to the biomass resources available, giving access to potentially large energy resources could improve the livelihood of the local community and ensure energy security. Tar is the greatest issue that requires solving for successful gasification (Cammarota et al., 2016). Identification of the various tar species generated during the experiments could be carried out. This would include identifying the different tar species generated from each single feedstock, and from there investigate the influence that blends of feedstock had on them. Introduction of the catalyst would further alter the potential tar yield from the system. Final additional work which could be carried out include the increased blend analysis through the LCA and further research into the economic impact of the blends as well.

8.8 Summary

Significant research was carried out during this PhD. Results were gathered from experimental analysis of biomass feedstocks and several modelling and simulation applications. Using ECLIPSE simulation software, validated results could be generated to ensure the accuracy of the producer gas composition, downstream application of the producer gas and economic analysis of the system.

The overall aim of this research or the gap that it was trying to fill was to investigate the influence that blends of sustainable biomass feedstocks have on the downdraft gasification and application process. This was found through a combination of small-scale experimental analysis, ECLIPSE simulation of the application process, LCA analysis of the environmental impact using SimaPro software and economic investigation using further ECLIPSE packages. Producer gas composition was found to change significantly with the introduction of the blended feedstock. CH_4 and CO concentrations increased compared to single feedstock, while H_2 content decreased. This led to an overall increase in producer gas LHV, as the blend proportion increased. Reactions which influenced this change were the water gas shift reaction, methanation reaction and Boudouard reaction. While temperature did have an influence on gas composition, due to the fluctuations found in reaction temperature results, no definitive trends or answers for this could be identified. To further improve producer gas quality a calcium catalyst, $CaCO_3$, was added. Once optimum loading had been identified, it had the effect of increasing producer gas H_2 content by 45% through limiting CO_2 production in the water gas shift reaction and promoting H_2. This increased the producer gas LHV from 4.16MJ/Nm^3 to 4.98 MJ/Nm^3, a 16.5% increase in total.

ECLIPSE simulation software allowed for validated producer gas composition results to be applied to downstream equipment, for accurate energy production results. Electrical and thermal efficiencies from the downstream equipment along with emissions were generated and compared to the 60/40 blend. Along with economic analysis of the system NPV, BESP and PBP were all found for the various scenarios set out, understanding the influence that blends had on them. Increased system efficiencies were found for the blended feedstock, with electrical efficiency increasing by 2.5% and thermal efficiency by 6.1%.

LCA analysis of the influence that blending had on the entire process showed promising results, where the environmental impact on the ecosystem, human health and resources was improved when using blends over traditional heat and electricity production methods. Poultry litter and digestate performed better than miscanthus in this regard. Improvements in local communities would be found if the technology was introduced, with few recent policy publications supporting the change to this low carbon renewable technology. Changes to the system to improve future results include addition of high temperature insulation and greater control over the carrier gas. Tar identification and destruction strategies would be the most critical next piece of research were the project to continue.

Chapter 9 – Conclusion

9.1 Introduction

In conclusion to this research project being completed, a discussion will take place on how the research which was undertook was used to reach the overall aim of the project. To accomplish the overarching aim, it was broken down into four simpler achievable goals. These goals as defined within the introduction chapter include process modelling, experimental study and model validation, process integration and assessment. Each of these project goals essentially became a work package which required solving. The results gathered from each of these project objectives, how they relate to each other, along with their impact will be discussed within this final section of the thesis. Continuing from this, the scientific outcomes of the research will be detailed. This includes any novel knowledge, techniques or information which through the work carried out in this research project has been identified. From these findings, any recommendations which this research can make to improve the uptake of the technology, or to make it more attractive to potential industry applications will be suggested in terms of recommendations for policy makers. This chapter will then conclude with the limitations of the work carried out. This has been discussed in brief in previous chapters but will be covered in greater detail within this chapter to ensure a complete understanding and explanation of why the limitations were accepted.

9.2 Aim & Objectives

As mentioned within the introduction, the overall aim of the project was divided into four objectives, to successfully carry out the research of interest to the highest standards. The total aim of this research project was:

Aim: to develop a comprehensive performance analysis of an entire biomass gasification system with novel blended feedstocks. This includes an economical concept for biomass supply chain management, pre-treatment, production of producer gas and utilisation of biomass/waste, by means of biomass gasification for electricity and heat production.

This aim was set out once the gap within the research had been identified and justified, as was discussed within Chapter 2 – A Review of Fuel Gas Production from Biomass and Biowaste. The use of downdraft gasification for sustainable biomass research was of central importance to the research, but from the literature review the use of blends of sustainable waste and low value biomass was acknowledged to be the gap in the knowledge which required this research to take place for an answer to be generated. A description of the objectives which were set out to reach the overall aim is given below:

Objectives:

1. *Process Modelling* – develop the feedstock supply chain and gasification process models for the integrated biomass gasification and CHP system. The models developed will be used to evaluate technical, economic and environmental performance of micro generation fuelled by blended biomass feedstocks

2. *Experimental Study and Model Validation* – Experimental work and analysis of selected feedstocks and blends for a range of process conditions, leading to pilot test results

3. *Process Integration* – Syngas produced by a downdraft gasifier will be cleaned up, analysed and fed to an internal combustion engine for the application of combined heat and power

4. *Assessment* – Techno-economic and environmental assessment of the full bioenergy production chain understanding the influence which the blends of biomass had on relevant process indicators

Through dividing the complex aim of the project into four individual objectives, the research becomes much more achievable. A gap in the knowledge can be then filled with the products and results of the work carried out. To ensure a complete understanding of the tasks of interest, a breakdown of each objective will be given. Process modelling related to the simulation and modelling of the entire downdraft gasification and producer gas application process. By using an appropriate simulation software, in this case ECLIPSE, which has been designed and created within Ulster University, accurate modelling of producer gas composition could be generated.

Through accurate simulation of the producer gas generation process as well as gas cleaning and upgrading, the generated model could be applied to downstream equipment for heat and electricity production estimation. The results of both the gasification and application process can then be utilised as the inputs for further research which will take place. The second objective was to carry out small scale experimental analysis of the appropriate biomass material in the downdraft gasification system found in Ulster University's Jordanstown campus. This experimental analysis included proximate and ultimate analysis of the biomass materials identified as being of interest, as well as downdraft gasification experiments where temperature and producer gas composition were monitored, recorded and later combined. Single feedstock as well as blended compositions were analysed experimentally in triplicate to ensure accuracy of the results generated. Once accurate producer gas composition has been obtained, the generated ECLIPSE models could be validated with the results to ensure their accuracy as well as the accuracy of their downstream applications. Process integration for the research was to experimentally apply the producer gas being generated from the downdraft process to a CHP system for heat and power generation. Unforeseen delays experienced during the course of the research being carried out meant that experimental application within the research was not carried out. Validated simulation results were used as indicators of CHP application potential. The final objective defined within this research was the assessment components of the project. Within this section both economic and environmental assessment of the impact that blending feedstocks have on the process were investigated. To carry out this analysis, further appropriate modelling software was employed. Environmental impact of blends was investigated using the LCA technique, through the use of SimaPro software. Economic analysis of systems was carried out with another ECLIPSE suite, the economic analysis package. Through comparing the electricity and heat generated from the blended feedstock system to the traditional sources of energy found in Northern Ireland and the UK, the environmental impact of the process can be evaluated and designated as beneficial or harmful. The techno economic analysis of the system allowed for a number of financial indices to be compared, such as NPV, BESP and PBP, to also understand the impact which the introduction of blends of feedstock could have on them. Once completed, all results will combine to create a comprehensive analysis of the process and evaluate the impact which blends of sustainable biomass feedstocks had.

9.3 Scientific Outcomes

Once the research had been completed, and the results of the various work packages had been analysed and combined, multiple scientific outcomes have been identified. These outcomes are listed below:

1. Blending of biomass feedstocks is beneficial to the downdraft gasification process, increasing LHV and application efficiencies. Max LHV increase of 12.9% was identified for the 40/60 blend of digestate and wood pellets. CHP efficiencies increased 2.5% for electrical and 6.1% for thermal when using the 60/40 blend
2. Blending of feedstocks is optimal for waste and low-quality biomass materials, through increasing carbon availability. 60/40 blend shows an increase of 24.2% in the carbon content of the feedstock
3. Optimum feedstock blend ratio for improved process performance is 60/40
4. LCA analysis of the process showed improvement in human health, ecosystems and resources when introducing the blended feedstock compared to traditional energy sources
5. Economic analysis of the process showed electricity generated to be between £99.16 and £3.23/MWh cheaper than grid electric for poultry litter systems. In total cheaper in 50% of poultry litter cases identified
6. Calcium based catalysts can improve process parameters through cracking of unwanted tar by-products increasing LHV by 16.4%

Results from the experimental and modelling analysis carried out on the downdraft gasification of sustainable blends of biomass feedstocks show that the introduction of blends of material will improve the performance of the system. This system improvement can be seen from the producer gas LHV and both the thermal and electrical efficiencies of the CHP system when the producer gas is applied downstream. With the introduction of wood pellets to replace a portion of the biomass feedstock increases in LHV are seen. For each feedstock, the increase is similar. Percentage increase in poultry litter LHV when compared to that calculated for the single feedstock were 0.3% for the 80/20 blend, 5.9% for the 60/40 blend and 7.3% for the 40/60 blend. Under the same conditions digestate producer gas LHV increased 1.2%, 6.8% and 12.9% when compared to single feedstock. Miscanthus increases were 0.7%, 4.4% and 10.4% respectively. Reasons for the increase in LHV include the increased carbon content available to the reaction for conversion as well as an increase in particular reactions taking place. These reactions are the methanation reaction, the water gas shift reaction and the Boudouard reaction. CHP efficiencies for the system improved from 20.3% electrical efficiency and 48.1% thermal efficiency for the single feedstock to 22.8% and 54.2% for the 60/40 blend of poultry litter and wood pellets. This is an increase of 2.5% and 6.1% respectively.

To ensure the maximum benefit is obtained from feedstock blending, the most appropriate application is with poor quality biomass. An example is through the use of poultry litter as the feedstock, which is formed from a mixture of heterogenous material and has a relatively low carbon content (33.6%). Introducing a wood pellet blend to improve producer gas LHV is beneficial as the average carbon content will increase with their introduction.

Multiple blends of feedstock were experimentally analysed using the downdraft gasification set up. From these experiments along with the modelling of environmental and economic impact, the 60/40 blend was identified as the optimum. This blend showed good increases in LHV, while not detracting from the financial indices to make the system unattractive.

LCA analysis of the heat and electricity generated from the application of the proposed systems producer gas showed environmental benefits when compared to traditional sources. Using SimaPro software, with the Ecoinvent Database 3.5 and the ReCiPe Midpoint (H) and Endpoint (H) methods the environmental impact of heat and electricity generated was compared to LPG and natural gas combustion, along with grid sourced electric. When the 60/40 blend of poultry litter and wood pellets was analysed through the LCA process, improvements in terms of environmental impact were observed. Endpoint results showed 123% improvement for human health, ecosystems and for resources when comparing 1kWh of electric generated to Northern Ireland grid electric. For 1MJ of heat a 100% improvement in each impact category was calculated when compared to traditional heat generation methods found in Northern Ireland such as LPG and natural gas.

Through the use of ECLIPSE economic simulation package, a number of financial indices were evaluated as well as the impact an introduction of blends of material will have on them. NPV, BESP and PBP for all proposed CHP systems were calculated. Poultry litter scenarios identified found the discounted PBP to be below 10 years for all cases defined after the base case. BESP was cheaper than grid electric in 14 of the 18 cases of interest and NPV of the system could be doubled under the correct conditions. When the blend was introduced the production of cheaper electricity decreased to 10 of 18 cases for the 80/20 blend, 9 of 18 for the 60/40 and 8 of 18 for the 40/60. Discounted PBP increased an average of between 1.5 – 2.9 years when blends of feedstock were introduced. NPV decreased by 20.5% for the 80/20 blend, 24.9% for the 60/40 and 28.2% for the 40/60 when compared to single feedstock.

Final scientific outcomes of the research relate to the addition of the calcium catalyst to crack the unwanted tar by-product. By using a 20% by weight loading factor, a 45% increase in H_2 content was seen leading to an 16.4% increase in LHV for the 60/40 blend of poultry litter and wood pellets. For the 60/40 blend of digestate, a 15.5% increase in LHV was found. Tar cracked into lighter compounds and released hydrogen from the bonds to increase gas H_2 content (Li et al., 2022).

9.4 Recommendations for Policy Makers

From the research carried out it has been proven that the introduction of sustainable blends of biomass material is beneficial for the downdraft gasification and producer gas application process. While benefits can be seen in terms of the electrical and thermal energy produced, the environmental impact of the process, and through the economic indices of interest, the application of the technology has yet to see any noteworthy uptake across Northern Ireland and the rest of the UK. Within this section recommendation for policy makers will be made. Policy makers can come in a variety of forms such as a person who has influence over policy decisions in government, in the local authority or in a relevant public body (Breen, 2012). The recommendations made here based on research carried out in this project and evidence gathered can be used to benefit both industry and the public, through improved waste management techniques, improved energy security and lower harmful impacts on human health.

Objective

The objective of the policy being recommended is to increase the uptake of gasification technology. This can occur nationally at first, with the UK and Ireland the main target market. Once uptake has reached an appropriate level, spreading the technology across Europe and further afield will become the objective. The primary aim of the policy is to utilise gasification technology to improve current waste management strategies.

Target Audience

The target audience of this policy will be ministers in national government positions, or those who have influence over national policy decisions. While lobbying of local authorities to garner support could be beneficial, this policy is aimed at a national level. Those who would benefit most from the introduction will be industries that generate a large volume of biomass or biowaste as a by-product or derivative of an anthropogenic process. Disseminating the results of the research carried out within this project to government bodies such as AFBI or DEFRA would gather support for the introduction of policy.

The Issue

The current issue within the agricultural industries amongst some others is the large volumes of waste materials being generated and lack of viable solutions for them. Current guideline suggest best practise for their disposal involves spreading of the material on land if possible, for the likes of slurries and manures. This will return nutrients to the land and offers a simple and effective method of disposal, despite the risks posed to local waterways by eutrophication. Other disposal options include processing the material offsite to dispense of it such as landfilling or treatment in a dedicated facility for example an AD plant. Landfilling is a last resort which should be avoided as it is a waste of the resource as well as potentially environmentally damaging from leachate that is produced. This, along with AD, involves paying for disposal through haulage costs or a gate fee at the processing facility, which in turn makes the disposal method less sustainable by increasing process costs.

Options

A number of options are possible to incentivise the uptake of gasification technology for waste biomass management. These include, but are not limited to feed in tariffs, auctions, green certificates, investment-based tax exemptions, investment subsidies and low interest loans. For Northern Ireland, the proposed policy will be tax-based exemptions to reduce the total capital cost and therefore the overall investment required.

Current Economic Climate

Due to the current economic climate, the government in Northern Ireland and the rest of the UK is unlikely to look favourably on offering a payment to users based on units of renewable energy produced. Previous mismanagement of the RHI within Northern Ireland led to the scheme closing itself to new applicants, and the tax payer being left to pay for the increased costs incurred (DfE, 2021b). Incentivising the uptake of gasification technology with this method is therefore unlikely. Much more possible for the region is a tax exemption or low interest loans to be provided by the government. Value added tax (VAT), income tax and import duty are all areas where the government could introduce favourable tax policy related to the proposed systems. Green certificates could also be an attractive option to incentivise their introduction. A tax exemption on the capital cost of the system could see users potentially investing. Low interest loans could also be provided by government where appropriate, due to the potential for broad application and the guarantee that the funding would be returned to the government.

Existing Strategies

This technology incentivisation would fit in well with a significant amount of policy already in place across the UK and Ireland. Examples include the NAPR, the WFD, and the government’s aim for net zero carbon emissions to name a few. By utilising gasification technology to handle biowastes and poor-quality biomasses, the need for disposal through land spreading or expensive additional processing will be avoided. This will have a significant benefit on the environment, as over application to land due to intensive farming practises has led to eutrophication of local waterways. In turn this will assist with the WFD’s goal of improving water quality across Europe. Further benefit to the user will be cost and time savings experienced through avoiding disposal. Brexit may have removed the UK from some of the EU's regulations, but they currently remain within the common agricultural policy to ensure their standards are followed across the island of Ireland. As the WFD is based on water catchment areas and not political boundaries, the UK will still be required to maintain water standards across the region. Both nationally and internationally, governments have committed to decarbonising their economies. Countries trying to achieve net zero emissions by the year 2050 if not before include France, Sweden, Hungary and Germany to name just a few in Europe. Globally New Zealand, Japan and South Korea have also committed (Carver, 2021). By supporting the introduction of this technology to generate low carbon electricity from existing waste resources, a large proportion of current demand could be generated and will assist with achieving the net zero goal.

International Examples

While previous mismanagement of renewable incentivisation legislation has made policy makers in Northern Ireland wary of introducing new strategies, there are many cases of where these policies are successfully executed around the globe to date. Examples of where these policies are already implemented and operate well include China, Brazil, Montenegro, USA, Australia and the EU to name a few. China offers numerous incentives for the introduction of renewable energy generation. These include tax supports, financial subsidies and feed in tariffs for all types of renewable energy sources such as wind, solar, geothermal and biomass (Zhao et al., 2016). Brazil also offers a number of incentives to promote the use of renewable energy, although theirs are slightly different to what is found in China. Examples of incentives that have been successful implemented in Brazil are auctions, net metering commercialisation of certificates and feed in tariffs (Aquila et al., 2017). Auctions invite multiple applications to produce renewable electricity, with the cheapest per kWh bid being successful. Commercialisation is another term for green certificate, where the generator receives a marketable certificate for the units of renewable energy produced. Final examples of successful renewable energy incentivisation can be seen in the USA, Australia and the EU. Tax supports, loans, feed in tariffs, green certificates and power purchasing legislation are all available across these jurisdictions to improve the uptake of renewable power technology (Abdmouleh et al., 2015). With widespread application globally, successful introduction for improved technology uptake can take place locally within Northern Ireland and the UK.

Real World Impact

The real-world impact of introducing such policy to the UK would be the potential to produce a large portion of current electric demand through carbon neutral methods. Industries which could take advantage of the introduction of such policy in Northern Ireland and the UK are the mushroom industry, the poultry industry and all those who operate wastewater treatment plants to name but a few. The mushroom industry could utilise the technology to handle spent mushroom compost (SMC) and wastewater treatment facilities could use it for wastewater sludge disposal. With over 22 tonnes of SMC generated weekly in Ireland alone in 2008, a figure which has risen in the interim due to the industries growth, and 1.4 million tonnes of sludge produced across the UK in 2020, both are ideal candidates for the proposed waste to energy generation systems (Aragón-Briceno et al., 2021; Jordan et al., 2013) The poultry industry generates 4.9 million tonnes of litter by-product annually, which could be utilised for onsite heat and electricity production as has been discussed throughout this research (Jeswani et al., 2019). If all the poultry waste in the UK were to be converted utilising the proposed technology and blending recommendation, up to 1.6% of the national electric demand of 2020 could be met (Martin, 2021). With most recent figures available showing 15.4 million tonnes of wastes produced from agriculture, fishing, forestry and mining across the UK annually, waste to energy technology has never been as attractive a solution as it currently is (Department for Environment Food and Rural Affairs, 2021). If a portion of this material was directed to energy generation, the aforementioned 1.6% of the national grid electric demand could be improved upon significantly.

Importance of Action

Without doubt, the current global climate crisis is the biggest threat to human life that we currently face. Ensuring a sustainable future is critical to minimise the threats caused by climate change. Changing from a fossil fuel based economy, reliant on importing harmful fuels across thousands of miles and international boundaries, to one who can provide their own energy through renewable resources is key for continued economic growth. All policy which supports the production of low carbon electricity should be promoted.

9.5 Limitations

All efforts were placed into carrying out the research of interest to the highest possible standard. The methodology employed followed all appropriate international and national standards and work was carried out in triplicate, and some cases more, to ensure accuracy and validity of the results. Despite these efforts, there were some inevitable limitations identified within the work. Some of these limitations have been mentioned previously within the research, but they will be elaborated upon here to ensure all are covered. The limitations identified include; the control of temperature and ER, tar capturing and identification, and the scope of the LCA analysis which was carried out.

Temperature

Throughout the experimental gasification analysis carried out as part of this research, the control over the reaction temperature has been an issue. Due to the simple design of the downdraft system being utilised, there is only one handle on the entire unit for controlling the multiple reaction parameters of interest such as temperature, air flow and pressure. When this one lever is utilised for multiple purposes, optimising any one of the parameters becomes problematic. To minimise the disruption caused by temperature fluctuations of the reactions, each experiment was carried out in triplicate, ensuring an accurate average value for the producer gas composition could be calculated. Another issue related to the lack of control is knowing the ER which the reaction is operating at. Without any air flow monitoring equipment, ER could not be accurately changed when an experiment was taking place. While estimates for this value could be gathered from the literature, further alterations to the system would be required to have greater control over it.

Tar

Tar is widely accepted as being the greatest barrier to successful application of gasification technology (Asadullah, 2014a). Through application of the calcium catalyst, some tar was broken into lighter components and additional producer gas constituents. The limitations related to the tar analysis of this research was the efforts to quantify the volume of tar generated, along with identification of the individual tar species. Further issues with the gasifier system design did not allow for the separation of tar and char generated from the experimental analysis. Along with some pieces of unconverted biomass material, all waste by-products were extracted through ports in the hearth, blast tube and cyclones. This, along with tar being captured in other vessels and pipelines of the system meant that accurate determination of the volume produced was impossible to obtain. Along with what can be best described as close estimation of tar quantities produced, the individual tar species involved where never identified which leaves a gap in the knowledge for the influence which blending had on its production. If the research were to continue, this would be the focus.

Scope of the LCA

While the LCA did follow the appropriate methodology in BS EN ISO 14040:2006+A1:2020 and the results generated are reliable through the use of SimaPro software, Ecoinvent Database and ReCiPe methods, there are some limitations to its application. The modelling was carried out with a focus on Northern Ireland and used figures and assumptions relevant to it where necessary. Examples of this include avoiding the necessity of transporting material for disposal an average of 50km. This is based on the geographical size of Northern Ireland, with west to east distance being approximately 120km, and disposal not requiring travel over half the length of the region. While this is suitable when the focus is on Northern Ireland and the rest of the UK, wider application of the results will be detracted from. This is also true of the technology compared, with natural gas and LPG combustion the main sources of thermal energy analysed during the LCA. While these technologies may seem outdated, they remain a prevalent source of energy across the region. Those who will most benefit from the introduction of the system are those who were already planning on changing their heat and electricity sources, as well as those willing to introduce new technology. Therefore, despite the imperfections which may be present in the research, it remains pertinent for the application of interest.

References

Abdmouleh, Z., Alammari, R.A.M., Gastli, A., 2015. Review of policies encouraging renewable energy integration. Renew. Sustain. Energy Rev. 45, 249–262. https://doi.org/10.1016/j.rser.2015.01.035

Abdoulmoumine, N., Adhikari, S., Kulkarni, A., Chattanathan, S., 2015. A review on biomass gasification syngas cleanup. Appl. Energy 155, 294–307. https://doi.org/10.1016/j.apenergy.2015.05.095

Abe, H., Katayama, A., Sah, B.P., Toriu, T., Samy, S., Pheach, P., Adams, M.A., Grierson, P.F., 2007. Potential for rural electrification based on biomass gasification in Cambodia. Biomass and Bioenergy 31, 656–664. https://doi.org/10.1016/j.biombioe.2007.06.023

Adams, P., Bows, A., Gilbert, P., Hammond, J., Howard, D., Lee, R., McNamara, N., Thornley, P., Whittaker, C., Whitaker, J., 2013. Understanding greenhouse gas balances of bioenergy systems 44.

Adams, P.W.R., McManus, M.C., 2014. Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation. Sustain. Energy Technol. Assessments 6, 129–140. https://doi.org/10.1016/j.seta.2014.02.002

Adams, P.W.R.R., McManus, M.C., 2014. Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation. Sustain. Energy Technol. Assessments 6, 129–140. https://doi.org/10.1016/j.seta.2014.02.002

AECOM, 2021. Advanced Gasification Technologies - Review and Benchmarking. London.

Ahmad, A.A., Zawawi, N.A., Kasim, F.H., Inayat, A., Khasri, A., 2016. Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. Renew. Sustain. Energy Rev. 53, 1333–1347. https://doi.org/10.1016/j.rser.2015.09.030

Al Moussawi, H., Fardoun, F., Louahlia, H., 2017. Selection based on differences between cogeneration and trigeneration in various prime mover technologies. Renew. Sustain. Energy Rev. 74, 491–511. https://doi.org/10.1016/j.rser.2017.02.077

Alauddin, Z.A.B.Z., Lahijani, P., Mohammadi, M., Mohamed, A.R., 2010. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review. Renew. Sustain. Energy Rev. 14, 2852–2862. https://doi.org/10.1016/j.rser.2010.07.026

AlNouss, A., McKay, G., Al-Ansari, T., 2020. Production of syngas via gasification using optimum blends of biomass. J. Clean. Prod. 242, 118499. https://doi.org/10.1016/j.jclepro.2019.118499

Anis, S., Zainal, Z.A., 2011. Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods: A review. Renew. Sustain. Energy Rev. 15, 2355–2377. https://doi.org/10.1016/j.rser.2011.02.018

Aquila, G., Oliveira, E. De, Rodrigo, A., Queiroz, D., Rotela, P., Nunes, M., 2017. An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience. Renew. Sustain. Energy Rev. 70, 1090–1098. https://doi.org/10.1016/j.rser.2016.12.013

Aragón-Briceno, C.I., Ross, A.B., Camargo-Valero, M.A., 2021. Mass and energy integration study of hydrothermal carbonization with anaerobic digestion of sewage sludge. Renew. Energy 167, 473–483. https://doi.org/10.1016/j.renene.2020.11.103

Arnif, I., Indartono, Y.S., Susanto, H., Adriansyah, W., 2018. Experimental study of gas cleaning system on biomass gasification. AIP Conf. Proc. 1984. https://doi.org/10.1063/1.5046625

Arnsfeld, S., Senk, D., Gudenau, H.W., 2014. The qualification of torrefied wooden biomass and agricultural wastes products for gasification processes. J. Anal. Appl. Pyrolysis 107, 133–141. https://doi.org/10.1016/j.jaap.2014.02.013

Arteconi, A., Brandoni, C., Evangelista, D., Polonara, F., 2013. Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe. Appl. Energy 87, 2005–2013. https://doi.org/10.1016/j.apenergy.2009.11.012

Asadullah, M., 2014a. Barriers of commercial power generation using biomass gasification gas: A review. Renew. Sustain. Energy Rev. 29, 201–215. https://doi.org/10.1016/j.rser.2013.08.074

Asadullah, M., 2014b. Biomass gasification gas cleaning for downstream applications: A comparative critical review. Renew. Sustain. Energy Rev. 40, 118–132. https://doi.org/10.1016/j.rser.2014.07.132

Assembly, N.I., 2021. EU exit and the Northern Ireland Protocol [WWW Document]. NI Direct. URL https://www.nidirect.gov.uk/articles/eu-exit-and-northern-ireland-protocol (accessed 12.13.21).

Assembly, N.I., 2012. Poultry Litter Utilisation and Disposal: Alternative Technologies to Fluidised Bed Combustion [WWW Document]. URL http://www.niassembly.gov.uk/assembly-business/official-report/committee-minutes-of-evidence/session-2011-2012/may-2012/poultry-litter-utilisation-and-disposal--alternative-technologies-to-fluidised-bed-combustion-/ (accessed 6.9.21).

Augustine, M.A., Sekhar, S.J., 2019. Improvement in the Calorific Value of Producer Gas from Rice Husk with Addition of Spent Tea Waste as Secondary Fuel. Energy and Fuels 33, 12492–12498. https://doi.org/10.1021/acs.energyfuels.9b03052

Aydin, E.S., Yucel, O., Sadikoglu, H., 2017. Development of a semi-empirical equilibrium model for downdraft gasification systems. Energy 130, 86–98. https://doi.org/10.1016/j.energy.2017.04.132

Balcas, 2021. Locally Manufactured ENPLUS A1 Bulk Pellets [WWW Document]. URL https://balcasenergy.com/online-shop/bulk-wood-pellets/ (accessed 9.2.21).

Barghi, S., Yin, X., Zhu, J., Miao, Q., Wu, C., Zhou, Z., 2013. Model validation of a CFB biomass gasification model. Renew. Energy 63, 317–323. https://doi.org/10.1016/j.renene.2013.09.040

Baruah, D., Baruah, D.C., 2014. Modeling of biomass gasification: A review. Renew. Sustain. Energy Rev. 39, 806–815. https://doi.org/10.1016/j.rser.2014.07.129

Basu, P., 2018. Biomass gasification, pyrolysis and torrefaction: Practical design and theory, Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory. Academic Press, Burlington, MA. https://doi.org/10.1016/C2016-0-04056-1

BEIS, 2021. Energy Prices: Non Domestic Prices. London.

Bhattacharya, S.C., Shwe Hla, S., Pham, H.L., 2001. A study on a multi-stage hybrid gasifier-engine system. Biomass and Bioenergy 21, 445–460. https://doi.org/10.1016/S0961-9534(01)00048-4

Biagini, E., Barontini, F., Tognotti, L., 2016. Development of a bi-equilibrium model for biomass gasification in a downdraft bed reactor. Bioresour. Technol. 201, 156–165. https://doi.org/10.1016/j.biortech.2015.11.057

BPC, 2017. Meat In The UK 2017. British Poultry Council, London.
Breen, C., 2012. 10 Guidelines for Writing Policy. Cent. Ageing Res. Dev. Irel.
Briesemeister, L., Kremling, M., Fendt, S., Spliethoff, H., 2017. Air-Blown Entrained-Flow Gasification of Biomass: Influence of Operating Conditions on Tar Generation. Energy and Fuels 31, 10924–10932. https://doi.org/10.1021/acs.energyfuels.7b01801
British Standards, 2020. BSI Standards Publication Environmental management — Life cycle assessment — Principles and framework, British Standard.
Broer, K.M., Brown, R.C., 2015. The role of char and tar in determining the gas-phase partitioning of nitrogen during biomass gasification. Appl. Energy 158, 474–483. https://doi.org/10.1016/j.apenergy.2015.08.100
Brown, R.C., 2019. Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power, 2nd ed. John Wiley & Sons, Incorporated.
Bunchan, S., Poowadin, T., Trairatanasirichai, K., 2017. A Study of Throat Size Effect on Downdraft Biomass Gasifier Efficiency. Energy Procedia 138, 745–750. https://doi.org/10.1016/j.egypro.2017.10.213
Cammarota, F., Di Gregorio, F., Arena, U., Parrillo, F., Salzano, E., 2016. Removal of naphthalene by activated carbons from hot gas. Chem. Eng. J. 291, 244–253. https://doi.org/10.1016/j.cej.2016.01.081
Cardoso, J., Silva, V., Eusébio, D., 2019. Techno-economic analysis of a biomass gasification power plant dealing with forestry residues blends for electricity production in Portugal. J. Clean. Prod. 212, 741–753. https://doi.org/10.1016/j.jclepro.2018.12.054
Carver, D., 2021. Global net zero commitments [WWW Document]. House Commons Libr. URL https://commonslibrary.parliament.uk/global-net-zero-commitments/#:~:text=Japan%2C Korea%2C Canada%2C and,emissions by 78%25 by 2035. (accessed 1.11.22).
Caslin, B., 2016. Energy Efficiency on Poultry Farms [WWW Document]. Teagasc Energy Fact Sheet. URL https://www.teagasc.ie/media/website/publications/2016/06.-Energy-Efficiency-on-Poultry-Farms.pdf (accessed 6.9.21).
Cassidy, R., Thomas, I.A., Higgins, A., Bailey, J.S., Jordan, P., 2019. A carrying capacity framework for soil phosphorus and hydrological sensitivity from farm to catchment scales. Sci. Total Environ. 687, 277–286. https://doi.org/10.1016/j.scitotenv.2019.05.453
Cathcart, A., Smyth, B.M., Lyons, G., Murray, S.T., Rooney, D., Johnston, C.R., 2021. An economic analysis of anaerobic digestate fuel pellet production: can digestate fuel pellets add value to existing operations? Clean. Eng. Technol. 3, 100098. https://doi.org/10.1016/j.clet.2021.100098
Chen, G., Guo, X., Cheng, Z., Yan, B., Dan, Z., Ma, W., 2017. Air gasification of biogas-derived digestate in a downdraft fixed bed gasifier. Waste Manag. 69, 162–169. https://doi.org/10.1016/j.wasman.2017.08.001
Chen, H., Forbes, E.G.A., Archer, J., Priall, O. De, Allen, M., Johnston, C., Rooney, D., 2019. Production and characterization of granules from agricultural wastes and comparison of combustion and emission results with wood based fuels. Fuel 256, 115897. https://doi.org/10.1016/j.fuel.2019.115897
Cheng, J., 2010. Biomass to Renewable Energy processes. Boca Raton, Fla.: CRC, c2010.
Cheng, L., Wu, Z., Zhang, Z., Guo, C., Ellis, N., Bi, X., Paul Watkinson, A., Grace, J.R., 2020. Tar elimination from biomass gasification syngas with bauxite

residue derived catalysts and gasification char. Appl. Energy 258, 114088. https://doi.org/10.1016/j.apenergy.2019.114088

Cheng, S., Wang, Q., Ji, H., 2010. Simulation of hydrogen production from biomass catalytic gasification. Proc. - 2010 Int. Conf. Digit. Manuf. Autom. ICDMA 2010 2, 370–374. https://doi.org/10.1109/ICDMA.2010.335

Chiang, K.Y., Chen, Y.S., Tsai, W.S., Lu, C.H., Chien, K.L., 2012. Effect of calcium based catalyst on production of synthesis gas in gasification of waste bamboo chopsticks. Int. J. Hydrogen Energy 37, 13737–13745. https://doi.org/10.1016/j.ijhydene.2012.03.042

Chockalingam, M.P., Palanisamy, N., Padmavathy, S.R., Mohan, E., Winsly, B.W., Santhappan, J.S., 2021. Techno-economic feasibility study on the application of downdraft gasifier in small-scale red clay bricks industries. Appl. Nanosci. https://doi.org/10.1007/s13204-021-01942-0

Cohen, A., 2022. Germany And France Clash Over EU's New “Green” Classifications for Nuclear Energy and Natural Gas [WWW Document]. Forbes. URL https://www.forbes.com/sites/arielcohen/2022/01/04/germany-and-france-clash-over-eus-new-green-classifications-for-nuclear-energy-and-natural-gas/?sh=1042c41d76b7 (accessed 1.7.22).

Copa, J.R., Tuna, C.E., Silveira, J.L., Boloy, R.A.M., Brito, P., Silva, V., Cardoso, J., Eusébio, D., 2020. Techno-economic assessment of the use of syngas generated from biomass to feed an internal combustion engine, Energies. https://doi.org/10.3390/en13123097

Cummer, K.R., Brown, R.C., 2002. Ancillary equipment for biomass gasification. Biomass and Bioenergy 23, 113–128. https://doi.org/10.1016/S0961-9534(02)00038-7

Cunningham, S., 2016. Donegal plant will deal with 25,000 tonnes of litter from north a year [WWW Document]. Irish News. URL https://www.irishnews.com/business/2016/03/08/news/donegal-plant-will-deal-with-25-000-tonnes-of-litter-from-north-a-year-442167/#:~:text=Donegal plant will deal with 25%2C000 tonnes of litter from north a year,-Anaerobic digestion plants&text=AN anaerobi (accessed 1.7.22).

DAERA, 2020. The benefits of using lime to maximise soil nutrient performance [WWW Document]. URL https://www.daera-ni.gov.uk/news/benefits-using-lime-maximise-soil-nutrient-performance (accessed 7.5.21).

DAERA, 2019. The Nutrient Action Programme Regulations (Northern Ireland). Northern Ireland.

Dai, J., Saayman, J., Grace, J.R., Ellis, N., 2015. Gasification of Woody Biomass. Annu. Rev. Chem. Biomol. Eng. https://doi.org/10.1146/annurev-chembioeng-061114-123310

Dasappa, S., Paul, P.J., Mukunda, H.S., Rajan, N.K.S., Sridhar, G., Sridhar, H. V., 2004. Biomass gasification technology - A route to meet energy needs. Curr. Sci. 87, 908–916. https://doi.org/10.1124/mol.107.040352

Dayananda, B.., Manjunath, S.H., K.B, G., Sreepathi, L.., 2013. A Experimental Approach On Gasification Of Chicken Litter With Rice Husk. Int. J. Innov. Res. Sci. Eng. Technol. 2, 63–67.

DCCAE, 2017. Support Scheme for Renewable Heat - Scheme Overview. Dublin.

de Mena, B., Vera, D., Jurado, F., Ortega, M., 2017. Updraft gasifier and ORC system for high ash content biomass: A modelling and simulation study. Fuel Process. Technol. 156, 394–406. https://doi.org/10.1016/j.fuproc.2016.09.031

de Priall, O., Gogulancea, V., Brandoni, C., Hewitt, N., Johnston, C., Onofrei, G., Huang, Y., 2021. Modelling and experimental investigation of small-scale gasification CHP units for enhancing the use of local biowaste. Waste Manag. 136, 174–183. https://doi.org/10.1016/j.wasman.2021.10.012

DECC, 2019. Solar Photovoltaics Deployment.

DECC, 2009. National Renewable Energy Action Plan for the United Kingdom, Department of Energy and Climate Change.

DEFRA, 2020. UK Government GHG Conversion Factors for Company Reporting. London.

DEFRA, 2019. Agriculture in the United Kingdom 2018.

DEFRA, 2008. UK Climate Change act. UK Clim. Chang. act.

DEFRA, 2003. Energy Crop Scheme.

Demirbas, A., 1997. Calculation of higher heating values of biomass fuels. Fuel 76, 431–434. https://doi.org/10.1080/15567036.2015.1115924

Department for Environment Food and Rural Affairs, 2021. UK Statistics on Waste. London.

Department of Energy & Climate Change (DECC), 2011. UK Renewable Energy Roadmap. UK Renew. Energy Roadmap 5, 293–298. https://doi.org/10.1021/es00108a605

Devi, L., Craje, M., Thüne, P., Ptasinski, K.J., Janssen, F.J.J.G., 2005. Olivine as tar removal catalyst for biomass gasifiers: Catalyst characterization. Appl. Catal. A Gen. 294, 68–79. https://doi.org/10.1016/j.apcata.2005.07.044

Devi, L., Ptasinski, K.J., Janssen, F.J.J.G., 2002. A review of the primary measures for tar elimination in biomass gasification processes. Biomass and Bioenergy 24, 125–140. https://doi.org/10.1016/S0961-9534(02)00102-2

DfE, 2022. Other Fuels [WWW Document]. Energy. URL https://www.economy-ni.gov.uk/topics/energy/other-fuels#:~:text=Liquified Petroleum Gas (LPG),-PG is mainly&text=The market in Northern Ireland,which has some 290%2C510 consumers. (accessed 1.10.22).

DfE, 2021a. Energy Strategy for Northern Ireland: The Path to Net Zero Energy. Belfast.

DfE, 2021b. Non-Domestic Renewable Heat Incentive Scheme: Future of the Scheme. Belfast.

Dutta, A., Cheah, S., Bain, R., Feik, C., Magrini-Bair, K., Phillips, S., 2012. Integrated process configuration for high-temperature sulfur mitigation during biomass conversion via indirect gasification. Ind. Eng. Chem. Res. 51, 8326–8333. https://doi.org/10.1021/ie202797s

Elsner, W., Wysocki, M., Niegodajew, P., Borecki, R., 2017. Experimental and economic study of small-scale CHP installation equipped with downdraft gasifier and internal combustion engine. Appl. Energy 202, 213–227. https://doi.org/10.1016/j.apenergy.2017.05.148

Emami Taba, L., Irfan, M.F., Wan Daud, W.A.M., Chakrabarti, M.H., 2012. The effect of temperature on various parameters in coal, biomass and CO-gasification: A review. Renew. Sustain. Energy Rev. 16, 5584–5596. https://doi.org/10.1016/j.rser.2012.06.015

EPC, 2021a. Energy Balance of Wood Pellets [WWW Document]. Bioenergy Eur. URL https://epc.bioenergyeurope.org/energy-balance-of-wood-pellets/ (accessed 11.25.21).

EPC, 2021b. ENplus [WWW Document]. Bioenergy Eur. URL https://epc.bioenergyeurope.org/enplus/#:~:text=The standard includes quality classes,and fulfill the highest requirements.&text=Industrial pellets are not

called,certified as “EN B”. (accessed 9.16.21).
Ependi, D.R., Saleh, A.R., Sudarmanta, B., 2019. The Experimental Study of The Effect of Air Preheating in MSW Pellet Multi-Stage. J. Technol. Sci. 30, 36–40.
Eri, Q., Peng, J., Zhao, X., 2018. CFD simulation of biomass steam gasification in a fluidized bed based on a multi-composition multi-step kinetic model. Appl. Therm. Eng. 129, 1358–1368. https://doi.org/10.1016/j.applthermaleng.2017.10.122
European Biomass Associtation, 2013. Forest sustainability and carbon balance of EU importation of north american forest biomass for bioenergy production.
European Commission, 2019. Brief on biomass for energy in the European Union. EC Publ. 1–8.
European Commission, 2014. Commission Regulation (EU) No 592/2014 of 3 June 2014 amending Regulation (EU) No 142/2011 as regards the use of animal by-products and derived products as a fuel in combustion plants.
European Parliament, 2018. Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Off. J. Eur. Union 2018, 82–209.
European Parliament, 2010. Directive 2010/75/EU Industrial Emissions. Off. J. Eur. Union L334, 17–119. https://doi.org/10.3000/17252555.L_2010.334.eng
European Parliament, 2009. DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union 1, 32–38.
European Parliament, 2000. DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy. Off. J. Eur. Union L327, 35–38.
Eurostat, 2021. RAMON - Reference And Management Of Nomenclatures [WWW Document]. CONCEPTS Defin. URL https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=DSP_GLOSSARY_NOM_DTL_VIEW&StrNom=CODED2&StrLanguageCode=EN&IntKey=33012951&RdoSearch=&TxtSearch=&CboTheme=&IsTer=&ter_valid=0&IntCurrentPage=1#:~:text=Primary solid biofuels is a,renewa (accessed 4.8.21).
Farzad, S., Mandegari, M.A., Görgens, J.F., 2016. A critical review on biomass gasification, co-gasification, and their environmental assessments. Biofuel Res. J. 3, 483–495. https://doi.org/10.18331/BRJ2016.3.4.3
Feisal, A., Surjosatyo, A., 2021. Techno-Economic Analysis of Municipal Solid Waste Gasification System for Electric Generation, Case Study: City at Central Java. IOP Conf. Ser. Earth Environ. Sci. 926, 012110. https://doi.org/10.1088/1755-1315/926/1/012110
Ferreira, S., Monteiro, E., Brito, P., Vilarinho, C., 2019. A Holistic Review on Biomass Gasification Modified Equilibrium Models. Energies 12, 160. https://doi.org/10.3390/en12010160
Forestry Commission, 2021. UK Wood Production and Trade: First Release. Edinburgh.
Francois, J., Mauviel, G., Feidt, M., Rogaume, C., Rogaume, Y., Mirgaux, O., Patisson, F., Dufour, A., 2013. Modeling of a Biomass Gasification CHP Plant : Influence of Various Parameters on Energetic and Exergetic Efficiencies. Energy Fuels 27, 7398–7412. https://doi.org/dx.doi.org/10.1021/ef4011466
Freda, C., Nanna, F., Villone, A., Barisano, D., Brandani, S., Cornacchia, G., 2019.

Air gasification of digestate and its co-gasification with residual biomass in a pilot scale rotary kiln. Int. J. Energy Environ. Eng. 10, 335–346. https://doi.org/10.1007/s40095-019-0310-3

Gambarotta, A., Morini, M., Zubani, A., 2018. A non-stoichiometric equilibrium model for the simulation of the biomass gasification process. Appl. Energy 227, 119–127. https://doi.org/10.1016/j.apenergy.2017.07.135

Gao, W., Farahani, M.R., Rezaei, M., Qudair Baig, A., Jamil, M.K., Imran, M., Rezaee-Manesh, R., 2017. Kinetic modeling of biomass gasification in a micro fluidized bed. Energy Sources, Part A Recover. Util. Environ. Eff. 39, 643–648. https://doi.org/10.1080/15567036.2016.1236302

Gautam, G., Adhikari, S., Brodbeck, C., Bhavnani, S., Fasina, O., Taylor, S., 2011. Gasification of wood chips, agricultural residues, and waste in a commercial downdraft gasifier. Trans. ASABE 54, 1801–1807.

George, J., Arun, P., Muraleedharan, C., 2018. Assessment of producer gas composition in air gasification of biomass using artificial neural network model. Int. J. Hydrogen Energy 43, 9558–9568. https://doi.org/10.1016/j.ijhydene.2018.04.007

Ghassemi, H., Shahsavan-Markadeh, R., 2014. Effects of various operational parameters on biomass gasification process; A modified equilibrium model. Energy Convers. Manag. 79, 18–24. https://doi.org/10.1016/j.enconman.2013.12.007

Gillespie, G.D., Everard, C.D., Fagan, C.C., McDonnell, K.P., 2013. Prediction of quality parameters of biomass pellets from proximate and ultimate analysis. Fuel 111, 771–777. https://doi.org/10.1016/j.fuel.2013.05.002

Goswami, L., Pakshirajan, K., Pugazhenthi, G., 2020. Biological treatment of biomass gasification wastewater using hydrocarbonoclastic bacterium Rhodococcus opacus in an up-flow packed bed bioreactor with a novel waste-derived nano-biochar based bio-support material. J. Clean. Prod. 256, 120253. https://doi.org/10.1016/j.jclepro.2020.120253

Government, U., 2019. UK becomes first major economy to pass net zero emissions law [WWW Document]. Gov.uk. URL https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (accessed 5.25.20).

Guest, G., Bright, R.M., Cherubini, F., Michelsen, O., Strømman, A.H., 2011. Life cycle assessment of biomass-based combined heat and power plants: Centralized versus decentralized deployment strategies. J. Ind. Ecol. 15, 908–921. https://doi.org/10.1111/j.1530-9290.2011.00375.x

Guo, F., Liang, S., Zhao, X., Jia, X., 2019. Catalytic reforming of biomass pyrolysis tar using the low-cost steel slag as catalyst. Energy 189, 116161. https://doi.org/10.1016/j.energy.2019.116161

Hamad, M.A., Radwan, A.M., Heggo, D.A., Moustafa, T., 2016. Hydrogen rich gas production from catalytic gasification of biomass. Renew. Energy 85, 1290–1300. https://doi.org/10.1016/j.renene.2015.07.082

Han, J., Kim, H., 2008. The reduction and control technology of tar during biomass gasification/pyrolysis: An overview. Renew. Sustain. Energy Rev. 12, 397–416. https://doi.org/10.1016/j.rser.2006.07.015

Hany, A., Kocher-oberlehner, G., Robu, V., Andoni, M., 2019. Optimization of a multiple-scale renewable energy-based virtual power plant in the UK. Appl. Energy 256, 113973. https://doi.org/10.1016/j.apenergy.2019.113973

Hasler, P., Nussbaumer, T., 1999. Gas cleaning for IC engine applications from fixed bed biomass gasification. Biomass and Bioenergy 16, 385–395. https://doi.org/10.1016/S0961-9534(99)00018-5

Heller, M.C., Keoleian, G.A., Mann, M.K., Volk, T.A., 2004. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renew. Energy 29, 1023–1042. https://doi.org/10.1016/j.renene.2003.11.018

Hill, S., 2021. Mineral Products Association.

Hongrapipat, J., Saw, W.L., Pang, S., 2012. Removal of ammonia from producer gas in biomass gasification: Integration of gasification optimisation and hot catalytic gas cleaning. Biomass Convers. Biorefinery 2, 327–348. https://doi.org/10.1007/s13399-012-0047-1

Horvat, A., Pandey, D.S., Kwapinska, M., Mello, B.B., Gómez-Barea, A., Fryda, L.E., Rabou, L.P.L.M., Kwapinski, W., Leahy, J.J., 2019. Tar yield and composition from poultry litter gasification in a fluidised bed reactor: effects of equivalence ratio, temperature and limestone addition. RSC Adv. 9, 13283–13296. https://doi.org/10.1039/C9RA02548K

Huang, Y., Anderson, M., Mcilveen-wright, D., Lyons, G.A., Mcroberts, W.C., Wang, Y.D., Roskilly, A.P., Hewitt, N.J., 2015. Biochar and renewable energy generation from poultry litter waste : A technical and economic analysis based on computational simulations q. Appl. Energy 61, 656–663. https://doi.org/10.1016/j.apenergy.2015.01.029

Huang, Y., McIlveen-Wright, D.R., Rezvani, S., Huang, M.J., Wang, Y.D., Roskilly, A.P., Hewitt, N.J., 2013. Comparative techno-economic analysis of biomass fuelled combined heat and power for commercial buildings. Appl. Energy 112, 518–525. https://doi.org/10.1016/j.apenergy.2013.03.078

Huang, Y., McMullan, J.T., Williams, B.C., 2000. Influences of coal type on the performance of a pressurized fluidized bed combustion power plant. Fuel 79, 1595–1601. https://doi.org/10.1016/S0016-2361(00)00022-3

Huang, Y., Rolfe, A., Rezvani, S., Herrador, J.M.H., Franco, F., Pinto, F., Snape, C., Hewitt, N., 2020. Converting brown coal to synthetic liquid fuels through direct coal liquefaction technology: Techno-economic evaluation. Int. J. Energy Res. 44, 11827–11839. https://doi.org/10.1002/er.5823

Huang, Y., Wang, Y.D., Rezvani, S., McIlveen-Wright, D.R., Anderson, M., Hewitt, N.J., 2011. Biomass fuelled trigeneration system in selected buildings. Energy Convers. Manag. 52, 2448–2454. https://doi.org/10.1016/j.enconman.2010.12.053

Huang, Y.F., Kuan, W.H., Chang, C.C., Tzou, Y.M., 2013. Catalytic and atmospheric effects on microwave pyrolysis of corn stover. Bioresour. Technol. 131, 274–280. https://doi.org/10.1016/j.biortech.2012.12.177

Huijbregts, M., Steinmann, Z.J.N., Elshout, P.M.F.M., Stam, G., Verones, F., Vieira, M.D.M., Zijp, M., van Zelm, R., 2016. ReCiPe 2016. Natl. Inst. Public Heal. Environ. 194.

IEA, 2021. Data & Statistics [WWW Document]. URL https://www.iea.org/data-and-statistics?country=UK&fuel=Electricity and heat&indicator=ElecGenByFuel (accessed 4.8.21).

IEA, 2020. Data and statistics [WWW Document]. Total energy supply by source. URL https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy supply&indicator=TPESbySource (accessed 4.5.21).

Inayat, M., Sulaiman, S.A., Kurnia, J.C., 2017. Investigation on the effect of blending ratio and airflow rate on syngas profile produced from co-gasification of blended feedstock. MATEC Web Conf. 131.

https://doi.org/10.1051/matecconf/201713103015

Inayat, M., Sulaiman, S.A., Sanaullah, K., 2016. Effect of blending ratio on co-gasification performance of tropical plant-based biomass. IET Conf. Publ. 2016. https://doi.org/10.1049/cp.2016.1331

Indrawan, N., Simkins, B., Kumar, A., Huhnke, R.L., 2020. Economics of distributed power generation via gasification of biomass and municipal solid waste. Energies 13, 1–18. https://doi.org/10.3390/en13143703

IRENA, 2017. Renewable Energy Benefits: Understanding the Socio Economics. Abu Dhabi.

Iribarren, D., Susmozas, A., Petrakopoulou, F., Dufour, J., 2014. Environmental and exergetic evaluation of hydrogen production via lignocellulosic biomass gasification. J. Clean. Prod. 69, 165–175. https://doi.org/10.1016/j.jclepro.2014.01.068

ISEA, I.S.E.A., 2016. Jobs in Solar PV, ISEA Factsheet. Dublin.

Jangsawang, W., Laohalidanond, K., Kerdsuwan, S., 2015. Optimum Equivalence Ratio of Biomass Gasification Process Based on Thermodynamic Equilibrium Model, Energy Procedia. Elsevier B.V. https://doi.org/10.1016/j.egypro.2015.11.528

Jeswani, H.K., Whiting, A., Martin, A., Azapagic, A., Kumar, H., Whiting, A., Martin, A., Azapagic, A., 2019. Environmental and economic sustainability of poultry litter gasification for electricity and heat generation. Waste Manag. 95, 182–191. https://doi.org/10.1016/j.wasman.2019.05.053

Jeya Singh, V.C., Sekhar, S.J., 2016. Performance studies on a downdraft biomass gasifier with blends of coconut shell and rubber seed shell as feedstock. Appl. Therm. Eng. 97, 22–27. https://doi.org/10.1016/j.applthermaleng.2015.09.099

Jordan, S.N., Holland, L.B., Linnane, S.U., 2013. Spent Mushroom Compost Management and Options for Use. Dundalk.

Kamble, P., Khan, Z., Gillespie, M., Farooq, M., McCalmont, J., Donnison, I., Watson, I., 2019. Biomass gasification of hybrid seed Miscanthus in Glasgow’s downdraft gasifier testbed system. Energy Procedia 158, 1174–1181. https://doi.org/10.1016/j.egypro.2019.01.303

Kaufman Rechulski, M.D., Schildhauer, T.J., Biollaz, S.M.A., Ludwig, C., 2014. Sulfur containing organic compounds in the raw producer gas of wood and grass gasification. Fuel 128, 330–339. https://doi.org/10.1016/j.fuel.2014.02.038

Ke, C., Zhang, Y., Gao, Y., Pan, Y., Li, B., Wang, Y., Ruan, R., Ke, C., Gao, Y., Liu, S., Pan, Y., Zhou, N., Wang, Y., Fan, L., Peng, P., Li, B., Ruan, R., 2019. Syngas production from microwave-assisted air gasification of biomass : Part 2 model validation. Renew. Energy 140, 625–632. https://doi.org/10.1016/j.renene.2019.03.024

Kempegowda, R.S., Skreiberg, Ø., Tran, K.Q., 2012. Techno-economic evaluations of various biomass CHP technologies and policy measures under Norwegian conditions. Energy Procedia 20, 1–10. https://doi.org/10.1016/j.egypro.2012.03.002

Kimming, M., Sundberg, C., Nordberg, Å., Baky, A., Bernesson, S., Norén, O., Hansson, P.A., 2011. Biomass from agriculture in small-scale combined heat and power plants - A comparative life cycle assessment. Biomass and Bioenergy 35, 1572–1581. https://doi.org/10.1016/j.biombioe.2010.12.027

Kinoshita, C.M., Turn, S.Q., Overend, R.P., Bain, R.L., 2002. Power Generation Potential of Biomass Gasification Systems. J. Energy Eng. 123, 88–99. https://doi.org/10.1061/(asce)0733-9402(1997)123:3(88)

Kirsanovs, V., Blumberga, D., Veidenbergs, I., Rochas, C., Vigants, E., Vigants, G., 2017. Experimental investigation of downdraft gasifier at various conditions. Energy Procedia 128, 332–338. https://doi.org/10.1016/j.egypro.2017.08.321

Kostyniuk, A., Grilc, M., Likozar, B., 2019. Catalytic Cracking of Biomass-Derived Hydrocarbon Tars or Model Compounds To Form Biobased Benzene , Toluene , and Xylene Isomer Mixtures. https://doi.org/10.1021/acs.iecr.9b01219

Kozlov, A., Svishchev, D., Donskoy, I., Shamansky, V., Ryzhkov, A., 2015. A technique proximate and ultimate analysis of solid fuels and coal tar. J. Therm. Anal. Calorim. 122, 1213–1220. https://doi.org/10.1007/s10973-015-5134-7

Kumar, A., Jones, D.D., Hanna, M.A., 2009. Thermochemical biomass gasification: A review of the current status of the technology. Energies 2, 556–581. https://doi.org/10.3390/en20300556

Kumar, M.S., Vivekanandan, S., 2016. Effect of Design and Operating Parameters on The Gasification Process of Biomass in An Updraft Fixed Bed : A Statistical Study. Int. J. Chem. Sci. 14, 2397–2419.

Laatikainen-Luntama, J., Kurkela, E., 2015. Air-Blown CFB Gasification of Forest Residues, Demolition Wood and Crushed Wheat Straw Pellets. 22rd Int. Conf. FBC 476–486.

Ladanai, S., Vinterbäck, J., 2009. Global Potential of Sustainable Biomass for Energy.

Lewandowski, I., Clifton-brown, J.C., Scurlock, J.M.O., Huisman, W., 2008. Miscanthus : European experience with a novel energy crop 19, 209–227.

Li, B., Magoua Mbeugang, C.F., Huang, Y., Liu, D., Wang, Q., Zhang, S., 2022. A review of CaO based catalysts for tar removal during biomass gasification. Energy 244, 123172. https://doi.org/10.1016/j.energy.2022.123172

Li, D.Z., Ma, J.Y., 2009. Wood biomass gasification process modeling and optimization of the parameters of control. 2009 Chinese Control Decis. Conf. CCDC 2009 5152–5157. https://doi.org/10.1109/CCDC.2009.5194994

Li, H., Chen, Q., Zhang, X., Finney, K.N., Sharifi, V.N., Swithenbank, J., Shari, V.N., Swithenbank, J., 2012. Evaluation Of A Biomass Drying Process Using Waste Heat From Process Industries: A Case Study. Appl. Therm. Eng. 35, 71–80. https://doi.org/10.1016/j.applthermaleng.2011.10.009

Liu, N., Wang, G., Wang, J., Wang, X., Li, L., Gao, Y., 2018. Application of updraft biomass gasifier for non-ferrous metal smelting. Energy Sources, Part A Recover. Util. Environ. Eff. 41, 1012–1021. https://doi.org/10.1080/15567036.2018.1539134

López-Mosquera, M.E., Cabaleiro, F., Sainz, M.J., López-Fabal, A., Carral, E., 2008. Fertilizing value of broiler litter: Effects of drying and pelletizing. Bioresour. Technol. 99, 5626–5633. https://doi.org/10.1016/j.biortech.2007.10.034

Macauley, C., 2016. Poultry-litter waste: Stormont lends more than £7m to plant near Ballymena - BBC News [WWW Document]. URL https://www.bbc.co.uk/news/uk-northern-ireland-36577281 (accessed 12.5.18).

Malatji, P., Mamphweli, N.S., Meincken, M., 2011. The technical pre-feasibility to use briquettes made from wood and agricultural waste for gasification in a downdraft gasifier for electricity generation. J. Energy South. Africa 22, 2–7. https://doi.org/10.17159/2413-3051/2011/v22i4a3224

Malik, A., Mohapatra, S.K., 2013. Biomass-based gasifiers for internal combustion (IC) engines-A review. Sadhana - Acad. Proc. Eng. Sci. 38, 461–476. https://doi.org/10.1007/s12046-013-0145-1

Mallick, D., Mahanta, P., Moholkar, V.S., 2020. Co-gasification of biomass blends:

Performance evaluation in circulating fluidized bed gasifier. Energy 192. https://doi.org/10.1016/j.energy.2019.116682

Manara, P., Zabaniotou, A., 2014. Indicator-based economic , environmental , and social sustainability assessment of a small gasification bioenergy system fuelled with food processing residues from the Mediterranean agro-industrial sector. Sustain. Energy Technol. Assessments 8, 159–171. https://doi.org/10.1016/j.seta.2014.08.007

Maneerung, T., Kawi, S., Wang, C.H., 2015. Biomass gasification bottom ash as a source of CaO catalyst for biodiesel production via transesterification of palm oil. Energy Convers. Manag. 92, 234–243. https://doi.org/10.1016/j.enconman.2014.12.057

Martin, V., 2021. Digest of UK Energy Statistics. London.

Michailos, S., Zabaniotou, A., 2012. A small-scale agricultural biomass CHP system - The SMARt project. 2nd Int. Conf. Commun. Comput. Control Appl. CCCA 2012 1–6. https://doi.org/10.1109/CCCA.2012.6417899

Molino, A., Larocca, V., Chianese, S., Musmarra, D., 2018. Biofuels production by biomass gasification: A review. Energies 11, 1–31. https://doi.org/10.3390/en11040811

Mondal, P., Dang, G.S., Garg, M.O., 2011. Syngas production through gasification and cleanup for downstream applications - Recent developments. Fuel Process. Technol. 92, 1395–1410. https://doi.org/10.1016/j.fuproc.2011.03.021

Moradi, R., Marcantonio, V., Cioccolanti, L., Bocci, E., 2020. Integrating biomass gasification with a steam-injected micro gas turbine and an Organic Rankine Cycle unit for combined heat and power production. Energy Convers. Manag. 205, 112464. https://doi.org/10.1016/j.enconman.2019.112464

Murakami, K., Sato, M., Tsubouchi, N., Ohtsuka, Y., Sugawara, K., 2015. Steam gasification of Indonesian subbituminous coal with calcium carbonate as a catalyst raw material. Fuel Process. Technol. 129, 91–97. https://doi.org/10.1016/j.fuproc.2014.08.023

Mutlu, A.Y., Yucel, O., 2018. An artificial intelligence based approach to predicting syngas composition for downdraft biomass gasification. Energy 165, 895–901. https://doi.org/10.1016/j.energy.2018.09.131

Muzyka, R., Chrubasik, M., Stelmach, S., Sajdak, M., 2015. Preliminary studies on the treatment of wastewater from biomass gasification. Waste Manag. 44, 135–146. https://doi.org/10.1016/j.wasman.2015.07.002

mylpg.eu, 2021. Chart of Fuel Prices in United Kingdom [WWW Document]. mylpg.eu. URL mylpg.eu (accessed 12.14.21).

NAAC, 2020. Contracting Prices Guide 2020. Peterborough.

Natividad Pérez-Camacho, M., Curry, R., Cromie, T., 2019. Life cycle environmental impacts of biogas production and utilisation substituting for grid electricity, natural gas grid and transport fuels. Waste Manag. 95, 90–101. https://doi.org/10.1016/j.wasman.2019.05.045

Ng, W.C., You, S., Ling, R., Gin, K.Y.H., Dai, Y., Wang, C.H., 2017. Co-gasification of woody biomass and chicken manure: Syngas production, biochar reutilization, and cost-benefit analysis. Energy 139, 732–742. https://doi.org/10.1016/j.energy.2017.07.165

Nguyen, T.L.T., Hermansen, J.E., Nielsen, R.G., 2013. Environmental assessment of gasification technology for biomass conversion to energy in comparison with other alternatives: The case of wheat straw. J. Clean. Prod. 53, 138–148. https://doi.org/10.1016/j.jclepro.2013.04.004

NiDirect, 2021. Fuel Poverty [WWW Document]. Dep. Communities. URL https://www.communities-ni.gov.uk/topics/housing/fuel-poverty (accessed 12.29.21).

Nikoo, M.B., Mahinpey, N., 2008. Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS. Biomass and Bioenergy 32, 1245–1254. https://doi.org/10.1016/j.biombioe.2008.02.020

NISRA, 2021. Electricity Consumption and Renewable Generation in Northern Ireland: Year Ending June 2021. Belfast.

NNFCC, 2019. Anaerobic digestion deployment in the United Kingdom.

Ofgem, 2021a. About the RO [WWW Document]. URL https://www.ofgem.gov.uk/environmental-programmes/ro/about-ro (accessed 4.6.21).

Ofgem, 2021b. Environmental Programmes [WWW Document]. URL https://www.ofgem.gov.uk/environmental-programmes (accessed 2.17.21).

Olgun, H., Ozdogan, S., Yinesor, G., 2011. Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues. Biomass and Bioenergy 35, 572–580. https://doi.org/10.1016/j.biombioe.2010.10.028

Ong, Z., Cheng, Y., Maneerung, T., Yao, Z., Tong, Y.W., Wang, C.-H., Dai, Y., 2015. Co-gasification of woody biomass and sewage sludge in a fixed-bed downdraft gasifier. AIChE J. 61, 2508–2521. https://doi.org/10.1002/aic.14836

Pandey, D.S., Kwapinska, M., Gómez-Barea, A., Horvat, A., Fryda, L.E., Rabou, L.P.L.M., Leahy, J.J., Kwapinski, W., 2016. Poultry Litter Gasification in a Fluidized Bed Reactor: Effects of Gasifying Agent and Limestone Addition. Energy and Fuels 30, 3085–3096. https://doi.org/10.1021/acs.energyfuels.6b00058

Patel, M., Zhang, X., Kumar, A., 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. Renew. Sustain. Energy Rev. 53, 1486–1499. https://doi.org/10.1016/j.rser.2015.09.070

Patra, T.K., Sheth, P.N., 2015. Biomass gasification models for downdraft gasifier: A state-of-the-art review. Renew. Sustain. Energy Rev. 50, 583–593. https://doi.org/10.1016/j.rser.2015.05.012

Patuzzi, F., Prando, D., Vakalis, S., Rizzo, A.M., Chiaramonti, D., Tirler, W., Mimmo, T., Gasparella, A., Baratieri, M., 2016. Small-scale biomass gasification CHP systems: Comparative performance assessment and monitoring experiences in South Tyrol (Italy). Energy 112, 285–293. https://doi.org/10.1016/j.energy.2016.06.077

Pedroso, D.T., Braga, L.B., Machin, A.B., Silveira, J.L., Machin, E.B., Proenza, N., Conti, L., 2015. Tar reduction in downdraft biomass gasifier using a primary method. Renew. Energy 78, 478–483. https://doi.org/10.1016/j.renene.2014.12.069

Pérez-Camacho, M.N., Curry, R., Cromie, T., 2018. Life cycle environmental impacts of substituting food wastes for traditional anaerobic digestion feedstocks. Waste Manag. 73, 140–155. https://doi.org/10.1016/j.wasman.2017.12.023

Pérez, J.F., Melgar, A., Tinaut, F. V., 2013. Modeling of fixed bed downdraft biomass gasification: Application on lab-scale and industrial reactors. Int. J. Energy Res. 38, 319–338. https://doi.org/10.1002/er.3045

Perondi, D., Manera, C., Godinho, M., Zattera, A.J., 2019. Performance evaluation of natural catalysts during the thermochemical conversion of poultry litter. Process Saf. Environ. Prot. 131, 144–151. https://doi.org/10.1016/j.psep.2019.09.007

Pham, X.H., Piriou, B., Salvador, S., Valette, J., Van de Steene, L., 2018. Oxidative pyrolysis of pine wood, wheat straw and miscanthus pellets in a fixed bed. Fuel Process. Technol. 178, 226–235. https://doi.org/10.1016/j.fuproc.2018.05.029

Pinto, F., André, R.N., Franco, C., Lopes, H., Carolino, C., Costa, R., Gulyurtlu, I., 2010. Co-gasification of coal and wastes in a pilot-scale installation. 2: Effect of catalysts in syngas treatment to achieve sulphur and nitrogen compounds abatement. Fuel 89, 3340–3351. https://doi.org/10.1016/j.fuel.2010.03.017

Prasertcharoensuk, P., Hernandez, D.A., Bull, S.J., Phan, A.N., 2018. Optimisation of a throat downdraft gasifier for hydrogen production. Biomass and Bioenergy 116, 216–226. https://doi.org/10.1016/j.biombioe.2018.06.019

Prestipino, M., Salmeri, F., Cucinotta, F., Galvagno, A., 2021. Thermodynamic and environmental sustainability analysis of electricity production from an integrated cogeneration system based on residual biomass: A life cycle approach. Appl. Energy 295, 117054. https://doi.org/10.1016/j.apenergy.2021.117054

Prins, M.J., Ptasinski, K.J., Janssen, F.J.J.G., 2003. Thermodynamics of gas-char reactions: First and second law analysis. Chem. Eng. Sci. 58, 1003–1011. https://doi.org/10.1016/S0009-2509(02)00641-3

Ptasinski, K.J., Prins, M.J., Pierik, A., 2007. Exergetic evaluation of biomass gasification. Energy 32, 568–574. https://doi.org/10.1016/j.energy.2006.06.024

Puig-Arnavat, M., Bruno, J.C., Coronas, A., 2010. Review and analysis of biomass gasification models. Renew. Sustain. Energy Rev. 14, 2841–2851. https://doi.org/10.1016/j.rser.2010.07.030

Puig-Arnavat, M., Shang, L., Sárossy, Z., Ahrenfeldt, J., Henriksen, U.B., 2016. From a single pellet press to a bench scale pellet mill - Pelletizing six different biomass feedstocks. Fuel Process. Technol. 142, 27–33. https://doi.org/10.1016/j.fuproc.2015.09.022

Rafaschieri, A., Rapaccini, M., Manfrida, G., 1999. Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels. Energy Convers. Manag. 40, 1477–1493. https://doi.org/10.1016/S0196-8904(99)00076-X

Raheem, A., Liu, H., Ji, G., Zhao, M., 2019. Gasification of lipid-extracted microalgae biomass promoted by waste eggshell as CaO catalyst. Algal Res. 42, 101601. https://doi.org/10.1016/j.algal.2019.101601

Raheman, H., Ghadge, S. V., 2008. Performance of diesel engine with biodiesel at varying compression ratio and ignition timing. Fuel 87, 2659–2666. https://doi.org/10.1016/j.fuel.2008.03.006

Rakesh, N., Dasappa, S., 2018a. A critical assessment of tar generated during biomass gasification - Formation, evaluation, issues and mitigation strategies. Renew. Sustain. Energy Rev. 91, 1045–1064. https://doi.org/10.1016/j.rser.2018.04.017

Rakesh, N., Dasappa, S., 2018b. Analysis of tar obtained from hydrogen-rich syngas generated from a fixed bed downdraft biomass gasification system. Energy Convers. Manag. 167, 134–146. https://doi.org/10.1016/j.enconman.2018.04.092

Ramachandran, S., Yao, Z., You, S., Massier, T., Stimming, U., Wang, C.H., 2017. Life cycle assessment of a sewage sludge and woody biomass co-gasification system. Energy 137, 369–376. https://doi.org/10.1016/j.energy.2017.04.139

Rapagnà, S., Savuto, E., Carlo, A.D., Gallucci, K., Foscolo, P.U., 2018. Integration of biomass gasification and hot gas cleaning processes. Chem. Eng. Trans. 67, 661–666. https://doi.org/10.3303/CET1867111

RenewableUK, 2019. Wind Energy Statistics [WWW Document]. URL https://www.renewableuk.com/page/UKWEDhome/Wind-Energy-Statistics.htm (accessed 5.14.19).

Rezaiyan, J., Cheremisinoff, N.P., 2005. Gasification technologies: a primer for engineers and scientists. Taylor & Francis, London.

Rolfe, A., Huang, Y., Haaf, M., Rezvani, S., Mcliveen-wright, D., Hewitt, N.J., 2018. Integration of the calcium carbonate looping process into an existing pulverized coal- fired power plant for CO2 capture : Techno-economic and environmental evaluation. Appl. Energy 222, 169–179. https://doi.org/10.1016/j.apenergy.2018.03.160

Rollinson, A.N., Williams, O., 2016. Experiments on torrefied wood pellet: Study by gasification and characterization for waste biomass to energy applications. R. Soc. Open Sci. 3. https://doi.org/10.1098/rsos.150578

Roy, P.C., Datta, A., Chakraborty, N., 2013. An assessment of different biomass feedstocks in a downdraft gasifier for engine application. Fuel 106, 864–868. https://doi.org/10.1016/j.fuel.2012.12.053

Ruiz, J.A., Juárez, M.C., Morales, M.P., Muñoz, P., Mendívil, M.A., 2013. Biomass gasification for electricity generation: Review of current technology barriers. Renew. Sustain. Energy Rev. 18, 174–183. https://doi.org/10.1016/j.rser.2012.10.021

S.A. Sulaiman, M. Inayat, H. Basri, F.M.G. and S.M.A., 2016. Effect of blending ratio on temperature profile and syngas composition of woody biomass co-gasification. J. Mech. Eng. Sci. 10, 2176–2186. https://doi.org/https://doi.org/10.15282/jmes.10.2.2016.20.0204

Safarian, S., Unnthorsson, R., Richter, C., 2020. Techno-Economic Analysis of Power Production by Using Waste Biomass Gasification. J. Power Energy Eng. 08, 1–8. https://doi.org/10.4236/jpee.2020.86001

Salem, A.M., Paul, M.C., 2018. Biomass and Bioenergy An integrated kinetic model for downdraft gasifier based on a novel approach that optimises the reduction zone of gasifier. Biomass and Bioenergy 109, 172–181. https://doi.org/10.1016/j.biombioe.2017.12.030

Salo, K., Mojtahedi, W., 1998. Fate of alkali and trace metals in biomass gasification. Biomass and Bioenergy 15, 263–267. https://doi.org/10.1016/S0961-9534(98)00019-1

Samson, A., Mos, M., Najser, J., Daroch, M., Gallagher, J., 2018. Gasification of Miscanthus x giganteus pellets in a fixed bed pilot-scale unit. Front. Energy Res. 6, 1–10. https://doi.org/10.3389/fenrg.2018.00091

Sansaniwal, S.K., Rosen, M.A., Tyagi, S.K., 2017. Global challenges in the sustainable development of biomass gasification: An overview. Renew. Sustain. Energy Rev. 80, 23–43. https://doi.org/10.1016/j.rser.2017.05.215

Sarker, S., Nielsen, H.K., 2015. Assessing the gasification potential of five woodchips species by employing a lab-scale fixed-bed downdraft reactor. Energy Convers. Manag. 103, 801–813. https://doi.org/10.1016/j.enconman.2015.07.022

Secco, D., de Souza, S.N.M., Nogueira, C.E.C., da Silva, M.J., Frigo, E.P., Rosa, H.A., Chaves, L.I., 2016. Small-scale power generation analysis: Downdraft gasifier coupled to engine generator set. Renew. Sustain. Energy Rev. 58, 491–498. https://doi.org/10.1016/j.rser.2015.12.033

Sette, E., Pallarès, D., Johnsson, F., 2014. The influence of operating conditions and fuel-feed location on fuel residence time in an indirect gasifier. Proc. 11th Int.

Conf. Fluid. Bed Technol. CFB 2014 589–594.
Shackley, S., Hammond, J., Gaunt, J., Ibarrola, R., 2011. The feasibility and costs of biochar deployment in the UK. Carbon Manag. 2, 335–356. https://doi.org/10.4155/cmt.11.22
Sharma, S., Basu, S., Shetti, N.P., Kamali, M., Walvekar, P., Aminabhavi, T.M., 2020. Waste-to-energy nexus: A sustainable development. Environ. Pollut. 267, 115501. https://doi.org/10.1016/j.envpol.2020.115501
Shayan, E., Zare, V., Mirzaee, I., 2018. Hydrogen production from biomass gasification; a theoretical comparison of using different gasification agents. Energy Convers. Manag. 159, 30–41. https://doi.org/10.1016/j.enconman.2017.12.096
Shepherd, A., Littleton, E., Clifton-Brown, J., Martin, M., Hastings, A., 2020. Projections of global and UK bioenergy potential from Miscanthus × giganteus—Feedstock yield, carbon cycling and electricity generation in the 21st century. GCB Bioenergy 12, 287–305. https://doi.org/10.1111/gcbb.12671
Shie, J.L., Lee, C.H., Chen, C.S., Lin, K.L., Chang, C.Y., 2014. Scenario comparisons of gasification technology using energy life cycle assessment for bioenergy recovery from rice straw in Taiwan. Energy Convers. Manag. 87, 156–163. https://doi.org/10.1016/j.enconman.2014.06.085
Shunichi Nakada, Deger Saygin, D.G., 2014. Global Bioenergy supply and demand projections. A working paper for REmap 2030, GCB Bioenergy.
Siegl, S., Laaber, M., Holubar, P., 2012. Green electricity from biomass, part II: Environmental impacts considering avoided burdens from replacing the conventional provision of additional functions. Waste and Biomass Valorization 3, 1–21. https://doi.org/10.1007/s12649-011-9091-5
SimaPro, 2019. SimaPro | The World's Leading LCA Software [WWW Document]. 2019. URL https://simapro.com/ (accessed 4.2.19).
Singh, V.C.J., Sekhar, S.J., Thyagarajan, K., 2015. Analytical and experimental studies on a 50 kWth downdraft gasifier with biomass blends available in the hilly regions of South India. Lat. Am. Appl. Res. 45, 145–155.
Slade, R., Bauen, A., Gross, R., 2010. The UK bio-energy resource base to 2050: estimates, assumptions, and uncertainties, UK ENERGY RESEARCH CENTRE. London.
Susastriawan, A.A.P., Saptoadi, H., Purnomo, 2020. Utilization of rice husk–sawdust as blending feedstock of small-scale downdraft gasifier. Energy Sources, Part A Recover. Util. Environ. Eff. 42, 700–708. https://doi.org/10.1080/15567036.2019.1600620
Susastriawan, A.A.P., Saptoadi, H., Purnomo, 2017. Small-scale downdraft gasifiers for biomass gasification: A review. Renew. Sustain. Energy Rev. 76, 989–1003. https://doi.org/10.1016/j.rser.2017.03.112
Tamili, N., Chuan, L.K., Sulaiman, S.A., Moni, M.N.Z., Inayat, M., Lo, M.Y.K., 2018. Co-Gasification of Corn and Coconut Residues in Downdraft Gasifier. MATEC Web Conf. 225, 1–6. https://doi.org/10.1051/matecconf/201822504001
Tańczuk, M., Junga, R., Werle, S., Chabiński, M., Ziółkowski, T., Ziółkowski, 2016. Experimental analysis of the fixed bed gasification process of the mixtures of the chicken manure with biomass. Renew. Energy 136, 1055–1063. https://doi.org/10.1016/j.renene.2017.05.074
Taufiq-Yap, Y.H., Wong, P., Marliza, T.S., Nurul Suziana, N.M., Tang, L.H., Sivasangar, S., 2013. Hydrogen production from wood gasification promoted by waste eggshell catalyst. Int. J. Energy Res. 37, 1866–1871.

https://doi.org/10.1002/er.3003

The Scottish Agricultural College, 2008. WILLOW SHORT ROTATION COPPICE : Is it commercially viable ? Agric. Rural Dev. Factsheet 1–5.

Tripathi, L., Dubey, A.K., Gangil, S., Singh, P.L., 2013. Waste water treatment of biomass based power plant. Int. J. ChemTech Res. 5, 761–764.

Trninić, M., Stojiljković, D., Manić, N., Skreiberg, Ø., Wang, L., Jovović, A., 2020. A mathematical model of biomass downdraft gasification with an integrated pyrolysis model. Fuel 265, 116867. https://doi.org/10.1016/j.fuel.2019.116867

V. Siemons, R., 2001. Identifying a role for biomass gasification in rural electrification in developing countries: The economic perspective. Biomass and Bioenergy 20, 271–285. https://doi.org/10.1016/S0961-9534(00)00085-4

Vaezi, M., Passandideh-Fard, M., Moghiman, M., Charmchi, M., 2012. On a methodology for selecting biomass materials for gasification purposes. Fuel Process. Technol. 98, 74–81. https://doi.org/10.1016/j.fuproc.2012.01.026

Valderrama Rios, M.L., González, A.M., Lora, E.E.S., Almazán del Olmo, O.A., 2018. Reduction of tar generated during biomass gasification: A review. Biomass and Bioenergy 108, 345–370. https://doi.org/10.1016/j.biombioe.2017.12.002

Vera, D., Mena, B. De, Jurado, F., Schories, G., 2013. Study of a downdraft gasifier and gas engine fueled with olive oil industry wastes. Appl. Therm. Eng. 51, 119–129. https://doi.org/10.1016/j.applthermaleng.2012.09.012

Waldheim, L., Nilsson, T., 2001. Heating Value of Gases from Biomas Gasification. Nyköping.

Wang, Shifeng, Wang, Sicong, Hastings, A., Pogson, M., Smith, P., 2012. Economic and greenhouse gas costs of Miscanthus supply chains in the United Kingdom. GCB Bioenergy 4, 358–363. https://doi.org/10.1111/j.1757-1707.2011.01125.x

Wang, Y., Yan, L., 2008. CFD studies on biomass thermochemical conversion. Int. J. Mol. Sci. 9, 1108–1130. https://doi.org/10.3390/ijms9061108

Wang, Z., Wang, F., Cao, J., Wang, J., 2010. Pyrolysis of pine wood in a slowly heating fixed-bed reactor: Potassium carbonate versus calcium hydroxide as a catalyst. Fuel Process. Technol. 91, 942–950. https://doi.org/10.1016/j.fuproc.2009.09.015

Ward, S., 2022. Forestry Statistics and Forestry Facts & Figures [WWW Document]. For. Res. URL https://www.forestresearch.gov.uk/tools-and-resources/statistics/forestry-statistics/ (accessed 1.7.22).

Watson, J., Zhang, Y., Si, B., Chen, W., Souza, R. De, 2018. Gasification of biowaste: A critical review and outlooks. Renew. Sustain. Energy Rev. 83, 1–17. https://doi.org/10.1016/j.rser.2017.10.003

WBA, 2016. Global Biomass Potential Towards 2035.

Weiland, F., Nilsson, P.T., Wiinikka, H., Gebart, R., Gudmundsson, A., Sanati, M., 2014. Online characterization of syngas particulates using aerosol mass spectrometry in entrained-flow biomass gasification. Aerosol Sci. Technol. 48, 1145–1155. https://doi.org/10.1080/02786826.2014.965772

Welfle, A., 2017. Balancing growing global bioenergy resource demands - Brazil's biomass potential and the availability of resource for trade. Biomass and Bioenergy 105, 83–95. https://doi.org/10.1016/j.biombioe.2017.06.011

Whitty, K.J., Zhang, H.R., Eddings, E.G., 2008. Emissions from syngas combustion. Combust. Sci. Technol. 180, 1117–1136. https://doi.org/10.1080/00102200801963326

Widjaya, E.R., Chen, G., Bowtell, L., Hills, C., 2018. Gasification of non-woody biomass: A literature review. Renew. Sustain. Energy Rev. 89, 184–193. https://doi.org/10.1016/j.rser.2018.03.023

Wolff, D., Walsh, E., McDonnell, K.P., 2013. Practical Experience with Woody Biomass in a Down-Draft Gasifier. J. Technol. Innov. Renew. Energy 2, 47–52. https://doi.org/10.6000/1929-6002.2013.02.01.6

Wood, S.R., Rowley, P.N., 2011. A techno-economic analysis of small-scale, biomass-fuelled combined heat and power for community housing. Biomass and Bioenergy 35, 3849–3858. https://doi.org/10.1016/j.biombioe.2011.04.040

Woolcock, P.J., Brown, R.C., 2013. A review of cleaning technologies for biomass-derived syngas. Biomass and Bioenergy 52, 54–84. https://doi.org/10.1016/j.biombioe.2013.02.036

WRAP, 2020. Our Plan for a Sustainable Planet. London.

WRAP, 2019a. WRAP and the circular economy | WRAP UK [WWW Document]. URL http://www.wrap.org.uk/about-us/about/wrap-and-circular-economy (accessed 4.2.19).

WRAP, 2019b. No Title [WWW Document]. WRAP Circ. Econ. URL http://www.wrap.org.uk/about-us/about/wrap-and-circular-economy (accessed 4.1.19).

Wu, H., Wang, X.-S., Dong, L., Asadullah, M., Li, C.-Z., Zhang, S., 2012. An advanced biomass gasification technology with integrated catalytic hot gas cleaning. Fuel 108, 409–416. https://doi.org/10.1016/j.fuel.2012.11.043

Yan, W.C., Shen, Y., You, S., Sim, S.H., Luo, Z.H., Tong, Y.W., Wang, C.H., 2018. Model-based downdraft biomass gasifier operation and design for synthetic gas production. J. Clean. Prod. 178, 476–493. https://doi.org/10.1016/j.jclepro.2018.01.009

Yang, J., Chen, B., 2014. Global warming impact assessment of a crop residue gasification project — A dynamic LCA perspective. Appl. Energy 122, 269–279. https://doi.org/10.1016/j.apenergy.2014.02.034

Yang, J., Kaewpanha, M., Karnjanakom, S., Guan, G., Hao, X., Abudula, A., 2016. Steam reforming of biomass tar over calcined egg shell supported catalysts for hydrogen production. Int. J. Hydrogen Energy 41, 6699–6705. https://doi.org/10.1016/j.ijhydene.2016.03.056

Yu, J., Guo, Q., Gong, Y., Ding, L., Wang, J., Yu, G., 2021. A review of the effects of alkali and alkaline earth metal species on biomass gasification. Fuel Process. Technol. 214, 106723. https://doi.org/10.1016/j.fuproc.2021.106723

Zabaniotou, A., Mitsakis, P., Mertzis, D., Tsiakmakis, S., Manara, P., Samaras, Z., 2013. Bioenergy technology: Gasification with internal combustion engine application. Energy Procedia 42, 745–753. https://doi.org/10.1016/j.egypro.2013.11.077

Zhang, R., Brown, R.C., Suby, A., Cummer, K., 2004. Catalytic destruction of tar in biomass derived producer gas. Energy Convers. Manag. 45, 995–1014. https://doi.org/10.1016/j.enconman.2003.08.016

Zhao, Z., Chen, Y., Chang, R., 2016. How to stimulate renewable energy power generation effectively ? e China ' s incentive approaches and lessons. Renew. Energy 92, 147–156. https://doi.org/10.1016/j.renene.2016.02.001

Appendices

Table A.1 Poultry Litter Scenarios Capital Cost: Values for all Capital Costs calculated using (Copa et al., 2020; Elsner et al., 2017; Jeswani et al., 2019)

120kW		**36kW**		**21kW**	
Gasifier & 120kW ICE		***Gasifier & 26kW ORC***		***Gasifier, 21kW ICE + Boiler***	
Feedstock Preparation	£25,835	Feedstock Preparation	£20,353	Feedstock Preparation	£19,661
Gasification System	£129,178	Gasification System	£101,767	Gasification System	£98,292
Power Generation Process (ICE-based)	£115,929	Power Generation Process (ORC-based)	£83,064	Power Generation Process (ICE-based)	£17,661
Grid Connection Cost	£51,558	Grid Connection Cost	£14,137	Grid Connection Cost	£0
Heat Recovery Circuit	£52,758	Heat Recovery Circuit	£50,709	Heat Recovery Circuit	£20,831
Total Equipment Cost	**£375,257**	Gas Burner	£18,686	Biomass Boiler (150kW)	£21,579
		Total Equipment Cost	**£288,716**	**Total Equipment Cost**	**£178,024**
Integration Cost	£75,051	Integration Cost	£57,743	Integration Cost	£35,605
Contingency	£37,526	Contingency	£28,872	Contingency	£17,802
Total Installed Cost	£487,835	Total Installed Cost	£375,331	Total	£231,431

Table A.2 BESP for Single Feedstock Scenarios

	Poultry Litter			**Digestate**			**Miscanthus**		
	120kW (ICE - CHP)	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*	*120kW (ICE - CHP)*	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*	*120kW (ICE - CHP)*	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*
	£/MWh			*£/MWh*			*£/MWh*		
Base Case	123.85	317.60	336.00	121.63	315.31	329.04	122.47	313.48	330.78
Case 1	93.84	247.10	221.74	101.62	266.97	253.33	151.13	380.13	437.44
Case 2	53.83	153.26	73.15	75.62	202.51	152.34	122.47	313.48	330.78
Case 3	42.92	119.66	9.25	64.75	168.18	87.62	111.35	279.69	265.69
Case 4	30.08	91.92	-38.36	52.09	139.89	39.00	98.03	251.91	218.08
Case 5	25.38	77.50	-65.73	47.42	125.15	11.35	93.25	237.4	190.16
Case 6	N/A			N/A			38.31	109.59	-28.93

Table A.3 Anaerobic Digestate Scenarios Capital Cost

120kW		**36kW**		**21kW**	
Gasifier & 120kW ICE		***Gasifier & 26kW ORC***		***Gasifier, 21kW ICE + Boiler***	
Feedstock Preparation	£19,610	Feedstock Preparation	£15,758	Feedstock Preparation	£15,118
Gasification System	£128,636	Gasification System	£103,369	Gasification System	£99,155
Power Generation Process (ICE-based)	£115,929	Power Generation Process (ORC-based)	£83,064	Power Generation Process (ICE-based)	£17,661
Grid Connection Cost	£51,558	Grid Connection Cost	£14,758	Grid Connection Cost	£0
Heat Recovery Circuit	£52,758	Heat Recovery Circuit	£50,709	Heat Recovery Circuit	£20,831
Total Equipment Cost	**£368,489**	Gas Burner	£18,686	Biomass Boiler (150kW)	£21,579
		Total Equipment Cost	**£286,344**	**Total Equipment Cost**	**£174,344**
Integration Cost	£73,698	Integration Cost	£57,269	Integration Cost	£34,869
Contingency	£36,849	Contingency	£28,634	Contingency	£17,434
Total Installed Cost	£479,036	Total Installed Cost	£372,247	Total	£226,647

Table A.4 Miscanthus Scenarios Capital Cost

120kW		**36kW**		**21kW**	
Gasifier & 120kW ICE		***Gasifier & 26kW ORC***		***Gasifier, 21kW ICE + Boiler***	
Feedstock Preparation	£20,598	Feedstock Preparation	£16,125	Feedstock Preparation	£15,694
Gasification System	£130,639	Gasification System	£102,272	Gasification System	£99,524
Power Generation Process (ICE-based)	£115,929	Power Generation Process (ORC-based)	£83,064	Power Generation Process (ICE-based)	£17,661
Grid Connection Cost	£51,558	Grid Connection Cost	£14,115	Grid Connection Cost	£0
Heat Recovery Circuit	£52,758	Heat Recovery Circuit	£50,709	Heat Recovery Circuit	£20,831
Total Equipment Cost	**£371,481**	Gas Burner	£18,686	Biomass Boiler (150kW)	£21,579
		Total Equipment Cost	**£284,971**	**Total Equipment Cost**	**£175,290**
Integration Cost	£74,296	Integration Cost	£56,994	Integration Cost	£35,058
Contingency	£37,148	Contingency	£28,497	Contingency	£17,529
Total Installed Cost	£482,925	Total Installed Cost	£370,462	Total	£227,877

Table A.5 80/20 Blend Scenario Technical Parameters

	120kW	**36kW**	**21kW**
CV (kWh/kg)	4.36		
Input (kg/h)	116.00	81.00	75.00
Thermal Input (kW_{th}/h)	506.27	353.52	327.33
Gasification Efficiency (%)	***68.0%***	***68.0%***	***68.0%***
Producer Gas Energy (kWh/h)	344.26	240.39	222.58
To CHP System (%)	***100.0%***	***100.0%***	***32.3%***
Total CHP Energy Input (kWh/h)	*344.26*	*240.39*	*71.89*
Heat Recovery Efficiency (%)	***85.0%***	***85.0%***	***85.0%***
Thermal Energy Output (kWh_{th}/h)	190.2	173.7	42.8
Electrical Efficiency (%)	***35.0%***	***15.0%***	***30.0%***
Electrical Power (kWh_e/h)	120.49	36.06	21.57
Drying Heat Consumption (kWh/h)	23.98	16.74	15.50
Electric Consumption (kWh_e/year)	140,000	140,000	140,000
Heat Used (kWh_{th}/year)	1,117,530	1,070,000	1,061,851
Heat Difference (kWh/year)	132,119	71,092	60,719
Electric for Export (kWh/year)	651,633	96,905	1,704
Producer Gas Energy Diverted to Boiler	**-**	**-**	**67.7%**
Boiler Thermal Energy (kW_{th}/h)	-	-	150.69
Boiler Efficiency (%)	**-**	**-**	**85.0%**
Thermal Energy from Boiler (kWh_{th}/year)	-	-	841,524
Sent to the grid (kWh/h)	99.2	14.7	-
On-Site Consumption (kWh/h)	21	21	21

Table A.6 80/20 Blend Scenarios Capital Cost

120kW		**36kW**		**21kW**	
Gasifier & 120kW ICE		***Gasifier & 26kW ORC***		***Gasifier, 21kW ICE + Boiler***	
Feedstock Preparation	£25,246	Feedstock Preparation	£19,776	Feedstock Preparation	£19,143
Gasification System	£130,441	Gasification System	£102,177	Gasification System	£98,894
Power Generation Process (ICE-based)	£115,929	Power Generation Process (ORC-based)	£83,064	Power Generation Process (ICE-based)	£17,661
Grid Connection Cost	£51,558	Grid Connection Cost	£14,109	Grid Connection Cost	£0
Heat Recovery Circuit	£52,758	Heat Recovery Circuit	£50,709	Heat Recovery Circuit	£20,831
Total Equipment Cost	**£375,931**	Gas Burner	£18,686	Biomass Boiler (150kW)	£21,579
		Total Equipment Cost	**£288,520**	**Total Equipment Cost**	**£178,109**
Integration Cost	£75,186	Integration Cost	£57,704	Integration Cost	£35,622
Contingency	£37,593	Contingency	£28,852	Contingency	£17,811
Total Installed Cost	£488,710	Total Installed Cost	£375,076	Total	£231,542

Table A.7 BESP for Blended Feedstock Scenarios

Poultry Litter: Wood Pellet Blend									
	80/20			**60/40**			**40/60**		
	120kW (ICE - CHP)	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*	*120kW (ICE - CHP)*	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*	*120kW (ICE - CHP)*	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*
	£/MWh			*£/MWh*			*£/MWh*		
Base Case	124.01	317.60	336.00	123.55	316.54	333.44	123.55	316.04	332.89
Case 1	125.98	320.80	340.76	130.17	327.54	348.91	134.15	333.25	357.79
Case 2	87.32	230.80	197.94	93.50	237.30	213.68	98.83	251.04	228.33
Case 3	76.22	197.02	133.48	82.47	203.70	149.78	87.73	217.35	164.43
Case 4	62.9	169.28	85.88	69.15	175.96	102.17	74.41	189.51	116.82
Case 5	58.14	154.77	58.23	64.41	161.50	74.71	70.36	175.05	89.36

Table A.8 Payback Period for Poultry Litter Blended Feedstock Scenarios

	80/20			**60/40**			**40/60**		
	120kW (ICE - CHP)	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*	*120kW (ICE - CHP)*	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*	*120kW (ICE - CHP)*	*36kW (ORC - CHP)*	*21kW (Standalone ICE)*
	Payback (Years)			*Payback (Years)*			*Payback (Years)*		
Base Case	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3
Case 1	20.7	20.2	20.6	22.0	22.0	22.0	22.0	22.0	22.0
Case 2	8.9	9.2	7.4	9.8	9.7	8.0	10.7	10.6	8.6
Case 3	7.7	7.8	5.8	8.4	8.1	6.2	9.0	8.7	6.6
Case 4	6.7	6.9	5.1	7.1	7.1	5.3	7.6	7.6	5.6

Table A.9 60/40 Blend Scenario Technical Parameters

	120kW	**36kW**	**21kW**
CV (kWh/kg)	4.57		
Input (kg/h)	110.00	77.00	71.00
Thermal Input ($\mathrm{kW_{th}}$/h)	502.70	351.89	324.47
Gasification Efficiency (%)	***68.0%***	***68.0%***	***68.0%***
Producer Gas Energy (kWh/h)	341.84	239.29	220.64
To CHP System (%)	***100.0%***	***100.0%***	***32.3%***
Total CHP Energy Input (kWh/h)	*341.84*	*239.29*	*71.27*
Heat Recovery Efficiency (%)	***85.0%***	***85.0%***	***85.0%***
Thermal Energy Output ($\mathrm{kWh_{th}}$/h)	188.9	172.9	42.4
Electrical Efficiency (%)	***35.0%***	***15.0%***	***30.0%***
Electrical Power ($\mathrm{kWh_{e}}$/h)	119.64	35.89	21.38
Drying Heat Consumption (kWh/h)	22.74	15.92	8.81
Electric Consumption ($\mathrm{kWh_{e}}$/year)	140,000	140,000	140,000
Heat Used ($\mathrm{kWh_{th}}$/year)	1,109,382	1,064,567	1,017,852
Heat Difference (kWh/year)	131,457	71,278	94,914
Electric for Export (kWh/year)	646,052	95,816	466
Producer Gas Energy Diverted to Boiler	**-**	**-**	**67.7%**
Boiler Thermal Energy ($\mathrm{kW_{th}}$/h)	-	-	149.37
Boiler Efficiency (%)	**-**	**-**	**85.0%**
Thermal Energy from Boiler ($\mathrm{kWh_{th}}$/year)	-	-	834,174
Sent to the grid (kWh/h)	98.3	14.6	-
On-Site Consumption (kWh/h)	21	21	21

Table A.10 60/40 Blend Scenarios Capital Cost

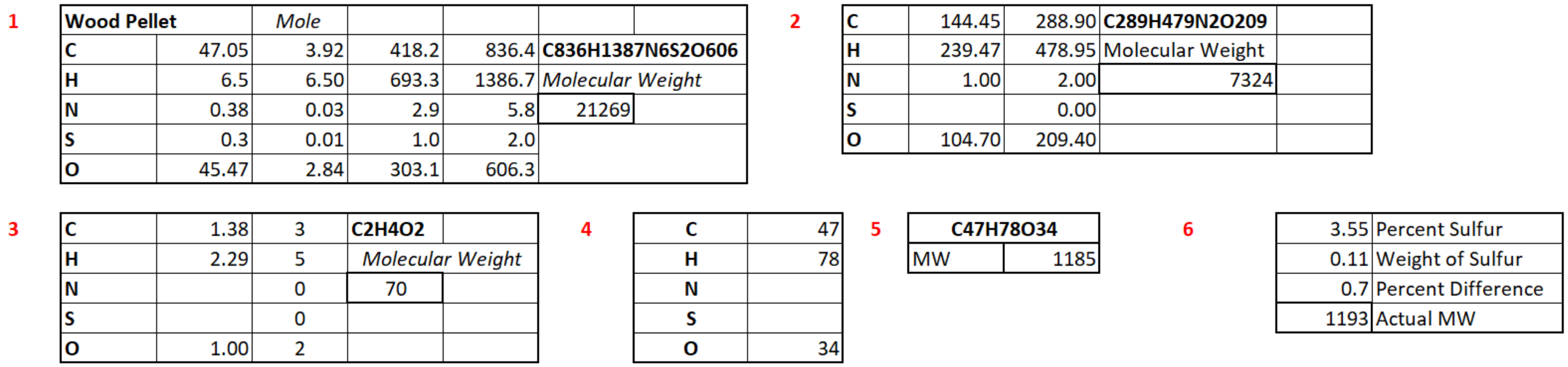
120kW		**36kW**		**21kW**	
Gasifier & 120kW ICE		***Gasifier & 26kW ORC***		***Gasifier, 21kW ICE + Boiler***	
Feedstock Preparation	£24,351	Feedstock Preparation	£19,107	Feedstock Preparation	
Gasification System	£129,815	Gasification System	£101,857	Gasification System	£98,306
Power Generation Process (ICE-based)	£115,929	Power Generation Process (ORC-based)	£83,064	Power Generation Process (ICE-based)	£17,661
Grid Connection Cost	£51,558	Grid Connection Cost	£14,083	Grid Connection Cost	£0
Heat Recovery Circuit	£52,758	Heat Recovery Circuit	£50,709	Heat Recovery Circuit	£20,831
Total Equipment Cost	**£374,410**	Gas Burner	£18,686	Biomass Boiler (150kW)	£21,579
		Total Equipment Cost	**£287,505**	**Total Equipment Cost**	**£176,820**
Integration Cost	£74,882	Integration Cost	£57,501	Integration Cost	£35,364
Contingency	£37,441	Contingency	£28,751	Contingency	£17,682
Total Installed Cost	£486,732	Total Installed Cost	£373,757	Total	£229,867

Table A.11 40/60 Blend Scenario Technical Parameters

	120kW	**36kW**	**21kW**
CV (kWh/kg)		4.77	
Input (kg/h)	106.00	74.00	68.00
Thermal Input (kW$_{th}$/h)	505.96	353.21	324.58
Gasification Efficiency (%)	***68.0%***	***68.0%***	***68.0%***
Producer Gas Energy (kWh/h)	344.05	240.19	220.71
To CHP System (%)	***100.0%***	***100.0%***	***32.3%***
Total CHP Energy Input (kWh/h)	*344.05*	*240.19*	*71.29*
Heat Recovery Efficiency (%)	***85.0%***	***85.0%***	***85.0%***
Thermal Energy Output (kWh$_{th}$/h)	190.1	173.5	42.4
Electrical Efficiency (%)	***35.0%***	***15.0%***	***30.0%***
Electrical Power (kWh$_{e}$/h)	120.42	36.03	21.39
Drying Heat Consumption (kWh/h)	21.91	15.30	14.06
Electric Consumption (kWh$_{e}$/year)	140,000	140,000	140,000
Heat Used (kWh$_{th}$/year)	1,103,950	1,060,493	1,052,345
Heat Difference (kWh/year)	144,925	79,626	60,781
Electric for Export (kWh/year)	651,143	96,703	512
Producer Gas Energy Diverted to Boiler	**-**	**-**	**67.7%**
Boiler Thermal Energy (kW$_{th}$/h)	-	-	149.42
Boiler Efficiency (%)	**-**	**-**	**85.0%**
Thermal Energy from Boiler (kWh$_{th}$/year)	-	-	834,444
Sent to the grid (kWh/h)	99.1	14.7	-
On-Site Consumption (kWh/h)	21	21	21

Table A.12 40/60 Blend Scenarios Capital Cost

120kW		**36kW**		**21kW**	
Gasifier & 120kW ICE		***Gasifier & 26kW ORC***		***Gasifier, 21kW ICE + Boiler***	
Feedstock Preparation	£23,745	Feedstock Preparation	£18,597	Feedstock Preparation	£17,910
Gasification System	£130,386	Gasification System	£102,117	Gasification System	£98,328
Power Generation Process (ICE-based)	£115,929	Power Generation Process (ORC-based)	£83,064	Power Generation Process (ICE-based)	£17,661
Grid Connection Cost	£51,558	Grid Connection Cost	£14,096	Grid Connection Cost	£0
Heat Recovery Circuit	£52,758	Heat Recovery Circuit	£50,709	Heat Recovery Circuit	£20,831
Total Equipment Cost	**£374,375**	Gas Burner	£18,686	Biomass Boiler (117kW)	£21,579
		Total Equipment Cost	**£287,269**	**Total Equipment Cost**	**£176,309**
Integration Cost	£74,875	Integration Cost	£57,454	Integration Cost	£35,262
Contingency	£37,437	Contingency	£28,727	Contingency	£17,631
Total Installed Cost	£486,687	Total Installed Cost	£373,450	Total	£229,201



1

Wood Pellet		*Mole*				
C	47.05	3.92	418.2	836.4	**C836H1387N6S2O606**	
H	6.5	6.50	693.3	1386.7	*Molecular Weight*	
N	0.38	0.03	2.9	5.8	21269	
S	0.3	0.01	1.0	2.0		
O	45.47	2.84	303.1	606.3		

2

C	144.45	288.90	**C289H479N2O209**	
H	239.47	478.95	Molecular Weight	
N	1.00	2.00	7324	
S		0.00		
O	104.70	209.40		

3

C	1.38	3	**C2H4O2**	
H	2.29	5	*Molecular Weight*	
N		0	70	
S		0		
O	1.00	2		

4

C	47
H	78
N	
S	
O	34

5

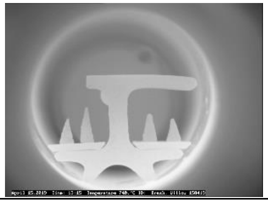
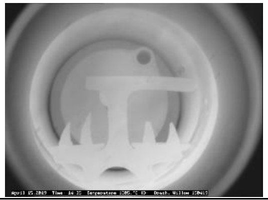
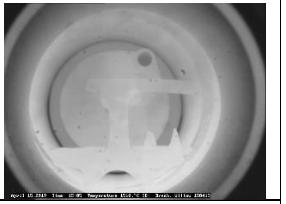
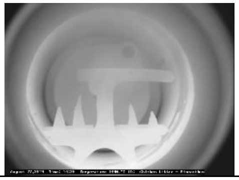
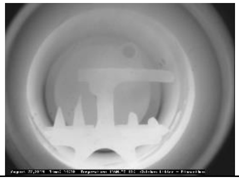
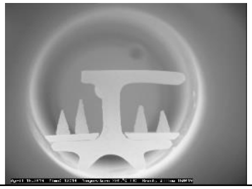
C47H78O34	
MW	1185

6

3.55	Percent Sulfur
0.11	Weight of Sulfur
0.7	Percent Difference
1193	Actual MW

Figure A.1 Molecular Weight Estimation Calculation Example

Table A.13 Results from Ash Melting Analysis

	Original	Shrinkage	Deformation	Hemisphere	Flow
Arboricultural Arisings	600°C 	740 °C 	1305°C 	1485°C 	1510°C 
Miscanthus	600°C 	845°C 	1090°C 	1160°C 	1285°C 
Poultry Litter	600°C 	1215°C 	1530°C 	N/A	N/A
Willow	600°C 	730°C 	1290°C 	1525°C 	1535°C