Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation

Adams, P.W.R.*[a,b] & McManus, M.C.[a,b]

[a] Department of Mechanical Engineering, Faculty of Engineering and Design,

[b] Institute for Sustainable Energy and Environment (I·SEE)

University of Bath, Claverton Down, Bath, BA2 7AY, United Kingdom

* Corresponding Author: paul.adams@bath.edu

Tel: +44 (0) 7815 152 594

Abstract

Biomass gasification is regarded as a sustainable energy technology used for waste management and producing renewable fuel. Using the techniques of life cycle assessment (LCA) and net energy analysis this study quantifies the energy, resource, and emission flows. The purpose of the research is to assess the net energy produced and potential environmental effects of biomass gasification using wood waste. This paper outlines a case study that uses waste wood from a factory for use in an entrained flow gasification CHP plant. Results show that environmental impacts may arise from toxicity, particulates, and resource depletion. Toxicity is a potential issue through the disposal of ash. Particulate matter arises from the combustion of syngas therefore effective gas cleaning and emission control is required. Assessment of resource depletion shows natural gas, electricity, fossil fuels, metals, and water are all crucial components of the system. The energy gain ratio is 4.71$MJ_{delivered}/MJ_{primary}$ when only electricity is considered, this increases to 13.94$MJ_{delivered}/MJ_{primary}$ when 100% of the available heat is utilised. Greenhouse gas emissions are very low (7-15gCO_2-e/kWh_e) although this would increase if the biomass feedstock was not a waste and needed to be cultivated and transported. Overall small-scale biomass gasification is an attractive technology if the high capital costs and operational difficulties can be overcome, and a consistent feedstock source is available.

Highlights

- **Life Cycle Assessment performed to assess environmental effects of biomass gasification**
- **Environmental impacts can include toxicity, particulates, and resource depletion**
- **Net energy analysis shows very positive energy gains and short energy payback period**
- **Low greenhouse gas emissions compared to fossil fuels and other bioenergy systems**
- **Efficient waste management technology producing renewable heat and electricity**

Keywords: Life cycle assessment, LCA, bioenergy, gasification, CHP, industry, greenhouse gas, waste management

1. Introduction

Industry is a major contributor to world energy demand and carbon dioxide (CO_2) emissions. In 2005 the industrial sector accounted for almost one-third of world primary energy use and approximately 25% of world energy and process-related CO_2 emissions [1]. The relationship between the GDP of a country and its energy consumption, known as the energy intensity of industry (or energy use per unit of economic output) demonstrates that a certain level of energy is required to provide the continued desire for economic growth and development. Nonetheless it is evident that most current methods of energy production entail adverse environmental impacts on a local, regional and global scale and often involve considerable resource uncertainties [3]. Solutions are therefore required which provide the energy required with minimal environmental impacts.

1.1. Potential value of bioenergy and biomass gasification

Renewable energy is of growing importance in addressing environmental and security concerns over fossil fuel use. Biomass can be used as a substitute for fossil fuels and may reduce the dependence on imports and/or the greenhouse gas emissions. Other benefits of bioenergy could include enhancing the rural economy, allowing industry to reduce waste and improve efficiency, and providing a more sustainable energy source to industry alongside more localised energy production. Consequently, the use of bioenergy in industry across Europe is expected to increase significantly over the next decade and beyond [4]. Nonetheless consideration also needs to potential negative effects of bioenergy including land use change, food versus fuel debate, resources required for bioenergy, imports of unsustainable biomass, and other complex issues [5, 6].

Wood and other forms of biomass including energy crops and industrial, agricultural and forestry wastes are some of the main renewable energy resources available [7]. Biomass gasification adds value to low or negative value feedstock by converting them to marketable fuels and products. A good example of this is the gasification of waste to produce heat and power, where the alternative could be landfill, incurring landfill tax, a gate-fee, transportation costs, and potentially increasing greenhouse gas emissions from fugitive landfill emissions (CH_4 having a much higher global warming potential (GWP) than CO_2).

Gasification is considered one of the more promising technologies in biomass applications [8]. Advantages can include higher efficiencies compared to combustion, perspectives in fuel synthesis, and application to a wide range of biomass feedstocks. There are some successful gasification facilities which operate in Europe and globally including the Güssing plant (Austria), the Viking gasifier (Denmark), and the Berkes gasifier technology (Uruguay) [9]. However, current utilisation of biomass gasification is low and so far has not achieved commercial status in the UK [10]. It has therefore been identified that there is a need to increase the knowledge of biomass gasification, particularly in regard to the energy and environmental aspects to industrial applications.

1.2. Aims and Objectives of the study

All forms of energy production give rise to environmental penalties or ‘side-effects’, regardless of whether it is carbon-emission related or not. The environmental impacts of the construction and operation of a biomass gasification plant are not well published. In order to assess small-scale biomass gasification for industrial applications, this study uses two well established methodologies from the environmental assessment ‘tool-box’: life cycle assessment (LCA) and net energy analysis [11]. The overall aim of the present study is to evaluate the potential environmental effects of a small-scale biomass gasification combined heat and power (CHP) plant, and assess the renewable energy potential for industry.

Objectives of the research using the case study presented can be summarised as:

- Provide a definition of the gasification system;
- Develop a life cycle inventory (LCI) of energy, material and resource inputs and outputs including waste and emission sources;
- Perform a ‘whole-system’ analysis of the gasification system using on-site wood waste;
- Complete a life cycle impact assessment (LCIA) to assess potential environmental impacts;

- Evaluate LCIA results using sensitivity analysis to assess key data assumptions;
- Assess implications of using different methods for the allocation of impacts between heat and power;
- Use the LCI data to assess the net energy gains and complete a net energy analysis.

The methodology is outlined in section 2 with the goal and scope further defined in section 4.

2. Methodology

2.1. Environmental Life Cycle Assessment

Life Cycle Assessment (LCA) studies the potential environmental impacts throughout a product's or system's life (i.e. from cradle to grave), from raw material acquisition through production, use and disposal [12, 13]. LCA is commonly applied as a tool which assesses the life cycle impacts of physical products. However, the same methodological framework can be applied to the analysis of services such as energy systems (e.g. [14]) and waste management (e.g. [15]). This paper performs an attributional LCA of the case study described above. However as renewable energy (both heat and power) are the services provided, a net energy analysis is also undertaken (see section 6.4).

The general purpose of LCA is to provide a holistic view of the emissions and resource requirements of a product system. When applied to biomass gasification, this means that the impacts of all activities involved in the extraction, refining, transport and use of the materials and fuels are considered. The comprehensive view provided by LCA allows environmental impacts to be assessed based on a whole system basis.

There are four main stages in the LCA process: goal and scope, inventory, impact and improvement assessment, and interpretation [12] and [13]. The LCA was performed using SimaPro 7.3 software [16] and the database ecoinvent 2.0 [17] for background data. This software enables the manipulation and examination of inventory data in accordance with the LCA ISO Standards. Other data has been collected from a variety of sources as described in the inventory (see section 5) [10].

2.2. Life Cycle Impact Assessment

In the life cycle impact assessment (LCIA) stage, an assessment is made of the potential human, ecological, and depletion effects of energy, water, and material usage; and the environmental releases identified in the inventory. The impact assessment is where the potential effects on the chosen environmental issues are assessed. This stage is further subdivided into three elements: classification, characterisation, and normalisation [13]. The LCIA attempts to establish a linkage between the product or process and its potential environmental impacts. Having built up the LCI an assessment is made of the potential impacts of the biomass gasification plant operation. In this study, results are characterised and normalised using ReCiPe impact assessment methodology [18].

The primary objective of the ReCiPe method is to transform the LCI into indicator scores which express the relative severity on an environmental impact category. In ReCiPe indicators are determined at two levels with 18 midpoint indicators and 3 endpoint indicators. ReCiPe uses environmental mechanisms as the basis for the modelling [18]. The data have been normalised with respect to average European emissions [16, 18], which allows a comparison of the importance of each category to be made without undertaking the more subjective valuation. This can be achieved using the notation of 'people emission equivalents', which can be defined for the present purposes as follows [10]:

$$\text{European emissions per capita} = \frac{\text{Total European output in each emission category}}{\text{Population of Europe}}$$

$$\therefore \text{People emission equivalents} = \frac{\text{Emissions from the process studied}}{\text{European emissions per capita}}$$

The approach used in this paper is to assess the normalised results at the endpoint to identify potential damages and key issues. Results are further analysed using the midpoint categories, as these indicators are chosen closer to the inventory result and hence have a lower uncertainty. Midpoint results are also easier to interpret from an engineering and scientific perspective, and provide additional use for comparison to other LCA and energy system assessments. A total of 18 impact categories were assessed using ReCiPe [18], however some categories have been omitted from the displayed results as they were found to have very negligible effects.

A sensitivity analysis was conducted to identify the parameters which had the largest effects on the results of the study. For both the plant construction and operation, various parameters were changed independently so the magnitude of its effect on the base case could be assessed [10]. Changing one variable at a time is useful to analyse the relative effects on the LCIA results. Each sensitivity case was assessed using ReCiPe (midpoint) to quantify the effect on emissions and resource consumption relative to the base case for plant operation.

2.3. Net Energy Analysis

Net energy analysis is a methodology whereby the energy required to manufacture a good, or create a service may be computed. It takes into account both direct and indirect energy use. To determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This idea is based on the First Law of Thermodynamics – that is, the principle of conservation of energy or the notion of an energy balance applied to the system [3, 19]. It leads to the technique of First Law or 'energy' analysis, sometimes termed 'fossil fuel accounting', which was developed in the 1970s in the aftermath of the oil crisis [20, 21]. Analysis is performed over the entire life cycle of the product or activity, 'from cradle to grave'. It yields the whole-life or 'gross' energy requirement (GER) of the product or service.

The system boundary for this net energy analysis is the same as used in the LCA. Data obtained in the LCI is therefore adequate to perform the net energy analysis. To calculate the GER for the plant construction and lifetime operation, the life cycle impact assessment method (LCIAM) Cumulative Energy Demand (CED) [22] was applied to the LCI. This LCIAM expresses results in terms MJ, valued as primary energy during the complete life cycle of the gasification plant.

Energy gain ratio (EGR) and energy payback period (EPP) are metrics that can be used to assess energy generation technologies [10]. The EGR is defined as the delivered energy output from a generator over its lifetime divided by the life cycle primary energy input. A positive (>1) value is possible for renewable energy sources, whereas non-renewable energy sources have a value (<1) which is a measure of resource depletion. The EPP is analogous to a financial payback period (often termed 'break-even point'), and represents the number of years that a system must operate until its delivered energy output equals the life cycle primary energy input.

3. Definition of the System

The conversion of biomass to energy includes a wide range of different types and sources of biomass, conversion options, end-use applications and infrastructure requirements [23]. The method of conversion will depend on the type and form of the feedstock utilised and what end fuel is required [24]. Biomass can be derived from a variety of sources including dedicated energy crops, agricultural residues and industrial wastes [25]. This paper outlines a case study that uses waste wood from a factory for use in an entrained flow gasification CHP plant. The basic system is described by Gallagher in a report for the UK Department of Trade and Industry [26], but with the actual plant receiving 200kg of wood waste an hour generating 230kW of net electricity and 500kW of heat per hour. A summary of the full biomass gasification system is presented here [10] and additional technical information on the gasification of biomass provided elsewhere [27-31].

Gasification is the conversion of biomass to a gaseous fuel by heating in a gasification medium such as air, oxygen or steam [9, 29]. The biomass feedstock is fed into the gasification reactor (gasifier) via an air-tight enclosure. Conversion of the feedstock into a producer gas (also known as 'syngas') takes place in the gasifier. A variety of different gasifier technologies can be used [9, 27, 29, 30]. This case study uses entrained flow gasification with air as the gasification medium. In practice air is most commonly used as the gasification medium for economic reasons. The processes of drying, pyrolysis, oxidation and reduction take place in the gasification reactor [27, 32, 33]. The basic chemical reactions which take place in the gasifier are described by McKendry [30].

Main components of the small-scale biomass gasification system include a wood feed hopper, feed screw, gasifier, gas burner, ash/char filter, ash collector, air filters, air blower, venturi gas scrubber, condenser, after-cooler and demister, gas engine, heat exchanger, and generator. Figure 1 provides a simplified schematic flow sheet for the biomass gasification system.

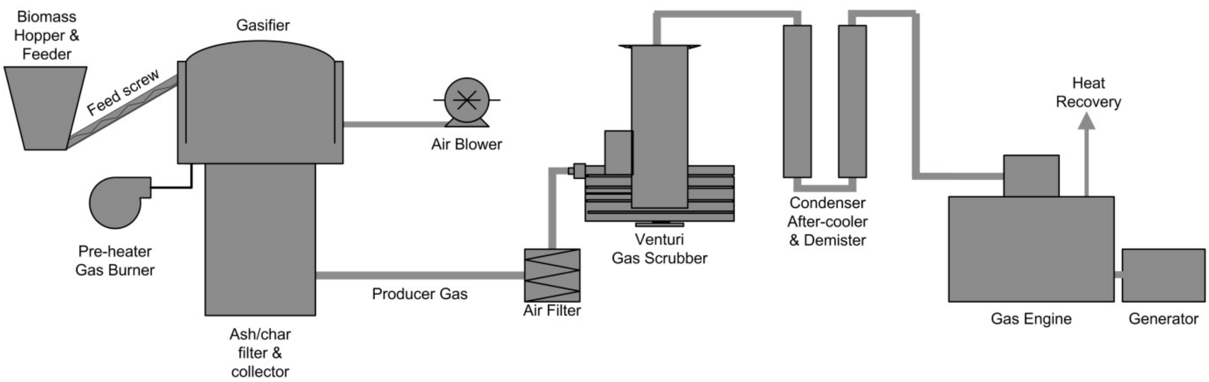

Figure 1: Simplified Schematic of the Gasification Process

In addition to the gasification process there are wider inputs to and outputs from the system. These flows of resources, products, and emissions are portrayed in Figure 2 giving an overview of the gasification plant with its system components that provides a high level process description. It should be noted that pre-drying is not required which is often different when purposely grown crops are used as a feedstock which have a high moisture content (30-50%).

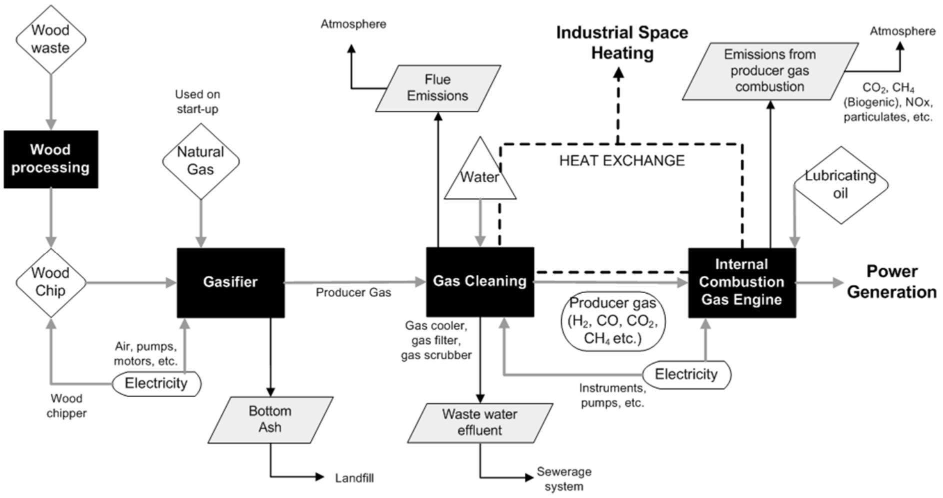

Figure 2: Description of the biomass gasification CHP system with main inputs, processes, outputs and emissions

Producer gas ('syngas') and heat are the main outputs from the gasifier. At the exit of the gasifier, the main desired products in the producer gas are the permanent gases (H_2, CO, CH_4, CO_2, and N_2). The composition of the producer gas varies depending on the feedstock used, type of gasification process and other subsequent processing. Table 1 displays the typical composition of the wood gasified in air. Therefore a typical wood gas would have a Lower Calorific Value (LCV) of 4.6MJ/m^3. Clearly this compares unfavourably to the LCV of natural gas (37-39MJ/m^3) or diesel (36-38MJ/l), which is generally the fuels used for non-biomass CHP systems [9, 10].

Table 1: Typical gas composition of wood gasified in air [26]

Gas	%vol./vol.
H_2	9.0%
O_2	1.2%
N_2	57.0%
CH_4	2.0%
CO	15.0%
CO_2	13.0%
Other C_xH_y	0.9%

Heat produced is available as a useful co-product from the CHP plant after some utilisation for internal gasification process heat. There are also undesired by-products which can include particulate matter, dust, soot, inorganic pollutants, alkali salts, and organic pollutants (tars and chars) as well as ash [9, 26, 29]. Wood gas invariably contains contaminants such as tar, char and ash particles which can cause wear, contamination and build up on moving parts and surfaces [26]; this is outlined below and in further detail in the discussion. Gas cleaning and/or modifications to CHP engines are therefore required to enable these systems to run on wood gas. The producer gas leaves the reactor with a certain pollutant load and enthalpy. In the subsequent steps of the process the heat contained in the producer gas is used for both the provision of internal process heat and for the extraction of heat. In various cleaning and cooling components the producer gas is subjected to cooling and wet scrubbing to satisfy the cleanliness requirements for later use in the gas engine [8, 9, 26, 29]. Alternative end-uses of the gas include a gas turbine, or micro gas turbine, and possibly a fuel cell.

4. Goal and Scope

The goal of the study is to identify and assess the potential environmental impacts of a biomass gasification system. The main function of the system studied is the production of renewable electricity and heat from biomass. A secondary function of the system is waste management. To achieve this, waste wood is put through a gasification process, the producer gas is then scrubbed and cleaned and used in an internal combustion gas engine modified for syngas. Electricity that is generated by the gas engine is either used for internal consumption or supplied to the electricity grid. The heat produced by the process is used for heating industrial buildings. The functional unit of the study is 1 MJ (or kWh) of energy produced. As both electricity and heat are produced, the environmental impacts of the system are partitioned and assessed using different allocation methods.

Figure 3 shows the system boundaries which include the raw materials, energy, transportation and materials used in the plant construction (note that 'raw materials' are substances such as primary metals, natural resources, etc. whereas 'materials' have undergone some change through production or manufacturing, e.g. stainless steel, equipment, etc.) Recycling and landfill of wastes and by-products is also included (see dotted line). The considered system includes: biomass processing, plant construction, energy conversion (operating life 20 years) and plant maintenance. Energy conversion is the operation of the biomass gasification plant from wood chipping through to use of the gas in the gas engine (see Figures 1 & 2). As this is a relatively new technology there is insufficient knowledge or information available about its end of life, therefore plant dismantling and disposal has not been considered in this study.

Environmental issues considered in the study include effects on human health (e.g. toxicity, particulates); ecosystems (e.g. acidification, eutrophication); land use; mineral, fossil, and water depletion; energy usage; and climate change. Environmental burdens relating to the storage of wood, dust from wood chipping, local air quality, and biodiversity impacts are not included in the study. Most of these are not usually included in an LCA as they are more localised impacts and difficult to quantify on a wider scale.

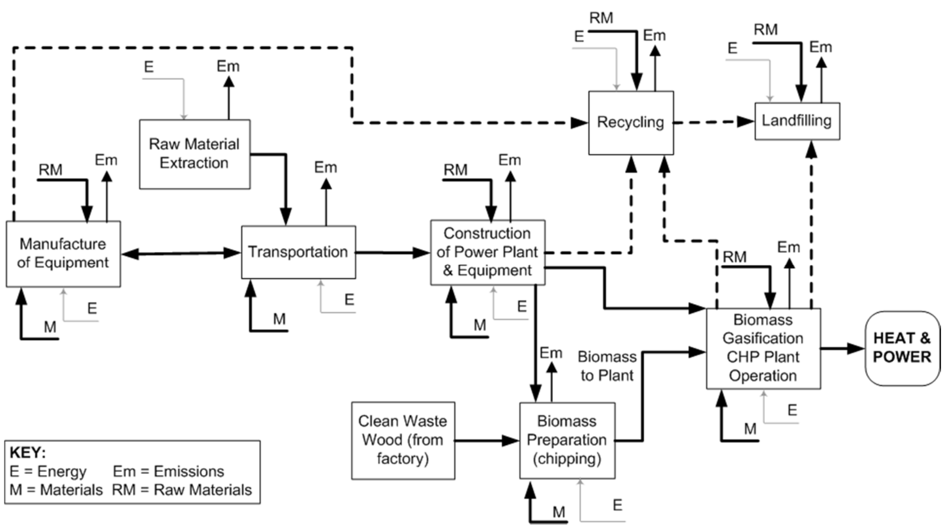

Figure 3: Overview of the system boundary for the biomass gasification plant construction and operation [10].

5. Life Cycle Inventory

The main purpose of the Life Cycle Inventory (LCI) is to identify and quantify the energy, water and materials usage and environmental releases (e.g. air emissions, solid waste disposal, and waste water discharges) [14]. In the inventory stage data collection was performed using practical data gathering, literature searches, or through the use of software. A description of the main aspects of the LCI is presented here, further detailed description of the LCI can be found in [10] and in the supplementary data.

The plant construction inventory was based on an equipment inventory supplied by the gasification company. There were also over 30 different companies which supplied equipment to the plant. All of these were contacted and most supplied the necessary data for the LCI. For a limited number of items no primary data could be obtained. In these cases the inventory data was either calculated or an equivalent item used from the ecoinvent database [17, 26]. As a final data quality check all items contained in the inventory were physically inspected, measured and materials verified to confirm completeness and accuracy of the inventory data (see supplementary data and [10]).

Wood waste is provided on site by a furniture factory, therefore for this case study no biomass production or transportation is included. Further details of the wood waste composition and assumed parameters are provided in the supplementary data. Rabl *et al.* [34] recommend that carbon dioxide (CO_2) should be counted explicitly at each stage of the life cycle. However it is assumed that carbon would have been sequestered in a relatively short time frame and would be released upon combustion of the producer gas, hence the net effect is zero CO_2 emissions from this waste feedstock.

Wood chipping takes place on site at the gasification plant. The chipper weighs approximately 2 tonnes and has a service of 30,000 hours (or 100,000 m^3 of wood) [17]. Energy consumption is 27 MJ/m^3 (~0.043 kWh/kg) of wood and this is modelled based on the LCI for the UK Grid [35]. Wood is fed into the system at a rate of 200 kg per hour.

Other than biomass feedstock, the main inputs to the plant during operation are electricity, natural gas, water, and lubricating oil. Electricity is consumed in the plant to provide power for pumps, motors and control equipment. Natural gas is used on each start-up to raise the temperature of the gasifier to allow gasification reactions to occur. Water is used in both the gas scrubbing system and the heat exchanger. Finally, lubricating oil is used in several moving parts, but primarily in the gas engine, and in the wood-chipper. Estimated annual operating hours were given as 7,000 hours by the plant developer, which gives a capacity factor of 80%. Whilst this is reasonable for a thermal powered CHP plant, a literature review of existing operating biomass gasification plants globally revealed an average total of approximately 2,500 annual operating hours [10]. This was calculated as an average from 10 different gasification plants [29]. 7,000 hours was used for the base case, but the lower operating hours of 2,500 is assessed in the sensitivity analysis. Table 2 summarises the main inputs to the operation of the gasification plant.

Table 2: Main biomass gasification plant operational inputs.

Input	Amount	Description
Waste wood	200 kg/hour	Assumed carbon neutral as no biomass production or transportation included in on-site waste product.
Wood chipping	31 MJ/hour (8.6 kWh)	Consists of electricity consumed in chipper.
Electricity	90 MJ/hour (25 kWh)	Approximately 10% comes from UK grid, with remainder produced internally from CHP generator.
Natural gas	270 MJ/start-up	Assumed 50 start-ups per year. Inventory includes upstream emissions from natural gas supply on a MJ delivered basis.
Water	60 litres/hour	Consumed to replace gas scrub water.
Lubricating oil	24.8ml/hour	Consumed to change lubricating oil. Calculated based on wood chipper and gas engine oil manufacturer requirements plus calculations of other minor uses of oil in plant.

The main desired outputs produced by the system are electricity and heat. There are also a large number of emissions and releases over the entire life cycle. This is due to the various upstream processes and the amount of materials used, as well as downstream processes such as waste disposal and emissions to air, water and soil. Owing to the large quantity of substances accounted for in the study, only the direct releases from the plant operation are described here. Indirect and upstream emissions are accounted for using ecoinvent [17] and ReCiPe [18].

No primary data could be obtained from the plant on the direct emissions from producer gas combustion. Essentially all carbon contained in producer gas components will end up as carbon dioxide when the producer gas is burned, provided that there is sufficient air and mixing [36]. Producer gas components contributing to CO_2 emissions include carbon monoxide, hydrocarbons, and the carbon dioxide itself. Other main emissions from producer gas combustion include nitrogen oxides (NO_x) and particulate matter. Potential localised environmental impacts associated with combustion are not accounted for in a LCA, these should instead be assessed through an Environmental Impact Assessment (EIA) to evaluate potential local air quality implications.

Emissions from the natural gas burnt are taken as equivalent to emissions from a natural gas atmospheric burner from the ecoinvent database [17]. It was not possible to obtain the exact total of ash produced from this gasification system. Therefore an average across a range of gasification plants was taken. Based on the literature survey of 22 gasification facilities performed during the development of ecoinvent [17] and the typical composition of wood [37], the amount of ash collected for this system is assumed to be 8.2 g/kg (see supplementary data) with ash collection based on cyclone collection [8]. Finally, a total of 60 litres of water are disposed to sewerage per hour from the gas cleaning and scrubbing process [26]. Table 3 summarises the main outputs and emissions from the gasification plant, and how these have been accounted for.

Table 3: Key biomass gasification plant operational outputs and emissions

Output / emission	Amount	Description / Data source
Net electricity output	230kW	The actual engine output is $255kW_e$ but the parasitic load of the plant requires an average of $25kW_e$ per hour.
Net heat output	500kW	This is the maximum available heat after some heat has been consumed by internal processes such as in the gasifier, as well as heat losses.
Natural gas emissions	270 MJ/start-up	Emissions are calculated based on combustion of natural gas emission factors from a typical atmospheric industrial natural gas burner [17].
Ash from Gasifier	8.2g/kg of wood (~1.64kg per hour)	Average composition of ash taken from ECN [37]. Transport to landfill assumed to be 20km, only 1 trip required per annum as total ash ~11.5 tonnes/year.
Waste water emissions	60 litres/hour	Arises from gas scrub water. Composition of waste water is modelled using data from Lunds Universitet [38].
Producer gas combustion emissions	2.9% (vol.) of each m^3 of producer gas (see Table 1)	For the modelling of producer gas combustion, it is assumed that CO is converted completely to CO_2, and that CO_2 does not react in the combustion process and is hence emitted as such. CH_4 and C_xH_y altogether are considered as 'natural gas' and modelled according to the emissions of the process 'natural gas burned in industrial furnace > 100kW (emissions only)'. H_2 is converted to water.

6. Results

6.1. Life Cycle Impact Assessment

During operation of the plant, direct environmental releases include wood ash, wastewater effluent, emissions from burning natural gas, and flue gas emissions from producer gas combustion. Indirect emissions arise primarily from the use of UK grid electricity and upstream processes such as natural gas production, metal extraction, and water supply. Results were normalised using ReCiPe (endpoint) to identify the impact categories with the highest people emission equivalent (PEE) values (see Figure 4). Endpoint results identified five key issues for the gasification plant operation: fossil fuel depletion, climate change, particulate matter formation, human toxicity, and terrestrial ecotoxicity. Metal depletion was found to be an issue due to plant construction. Water depletion may also be an issue but there is currently no damage model available in ReCiPe [18]. Normalisation showed several impact categories (e.g. ozone depletion, acidification, eutrophication, radiation, water ecotoxicity, land occupation and transformation) have very small PEE values (< 0.06) and are therefore not further considered here as the cut-off selected was PEE values of ≥ 0.1.

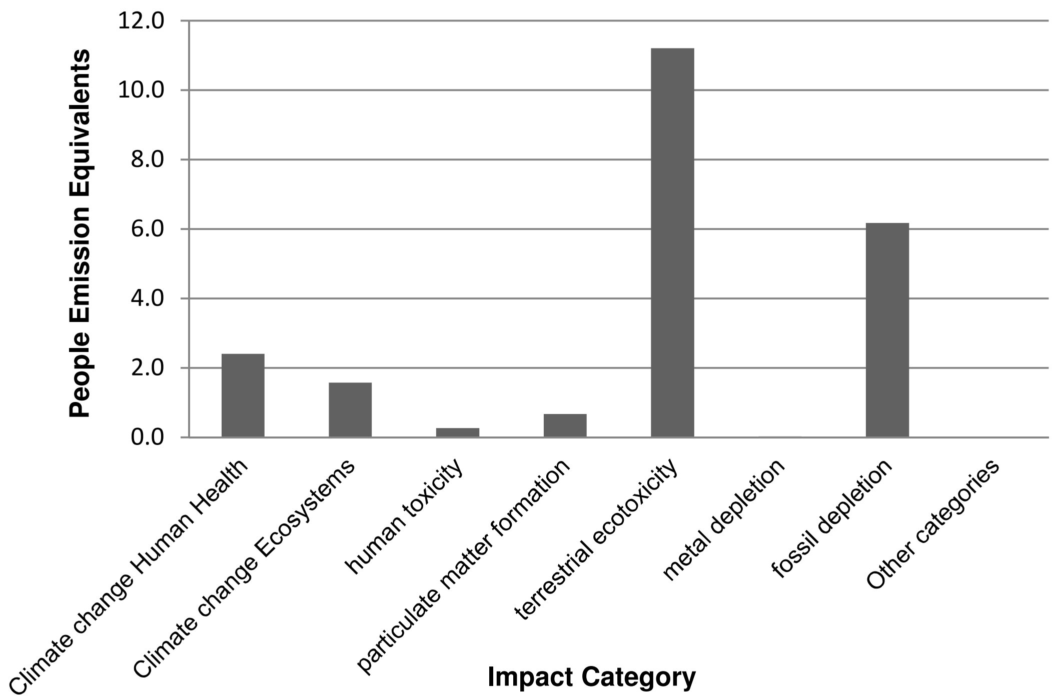

Figure 4: Normalised data for annual biomass gasification plant operation (ReCiPe endpoint [H] v1.01)

Characterised midpoint data for one year of operation (assuming 7,000 hours) shows that each impact category is affected by different aspects of the plant operation (see Figure 5). It can be seen that UK grid electricity used in the plant and wood chipping contribute most to climate change, particulate matter formation (PMF), and fossil fuel depletion. Natural gas combusted on start-up also contributes 15-20% to climate change and fossil depletion impact categories. Wood gas ('syngas') combustion made up approximately 12% of the PMF category, although primary data was not obtained so this result is uncertain and assessed further in the sensitivity analysis. ReCiPe (midpoint hierarchical [H]) results are summarised in Table 4 with further results provided in the supplementary data.

Ash was found to contribute almost 100% to the terrestrial ecotoxicity impact category primarily due to Phosphorus content with its high characterisation factor. Ash was also the major component of the human toxicity impact, with upstream emissions from the UK electricity grid also contributing. Direct use of mains water supplied to the gas cleaning system contributes just over half of the water depletion impact category with water use from upstream electricity supply comprising most of the remainder. Waste water was not found to have much of an impact to any of the impact categories.

Metal depletion is mainly caused by the construction of the plant, with most of the remaining contribution coming from the construction of the wood-chipper used to process the waste wood chips. Plant construction was not found to make a notable contribution to any of the other categories due to the relative impact being amortised over 20 years. Lubricating oil was found to make a small contribution (<5%) to fossil fuel depletion and climate change.

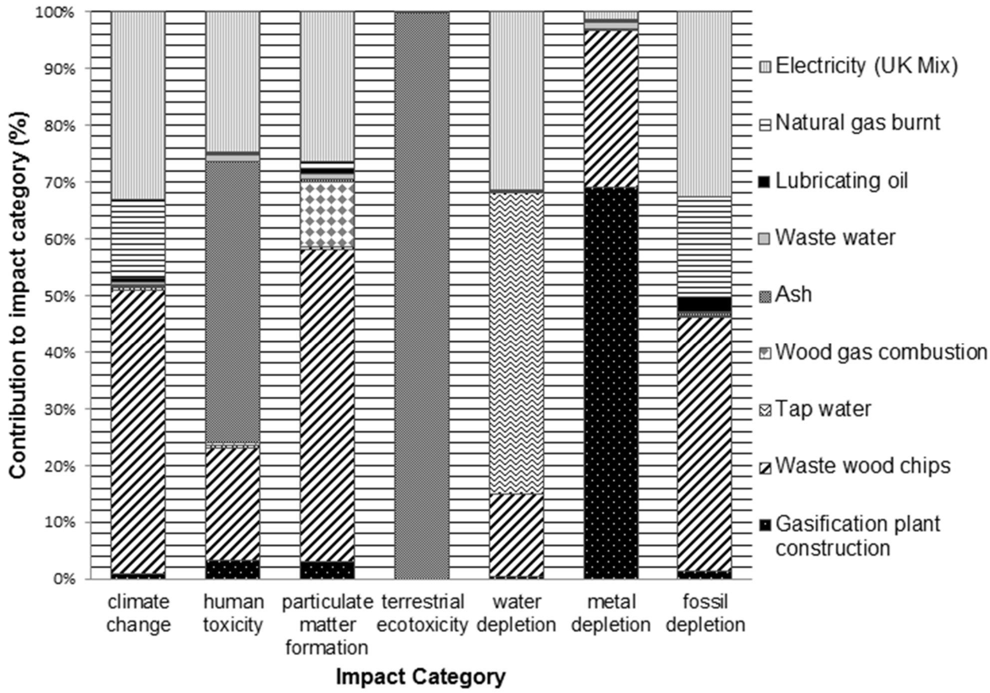

Figure 5: Characterised data for annual biomass gasification plant operation (ReCiPe midpoint [H] v1.01)

Table 4: Characterised results for annual biomass gasification plant operation (ReCiPe midpoint [H] v1.01)

Impact category	Per MJ (electricity only)	Annual Total	Unit
climate change	0.00599	**34,722**	kg CO_2 eq.
human toxicity	0.00133	**7,713**	kg 1,4-DB eq.
particulate matter formation	0.00001	**52**	kg PM10 eq.
terrestrial ecotoxicity	0.00266	**15,446**	kg 1,4-DB eq.
water depletion	0.00016	**928**	m^3
metal depletion	0.00165	**11,919**	kg Fe eq.
fossil depletion	0.00203	**11,734**	kg oil eq.

6.2. Sensitivity Analysis

Several sensitivity analyses were undertaken for this study to analyse the assumptions made in the LCI [10]. The rationale for selecting sensitivity cases is based on assessing the relative importance of the main operational parameters as described in the LCI (see section 5). The most significant findings are summarised in Table 5 with additional description provided here and results provided in the supplementary data. In case A it was found that reducing annual operating hours to 2,500 substantially reduces the annual environmental load as expected. The main effect of lower operating hours is the capacity factor reduces to 29% from 80% and therefore the relative impact of plant construction (i.e. metal depletion) increases.

In case B switching to diesel powered wood chipping was found to reduce primary energy use and GHG emissions, but increased particulate emissions. Case C primarily affects the amount of natural gas consumed as each start-up requires the gas burner to be operated. 100 start ups in the year doubles the contribution of natural gas to fossil depletion and climate change. Case D was difficult to model due to inconclusive data being available on alternative ash compositions. Therefore the individual elements were assessed which showed that phosphate followed by various metals made the largest contribution to eutrophication and the toxicity impact categories. The potential effect of ash disposal is further analysed in the discussion.

Case E assessed the data uncertainties associated with producer gas combustion emissions. UK emission limits for CO (150mg/m^3), Nitrous Oxide (350mg/m^3), Particulate Matter (20mg/m^3), Hydrocarbons (20mg/m^3) were modelled, being the worst case scenario [39]. PMF was found to increase significantly due to higher releases of NO_x and particulates. There was also an increased impact on terrestrial acidification and marine eutrophication under this sensitivity. However these results are inconclusive due to insufficient primary data being available from the plant. It is clear that an EIA will be required at the plant to ensure emission limits are adhered to for biomass gasification to meet local air quality requirements; this was outside the scope of the LCA.

Table 5: Summary of main sensitivity analyses performed

Case letter	Sensitivity case	Base case (original LCI data)	Sensitivity (changed LCI data)
A	Low annual operating hours	7000 hours (Capacity Factor is 80%)	2500 hours (Capacity Factor is 29%)
B	Wood chipping with diesel	Electrical wood-chipper	Diesel powered wood-chipper
C	No of plant start ups	50 start-ups per annum	100 start-ups per annum
D	Ash composition	Average composition of ash [37]	Individual compositions
E	Producer gas combustion emissions	CH_4 and C_xH_y modelled as natural gas burned in an industrial furnace	UK emission limits [39]

6.3. Allocation of impacts between electricity and heat in CHP production

CHP offers a rise in fuel efficiency leading to a decrease of environmental burdens per unit of useful energy. Different options exist for the attribution of environmental impacts to either electricity or heat [40]. In this paper allocation based on thermodynamic (energy and exergy) and economic parameters are assessed to portray the impact on the final results.

Energy allocation is based on the energy content of the annual electricity and heat production. Total energy production is 5,110MWh (32% electricity and 68% heat) which means both electricity and heat have the same emissions on a per MWh (or MJ) basis.

Exergy allocation is based on the exergy content of the annual electricity and heat production. The exergy content of electricity and heat is characterised by the Carnot-factors (ηC) with $\eta C = 1$ for electricity and $\eta C = 0.2$ for heat [40]. The annual exergy production is 2,310MWh (70% electricity and 30% heat).

Economic allocation uses final product prices. Data on industrial user prices were obtained from DECC as 9.17p/kWh (electricity) and 2.35p/kWh (gas) at 2012 prices [41]. Electricity assumes UK grid prices and gas has been used as the most common fuel for heating in the UK. This gives a total annual energy cost of £229,887 (64% from electricity and 36% from heat).

The three allocation methods produce different results which are summarised in table 6 using climate change (34,722kg CO_2-e) for example data. This shows that using exergy or economic allocation results in higher emissions being allocated to electricity, due to the higher value of electricity.

Table 6: Comparison of energy, exergy and economic allocation using CO_2-e emissions for electricity and heat

Allocation method	Electricity (g CO_2-e/kWh)	Heat (g CO_2-e/kWh)
Energy (32:68)	6.8	6.8
Exergy (70:30)	15.0	3.0
Economic (64:36)	13.9	3.5

6.4. Net Energy Analysis

Conventions in energy analysis require the output from a system to be measured on a 'delivered' basis. This means in a CHP unit it is the actual electricity and heat delivered to the end-user that is accounted for, and not necessarily the total amount produced. Distribution and transmission losses for the electricity and heat losses through heat transfer are assumed to be zero. In the system studied it is assumed that all electricity produced is consumed either locally or fed back into the grid. Conversely the demand for heat cannot be considered to be constant if it is used for industrial space heating. For example, there is a high demand for heat in the colder winter months, but minimal demand in the hotter summer months. Therefore, results presented in Table 7 are for 3 different cases: no heat is consumed (0% heat); half of the heat is consumed (50% heat); all of the heat is consumed (100%).

Table 7: Net energy analysis results: EPP and EGR of 3 delivered heat case studies

Scenario	Gross Energy Output	EPP (years)	EGR ($MJ_{delivered}$ / $MJ_{primary}$)
0% heat	1 MJ electricity	0.39	4.71
50% heat	1 MJ electricity & 0.98 MJ heat	0.17	9.32
100% heat	1 MJ electricity & 1.96 MJ heat	0.11	13.94

The plant has an energy payback of 0.39 years (less than 5 months) even when the heat is not utilised. The energy payback improves as more of the heat is consumed. However, it needs to be considered that biomass production and transportation are not included in this study. Using waste on site will therefore produce much more favourable net energy results than cultivating biomass off-site. As a comparison, the EPP was found to be more favourable than several renewable micro-generation technologies [42]. Cumulative Energy Demand (CED) results are presented in the supplementary data.

The EGRs of the 3 heat case studies were all found to be positive and comparable to other biomass technologies [43]. As the proportion of heat utilised increases, so does the EGR, with analogous results for the EPP. In comparison to UK grid electricity (EGR ~ 0.33), or a natural gas power plant (EGR ~ 0.43), the EGR is significantly higher [10, 42].

7. Discussion

7.1. Life cycle impact assessment findings

Results from this study show that small-scale biomass gasification shows good potential for use in industry. Environmental impacts are relatively low overall when compared to fossil fuel based CHP systems. For instance, using climate change impact category as a benchmark, diesel generators have GHG emissions around 310-360g CO_2-e/kWh$_e$ with natural gas being around 240-270g CO_2-e/kWh$_e$ [17, 18, 43] Compared to 7-15g CO_2-e/kWh$_e$ in this study and 5-163g CO_2-e/kWh$_e$ [43] or 25-237g CO_2-e/kWh$_e$ [44] for other bio-electricity systems. Climate change mitigation is a key driver for the development of bioenergy and this study demonstrates the GHG advantages of using a wood waste product for energy generation. Nonetheless these results should be set in context as wood waste is not always available and the alternative could be cultivation and transportation of woody biomass with much higher GHG emissions. In the present study the growth of biomass, harvesting, transportation, pre-processing, and drying (which can all have notable GHG emissions [10, 43, 44]) are outside the scope. The GHG benefits of bioenergy systems are widely debated in the literature [45] with some studies demonstrating higher GHG emissions than fossil fuel alternatives [46].

Other impact categories results, such as particulate matter formation (PMF) and ash disposal, produced more uncertain findings. PMF for biomass gasification is primarily determined by the composition of the biomass feedstock and the gas cleaning equipment used. In comparison diesel and natural gas CHP systems do not require the disposal of ash by-products although PMF can be an issue. The results generated for PMF in this study use an average composition and general assumptions on emissions therefore this is an area for further work to assess local air quality.

These LCIA findings demonstrate the importance of assessing the local receiving environment through EIA. For example, as the results displayed here are based on the European region it could be misleading to imply that wood ash sent to landfill poses a risk to human health or ecosystems. Indeed application of wood ash to agricultural and forest soils is an efficient way of removal and in forestry it is particularly interesting to recycle the exported nutrients [47]. Application of wood ash in agriculture does not present any major risk for the environment, provided that no excessive amounts are applied and only ashes from burning of pure wood residues are used [47].

7.2. Net energy analysis

Using the Energy Gain Ratio (EGR) as a metric provides a sound reason for installing CHP systems due to the additional amount of useful energy produced. It is acknowledged by the authors that both 0% and 100% heat utilisation is unrealistic in practice due to heat losses and thermodynamics. However these scenarios allow the reader to use the results and apply different heat utilisation percentages.

Similarly to the climate change impact category the EGR for this system would reduce where additional life cycle stages were required. Energy intensive areas in a supply which used purposely grown crops can include fertiliser production, diesel used in farm machinery, drying, and other pre-processing. Clearly the EGR results would reduce as alternative biomass supply chains and processing steps were considered [43, 44].

Energy payback period (EPP) for the present study demonstrates that the energy consumed in constructing the facility is paid back during the first year of operation. This is only possible with renewable sources of energy such as biomass due to the small amount of non-renewable fuels required in the supply chain. The detailed inventory developed for plant construction showed that embodied energy in the facility materials should be taken into account. Nonetheless over the life time of the facility the energy produced means that plant construction has a relatively low impact. Assuming 7,000 hours of operation per year means that plant construction accounts for fewer than 15% of the non-renewable energy consumed in the supply chain. When the EGR is taken into account this means plant construction embodied energy corresponds to approximately 1% to 3% of the total energy produced.

7.3. Allocation of environmental impacts between heat and electricity

As CHP offers a rise in fuel efficiency which leads to a decrease in environmental burdens emitted per unit of useful energy, it is important to select the most appropriate allocation method. A CHP plant is operated to primarily satisfy a predefined demand of electricity or heat, therefore the additional production of heat or electricity can be considered as a side-effect [40]. Energy allocation would appear to make the most sense and is perhaps the most simple of the three approaches presented in this paper. However energy allocation only takes account of the quantity of energy and not the quality. Exergy allocation is therefore more appropriate when the value of energy is considered, although Carnot-factors are not straightforward to obtain. Interestingly using economic allocation produces similar results to exergy allocation which is perhaps also a reflection of taking the value into account.

Different methodologies exist for calculating greenhouse gas emissions for bioenergy each of which has a different approach to allocation. For instance the EU Renewable Energy Directive (RED) allocates co-products by energy content, whereas the PAS2050 method recommends that co-product allocation should be avoided by applying system expansion, but if this is not practicable, allocation should be done by market value [48]. The RED recommends allocation by energy content as this method is “easy to apply, is predictable over time, and minimises counterproductive incentives”. Out of all the allocation methods, allocation by price may be more widely applicable, though the results may vary over time and location. The allocation method selected should depend on the goal and scope of the LCA study. As demonstrated in this paper different allocation methods produce different results which make comparisons to other fuel cycles more difficult and complex. Regardless of the allocation method applied it is apparent that reductions of emissions are obtained by replacing fossil fuelled energy systems with biomass systems [40].

7.4. Key issues for the development of biomass gasification

Key issues for industry regarding the development of biomass gasification include the availability and quality of feedstock, dependency on fossil fuels in the supply chain, gas clean-up, capital costs, economic cost of emission abatement technologies, and operational problems associated with technology [8, 9, 10, 29, 42, 43]. Each of these issues is discussed in further detail below.

7.4.1. Feedstock availability and quality

Feedstock availability is an important issue as purposely grown energy crops will add to the cost of a biomass gasification system. Wastes and residues are a limited resource hence for bioenergy to develop energy crops are likely to be required. This is likely to significantly increase the environmental burden primarily through land use and the application of inorganic fertilisers [10]. In comparison, biomass wastes are assumed to not have the environmental impacts from their original production attributed, and therefore have a zero GHG burden [49] as recognised by the EU RED [48].

In attributional LCA methodology if a product is a genuine waste then no upstream impacts are allocated at the point it becomes a waste. In practice waste and residue systems are often credited with high levels of GHG savings based on assumptions about the counterfactual, i.e. what would have happened to the material if it had not been used for bioenergy. Natural decay or disposal of biomass and wastes may result in releases of greenhouse gases such as methane or nitrous oxide, which have a much higher global warming potential (GWP) than CO_2 so there is potentially a very substantial benefit in using the material for bioenergy. However, there is a need to carefully consider the appropriate counterfactual in order to accurately assess the GHG balance. Consequential LCA is an area of substantial research for bioenergy systems and is an essential tool for policy-makers [45, 46, 50], however it is outside the scope of this study.

The quality of the biomass source is a crucial consideration as the feedstock composition will determine the efficiency and subsequent emissions from the gasification process [29]. Biomass feedstock is very versatile in its morphology and physical characteristics which have led to many different designs of gasifier being developed [27, 29, 30]. Although in theory it may be possible to gasify all types of feedstocks, in practice the type of gasification system employed will depend on the type and form of the feedstock. The exact design and specification will depend on a variety of factors including: feedstock; size of plant; gasification medium; end-use of producer gas; and other engineering factors [9, 42]. Drying of feedstock is usually required where energy crops are used for gasification. Drying was not required in this system due to the low moisture content (7%) of the wood waste feedstock. Where drying and additional biomass processing steps are required it is apparent that the environmental burdens will increase [44]. The main increased impacts of drying are additional use of energy and higher GHG emissions, which in turn can make the net energy analysis results less favourable.

7.4.2. Dependency on fossil fuels in the supply chain

Fossil fuels are used in different aspects of plant construction and operation. Natural gas is burnt when the plant is started-up and UK grid electricity is consumed for wood chipping and general plant operation. This reliance on natural gas for heat and grid electricity reduces the sustainability of biomass gasification, since natural gas and much of the electricity generation is from non-renewable sources. Conversely the main function of the biomass gasification plant is to produce renewable CHP. The net energy analysis demonstrates that positive energy gains are made displacing demand for non-renewable fuel, but it is likely the system will always have some dependence on fossil fuels.

7.4.3. Gas clean-up

Raw syngas contains containments that must be mitigated to meet process requirements and pollution control regulations. When syngas is applied to heat and power applications each contaminant can create specific downstream hazards. Various technologies exist to purify the raw synthesis gas which is produced by gasification [8, 9, 51]. Some methods are capable of removing several contaminants in a single process such as wet scrubbing employed in this case study, whilst others will focus on the removal of only one contaminant. For successful gasification of biomass gas cleaning is a crucial stage of the process. Further discussion on its importance and detailed information on different gas cleaning technologies are available in the literature [8, 9, 51].

7.4.4. Capital costs and the economics of emission abatement technologies

With small-scale CHP systems the capital cost relative to the energy generated is high compared to larger scale dedicated electricity-only or heat-only systems [52]. This means investing is this technology may be risky due to the returns on investment being less favourable as the capital and maintenance costs are spread over low energy generation. Emission abatement technologies for gasification, such as gas scrubbing and secondary treatment of exhaust gas, are an additional cost which is incurred to comply with the relevant engine requirements and emission limits [51]. The economics of small-scale gasification are therefore uncertain and require efficient operation in order to justify the relatively high capital costs.

7.4.5. Operational problems associated with technology

Some problems exist with gasification which has restricted the commercial development of the technology. Potential issues can include high moisture content, high ash content, volatile compounds, large particle size, tar build up, dust, amongst other issues [9, 27, 29, 30, 32, 33, 50]. This can restrict the development and implementation of biomass gasification due to problems demonstrating technical and commercial feasibility. Perhaps the main technical constraints arise from the variability of biomass feedstocks which makes it difficult to optimise the gasification process for consistent physical characteristics. Other barriers include the lack of experience in operating gasifiers, access to finance due to concerns about technology viability, perceived technology risk due to securing long term waste feedstock contracts, legislative issues and uncertain market conditions for investment [53, 54]. Several of the technical problems can be addressed through appropriate use of technology and improved technical knowledge of plant operators [8, 9, 51]. Obtaining a securing a feedstock with consistent properties will assist developers in designing and operating gasification facilities efficiently and effectively. Appropriate Government support and commitment from investors can address several of the potential legal and financial constraints.

8. Concluding Remarks

The study analysed the potential environmental impacts and renewable energy generation of biomass gasification through the techniques of attributional LCA and net energy analysis. It has been shown that the energy gains are positive and the environmental burdens are reduced when compared to the fossil fuel alternatives for CHP. These findings are consistent with related studies in the literature which performed consequential LCA of biomass CHP [55, 56]. Eriksson *et al.* found that biomass and waste CHP offer low net energy and GHG emissions [55]. Kimming *et al.* also suggest considerably reduced energy use and GHG emissions compared to scenarios based on fossil fuel, but have higher acidifying emissions [56]. However despite the energetic advantages of the thermo-chemical conversion of biomass into producer gas (e.g. CHP) [56], in comparison to combustion systems there are additional by-products which are produced during the more complex operation. The wastes and emissions from gas cleaning, ash disposal, and producer gas combustion can be hazardous to human life and/or the environment. To avoid damages to human health and ecosystems, emission limits from several directives and laws with regard to solid, liquid and gaseous emissions have to be fulfilled (e.g. 'IPCC Directive' and related legislation) [9, 51].

Biomass is widely regarded as a renewable resource and whilst much research has focused on the net energy and carbon balances [10, 43, 44], full attention is not always provided to resource depletion in different bioenergy systems. This paper has identified that fossil fuels, water, minerals and other resources are all consumed in direct and upstream processes required for operation of the CHP plant. Resource depletion issues should be taken into account when assessing energy systems.

If operational problems of biomass gasification along with the potentially prohibitive capital costs can be overcome, then the energetic and environmental benefits of small-scale biomass gasification CHP use in industry are clear. Reliable and consistent biomass feedstocks are required to ensure efficient operation of the plant and provide reliable returns on investment. Biomass gasification utilisation in industry has the potential to meet several policy objectives including improved energy security, reduced greenhouse gas emissions, improved waste management, and reduced fossil fuel use [57, 58, 59]. Nonetheless it is recognised that there is still some dependency on fossil fuels in the supply chain, the technology is resource constrained, and emissions need to be appropriately managed.

The main barriers to further development of biomass gasification include access to finance for the capital expenditure, planning and legislative issues, and the availability of consistent biomass feedstock [53].

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