Using agricultural residues to support sustainable development:

A case study of coffee stems gasification to supply energy demands in rural areas of Colombia

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the Faculty of Science and Engineering

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Abstract

The development of sustainable bioenergy plays an active role in the decarbonisation of the energy sector. Unlike other renewables, bioenergy has the potential to expand its applications beyond climate change mitigation by providing complementary environmental and socio-economic benefits that support the Sustainable Development Goals. The deployment of bioenergy could be particularly beneficial in the rural areas of many low and middle-income countries where traditional uses of biomass still prevail.

Locally available biomass in rural areas, such as agricultural residues, could be harnessed in more efficient and sustainable manners, and this could be promoted with bioenergy development. The roll-out of these technologies also arises challenges across the environmental, economic and social dimensions, especially for emergent technologies. Tackling these challenges requires a wider understanding of bioenergy technologies' impacts across these dimensions, and this could be achieved through comprehensive and integrated assessments that investigate these dimensions. This research, therefore, seeks to gain further knowledge to unfold the following questions; how bioenergy technologies using agri-residues could be sustainably and feasibly deployed?, and what are the wider co-benefits, from a sustainable development perspective to rural communities and agro-industries?.

This study aimed to evaluate the feasibility of small-scale gasification systems to generate power and heat, using indigenous agricultural residues, to meet the energy demand of rural areas. Considering also that bioenergy is set within local contexts, this research was framed in a case study on the coffee sector in Colombia, using coffee stems as feedstock. The methodology in this research consisted of a combination of multidisciplinary approaches, comprising process modelling for a technical assessment, lifecycle assessment (LCA) and techno-economic analysis.

The results of the technical assessment indicate that the gasification of coffee stems could generate a fuel gas suitable for power generation in engines. In addition, the heat recovery and integration to supply the demand for coffee processing could enhance the conversion efficiency of the system. The LCA results show that deploying the coffee stems gasification-CHP system could impact positively on many environmental issues, including climate change, when traditional biomass uses and energy production using fossil fuels are replaced. However, trade-offs should be considered for certain scenarios, such as those replacing grid electricity with high-hydropower generation.

The evaluation of the economic feasibility indicates that costs of power generation in the gasification systems could equalise the costs of Diesel-power generation when the system reaches high capacity factors. Matching the grid-electricity tariffs is more difficult to attain even at high capacity factors. The integration of the heat vector in the coffee processing chain contributes to fuel savings and could be translated into a heat credit that reduces the power generation costs.

The key findings from this research were integrated under a multidimensional framework that prompted discussions on pivotal drivers, synergies and trade-offs of this bioenergy system. The synergies relate to the importance of balancing the biomass availability and the energy demand in context-specific agricultural sectors. It also emphasises the usefulness of harnessing the biomass conversion by implementing heat recovery pathways in the system, and of maximising the utilisation of the system (increasing the capacity factor) to enhance the system's feasibility.

The framework also contributes to understanding how bioenergy from agricultural residues could contribute achieving the Sustainable Development Goals. The multidimensional framework highlights potential co-benefits to rural communities, in relation to improving energy access and health, promoting sustainable agriculture and economic growth, and reducing inequalities in rural areas.

In conclusion, this research supports the overarching argument that bioenergy technologies have the potential to deliver energy demands in rural areas while tapping the potential of agricultural residues. Overcoming barriers to these systems deployment is still challenging. Yet, the synergies identified across all the dimensions could help to attain the system's feasibility and sustainability. Furthermore, wider societal co-benefits to rural communities could also be realised, as suggests the strong correlation between bioenergy and the Sustainable Development Goals.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institutes of learning.

Copyright statement

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During the PhD programme, two papers were published in peer-reviewed journals:

1. **Garcia-Freites, S**., Welfle, A., Lea-Langton, A., Gilbert, P., Thornley, P. (2019). The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector. *Biomass Conversion and Biorefinery*, pp.1–16. Available from: https://doi.org/10.1007/s13399-019-00480-8

2. Gough C., **Garcia-Freites S.**, Jones C., Mander S., Moore B., Pereira C., Röder M., Vaughan N., Welfle A. (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5˚C. *Global Sustainability* 1 (e5): pp. 1-9. https://doi.org/10.1017/sus.2018.3

The abstract of a third paper looking into the *Environmental synergies and trade-offs associated with bioenergy from agro-residues in the Global South* has been accepted for the special issue "Modern bioenergy approaches in international development" of the Journal Biomass and Bioenergy and is under preparation.

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CHAPTER 1. INTRODUCTION

This chapter introduces this doctoral research thesis titled *"*Using agricultural residues to support sustainable development: *a case study of coffee stems gasification to supply energy demands in rural areas of Colombia"*. The study was developed within the Tyndall Centre for Climate Research at the University of Manchester and funded by a scholarship program from the local government of *Departamento del Atlántico* in Colombia.

The aim of this doctoral research evolved over the years. First, it responded to increasing research attention on Bioenergy with Carbon Capture and Storage (BECCS), and thus, initially sought to conduct a general assessment on BECCS technologies. It later moved towards a specific topic that attended the research needs of Colombia as a developing country, one of which focused on exploring the potential of renewable resources to improve clean energy access to rural areas and boost agricultural and rural development.

This chapter is structured into six sections. Section 1.1 sets the context of this research, introducing the key role of bioenergy for mitigating climate change and on wider sustainability issues. Section 1.2 explains the motivation behind this research and the specific interest in examining Colombia as a case study. Section 1.3 presents the overall aim and specific objectives. Section 1.4 discusses the scope of this research project, and finally, section 1.5 outlines the thesis structure explaining how each chapter contributes to the research aim.

1.1 Research context

Modern bioenergy systems, when deployed sustainably, are expected to play a prominent role across the decarbonisation of different sectors. Beyond the greenhouse gas (GHG) emission reductions, bioenergy is also expected to complement the role of variable renewable energy sources by enhancing energy security and providing complementary environmental and socio-economic benefits (OECD/IEA 2017). It also has strong synergies with the agricultural and forestry sector, as well as with waste management issues. In addition, bioenergy is regarded for its potential to support the achievement of almost all the Sustainable Development Goals (SDGs), particularly in low and middle income (LMI) countries (Renzaho et al. 2017).

This section aims to provide a context to this research, by exploring the instrumental position of bioenergy in the global energy mix for tackling climate change and contributing to sustainable development, especially in developing countries. Furthermore, it also discusses the potential positive impact of bioenergy on LMI countries, particularly in improving access to clean energy and energy security, while achieving the adopted UN Sustainable Development Goals.

1.1.1 Role of bioenergy in the global energy mix

The conversion of biomass, in traditional and modern uses, into energy carriers, such as electricity, heat and biofuels, is the largest contributor to global renewable energy supply (REN21 2017), beyond hydropower and other renewables (IEA 2018). As of 2017, it provided almost 57.9 EJ of the world's primary energy, accounting for almost 10% of the primary energy demand. Modern bioenergy and traditional use of biomass contribute each with 5.2% and 4.7%, respectively (IEA 2018), whereas hydropower and other renewables supply 2.5% and 1.8%, respectively, to the world primary energy demand (IEA 2018).

Since 2009, the consumption of modern bioenergy has exceeded the utilisation of traditional biomass (REN21 2018). The traditional use of biomass refers to the direct burning of solid biomass (i.e., fuelwood, agricultural residues and animal waste) for cooking and heating purposes. These uses derive into unsustainable biomass sourcing, low conversion efficiencies (10%-20%) and high emissions of particulates, NOx, VOCs and black carbon which affect human health and environment (OECD/IEA 2017). In low and middle-income countries, they are still a major source of energy with a 49% share of the population relying on traditional biomass. This is predominant in Sub-Saharan Africa (84%) and developing countries in Asia (49%). In countries in the Middle East, Central and South America, like Colombia, these shares are lower, 12% and 5%, respectively (IEA 2017d).

Modern bioenergy encompasses more sustainable and efficient biomass conversion technologies to produce energy for industry, power generation or transport fuels (IEA Bioenergy 2007). Currently, it is the largest renewable source contributing to more than half (54.5%) of all renewable energy production (IEA 2018). Therefore, within this thesis, the word bioenergy refers to modern bioenergy technologies and excludes the traditional use of biomass.

Figure 1 illustrates the distribution of biomass conversion by end-use in 2015, including traditional biomass, and the growth of modern bioenergy markets, i.e. heat, electricity and biofuels for transport. The contribution of bioenergy in these sectors is further examined below.

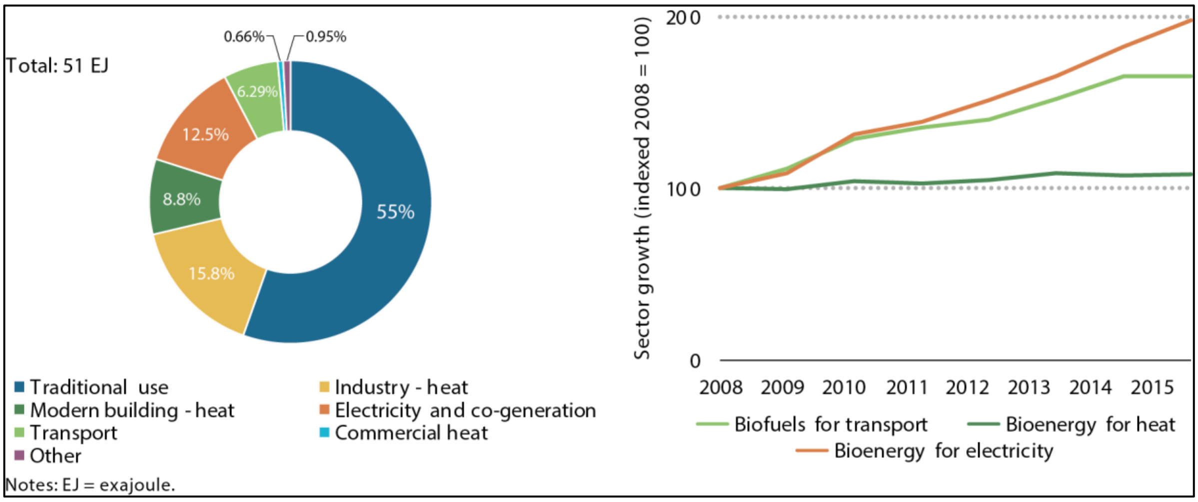


Figure 1. Biomass resources consumption by end-use in 2015 (left)
Modern bioenergy growth by sector (right). (OECD/IEA 2017)

Bioenergy for modern heat supply

The largest application of bioenergy is for heat supply, contributing 70%[1] to the renewable energy consumption for heat by 2015. Most of the heat provision is for industrial processes (63%), followed by modern heating for buildings and heat for agriculture (OECD/IEA 2017). The most common and widely deployed bioenergy technology for heat generation is the biomass combustion in boilers and stoves. The biomass gasification at small-scale applications is still on early market development (Bauen et al. 2009; OECD/IEA 2017).

The penetration of bioenergy in the heat market with a 1% growth rate between 2010 and 2015 has become stagnant relative to applications for the production of electricity and transport fuels, as Figure 1 shows. In some parts of the European Union, there is a well-developed bioenergy market as a result of introducing policy support mechanisms (i.e. Renewable Energy Directive) (OECD/IEA 2017). However, in the rest of the world, particularly in developing countries, there have been insufficient policies and mechanisms that support the development of this sector. This has hindered the rollout of this market, slowing the transition from the traditional biomass uses for heating and cooking (OECD/IEA 2012). For instance, improving the legislation for waste and residues management (e.g. effective banning of open-field burning) could contribute to converting this type of residues as a strong driver for bioenergy production (FAO/GBEP 2007).

[1] This number excludes bioenergy heat contribution to renewable commercial heat and the traditional use of biomass

Bioenergy for electricity generation

Bioenergy applications for electricity generation (and cogeneration) come second after heat, with the largest use of biomass. Nationally available resources are usually driving this consumption; hence, a range of feedstock is available, most of them in solid form. Regarding the technologies, there is a varied group of widely deployed and early commercial processes at different scales, e.g. combustion combined to steam cycles, co-firing, gasification coupled to engines or turbines, and anaerobic digestion with engines (IEA Bioenergy 2007; International Renewable Energy Agency 2019).

In relation to solid biomass, a global wood pellet market has developed over the years for industrial and heating purposes, with an increase in consumption by 60% between 2010 and 2016 (OECD/IEA 2017; Bauen et al. 2009). Most of the global pellet production comes from North America and the European Union, where over 50% of the production is traded internationally to countries with insufficient forestry resources, such as the UK. This has promoted the implementation of certification schemes to monitor and certify the sustainability and fuel characteristics of the wood pellets (OECD/IEA 2017).

In 2016, bioenergy for electricity generation supplied 2% (500 TWh) of the global electricity production, ranking below the contribution of other renewables, such as hydro and wind resources. The bio-power installed capacity reached the 110 GW, increasing at an annual average growth of 6.5% since 2010, as the market with the fastest growth rate among bioenergy, yet, this just represented 4% of capacity additions among all renewables resources (OECD/IEA 2017).

Certain factors have become constraints to electricity generation from bioenergy, such as a higher electricity generation costs relative to mature technologies and the cost competition with variable renewable energies. However, electricity from bioenergy can still be cost-competitive in many cases, playing a complementary role by its dispatchable nature, higher capacity factors, the potential for cogeneration, and other benefits, like, agricultural development and waste management (OECD/IEA 2017; OECD/IEA 2012).

Many other countries that have an important availability of indigenous biomass resources have yet to realise their potential (OECD/IEA 2017). This is the case of Colombia which has a large share of hydropower generation, with 63.3% of the total electricity demand in 2018 (XM 2019). However, it could diversify its mix and utilise the energy potential of other renewables sources, such as wind, solar and bioenergy when it is sustainable to deploy (UPME 2015).

Bioenergy for transport fuels

The production of conventional transport biofuels, such as bioethanol from sugar and starch-based crops and biodiesel from oil-crops and hydro-treated vegetable oil contributed 4% of the global demand for road transport fuels. This market is mostly policy driven by country-level obligations that stipulate blending of biofuels at low levels (OECD/IEA 2017), aiming to reduce GHG emissions, particulate matter and tackle rising fossil fuel prices.

Bioethanol production takes place in a few countries, with the United States and Brazil at the top with an 85% share of the total world's production in 2016 (OECD/IEA 2017). The production of biodiesel has a more even distribution, with almost 70% of global production led by the United States, Brazil, Germany, Argentina and Indonesia (IRENA 2019b). From the demand side, over 90% of biofuels consumption comes from the United States, Brazil, the European Union and China.

In Colombia, this market is also well-established with the production of first-generation biofuels at large-scales and with country-level mandates for blending with fossil fuels. This market is also growing as the mandates for biofuels shares in the blends increase, as well as the domestic demand for petrol and diesel (FedeBioCombustibles 2019). The nature of this market, with large-scale deployments and a land tenure distributed among a few large land-holders (UPME 2015), suggests that further deployment of this sector will benefit a few large-scale companies. Also, a transition to second-generation biofuels utilising agricultural residues is still far from deployment (Gonzalez-Salazar, Venturini, et al. 2014). This suggests that the biofuel sector demands less attention, particularly from research framed within the evaluation of bioenergy deployment that could benefit smallholders, especially farmers, which are often neglected by the government's policies.

Overall, bioenergy deployment is playing an important role across all markets; it is the largest renewable energy source in the heat and biofuel market, and the participation in the power sector is projected to increase. Bioenergy penetration in these markets finds competition against alternative renewable technologies (e.g. wind and solar energy) with improved performance and lower costs, and with current low fossil fuels prices. This competition intensifies when technology-neutral support measures are employed, which will drive the focus on the lowest-cost energy technology solution. Bio-heat and bio-electricity generation require large scale developments to benefit from economies of scale; however, this is only feasible if the infrastructure exists. Distributed generation systems favour technologies that are low cost at small scale, however, that is not the case of bioenergy (Thornley, Brammer, et al. 2009). Other limitations are the lack of policy and regulatory framework, which is considered essential to deliver project investments.

1.1.2 Bioenergy and climate change

The urgent and ambitious measures needed to limit the global temperature increase below 2°C, as established by the UNFCC Paris Agreement, have bioenergy among the portfolio of technologies needed to penetrate in the renewable energy market to mitigate climate change (OECD/IEA 2017; IRENA 2019a). Bioenergy is expected to play a pivotal role in delivering emissions reductions in those sectors that are more difficult to decarbonise, like aviation and shipping; and complement other renewable technologies in electricity and heat markets.

Additionally, Bioenergy with Carbon Capture and Storage technologies (BECCS) have the potential to deliver negative emissions while producing power, heat and biofuels vectors (ETI 2018). Most of the 2°C (2DS) emissions scenarios are, then, heavily reliant on the global and large-scale deployment of BECCS to remove CO_2 from the atmosphere and attain net negative carbon emissions (IPCC 2013; ETI 2018; Gough et al. 2018).

Despite this, studies from the IEA (OECD/IEA 2017; IEA 2017c) report that the current rate of bioenergy deployment across different markets is falling short to meet the 2DS target. The progress of bioenergy into effectively contributing to achieving this target would require a set of measures across different energy markets and sectors. The transport sector requires a shift towards more sustainable biofuels capable of better GHGs performance and a more geographically-balanced distribution of the demand for transport biofuels (OECD/IEA 2017).

The heat demand from the industry sector will represent the second-largest bioenergy utilisation, deriving into fossil fuel replacement and emissions reductions. For the residential sector, heat generation from traditional biomass is expected to reduce considerably by 40% in the 2DS, and in parallel to increase the integration of more advanced applications, such as district heating systems or low carbon gas networks (OECD/IEA 2017).

Finally, the electricity generation from bioenergy is projected to double in a 2DS (from 2015 to 2060). The contribution of bioenergy in this sector is more constrained to certain conditions to make it feasible over time, such as low-cost generation relative to other sources and strong complementary drivers. Examples of the last one are potential waste management solutions and cogeneration in industries and capability to complement high levels of variable renewable energies, providing flexibility to the systems (OECD/IEA 2017; IRENA 2012).

Overall, bioenergy applications are expected to be more extensive, and its deployment, beyond traditional biomass conversion, to reach other regions where vast amounts of biomass remain untapped but can be sustainably removed (FAO 2010; OECD/IEA 2012). Concerning this, Colombia has the potential to integrate bioenergy vectors and contribute to supplying local energy demands by utilising its indigenous biomass more efficiently (UPME 2015;

Gonzalez-Salazar, Morini, et al. 2014). This could potentially contribute to replacing the consumption of fossil fuels and avoiding damage to stocks when agri-residues are available for use.

1.1.3 Bioenergy: synergies and challenges in the agriculture sector

Bioenergy also has greater potential, relative to other renewables, to contribute to wider environmental, economic and social impacts (Thornley, Upham, et al. 2009; Adams 2011); proven it is produced sustainably. Beyond the energy sector, bioenergy also has a key role and is strongly intertwined with the agricultural, forestry and waste management sectors (OECD/IEA 2017).

Bioenergy production has a close intersection with agriculture, with a mutually beneficial relationship; that could also emerge concerns when balancing risks and benefits (McManus and Taylor 2017). On one side, agriculture provides feedstock for bioenergy production (Maltsoglou et al. 2014), contributing 10% of the total biomass feedstock for bioenergy (World Bioenergy Association 2017). On the other, bioenergy incentivises investments and employment in agriculture and improves energy access in rural areas, enhancing rural development (FAO 2010).

Many developing countries rely heavily on agriculture for their economies and therefore have a potential abundance of agricultural residues and waste resources. This co-dependency can also put pressure on resource demands (i.e. agricultural products, water and land-use) by competing with other markets, such as food production (Maltsoglou et al. 2014), and generating potential threats to soil fertility, water quality, and biodiversity (Welfle et al. 2014).

The utilisation of agricultural residues and livestock manure could potentially minimise these risks (OECD/IEA 2017). International research institutions, such as the OECD/IEA, FAO, IEA Bioenergy and the World Bioenergy Association have recommended whenever feasible, to expand the sustainable use of agricultural residues and by-products in bioenergy applications (OECD/IEA 2017; FAO 2010; IEA Bioenergy 2011; World Bioenergy Association 2017). In addition, the utilisation of these residues in efficient bioenergy application helps to displace traditional uses of biomass, reducing air pollution, and lowering risks of respiratory illnesses and premature deaths (Hazell and Pachauri 2006).

Using agricultural residues to produce bioenergy vectors, however, is constrained to certain conditions to make it feasible, such as sufficient biomass resources supply for the system's operation and a reduced competition over the resources for other practices and/or markets

(FAO 2010; Hazell and Pachauri 2006). Furthermore, using agri-residues close to the point of the generation to deliver local energy demands could reduce lifecycle emissions and logistics costs from biomass collection and transportation (OECD/IEA 2017).

1.1.4 Bioenergy contribution to the Sustainable Development Goals

Part of the motivation for a global-scale deployment of modern bioenergy over traditional biomass is its potential to contribute to sustainable development through the three dimensions: environmental, societal and economic. This is particularly essential in many low, and middle-income countries where achieving sustainability is most important to support their growing economies (The World Bank 2017b; IEA 2017b). Concerning this, the adoption of the *2030 Agenda for Sustainable Development* developed by the United Nations (2015) and portrayed in the Figure 2 is an adequate platform to understand how bioenergy could contribute towards the achievement of the Sustainable Development Goals.

Figure 2. SDGs of 2030 Agenda for Sustainable Development. Source: (United Nations 2015)

Beyond the obvious contributions to the SDG 7 and SDG 13, the pivotal role of bioenergy in the development of other sectors, like agriculture, forestry and waste management, can expand its impacts and support attaining other SDGs. This is the case for SDG 2, SDG 3, SDG 8, SDG 10 and SDG 12 (Rosenthal et al. 2018).

1.1.5 Deploying sustainable bioenergy systems for rural energy access

Different bioenergy technologies, such as anaerobic digestion (AD) and gasification, have the potential to deliver rural energy access at small-scale applications when there is the availability of indigenous biomass residues (IEA 2017c; Hazell and Pachauri 2006). This could be largely beneficial in LMI countries reporting untapped agricultural residues in traditional biomass uses, and on the other hand, remaining challenges to access to clean and reliable energy (The World Bank 2017a; IEA 2017b).

The diverse characteristics of agricultural residues (i.e. moisture content, lignocellulosic composition, density and heating value) expand the range of possibilities for biomass conversion technologies into power and heat vectors (Basu 2013a). Some of these technologies are well-commercially deployed, such as combustion and AD, or at early commercial statuses, such as gasification and pyrolysis. Yet their implementation is still limited in rural areas and agroindustries of developing countries, where traditional practices still prevail (OECD/IEA 2017; Bauen et al. 2009).

There is a significant opportunity to develop emergent bioenergy technologies. This is the case of biomass gasification that has proven higher conversion efficiencies, flexibility, and improved environmental performance, particularly at small-scale applications (Basu 2013d; Bauen et al. 2009; Nguyen et al. 2013).

The deployment of bioenergy systems could bring wider benefits, but also give rise to challenges, across the environmental, economic and social dimensions. This, therefore, demands for an integrated assessment that looks into the impacts across each dimension but also on how their interconnection mutually enhances or limits these wider benefits (Thornley, Upham, et al. 2009). To overcome the limitations of using agri-residues and promote a sustainable utilisation requires an analysis of the resource supply and energy needs balance for sector-level. Such an integrated approach can provide a thorough understanding of the merits and impacts of implementing bioenergy systems in rural areas, informing on pathways to achieve the system’s feasibility and sustainability.

Current findings suggest that, in many cases, this wider understanding has been absent (FAO 2010), leading to a slow roll-out of the technologies or an unsuccessful implementation of projects. Therefore, in this challenging times that need urgent climate actions, together with achieving sustainable development, expanding our scientific knowledge on this matter is important to overcome the bottlenecks for bioenergy implementation (Souza et al. 2017).

1.2 Research rationale

Globally, wind and solar PV penetration have overtaken bioenergy deployment in the power sector (IRENA 2019a). Among all renewable energy sources, bioenergy faces wider sustainability-related challenges, particularly with land-use change, food security and biodiversity preservation. There are multiple scenarios where sustainable use of biomass can provide wider environmental, social and economic benefits, particularly at local or regional levels (Souza et al. 2017). This is the case of agricultural residues application to provide the energy for rural communities and agro-industries. By understanding the drivers and limitations for deploying these systems, this research intends to address the gaps associated with sustainable utilisation of agri-residues in small-scale bioenergy applications to provide clean energy alternatives to LMI countries.

Colombia is a middle-income country in South America with an agricultural sector that frequently exhibits a reflective symmetry related to the biomass supply-energy demand of the sector that remains untapped. On one side, there is significant potential from biomass residues for bioenergy production (UPME 2015; Gonzalez-Salazar, Morini, et al. 2014; Escalante et al. 2011), and on the other, an opportunity to enhance decentralised energy access and security in rural areas (Gaona et al. 2015).

However, there is high relevance and rationale to use this sector as a case study in this research to provide a further understanding of how bioenergy systems using agricultural residues could be sustainably deployed in rural areas. It also intends to assess trade-offs that could hinder the system's implementation and identify synergies across the sustainability dimensions that could maximise benefits, minimise limitations and facilitate achieving the SDGs.

1.3 Research Aim and Objectives

This research aims to evaluate the feasibility of deploying small-scale gasification technologies, using agricultural residues to generate power and heat vectors for the energy demands in rural areas. The specific objectives are to:

1.3.1 Specific objectives

1. Evaluate the biomass energy potential of agricultural residues in Colombia and define a feasible agricultural sector and type of agri-residue for the case study
2. Evaluate the technical performance, through the mass and energy balance, of a small-scale biomass gasification-power generation and/or CHP system.

3. Analyse the potential match between the energy demand and biomass resource availability of the selected agricultural sector in Colombia.
4. Assess the potential environmental impacts of deploying gasification systems for power and/or heat generation, considering the effect of different counterfactual scenarios on the environmental sustainability of the system, and
5. Evaluate costs and analyse the economic feasibility of deploying small-scale gasification systems of agricultural residues for power and heat generation.

1.4 Research scope

This research explores the potential and feasibility of emergent bioenergy technologies, such as gasification, to deliver rural energy solutions using the agricultural sector of Colombia, as a case study. Bioenergy development is set within local contexts; therefore, it is recognised that the specific results of this research may be unique to the case study. Therefore, although results are not directly replicable, they contribute to building knowledge on how the techno-economic performance and environmental impacts could inform and determine the system's feasibility. This understanding also allows to identify the system's potential merits and address the trade-offs.

Furthermore, the multidimensional framework (Figure 34) developed to integrate the research findings on the benefits and trade-offs to the system's deployment, and align pivotal factors with the SDGs could also be transferred to different contexts. It can be applied to assess the bioenergy potential in other LMI countries with similar socio-economic achieving as Colombia and that seek for renewable energy solutions in rural areas.

This research does not encompass a direct assessment of the social dimension associated with the deployment of bioenergy technologies. However, the importance of certain issues, such as the public perception and participation of rural communities on bioenergy technologies deployment is acknowledged in this research. Furthermore, wider societal implications to these systems deployment in rural communities were identified in the multidimensional framework through the correlations of bioenergy with the SDGs.

1.5 Thesis structure

This thesis is organized into eight chapters, in addition to the introduction:

Chapter 2. *The energy landscape in Colombia*

This chapter presents an overview of the socio-economic context and energy systems setting of Colombia. It follows a description of the role of renewable energies and the context of GHGs emissions from different sectors. Finally, it presents an outlook of the renewable energy landscape, focussing on the potential of bioenergy production from agricultural residues in rural areas. This particular outcome contributed to achieving the *first objective* by evaluating the different agriculture sectors having the highest biomass energy potential from agri-residues and outlining the challenges and opportunities to realise their utilisation in the sector.

Chapter 3. *Biomass and Bioenergy*

This chapter presents a review of a series of relevant concepts on biomass and bioenergy technologies. The chapter provides an overview of the general concepts on biomass and bioenergy technologies and gives a detailed review of theoretical concepts and practicalities of biomass gasification. The outcomes of this chapter provide the scientific bases for the selection of gasification for the study case and the key parameters that should be assessed to determine the system's technical performance. Therefore, the theoretical review presented in this chapter contributed to realise all the specific objectives of this research.

Chapter 4: *Methodology*

This chapter presents a detailed description of the methods applied to evaluate the technical and economic feasibility and potential environmental impacts of deploying small-scale gasification-CHP systems. The chapter structure comprises the description of the approaches followed for: the selection of the agricultural residue and sector; basic design and process modelling of gasification system; lifecycle assessment and techno-economic assessment. The outcomes of this chapter provide the conceptual framework, scope and practicalities to apply the methods required to attain the research aim; therefore, they support all the specific objectives of this research.

Chapter 5: *Technical assessment of gasification for CHP generation*

This chapter presents the results of the technical assessment of the biomass gasification-CHP system, using the process modelling approach. It also introduces the selection and justification of the agricultural residue and sector for the case study. The chapter comprises the description of the case study on the Colombian coffee sector and also the results of the process modelling of the biomass gasification for power and heat generation system. Finally, it presents an analysis of the balance between biomass availability and energy demand of coffee farms in Colombia. The outcomes presented in this chapter contributed to attaining the second objective by providing key data that informs on the technical feasibility of the coffee stems gasification system. Furthermore, the analysis of the energy demand and biomass availability at coffee farms level contributed to achieving the third objective informing on the suitability of operating scales and type of coffee farms where these systems could be potentially deployed.

Chapter 6: *Lifecycle assessment of the small-scale gasification-CHP system*

This chapter presents the LCA of the coffee stems gasification system for power and heat generation. It contains original findings on the environmental feasibility of using locally available agri-residues in small-scale bioenergy systems to generate decentralised energy. It also highlights the importance of examining counterfactuals to identify wider benefits and trade-offs related to the implementation of these systems. The chapter structure follows the framework of an LCA according to ISO standard 14040: Goal and scope, Lifecycle inventory, Lifecycle impact assessment and the interpretation of results. This LCA contributed to the fourth objective by assessing a range of potential environmental impacts along the lifecycle of this bioenergy system while considering the significant influence of different counterfactual scenarios.

Chapter 7: *Techno-economic assessment of the small-scale gasification-CHP system*

This chapter presents the results of the techno-economic assessment of the small-scale gasification-CHP system. The chapter comprises the estimations of the capital and operating costs for the gasification plant and sensitivity analysis for the levelised cost of electricity (LCOE) of this plant. Finally, it introduces an LCOE-based comparison between the bioenergy system and a diesel-based generation system to assess the economic competitiveness of the proposed system. These outcomes contributed to achieving the sixth objective by evaluating the estimated costs of the system and analysing the economic feasibility of generating bio-electricity and bio-heat for the coffee farms, compared to current forms of rural energy supply.

Chapter 8: *Multidimensional framework to assess bioenergy feasibility and correlations to the Sustainable Development Goals*

This chapter integrates, in the form of a multidimensional framework, the main findings of this thesis and discusses synergies that could contribute, but also trade-offs that should be addressed, to attaining feasible and sustainable bioenergy systems in rural contexts. Through this multidimensional framework, these key outcomes were aligned with relevant Sustainable Development Goals to identify wider societal co-benefits that could be achieved with this system's deployment. Hence, this synthesis of potential benefits and limitations, overall, supported the research aim by guiding on the feasibility and sustainability of these bioenergy systems in rural contexts.

Chapter 9: *Conclusions and recommendations*

This chapter, first, provides an overview of the key findings and contributions of this research and correlates them with the specific objectives in this research. It sets general recommendations on steps and actions forward that could contribute towards achieving feasible and sustainable small-scale bioenergy systems in rural areas; with specific key points to stakeholders in the policy sector and social organisations. It also outlines opportunities for future research and highlights the originality of this research, its contributions to the body of knowledge and their dissemination. Finally, the chapter closes this thesis with the concluding remarks.

CHAPTER 2. ENERGY LANDSCAPE IN COLOMBIA

Colombia is experiencing an energy transition that is enabling further penetration of renewable resources, beyond large-scale hydro into its energy mix. More than 96% of the population has access to electricity through the National Interconnected System (SIN in Spanish). However, nearly one million people still lack access to energy in isolated rural areas that account for approximately two-thirds of the national territory. In these areas, known as Non-interconnected zones (ZNI in Spanish), electricity is supplied mainly by Diesel generators and in smaller scale by hybrid systems (Solar PV-Diesel) or small hydropower plants (Rodríguez-Urrego and Rodríguez-Urrego 2018).

This chapter sets the energy landscape in Colombia from two sides, on one side, the socio-economic and governance aspects that are hindering a diversified penetration of renewables in the energy mix. On the other, it presents an overview of the current energy and environmental policies that are paving the way to extend renewables energy integration in the country. The chapter covers introductory information of Colombia's socio-economic and energy system context. Then, a description of the status of renewable energies and GHG emissions is provided. The last section presents an overview of the biomass potential from agricultural residues, their opportunities and challenges for energy use.

2.1 Colombia's context

2.2.1 General information

Colombia is located in the northwest of South America with an extension of 1,141,748 km^2 and two coastlines, one to the north with the Atlantic Ocean (Caribbean Sea) and one to the west with the Pacific Ocean. The country has land borders with Venezuela and Brazil to the east, Panama to the west and Ecuador and Peru to the South. Colombia is, after Brazil, the second most biodiverse country in the world, and the first country in biodiversity per area (World Bank Group 2019). It also has abundant natural resources, holding the sixth-largest renewable water resources and vast extensions of arable land (Gonzalez-Salazar et al. 2017).

The country has a population of 45.5 million inhabitants (DANE 2018), ranking as the third most populous country in Latin America. The majority of the population (77.8%) lives in urban centres and the rest (22.2%) in rural areas (DANE 2018).

Colombia is experiencing a relevant post-war period, after 50-years of armed conflict with the FARC guerrilla group, the government and FARC signed a peace agreement in 2017. Although there are many issues to solve on the implementation of the peace agreement, it is expected to influence positively on rural communities development and enhance a more sustainable agricultural sector (Gonzalez-Salazar et al. 2017).

2.2.2 Economy and the role of agriculture

Colombia is classified as a middle-income country by The World Bank (2017b) and the fourth-largest economy in Latin America, behind Brazil, Mexico and Argentina. The GDP in 2017 was reported to be USD 314,458 billion and it has shown steady growth over the last 30 years. Despite this, Colombia is considered a country with high inequalities, with 27% of the total population living under the poverty line, and in rural areas, this number rises to 40% (The World Bank 2017a).

By 2016, the contribution of the economic sectors to the GDP growth was as follows: services (59.6%), construction (17%), oil and mining (8.5%), agriculture (6.4%) and manufacturing (2.1%) (Nieves Zarate and Hernández Vidal 2016). For the last 30 years, the country has shifted from an agricultural economy towards a more industrialised and service-based economy, boosting the economic growth from 4 % to 5% annually (Gonzalez-Salazar, Venturini, et al. 2014).

The rural sector has been strongly affected by two dynamics: drug trafficking and the civil war with guerrillas and paramilitary. The current rural development model is still unequal for small farmers and rural communities, favouring the few large landholders (UNDP 2011). In particular, the development of the sector has stagnated due to weak regulations on land ownership and unequal distribution, lack of development in the land market, trading barriers and rural violence (OCDE 2015). However, agriculture and the derived agroindustries still are an important source of local employment and foreign earnings from the exports of coffee, cut-flowers, bananas and other fruits and vegetables (OEC 2018). The different climate zones and topography of the country enable the cultivation of a wide range of crops and the production of many agricultural commodities (UPME 2015).

2.2.3 Colombian energy system

Colombia has a diverse energy matrix that has been transformed over the last decades due to socio-economic and political reasons (Gonzalez-Salazar 2016). Between 1975 and 2014, the total primary energy supply (TPES) grew from 197.5 to 472 TWh, showing an average annual growth rate of approximately 2.3%. The primary energy production is highly dominated by fossil fuels (i.e. coal, crude oil and natural gas) summing up to 92.6% of the total production, with a large fraction (69%) of fossil fuels exports (IEA 2016). The remaining share accounts for renewable resources in the form of biomass (3.8%) and hydro (3.2%). Figure 3 shows the energy balance of Colombia covering primary energy production, primary energy supply and final consumption.

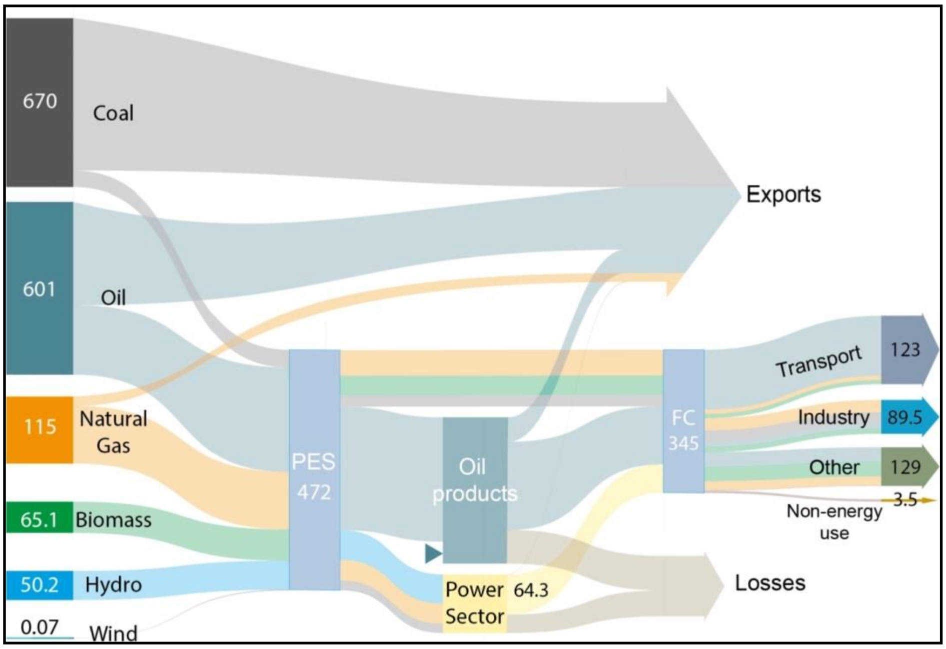


Figure 3. Colombian primary energy balance and final consumption in 2014
Source: (Pupo-Roncallo et al. 2019) - Note: All numbers in TWh

The transportation sector is the largest energy consumer accounting for approximately 39% of the total final consumption. Natural gas and oil products dominate this sector's consumption. Other intensive energy use segments such as industry and the residential sector accounted for 25% and 19% of the final consumption, respectively (Pupo-Roncallo et al. 2019). The percentage contribution of the different fuels to the primary energy supply and to the final energy consumption have not changed significantly from 2014 to 2017, the latest year with data available on the energy balance (IEA 2017a).

2.2.4 Power sector in Colombia

Power generation in Colombia represents 17.4% of the final energy consumption in the country (IEA 2016), with an installed capacity of 17.3 GW by April 2019 (XM 2019). It has been dominated historically by large-scale hydropower generation, accounting for 63.3% of total installed capacity and complemented by large-scale fossil fuel power generation with 29.4% (XM 2019).

The electricity supply comprises two systems: the National Interconnected Grid (SIN in Spanish) and the Non-Interconnected Zones (ZNI in Spanish). The SIN is a large and centralised system that covers 96% of the population connecting a third of the national territory. The ZNI covers two-thirds of the national area (see Figure 4) that is inhabited by 4% of the population, most of them live in isolated rural areas (Bachra et al. 2015) of which nearly 1.2 million have no access to electricity (Gaona et al. 2015).

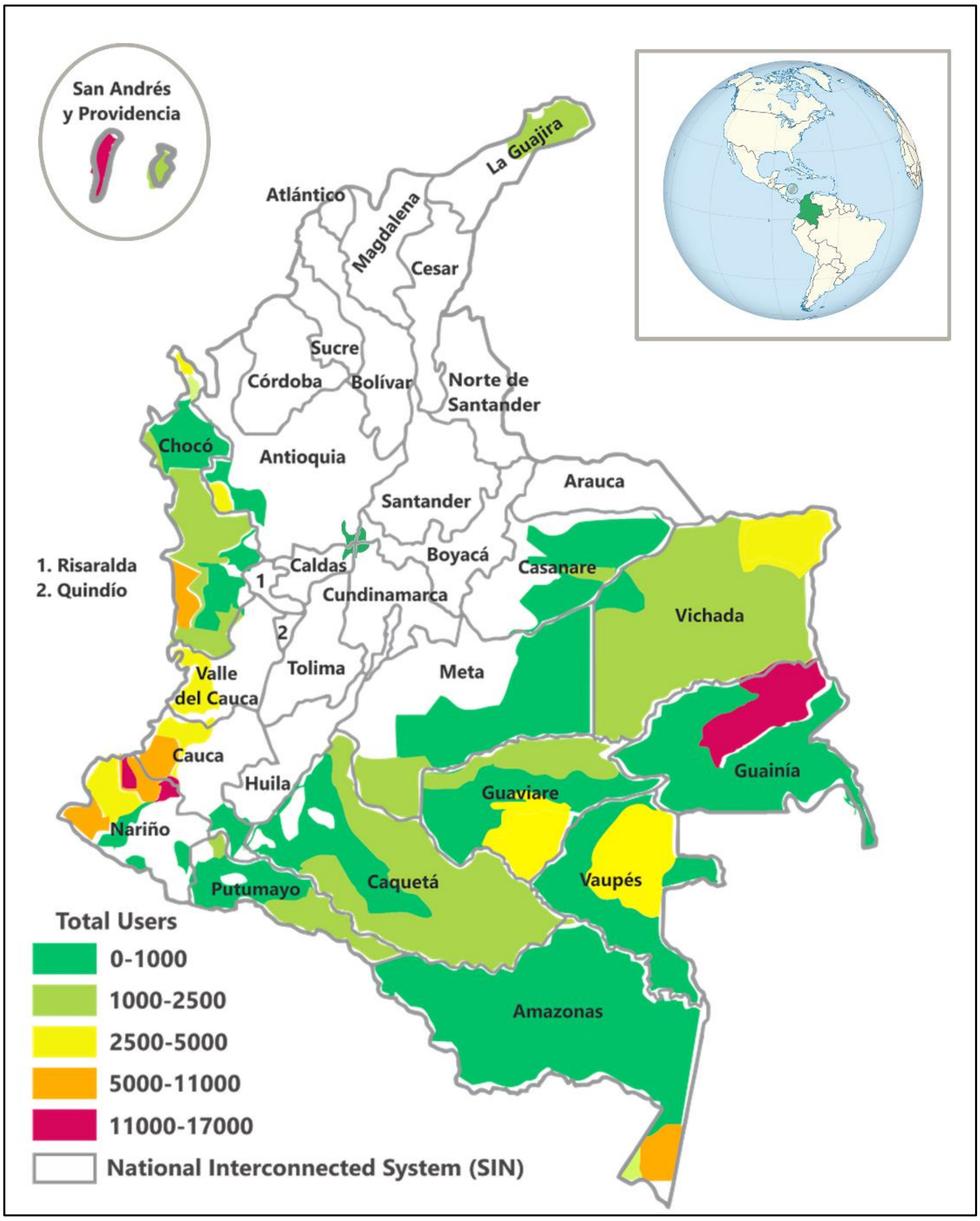


Figure 4. Non-interconnected zones (ZNI) in Colombia.
Source: (Rodríguez-Urrego and Rodríguez-Urrego 2018)

The high hydropower generation has resulted in a power sector with low carbon intensity compared to other countries in Latin America (Calderón et al. 2015). However, this strong hydro-power reliance has left the country vulnerable to energy shortages during drought periods, mainly caused by El Niño Southern Oscillation (ENSO) (UPME 2015; OECD 2014). These events are expected to become more severe and continuous in the future due to climate change effects (UPME 2015).

Another important aspect of the electricity system in Colombia is the poor quality of the electricity supply, especially in rural areas. This is mainly due to an inadequate infrastructure (low transmission capacity lines), deficiency in resources allocated for power generation and public order problems (Gaona et al. 2015; Bachra et al. 2015). All these have caused an unreliable and costly electricity service (Bachra et al. 2015).

In the ZNI, electricity is mainly supplied by diesel generators (92%), with solar PV and biomass systems providing the remaining 8% (Gaona et al. 2015). This distribution could be more balanced towards higher renewable-based power generation as there is a large potential of non-hydro renewable resources in rural areas in Colombia (Gómez-Navarro and Ribó-Pérez 2018). A more decentralised and diverse power mix could enhance energy access in off-grid areas and help to reduce power losses (Hernandez et al. 2011). A good example of this is the successful deployment of microgrids in remote rural regions such as Choco and La Guajira, demonstrating a feasible solution for distributed generation schemes (Gaona et al. 2015). Additionally, recent policies, such as the Law 1715 of 2014 that regulates the integration of renewable energies in the country (Congreso de Colombia 2014), are setting the conditions to increase the penetration of renewable energy sources in the national energy mix.

2.2.5 GHG emissions

The contribution of Colombia into regional (7%) and global (~0.22%) energy associated CO_2 emissions is relatively low compared to other Latin American countries with similar economies (Global Carbon Atlas 2017). This is the result of lower energy consumption and a clean power matrix dominated by hydropower generation (Calderón et al. 2015). The global average of electricity-related emissions is approximately 42%, whereas, in Colombia, this accounts for only 8.5% of the total emissions (Olaya et al. 2016).

Figure 5 shows the emissions by sector in 2012. The AFOLU (Agriculture, Forestry and Land Use) and energy sectors evidence the highest contribution to national emissions. The main driver in the AFOLU sector is deforestation. While in the energy sector, transport and energy industries account for the highest shares (Government of Colombia 2015; IDEAM 2015). As indicated in section 2.2.3, transportation is the largest energy user and therefore, the largest source of CO_2 emissions. This is due to the growing freight activity, fast urbanisation and increasing incomes and motorisation rates (OECD/ECLAC 2014; Román et al. 2018).

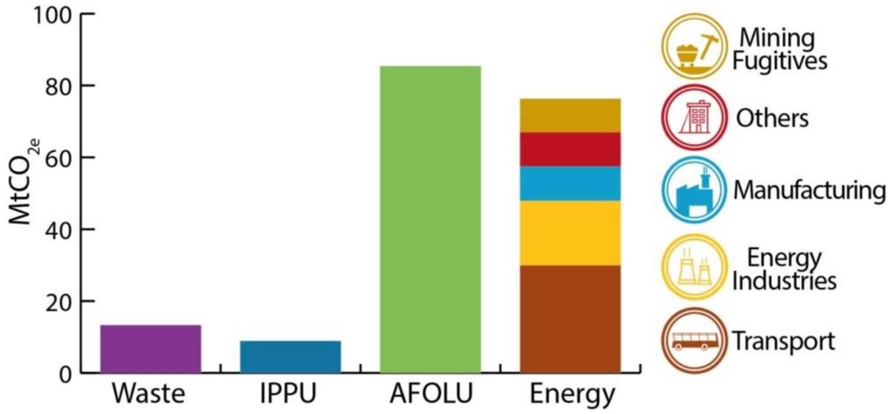


Figure 5. Colombian GHG inventory in 2012. Source: (Pupo-Roncallo et al. 2019)
IPPU: Industrial Processes and Product Used – AFOLU: Agriculture, Forestry and Land Use

Colombia adopted in December 2015 a new legally binding agreement during the COP21 where it committed an unconditional 20% reduction on its GHG emissions by 2030, with respect to the projected Business-as-usual (BAU) scenario (Government of Colombia 2015). The total GHG emissions could reach 335 Mt $CO_{2,}$eq in 2030 according to the Colombian government (BAU scenario) if a series of mitigation measures are not applied, from which 146.9 Mt $CO_{2,}$eq are projected to be produced in the energy sector (Cadena et al. 2016). However, other studies have estimated different values for future GHG emissions. ECLAC (2013) estimates energy-related emissions to grow by up to 200 Mt $CO_{2,}$eq by 2030, and a total generation of 400 Mt $CO_{2,}$eq for the same year. Calderon et al. (2015) examined four different models (GCAM, TIAM-ECN, Phoenix and MEG4C) and concluded that emissions in the energy sector might grow up to 160 Mt CO_2,eq in 2030. They suggest that coal-based electricity generation may increase in the future due to the large availability of the mineral reserves at a lower price.

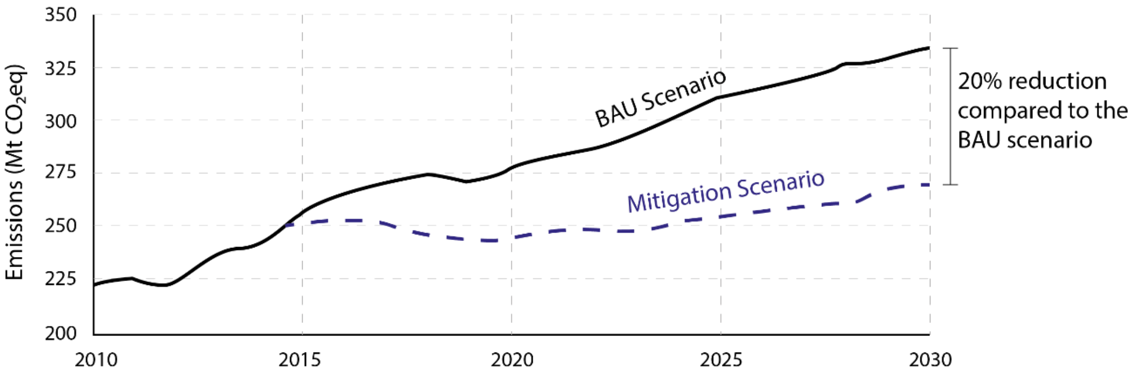


Figure 6. Mitigation target for Colombia. Source: (Gobierno de Colombia 2015)

2.2.6 Policies for renewable energy generation

Over the last five years, a new set of regulations and plans defined by the national government to promote and regulate the integration of non-conventional renewable energies sources (NCRES) into the energy matrix have emerged. These plans are the main results of the commitments presented in the National Determined Contribution (NDC) for COP 21. Within the Colombian context, NCRES refers to those renewable energy resources that are environmentally sustainable and available worldwide (such as small-scale hydro-based energy, biomass, wind, solar, geothermal and tidal energy).

Table 1 summarises the climate change mitigation strategic laws and policies to promote the integration of renewable energies defined by the Colombian government during the last five years. Despite the comprehensive character of the Law 1715, few mechanisms are currently in place trying to achieve wider integration of non-conventional renewable energies, particularly for small-scale self-energy generators.

Table 1. Strategic laws from climate change mitigation and integration of renewable energies by the Colombian government

Policies – Laws	Main features of the laws/agreements/regulations	Decrees and other mechanism deriving from main laws
Law 1715 of 2014, regulates the integration of renewable energy into the energy system	Establish a legal framework and mechanisms to promote the use of non-conventional renewable energies and foster investment, research and development of cleaner technologies. Main features of this Law that relate to RETs: - Fiscal incentives to investments on projects of renewable energies - Deliveries of energy surplus into the network for all self-generators, with energy credits for small self-generators using RE. - Bi-directional metering, simple mechanisms for connection and delivery of energy surplus for small-scale self-generators. - Energy sales from distributed energy generators - Substitution of diesel-based generation in Non-Interconnected Zones	**Decree 2143 of 2015**, defines the guidelines to apply fiscal incentives for investing in projects of non-conventional renewable energies: **1. Special income tax deductions:** It allows reducing up to 50% of taxable income during the first five years of the project operation. **2. Value-Added Tax (VAT) and Custom Tariffs exemption:** allows an exemption of the VAT and CT for equipment and services that are used for the generation and use of renewable energies. **4. Accelerated depreciation** (an accounting-related mechanism), allows the accelerated depreciation of machinery, equipment and civil infrastructure that is used for renewable energy generation.
Law 1819 of 2016, in articles 221, 222 and 223 establishes a national carbon tax	**Article 221.** establish a national carbon tax on liquid fuels used on energy purposes, through combustion processes. The taxpayers are those acquiring fossil fuels from producers or importers. **Article 222.** Set a specific tariff considering CO_2 emission factors for each fuel, in \$15,000 COP/ ton CO_2 (5 USD/ton CO_2) **Articles 223**: Stablish that funds collected from the carbon taxes will be invested on topics related to coastal erosion, water sources and ecosystems conservation	**Decree 1625 of 2016,** defines guidelines to the implementation of the national carbon tax
Law 1931 of 2018, establishes guidelines for managing climate change	Establish guidelines for the management of climate change in the decisions of local and national public institutions to take actions on climate change adaption and GHGs mitigation -Defines the orientation and missions of the National System for Climate Change and creates the National Council on Climate Change - Defines instruments for planning and management of climate change - Stablishes an Emissions Trading Scheme (ETS) program, where the funds generated for the ETS should be reinvested in initiatives for GHG emissions reduction and climate change adaptation.	**Art. 12.** Renewable energies and mitigation of GHGs- National and local governmental institutions will consider within the preparation of the corresponding Development Plans regulations that promote non-conventional renewable energies and energy efficiency measures.
Final Agreement to end the armed conflict and build a stable and lasting peace	Section 1.3 of the final agreement introduces a **National Plan for an Integrated Rural Reform** that comprises actions on infrastructure and land improvement. - Measures on Electricity infrastructure and connectivity: to ensure the conditions for a decent life and improving connectivity, the National Government will design and implement a National Rural Electrification Plan and a National Rural Connectivity Plan.	

2.3 Renewable energy potential in Colombia

The country has the potential to deliver further renewable energy generation beyond hydropower, with significate resources from wind, solar, geothermal and biomass due to its geographical location and different climate zones (UPME 2015). Most of this potential remains untapped, accounting for just 1% of the total installed capacity (XM 2019). The status of power generation from non-hydro renewable resources and their estimated potentials are described in this section.

2.3.1 Wind energy

The annual wind energy potential in Colombia is estimated to be approximately 81.2 TWh representing an installed capacity of up to 25 GW (Pupo-Roncallo et al. 2019) available in specific regions of the country (UPME 2015; Vergara et al. 2010). Vergara et al. (2010) illustrate the strong complementarity between wind and hydropower, especially during dry periods where hydro resources are limited.

Since 2004, the wind power installed capacity has remained the same in the country, with 19.5 MW installed capacity from one wind farm that contributes to scarcely 0.1% of the annual electricity demand (XM 2019). The development of wind energy projects have stagnated due to different reasons: an inadequate transmission infrastructure that limits the delivery of generated electricity to different regions of the country, difficulties in the project's acceptance by the local communities, and a weak regulatory framework for variable renewables (UPME 2015).

2.3.2 Solar energy

Colombia has a substantial solar energy potential with average solar radiation of 4.5 kWh/m^2/day, higher than the world average of 3.9 kWh/m^2/day, and with a regular availability throughout the year due to minimal seasonality (IDEAM - UPME 2017). The use of this resource is very poor, and it has been concentrated in the utilisation of micro-scale solar photovoltaic-PV technology (usually less than 10 kWp) to supply power demand in the commercial and residential sector (including areas of the ZNI). Off-grid installed capacity is estimated to be approximately 5.28 MW, and 46% of this represents distributed applications in the Non-Interconnected Zones (Rodríguez-Urrego and Rodríguez-Urrego 2018).

In the last two years, the utility-scale capacity of solar-PV has reached 17.86 MW (XM 2019). These represent less than 0.1% of the total installed capacity of the SIN. However, an installed capacity of nearly 1600 MW is expected by 2030 (Pupo-Roncallo et al. 2019).

2.3.3 Geothermal energy

The location of Colombia over the pacific ring of fire provides attractive features for the exploitation of geothermal resources. The estimations of the energy potential for power generation ranges between 1-2 GW (UPME 2015). This potential is available in specific locations with active volcanic zones within the national territory (e.g. *Nevado del Ruiz Volcano*) and the borders with Ecuador (UPME 2017b).

Currently, there are no geothermal power plants in operation, and the main hurdles to achieving this have been the high costs and risks during the exploration stages and inexistent regulatory framework for exploiting these resources (UPME 2015). It is expected that by 2020 the first geothermal plant in the country will start operations. The project is being led by ISAGEN in the department of Caldas, and its installed capacity will be 50 MW (Salazar et al. 2017).

2.3.4 Biomass for energy

Colombia has a large biomass energy potential from a wide range of feedstock (fuel crops, forestry and agricultural residues, and animal waste) that can deliver different forms of energy products. A recent study by Gonzalez-Salazar et al. (2014) estimated a biomass energy potential of 23.6 GW (744,000 TJ/year) that includes agricultural and forestry residues, animal wastes and municipal solid waste (MSW). This value varies in other reports ranging between 245,000 – 608,000 TJ/year, which strongly depends on the methodology for estimation, types of biomass included and year of the assessment.

Bioenergy plays an important role in the energy sector, supplying 16.7% (207.7 PJ) of the total final energy consumption in the country (IEA 2016). Although this value is low compared with hydropower, it is the second-largest renewable resource for power generation representing 0.84% of the total installed capacity. Currently, the main uses of biomass for energy conversion, in order of participation, are the following: (Gonzalez-Salazar et al. 2017; UPME 2017b):

- Wood fuel for cooking, mainly in rural areas and with inefficient devices; also for charcoal production
- Cogeneration of cane bagasse and palm oil residues (i.e. fibre, stone) for steam production
- Fuel crops of sugarcane for bioethanol production and palm oil for biodiesel to blend these biofuels with gasoline and biodiesel, respectively
- Combustion and gasification of agri-residues for heat generation in the industry sector and production of methane from water treatment plants

- Production of biogas and landfill gas collection for CHP generation with still fewer applications at a demonstration or pilot-scale plants

Despite this current uses, several reports (Escalante et al. 2011; UPME 2003; UPME 2015; Gonzalez-Salazar, Morini, et al. 2014) also suggest that a vast amount of biomass resources remains untapped or inefficiently used for various reasons. In relation to this, a *Bioenergy Technology Roadmap for Colombia* by Gonzalez-Salazar, Venturini, et al. (2014) identified four niches of opportunities to support the deployment of bioenergy technologies in Colombia:

1. Increasing the share mandates of biofuels (i.e., bioethanol to E20 by 2025 and biodiesel to B30 in 2030) - Implement an E85 bioethanol program by 2030.
2. Start producing renewable diesel and achieve a 10% contribution to diesel production by 2030.
3. Start using 5% of total biomass residues and 1% of total animal waste to produce biomethane and inject it to the natural gas grid by 2030.
4. Increase to 10% the share of renewable resources in the power generation mix by boosting the implementation of biomass residues-based power generation and CHP.

From the opportunities identified by Gonzalez-Salazar et al. (2014) to support bioenergy development in Colombia, this research fits well with the fourth niche. It supports the rationale of this research and reinforces the importance of using biomass residues for power and heat generation, particularly from biomass residues

2.4 Biomass residues potential for energy conversion in Colombia

The different climate zones and topography of the country enable the cultivation of a wide range of crops and the production of many agricultural commodities (UPME 2015). The supply chain of many of these agricultural products generates large amounts of by-products and residues, with their final use extending from soil replenishment, bio-products, bioenergy, open-field burnings or land disposal.

Currently, the largest utilisation of biomass residues is the bagasse combustion for cogeneration of electricity and steam (heat). This technology is now well-established in Colombia consisting of a system that integrates a bagasse-fired boiler, a steam turbine, a pump, a steam condenser and a generator. Both electricity and steam supply the energy demand of the sugarcane mills, and the surplus of electricity is fed to the power grid (UPME 2017a). In a minor extent, the residues generated during the palm oil extraction are burned in boilers to produce steam for process heat (Gonzalez-Salazar, Venturini, et al. 2014).

However, nearly half of the biomass residues potential in Colombia remains untapped (Gonzalez-Salazar, Morini, et al. 2014). Biomass residues can represent a significant resource for energy generation with an estimated energy potential of 450,000 TJ (by 2012). This theoretical potential disaggregates into 330,000 TJ/year of agricultural residues (i.e. crop and agro-industrial residues), 117,000 TJ/year of animal waste and 410 TJ/year of municipal solid waste (UPME 2015).

As the numbers indicate, the potential of agricultural residues almost triples the one from animal waste. Therefore, considering this larger potential from agri-residues and prioritised research areas in Colombia, this biomass residues category is selected to explore the potential utilisation of biomass residues to deliver power and heat to agroindustry and rural areas through thermochemical conversion processes. Several barriers exist to achieve a wider realisation of the biomass residues potential: lack of technology awareness in the rural sector, high investment costs of the technologies for small farmers/agroindustries and lack of financial incentives to deploy them. Additionally, inflexible technical requisites and regulatory measures have also hindered the deployment of small-scale bioenergy systems. For example, the role of cogenerator is only recognised when plants achieve a minimum electrical efficiency, which is harder to attain for smaller plants. Furthermore, the cogeneration activity is restricted to productive industries, excluding utilities and non-industrial companies, like hospitals and hotels (UPME 2015).

2.4.1 Examining the potential of agricultural residues in Colombia

The biomass potential from agricultural residues was examined further to identify those feedstocks that provide the highest resource potential, suitable characteristics for bioenergy conversion, as well as the rural context in which they are produced. For this revision, the results reported by the *Atlas of Biomass Residues Energy Potential in Colombia* commissioned by the UPME to Escalante et al. (2011) are used as a baseline and are further complemented by other studies. The intended outcome of this revision is the selection of the agricultural residue as the feedstock to the bioenergy system to then develop the case study, which is presented later in Chapter 5. These results are obtained following the approach described in Chapter 4.1.

Table 2 lists the top-five rank of crops yielding the highest theoretical energy potential from their agricultural residues in Colombia, reported by Escalante et al. (2011). This table also includes information about the crop production, type of residues, source and amount of biomass generated per year. Broadly, the agricultural residues are classified in this table as field residues (FR) which are generated during the crop harvesting or maintenance, and the agro-industrial residues (AR) produced after the main crop product is processed.

Table 2. Top-five rank of agricultural residues by energy potential in Colombia
Adapted from (Escalante et al. 2011)

No.	Crop	Production [t/year]	Type of residue	Residue source	Amount of residue [t/year]	Energy potential [TJ/year]
1	*Sugar cane*	2,615,521	Leaves	FR	8,525,718	41,707
			Bagasse	AR	7,008,873	76,872
2	*Jaggery cane*	1,514,878	Leaves	FR	5,680,790	62,305
			Bagasse	AR	3,832,640	18,749
3	*Coffee*	942,327	Stems	FR	2,849,596	38,561
			Pulp	AR	2,008,192	7,206
			Husk	AR	193,460	3,339
4	*Rice*	2,463,689	Straw	FR	5,789,669	20,699
			Husk	AR	492,738	7,136
5	*Corn*	1,368,536	Stover	FR	1,278,213	12,569

Note: FR: Field residue – AR: Agro-industrial residue

Afterwards, to gain a better understanding on how these agricultural residues could be used, the context and scale of the crop cultivation, the current utilisation of the agri-residues and potential opportunities for more efficient applications were explored through the literature. Together with the aim of this research, this additional revision guided a delimitation and final selection of an adequate feedstock for the study case.

1. Sugarcane bagasse-leaves-tops

Most of the sugarcane bagasse (estimated 96% of its production) is used as solid fuel in cogeneration plants to produce electricity and low-grade heat. The remaining 4% of the bagasse is used in the pulp and paper industry and for cattle feeding (UPME 2003). By 2017 the total installed capacity for power generation was 263 MW, with a 100 MW net power capacity available as surplus to the power grid. This installed capacity is expected to increase in the future as part of an expansion plan with more ethanol distilleries plants and more sugarcane cultivation areas (ASOCAÑA 2018).

The leaves and tops are also an abundant lignocellulosic biomass resource obtained after the sugarcane harvesting (Escalante et al. 2011; Gonzalez-Salazar, Morini, et al. 2014). In Colombia, as a result of the sugarcane manual harvesting, 70% of these leaves are burned to facilitate the collection of the stalks (IDB-MME and Consorcio CUE 2012). These leaves are then left on the field for soil replenishment (Gonzalez-Salazar, Morini, et al. 2014).

If the mechanical harvesting would be a more predominant practise, a fraction of this residue could be used more efficiently, discounting the portion for soil replenishment: 30-40%. In this case, the co-firing (with the bagasse) option is considered an alternative close to implementation, considering the maturity of this technology and the lower costs incurred on biomass transportation expenses and investment on equipment just for leaves separation and grinding (UPME 2015).

Between these two residues, the sugarcane agroindustries already utilise the bagasse potential in cogeneration plants, with possibilities of further feasible increments in the process conversion efficiency (ASOCAÑA 2018; UPME 2003). On the other hand, the leaves and tops have an untapped potential that could be further developed in on-site bioenergy projects, such as in cofiring plants. Due to the structure of the land tenure and nature of the sugarcane sector in Colombia, concentrated in a few large-scale sugarcane plants, the utilization of these agricultural residues potential would be more feasible at large-scale agroindustry level, with direct impact on large-scale sugarcane producers.

2. *Jaggery cane (panela) bagasse and leaves*

The residues from jaggery cane crops, producing a form of raw sugar, also represent a good biomass resource potential for energy production in Colombia, ranking second among the other residues (Escalante et al. 2011). The context of this agro-industry sector is yet different from the large-scale sugarcane industries; these are more dominated by informal small farming businesses for mere family subsistence purposes (UPME 2003). As a result of this, the jaggery cane sector features more irregular cultivation periods and plantations with scattered locations across the country. In this sector, 5% of the national production is concentrated on farms with crops areas greater than 50 hectares, with productions higher than 300 kg/h of raw sugar cane (UPME 2003).

The issues around the scattered locations and continuity of the cultivation periods have hindered an adequate evaluation of the real resource availability and further deployment of bioenergy applications, even at small scale applications. Unless the structure of the raw sugar cane cultivation changes in the future, the utilisation of these residues is likely to continue within the same milling farms *(trapiche)* for green compost, cattle feed or as fuel in boilers for steam generation to process the final product (raw sugar).

3. Coffee husk and stems

The coffee cultivation-processing chain produces a vast amount of residues, representing more than 90% of total biomass input, in the form of coffee stems, pulp, mucilage, husks and grounds (Rodríguez Valencia and Zambrano Franco 2010). The most suitable residues for thermochemical conversion processes are the coffee husks, grounds and stems (Rodríguez Valencia and Zambrano Franco 2010); with the coffee stems representing the highest energy potential in the rural coffee sector, as a result of higher resource amount and the heating value (19.75 MJ/kg) (Escalante et al. 2011).

The coffee stems are collected after coffee trees pruning. In Colombia, this practice is carried out after cultivation periods of five to six years to maintain the yield of coffee cherry production per cultivated area (Arcila Pulgarín 2007). These results into an average of 16 ton/ha of dry-wood with a density of 5,000 coffee trees/ha, producing approximately 0.6 kg of stems per kg of coffee cherries (Rodríguez Valencia and Zambrano Franco 2010). Currently, the coffee stalks are generally used as cooking fuel in traditional rural cookstoves and to a minor extent as a solid fuel for the coffee bean drying (Rodríguez Valencia and Zambrano Franco 2010). Other farming practices are open-burnings and land disposals for decomposition (Dinero 2009).

The use of coffee husks has been reported for direct combustion in rudimentary boilers for coffee bean drying, however not enough information is available about the use and conversion efficiency of this residue in Colombia. The coffee husk represents 4.2% of the fresh berry, and it has a heating value of 17.90 MJ/kg (Rodríguez Valencia and Zambrano Franco 2010).

An investigation by Oliveria and Franca (2015) in Brazil indicates that the combustion of coffee husk generates high values of NOx emissions, implying the need for NOx emission reduction techniques. Also, coffee husks can devolatilize easy upon heating, requiring water cooling or short residence times to avoid pyrolysis in the feeding systems. Because of the toxic components in coffee husks, such as caffeine, tannins, and polyphenols, coffee husks also have restrictive use as animal feed (Oliveira and Franca 2015).

The use of coffee pulp has proven less suitable for thermochemical conversion pathways due to its high moisture content, but more fit for biochemical conversion routes such as fermentation for bioethanol production (Rodríguez Valencia and Zambrano Franco 2010). Coffee grounds have a higher heating value (29 MJ/kg on dry basis) and are used by coffee manufactures companies as solid fuel to feed boilers for steam generation (Rodríguez Valencia and Zambrano Franco 2010), yet this potential application is outside the rural coffee sector, therefore is beyond the scope of this research.

4. Rice straw and husks

The utilisation of rice straw is not reported in any of the studies above evaluating the biomass energy potential in Colombia, yet it is suspected that it could be burned in open-air, as it is the most common practice globally (Minas 2018). Rice straws feature high content of silicon dioxide (SiO_2) which makes it potentially useful as a ceramic raw material with further applications as a construction material (Guzmán A et al. 2015).

The potential of rice straw for energy conversion have been explored in countries like India, the Philippines and Vietnam (Minas 2018). For energy applications, the high content of SiO_2 and physical characteristics of rice straw are limiting factors; hence the studies and project have focused on combustion for power and heat generation, and anaerobic digestion for biogas and electricity generation. In Colombia, the aforementioned potential applications (i.e. as biomaterial or solid for bioenergy) have not been explored.

Currently, the rice husks in Colombia have different end-uses, from non-energy to energy applications. Among the non-energy uses, the husks are commercialized as animal food and as fertiliser for gardening; yet estimations indicate that just 5% of the available resource is used (UPME 2003).

Energy applications are also potentially feasible as this feedstock has a relatively high heating value (15.5 MJ/kg) and low moisture content (9.93%) (Escalante et al. 2011). The most common energy application is for power and heat generation at rice processing plants to supply their internal energy demand (Quispe et al. 2017). Additionally, the ashes produced after the rice husk combustion can be sold as a by-product to the cement industry.

The high content of silica (over 90% SiO_2) in the rice husk ash (Quispe et al. 2017) makes it a highly abrasive material that requires combustion furnaces and boilers with special design and manufacturing features that increase the investment costs (Demirbas 2005; UPME 2003). In addition, the low bulk density of the rice husks also makes almost technically impractical to transport and concentrate in places different than the milling factories. The cogeneration process is then recommended to be carried out in-situ (UPME 2003), or rice husks densification into briquettes (Quispe et al. 2017), with associated higher costs.

Considering the facts above, studies in Brazil and Thailand (UPME 2003) suggest that cogeneration projects with rice husks could be economically feasible only for rice production rates higher than 100 ton/day and plants with operating capacities of 80%. By 2003, 44% of the rice production in Colombia was produced in mills with the mentioned characteristics. This production was concentrated in seven rice milling factories with a total average cogeneration potential of 97 MWh/year from the rice husks resources (UPME 2003).

Projections from different studies in Colombia by UPME (UPME 2003; 2015) and Gonzalez-Salazar, Morini, et al. (2014) estimate that this bioenergy application can expand further in the rice agroindustry. Still, the feasibility of deploying rice husk-based cogeneration projects needs an in-depth techno-economic assessment due to the unfavourable physical and chemical properties of this type of biomass.

5. Maize field residues: stover

In Colombia, this field residue is mainly used in the farming (livestock) sector as animal fodder and as green compost for soil replenishment (UPME 2003). Hence, an energy end-use would have to compete with a well-established current application. In addition to this, the maize agro-industry has lower participation in the agriculture sector, with unstable production rates each year, related to changes in the cultivated land and its localization. These factors can hamper the utilisation of these residues for bioenergy applications, despite the favourable characteristics of this feedstock with low moisture content (average MC 7-10% wt).

CHAPTER 3. BIOMASS AND BIOENERGY

This chapter presents a literature-based review of relevant concepts on biomass and bioenergy technologies. This review provides the foundation in which this research is developed, particularly in the selection of a suitable bioenergy technology for the conversion of the agricultural residues.

Section 3.1 overviews general biomass concepts, covering types of feedstock, composition, physical and thermodynamic properties relevant for biomass energy conversion. Section 3.2 introduces the types of bioenergy conversion technologies. Finally, section 3.3 revises in more detail the gasification technology, including theoretical concepts and specifics for gasifier's design and operation.

3.1 Biomass as an energy source

3.1.1 Biomass definition

Biomass refers to any organic matter that originates from plants, animals or microorganism species. The sources of biomass include primary products and by-products from forestry, energy and agricultural crops, aquatic plants and algae. It also covers non-fossil organic and biodegradable organic fractions of industrial and municipal wastes (Krajnc 2015).

3.1.2 Biomass types

Biomass is broadly categorised by the source from where it originates. Primary biomass derives directly from plants or animals, and secondary biomass is obtained after a conversion process from any biomass-derived products. Table 3 shows the biomass classification and sub-categorization, according to the European Committee for standardization (Basu 2013a):

This research focuses on secondary biomass (waste and residues) uses to produce bioenergy vectors (i.e. power and heat) in rural areas. The potential of this type of biomass in Colombia was discussed further in Section 2.4, along with the characteristics of the sector where the residues originate.

Table 3. Biomass categories and subcategorization. Adapted from (Basu 2013a)

Primary biomass	Terrestrial biomass	Forest biomass
		Grasses
		Energy and cultivated crops
	Aquatic biomass	Algae
		Water plant
Secondary biomass *Waste and residues*	Municipal waste	Municipal Solid Waste
		Landfill gas
		Sewage
	Agricultural Solid Waste	Livestock and manures
		Agricultural crop residue
	Forestry residues	Bark, leaves, floor residues
	Industrial waste	Demolition wood
		Waste oil/fat

3.1.3 Structure of biomass

The structure of plant-based biomass is formed of extractives, ash and cell walls (Basu 2013a). The extractives are the non-structural biomass components that are soluble in water or ethanol during extractions and include sucrose, protein, oil, and starch (Sluiter et al. 2008). Ash is also a non-structural inorganic component of biomass (Basu 2013a).

The cell walls are composed of the following polymers: cellulose (40-50% of biomass weight), hemicellulose (25-30% wt.) and lignin (15-25% wt.). The first two components give strength to the plant structure; cellulose is the main structural component and the major contributor to tar formation during biomass gasification, the hemicellulose has lower strength and tends to yield more gases than tar (Basu 2013a). Lignin is a complex highly branched polymer that holds the cellulose and hemicellulose fibres together, providing structural protein rigidity and avoiding the entrance of microorganisms (Molino et al. 2016; Escalante et al. 2011).

Lignocellulosic biomass

This biomass encompasses herbaceous biomass and woody biomass with a high content of lignocellulosic material. Table 4 summarises the main differences between herbaceous and woody biomass.

The herbaceous biomass resources are purpose-grown crops (i.e. agricultural and energy crops) and agricultural residues. The first ones have short harvesting cycles, requiring seasonal collection, treatment and storage; the second ones correspond to the biomass left in the field after the crop harvesting (e.g. straw, stalks and prunings) or produced after the crop processing, e.g. bagasse, husks and shells (IRENA 2019c). Woody biomass is produced mainly in forests, whether primary products or residues (e.g. trees or parts of trees, such as trunks, branches, bark and tops). This type of biomass can be harvested during all seasons, but with longer growth timescales (Adams et al. 2013).

Table 4. Key differences between woody and herbaceous biomass

	Woody Biomass	Herbaceous Biomass	
High lignin content			Low lignin content
Low to medium ash content	Forestry product and by-products	Agricultural residues	High ash content
High ash melting temperature			Low ash melting temperature
Bulky	Wood processing products		Vey bulky
Slow decomposition		Energy crops	Fast decomposition
Continuos harvest	Wood agricultural products		Seasonal harvest
No binder requirement to pelletise/briquette			Binder requirement to pelletise/briquette

3.1.4 Biomass composition

Biomass is composed of organic compounds, i.e. carbohydrates, fats and proteins that are comprised of carbon, hydrogen, oxygen, and nitrogen; a small number of inorganic compounds, like ash; and water. Depending on the source of biomass, it can also contain chlorine, sulphur, and other organic compounds.

Ultimate analysis

The ultimate analysis specifies (on a dry-basis) the basic elements of the biomass: Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Sulphur (S) and Chlorine (Cl), the inorganic component, ash, and the moisture content. Not all biomass contains all these basic elements; for instance, the sulphur content in lignocellulosic biomass is low (Basu 2013a). The ultimate analysis is generally expressed on a *dry-basis*.

Proximate analysis

The proximate analysis indicates the gross composition of the biomass, which includes the volatile matter, fixed carbon, ash and moisture, giving broad information about how a material will behave thermally (Jenkins 2014). Proximate analysis can be expressed as an *as-received* basis, *air-dry* basis (i.e. the surface moisture is neglected), *total dry* basis (i.e. total moisture content is removed) and *dry-ash free* basis (i.e. total moisture and ash content are removed)

(Basu 2013a). A brief explanation of the components of the proximate analysis is presented below:

- **Volatile matter (VM)** is the portion of matter in a fuel that is released as condensable and non-condensable gases when the fuel is heated (Basu 2013a). The volatiles include the carbon, hydrogen, nitrogen, oxygen, sulphur and moisture content. For biomass the VM can range between 50 – 80% (Ahrenfeldt, Bain, van de Beld, et al. 2005), giving an idea of the flame's length when the biomass is used for combustion (Escalante et al. 2011). In gasification applications, the VM can impact the tar production in gasifiers (Ahrenfeldt, Bain, van de Beld, et al. 2005).

- **Fixed carbon (FC)** is the fraction of residual carbon that remains in the char after the volatile matter distillates in the pyrolysis process and excludes the ash and moisture content (Escalante et al. 2011; Basu 2013a). The FC content is not a fixed quantity and depends on the amount of VM, therefore fixed carbon fraction can be determined by difference, using Equation 1 (Basu 2013a):

$$\boldsymbol{FC = 1 - VM - Moisture - Ash} \qquad \text{Equation 1}$$

  For biomass gasification, FC is an important parameter because the conversion of fixed carbon into gases helps to determine the rate of gasification, which in turn is used to define the size of the gasifier (Basu 2013a).

- **Ash** is the inorganic solid material that remains after the fuel burns completely. Primary components of ash are silica, aluminium, iron and calcium, and in lower quantities: magnesium, titanium, sodium, and potassium (Jenkins 2014; Basu 2013a). Ash content in biomass ranges between 0.1% for wood up to 15% for some agricultural products, hence its influence on the design of the reactor's ash removal system (Ahrenfeldt, Bain, van de Beld, et al. 2005). When the ash in the biomass (e.g. straw, grasses and demolition wood) has high amounts of alkali metals or halides, this can reduce the fuel's heating value and lead to agglomeration, fouling, and corrosion in boilers and gasifiers (Basu 2013a). It also affects the overall biomass handling and processing cost (Jenkins 2014; Basu 2013a; McKendry 2002a).

- **Moisture** is the amount of water in the biomass and is represented as a percentage of the material's weight (Ahrenfeldt, Bain, van de Beld, et al. 2005). Biomass generally has a high moisture content (MC), which can vary with the time of harvest (McKendry 2002a). In thermochemical conversion processes, MC is a crucial biomass property. High moisture levels reduce the energy output since the energy spent for the moisture evaporation is not recoverable, affecting the overall performance of the process (Basu 2013a). For this reason, biomass with a moisture content below 50% is appropriate for thermal processing technologies (i.e. combustion and gasification), generally requiring a pre-drying stage.

Instead, biomass with higher MC (> 50% wt.) is more suitable for biochemical conversion processes, like fermentation or anaerobic digestion. For the majority of the energy conversion process, the moisture content of the material has to be < 30%, implying that previous drying process has to be done and the costs of processing increase (McKendry 2002a; Escalante et al. 2011).

- **Alkali metals** in biomass are composed of sodium (Na), potassium (K), magnesium (Mg), phosphorus (P) and calcium (Ca), and their presence can be significantly harmful to biomass thermochemical conversion. Particularly, when alkali metals react with silica, they produce a dense liquid that causes blockage of airways in equipment, like boilers and furnaces (McKendry 2002a).

  In gasifiers, when corrosive alkali components, like chlorine and sulphur, are present in the biomass feedstock, they can cause damage to the gasifiers in a similar way as solid contaminants do. Therefore, special considerations are required in the metallurgy and refractory design of gasifiers in order to minimize excessive corrosion in the equipment (Worley and Yale 2012).

3.1.5 Physical and thermodynamic properties

Biomass can be characterised through different physical and thermodynamic properties. The most relevant properties of biomass as an energy source are described in this section:

Physical properties:

- **True density:** it is referred to the total biomass weight per unit of the actual volume occupied by the solid component of biomass, as equation 2 indicates. The calculation of the true density is difficult due to the measuring of the solid volume. (Basu 2013a).

$$\rho_{true} = \frac{total\ mass\ of\ biomass}{solid\ volume\ in\ biomass} \quad \text{Equation 2}$$

- **Apparent density:** it relates to the total mass per unit of apparent volume of biomass, including solids and internal pores. This density excludes the interstitial volume between biomass particles packed together, which is accounted for in the bulk density (Basu 2013a). Apparent density is expressed as:

$$\rho_{apparent} = \frac{total\ mass\ of\ biomass}{apparent\ volume\ of\ biomass} \quad \text{Equation 3}$$

- **Bulk density:** it is the most common density expression when processing biomass and is defined as the weight of material per unit volume of the as-produced biomass material (Equation 4). The bulk volume includes the interstitial volume between the particles; therefore depending on how the biomass is packed. The bulk density for biomass can vary widely between 100 – 1000 kg/m^3. To determine the biomass bulk density, the standard ASTM E-873-06 can be applied (Basu 2013a).

$$\rho_{bulk} = \frac{total\ mass\ of\ biomass\ particles\ or\ stack}{bulk\ volume\ occupied\ by\ biomass\ particles\ or\ stack} \quad \text{Equation 4}$$

The bulk density affects the capacity and costs associated with biomass handling, transporting, storing and biomass behaviour during subsequent biochemical and/or thermochemical processing (McKendry 2002a). Fuels with a high bulk density have better energy per unit volume relation, requiring equipment of smaller size and allowing larger periods between material loads. On the contrary, fuels with low bulk density need higher space for storage and transportation and present problems when flowing under gravity, thus complicating the combustion process and increasing costs (Escalante et al. 2011; McKendry 2002a).

Thermodynamic properties

- **Thermal conductivity:** refers to the ability of a material to transfer or conduct heat. During the heating of biomass, the thermal conductivity is an important parameter as their anisotropic characteristics cause the heat conduction to be different along and across the biomass fibres. This affects biomass behaviour during pyrolysis. Thermal conductivity in biomass feedstock depends on the moisture content, porosity, and temperature; some of these variables also depend on the degree of biomass conversion. (Basu 2013a).

- **Specific heat**: indicates the heat capacity of biomass, and strongly depends on its moisture content and temperature, rather than on the biomass species or density. It also shows some influence on the type and source of biomass. Some wood biomass species show an increase of the specific heat with temperature (Basu 2013a).

- **Heat of reaction:** indicates the amount of energy released or absorbed during a chemical reaction. The heat of reaction is negative in exothermic reactions, where heat is released, and positive for endothermic reactions, meaning heat has to be supplied to drive the reaction. In combustion processes, the heat of reaction refers to the heat of combustion (Basu 2013a).

- **Ignition temperature:** it is an important parameter for fuels that undergo combustion, which can only be viable for temperatures above the ignition temperature since at this point the heat generation rate is equal or higher to the rate of heat loss. Biomass has a lower ignition temperature than coal because it has higher volatile matter content (Basu 2013a).

- **Heating value:** indicates the energy content per unit of mass or volume that is released when the biomass is burnt in the presence of air. The real amount of recoverable energy of a fuel depends on the conversion technology, as also varies the form of the end product (e.g. combustible gas, oil, steam) (McKendry 2002a). The moisture content affects the biomass heating value, by proportionally reducing it as moisture increases. The heating value can be expressed as High Heating Value (HHV) or Low Heating Value (LHV). The HHV indicates the maximum amount of energy that could be potentially recoverable from a specific biomass source, including the latent heat of water vaporization that is not available for use. The LHV, in contrast, excludes the latent heat of water vapour (McKendry 2002a). The LHV is lower than the HHV and is calculated using equation 5, from (Jenkins 2014):

  $$\boldsymbol{LHV = HHV - mh_{fg}} \quad \text{Equation 5}$$

  Where *m* is the mass of H_2O in the products per unit mass of fuel and h_{fg} is the latent heat of vaporization at the specified temperature (Jenkins 2014). The LHV is an adequate indicator of the amount of energy available for use in the biomass since in most processes, the gases are exhausted in temperatures above saturation point (Jenkins 2014). The heating value of biomass is lower than most fossil fuels because of the lower density and higher oxygen content of biomass compared to most fossil fuels (Basu 2013a).

3.1.6 Biomass characterisation methods

The characterization of biomass requires the determination of its physical properties and chemical components, by means of certain experimental procedures. The biomass characterisation is important as it helps to inform the selection of the most appropriate conversion technology to transform the biomass into the desired energy carries. Determining these characteristics also allows making initial projections of the economic and environmental benefits of its transformation. Some key characterisation methods are the followings:

- **Physical analysis:** it determines the apparent density, moisture and colour of the biomass sample (Escalante et al. 2011).
- ***Proximate and ultimate analysis:*** determines the gross components and basic chemical elements of the biomass, respectively. The experimental procedure for this analysis is the *ASTM E870 – 82 Standard Test Method for Analysis of Wood Fuels* which includes a test method to determine the Gross Calorific value (ASTM International 2019).
- ***Structural analysis:*** quantifies the proportion of lignin, cellulose, and hemicellulose in a sample of biomass (Escalante et al. 2011).
- ***Thermogravimetric analysis (TGA):*** consists of the heating of a material sample at a constant heating rate, inside inert atmosphere conditions (N_2 or He), while the fuel's mass is continuously measured. The data obtained are plotted to obtain a TGA plot, which provides a characterization of the behaviour of the material during pyrolysis. The shape and change of the rate of these curves represent the relation of the mass sample with changing temperature, and the rate of mass loss (first derivative of sample mass with time), varies with the type of biomass material (Jenkins 2014).

3.2 Bioenergy

The concept of bioenergy broadly encompasses the energy produced from biomass, in the form of electricity, heat, mechanical power or as biofuel carriers. Then, the bioenergy technologies are the processes that transform raw biomass to produce power, heat and/or solid, liquid and gas biofuels (i.e. bioethanol, methane, and biodiesel) (Basu 2013d).

3.2.1 Drivers for bioenergy conversion

Some of the environmental, social, economic and political drivers for the biomass conversion into energy over fossil fuels are revised here:

Renewable source of energy: the energy contained in biomass derives from the sun, this energy is captured through the natural *photosynthesis* process (Willilams et al. 2017). Therefore, biomass is continuously formed by the interaction of plants, animals or microorganisms with water, sunlight, CO_2, air and soil. Biomass-derived from plants, unlike fossil fuels, can be cultivated in long or short rotation periods (Basu 2013a).

Carbon neutrality and other environmental benefits: bioenergy has the potential to be *carbon-neutral* as the CO_2 emitted from the action of microorganisms or an energy conversion process balances with the atmospheric CO_2 recently absorbed during the biomass growing process; therefore bioenergy can take part of the global carbon cycle (Basu 2013d). A lifecycle analysis approach is, yet, necessary to assess the carbon neutrality of bioenergy, as the emissions from land-use and biomass production and conversion system should also be accounted (Willilams et al. 2017).

In addition, the carbon intensity of biomass is also lower than for fossil fuels, such as coal, because biomass has a lower C/H ratio. Fresh biomass also contains smaller amounts of sulphur, which produces cleaner emissions with less sulphur content.

Social and economic benefits: as biomass is an indigenous fuel source in many countries, it has the potential to diversify the fuel-supply matrix and provide energy security and independence, also promoting agricultural and rural development, e.g. employment generation (Basu 2013d; McKendry 2002a).

3.2.2 Bioenergy conversion technologies

Different conversion routes can deliver the same energy products, i.e. power, heat and biofuels; each one requiring specific biomass characteristics and serving particular energy demands and operation scales. Biomass energy conversion technologies are broadly classified as thermochemical, biochemical/biological and physicochemical processes.

The selection of the conversion process is mainly influenced by the amount of biomass and its characteristics, the end-use energy requirements, the environmental regulations, the economic conditions and specific project factors (McKendry 2002b). Figure 7 shows multiple interactions between diverse biomass feedstock and the different conversion routes to produce a range of energy products.

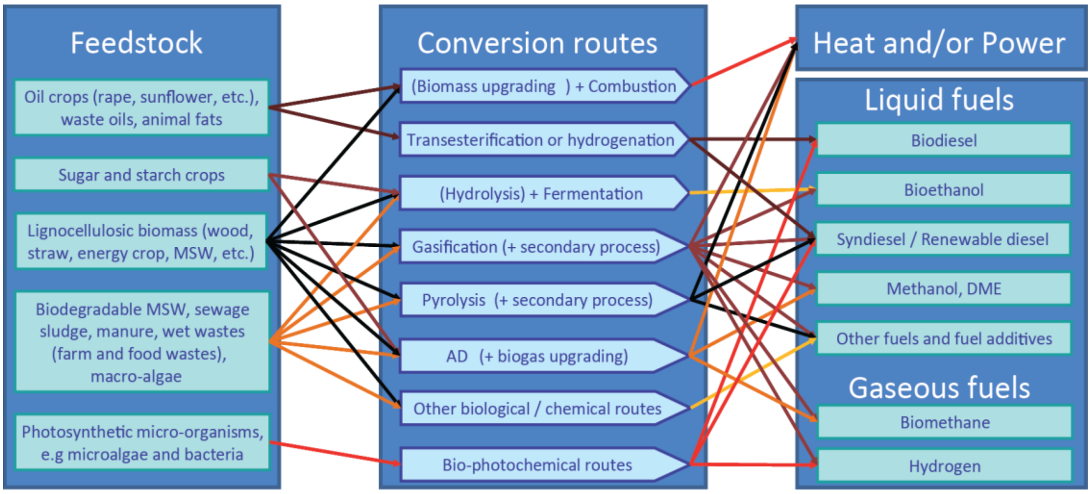


Figure 7. Mapping the interaction between biomass feedstock, conversion routes and energy products.
Adapted from (Bauen et al. 2009)

Other routes known as biomass densification processes (i.e. pyrolysis, pelletisation, hydro-thermal upgrading and torrefaction) upgrade the characteristics of bulky raw biomass into higher density biomass carriers that are easier to store, transport and transform in subsequent processes.

3.2.3 Thermochemical conversion routes

In the thermochemical conversion routes, the biomass undergoes chemical degradation induced by high temperatures to produce gases for direct utilisation (i.e. power and/or heat generation) or further synthesis into fuels and chemicals (Bauen et al. 2009). These pathways generally require an external input of energy (heat) and a biomass feedstock with lower moisture content (Basu 2013d). The main thermochemical conversion routes are:

Combustion: is the most mature thermochemical conversion route and involves an exothermic reaction (oxidation) between biomass and an oxygen-rich environment to convert the chemical energy stored in the biomass into heat, power and/or electricity. Combustion produces hot flue gases, comprising mainly CO_2 and H_2O, at high temperatures ranging between 800 to 1000°C (McKendry 2002b; Basu 2013d). Although almost any type of biomass could be combusted, it is more viable for those ones with a moisture content below 50% wt (McKendry 2002b).

Different types of equipment are available to burn the biomass for power and/or heat generation, such as boilers, stoves, furnaces or steam turbines (McKendry 2002b). The scale of combustion plants stretches from very small scale (e.g. distributed cogeneration units of 10-100 kW_e) to large-scale industrial plants (e.g. dedicated biomass power plants of 30-100 MW_e) (Bauen et al. 2009). Net efficiencies and investment costs vary depending on the system's scale and end-use application, e.g. 70-90% for industrial heat generation (1-5 MW_{th}) and 20-40% for power generation (20 - > 100 MWe) (IEA Bioenergy 2007).

Biomass co-firing in coal-fired power plants has also become an attractive alternative as its more cost-effective and derives into higher conversion efficiency rates (30-40%), compared to dedicated biomass combustion (McKendry 2002b; Bauen et al. 2009).

Gasification: it is a less commercially mature technology than combustion. It consists on the partial oxidation of biomass in an oxygen-deficient environment at high temperatures (800 - 900°C) to produce a gas mixture, rich in CO and H_2, known as producer gas (McKendry 2002b). The gasification mediums include air, pure oxygen, steam or a mixture of these (Basu 2013d).

The producer gas has a low LHV of (4-6 MJ/Nm^3) and can be burnt directly in a gas turbine or engine, or upgraded into syngas, as a chemical feedstock for the production of biofuels and biochemicals. Biomass gasification has shown advantages over biomass combustion, as a more feedstock-versatile process that yields higher conversion efficiencies, lower emissions, and better economics at small and large scale applications (Bauen et al. 2009; Basu 2013d).

The scales of operation, net efficiencies and investment costs also vary with the gasification technologies producing different end-products. Small-scale applications for heat generation are commercially available with capacities of hundreds of kW_{th} and efficiencies between 80%-90%. Gasification for CHP generation is in early commercial stages, with capacities between 0.1-1 MW_e and electrical efficiencies yielding 15%-30% and overall efficiencies between 80-90% (IEA Bioenergy 2007).

Large-scale applications combine gasification and further combustion in a gas turbine (with heat recovery) in systems called Biomass Integrated Gasification-Combined cycle (BIGCC). This integration could ensure higher conversion of electrical efficiencies (40%-50%) and typical plant capacities of 30-200 MW_e (McKendry 2002b). This technology is still at a demonstration stage (Bauen et al. 2009; IEA Bioenergy 2007).

Pyrolysis: is the controlled thermal decomposition of biomass to produce liquid (bio-oil), solid or gaseous (syngas) fractions by heating the biomass in the absence of air and at temperatures around 300-500°C (Basu 2013d). Pyrolysis is used as an independent conversion route, but it is also an intermediate step of combustion and gasification before complete or partial oxidation of primary components (McKendry 2002b).

There are two types of pyrolysis processes, fast and slow, each one with different resident times and proportions of solid, liquid and gas fractions (Bauen et al. 2009). Fast pyrolysis favours the production of bio-oil at temperatures around 500 ^{o}C, with a conversion efficiency of up to 80% (Bridgwater et al. 2002). This process is a commercially available technology, where bio-oil is used as fuel in engines and turbines for power production (IEA Bioenergy 2007), and as feedstock in refineries. However, some technical and economic issues related to the quality, consistency and long-term stability of the bio-oil have to be overcome (McKendry 2002b; IEA Bioenergy 2007). Oppositely, slow pyrolysis produces bio-char through a carbonisation process with biomass-to-biochar yields of up to 35% (McKendry 2002b).

Pyrolysis is a commercially available technology considered a biomass pre-treatment process as bio-oil has a higher energy density (per volume) than pellets or torrefied biomass, hence, reducing costs of handling, storing and transportation (Bauen et al. 2009). This bioenergy route has also shown promising advantages for the conversion of waste biomass into useful liquid fuels.

Liquefaction: is a hydrothermal conversion of biomass into a stable oily-liquid hydrocarbon, by putting in biomass with water at temperatures between 300-350^{o}C and high pressures (5-20 MPa) using a catalyst (Basu 2013d). The interest in liquefaction is lower than of pyrolysis because the reactor and fuel feeding system are more complex and more expensive (McKendry 2002b).

3.2.4 Biochemical conversion routes

In biochemical conversion processes, living microorganisms, such as bacteria and enzymes, break down the biomass into smaller molecules to produce liquid, solid and gas fractions. Biochemical conversion processes occur at slower paces than thermodynamic processes, requiring lower external energy input (Basu 2013d; Bauen et al. 2009). The main biochemical conversion routes are:

Fermentation: involves the breakdown of complex organic molecules of biomass into sugars using acid or enzymes, and further conversion of sugars into ethanol or other chemicals by the action of yeasts (Basu 2013d; McKendry 2002b). The fermentation of starch- and sugar-based biomass crops to produce bioethanol, i.e. 1st generation biofuels, is a technically mature and commercially available process (Basu 2013d; Bauen et al. 2009).

The conversion of lignocellulosic biomass into ethanol, classified as 2nd generation biofuels, is at the transition between research & development and demonstration stage. This process is more complex due to the difficulty of breaking down cellulosic material into fermentable sugars, requiring acid or enzymatic hydrolysis pre-treatment (McKendry 2002b; Bauen et al. 2009).

Anaerobic digestion (AD): is the biological degradation of biomass into biogas and a solid residue (i.e. digestate) by the action of bacterias in an oxygen-free (anaerobic) environment. AD is a suitable technology to biodegrade biomass with high moisture content, such as sludge, animal manure and wet agri-residues (MC: 80%-90% wt.) (Bauen et al. 2009; McKendry 2002b). AD is a well-established technology, with typical capacities up to several MWe and electrical efficiencies ranging between 10-15% (IEA Bioenergy 2007), where the economic viability largely depends on the availability of free and very cheap biomass (Bauen et al. 2009).

The biogas is principally a mixture of methane, carbon dioxide and other small quantities of other gases, with an energy content of 20-40% the LHV of the biomass feedstock (McKendry 2002b). This biogas can be used directly for power (or CHP) generation or upgraded to natural gas (i.e. biomethane) for injection into the grid. The digestate has applications as fertiliser (Bauen et al. 2009).

3.2.5 Physicochemical conversion routes

Mechanical extraction: consist of a mechanical process to convert oil crops-based biomass (e.g.rapeseed, soybean, palm oil, Jatropha) into vegetable oils. This process is generally followed by a transesterification process with alcohol to produce a methyl ester or biodiesel (Bauen et al. 2009; Basu 2013d; McKendry 2002b). This route is also categorised as part of the first generation biofuels pathways and it is a commercial technology.

3.2.6 Bioenergy technology selection for study–case

Section 3.2 presented an overview of the main bioenergy technologies at different levels of readiness for deployment to produce electricity, heat and biofuels. For the technology selection of this research study-case, aspects such as the characteristics of the selected agricultural residue and the reported technical and environmental performance of the technology at small-scale applications were considered. Biomass gasification was chosen over other suitable alternatives, such as combustion and anaerobic digestion because it has shown to be a:

- Suitable for the conversion of lignocellulosic woody biomass with low moisture content, such as coffee stems (McKendry 2002c). Refer to chapter 5.1 for the selection of the Colombian agricultural residue.
- Cleaner technology, producing lower GHG emissions compared to others, such as combustion, contributing to reduce costs of gas cleaning equipment (Basu 2013d).

- Higher energy conversion efficiencies, as exergy losses due to the internal thermal energy exchange, are lower in gasification than combustion (Prins and Ptasinski 2005),
- The producer gas from a gasification system enables coupling it with an internal combustion engine (ICE) and/or combined heat and power (CHP) unit. In cases of power generation in rural areas is more practical and economical than using a combination of boiler-steam engine-condenser (Basu 2013d).

Following on from the selection of gasification selection, the section below provides further information about this technology, current drivers and challenges, key biomass and process parameters to consider, and different gasifier designs available for a range of applications.

3.3 Biomass gasification

Biomass gasification has evidenced over the years that is a bioenergy pathway with the potential to convert efficiently a range of biomass feedstocks into a cleaner fuel gas for small and large-scale applications. It is a thermochemical conversion process where solid biomass is heated inside a reactor and put in contact with a gasification agent such as air, oxygen or steam (or a combination these), to obtain a gaseous mixture (Baruah and Baruah 2014). Different from combustion where during oxidation chemical bonds are broken to release energy; in gasification, the intrinsic energy in the biomass is packed into chemical bonds to produce a combustible gas in two processes, devolatilization and partial oxidation (McKendry 2002c). Overall, gasification adds hydrogen (H) and removes carbon (C) from the fuel to produce a fuel gas with a higher H/C ratio, combustion, instead, oxidizes H and C into water and CO_2 (Basu 2013c).

The main factors that influence the performance of the gasification process are the biomass characteristics (physical and chemical properties), the operating parameters of the process and the gasifier design. This section revises in detail the last two aspects, whereas the influence of biomass characteristics was reviewed previously in section 3.1 of this chapter.

3.3.1 Biomass gasification: drivers and challenges

Gasification of fossil fuels, like coal and oil, is a relatively old technology exploited many years ago during the Second World War (Muresan et al. 2013). Nevertheless, biomass gasification is a less mature technology compared to combustion, which has received more attention recently intending to boost the technology’s development. Additional advantages that have triggered interest on biomass gasification from the energy and industry sectors have been reported by different scholars (Basu 2013d; Bauen et al. 2009; Ahrenfeldt, Bain, Bhattacharya, et al. 2005; McKendry 2002b; Kirkels and Verbong 2011) and are listed below:

- ✓ A highly versatile process that can handle a wide range of biomass feedstock
- ✓ The producer gas has the potential to deliver primary energy carriers, like electricity and heat, or to be upgraded it into syngas (i.e. higher quality gas mixture) as an intermediate carrier for the production of biofuels and chemicals
- ✓ Gasification systems can be integrated for co-generation purposes in industries, like bio-refineries, where all the gasification products can be utilised
- ✓ Cleaner combustion of the producer gas, since impurities can be removed with a pre-combustion cleaning stage, and the volume of the producer gas is smaller than flue gases
- ✓ More efficient combustion process as the exact air requirement can be mixed for optimum combustion; also, producer gas combustion in ICEs or turbines has higher conversion efficiencies over steam turbine devices
- ✓ In addition to lower GHG emissions, gasification can generate lower amounts of other major contaminants, such H_2S instead of SO_2, and N_2 and NH_3, instead of NOx, plus a reduction in particulate matter emissions.
- ✓ The water consumption in a gasification-based power plant is much lower than in conventional (combustion) power plants by incorporating process water recycling systems.
- ✓ As an alternative to natural gas, it has the possibility to be transported in pipelines.
- ✓ Since gasification competes more directly with natural gas-based technologies, the increase of natural gas prices has pushed forward the economic feasibility of gasification technology.

Biomass gasification for power and heat generation is at early-commercial deployment status and still faces several challenges. These have received considerable attention through applied research, with the purpose of overcoming or minimising their detrimental effect on the technologies deployment.

1. Tar formation: Tars are a complex mixture of condensable organic compounds (e.g. heavy hydrocarbons) produced in the pyrolysis stage of the gasifier (Basu 2013c). Vapour tars condense in low-temperature zones forming an undesirable thick and highly viscous liquid that can cause plugging of downstream equipment, catalyst deactivation and formation of carcinogenic elements (Pereira et al. 2012).
The nature of tar components is largely determined by the type of biomass feedstock, followed by the gasifier design and operating parameters (i.e. temperature, gasifying agent, equivalence ratio and residence time) (McKendry 2002c; Pereira et al. 2012). Tar formation

can be tackled following two different approaches. Primary treatment minimizes tar concentration by optimizing the gasification process with an adequate configuration of the operating parameters, modification of gasifier design and/or use of catalysts. Secondary treatment incorporates post-gasification cleansing stages of the product gas to remove tar and other contaminants (Pereira et al. 2012). Tackling with tars also derives into an economic limitation for biomass gasification because costly gas cleaning equipment is required in many cases (Jenkins 2014).

2. High moisture content in biomass has harmful effects on the gasifier operation, product gas composition, and heating value. The tolerance of high moisture content mostly depends on the gasifier design and this is described later in the gasifier design section. If required, the biomass moisture content can be reduced with pre-drying processes, with the counter effect of increasing process energy penalties and costs (Pereira et al. 2012; Basu 2013c). Alternatives for pre-drying processes are natural drying on fields and this requires long drying times but not external heat input. Mechanical drying is highly effective but more expensive (Ahrenfeldt, Bain, van de Beld, et al. 2005).
Novel biomass gasification technologies, such as supercritical water gasification, are also emerging and can process wet biomass (MC > 70% wt.) without pre-drying and produce a hydrogen-rich gas (Heidenreich and Foscolo 2015). This technology is suitable for large-scale applications.

3. Secondary equipment: Biomass gasification for energy generation demands a clean gas with relatively high-energy content requiring secondary equipment for the biomass pre-treatment and gas cleaning systems and for tackling the mentioned technical drawbacks. This auxiliary equipment increases the cost of the entire process at the expense of producing a good quality product gas with lesser contaminants (Pereira et al. 2012; Heidenreich and Foscolo 2015).

The level of cleaning requirement for the product gas depends on its end-use application. ICEs require a gas with particulate concentration below 50 mg/Nm^{-3} and tars below 100 mg/Nm^{3}; for gas turbines, particulate concentration below 30 mg/Nm^{-3} and for methanol synthesis, particulate concentration below 0.02 mg/Nm^{-3} (Woolcock and Brown 2013).

3.3.2 Gasification steps

Gasification involves processes with mass and heat transfer, pressure changes and several chemical reactions. The overall process is usually divided into four main steps (Baruah and Baruah 2014; Jenkins 2014; Puig-Arnavat et al. 2010; Molino et al. 2016):

Drying: consist in the evaporation of the moisture in the solid feedstock to levels between 10-20% wt., by heating the biomass at temperatures ranging between 100-200°C. The heat requirement is generally taken from the oxidation stages of the process (Molino et al. 2016; Basu 2013c).

This step is described by the following relation:

$$Wet\ biomass \xrightarrow{heat} Dry\ biomass + H_2O(g)$$

Pyrolysis: consists of the thermochemical decomposition of the matrix carbonaceous materials inside the biomass, by a heating process in the absence of oxygen. This is an essential step in the gasification process, due to the high-volatile contents of biomass (70-86% on dry-basis). The cracking of the biomass chemical bonds takes place, thus forming different products of low molecular weight in the form of liquid, solid and gaseous phases (Molino et al. 2016).
The gaseous fraction is a mixture of volatiles gases (mainly H_2, CO, CO_2, and light hydrocarbons) incondensable at ambient temperature, and normally representing 70-90 wt.% of the biomass feed. The solid fraction consists mainly of ash and char, as the carbon content fraction with a high heating value. This solid fraction strongly depends on the gasifier design, as higher fractions (20-25 % wt.) are obtained in fixed bed gasifiers and lower ones (5-10 % wt.) in fluidised bed gasifiers. The liquid fraction, also known as tars, varies depending on the feedstock composition, processing conditions and gasifier type (Woolcock and Brown 2013; Molino et al. 2016).

The pyrolysis reaction is endothermic and takes place in the absence of oxygen at temperatures around 200-700 °C. The process is schematized in the following reaction (Molino et al. 2016):

$$Biomass \xrightarrow{yields} H_2 + CO + CO_2 + CH_4 + H_2O + Tar + Char \qquad (endothermic)$$

Oxidation: involves the reaction between the carbonaceous matter and a sub-stoichiometric oxygen amount to oxidise only a part of the fuel (Molino et al. 2016). This results in a gas mixture of CO, CO_2, H_2O, and N_2 when air is used as a gasifying agent. The oxidation reactions are exothermic and provide the energy required in the endothermic reactions within the gasifier (Molino et al. 2016; Puig-Arnavat et al. 2010).
The oxidation reactions are generally faster than gasification reactions under similar conditions (Basu 2013c). The main reactions that take place in this stage are the following:

Complete oxidation or char combustion: $C + O_2 \rightarrow CO_2 \quad \Delta H = -394\ kJ/mol$

Partial oxidation: $C + \frac{1}{2}O_2 \rightarrow CO \quad \Delta H = -111\ kJ/mol$

Hydrogen combustion: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad \Delta H = -242\ kJ/mol$

Reduction: this stage comprises several reactions between the products of pyrolysis and oxidations steps, i.e. char and the gas mixture, to produce the final producer gas. The main reactions occurring at this stage are in chemical equilibrium, and overall the stage is considered as allo-thermal (Molino et al. 2016; Basu 2013c):

$C + CO_2 \leftrightarrow 2CO \quad \Delta H = 172\ kJ/mole$ (Boudouard reaction)

$C + H_2O \leftrightarrow CO + H_2 \quad \Delta H = 131\ kJ/mole$ (Water-gas reaction)

$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -41\ kJ/mole$ (Water-gas shift reaction)

$C + 2H_2 \leftrightarrow CH_4 \quad \Delta H = -75\ kJ/mole$ (Methanation or Hydrogasification reaction)

The temperature at the reduction zone ranges between 800-1100 °C, playing a key role in the overall gasification process as it determines the characteristics of the producer gas and of the solid residue. High temperatures favour char oxidation and reduction, however, they assist in the reduction of the energy content of the syngas and promote ash sintering (Molino et al. 2016).

3.3.3 Gasifiers operating parameters

The performance of biomass gasifiers can be characterized mainly by the producer gas composition, which further affects the gas heating value, and the gasification process efficiency. Gas composition is influenced by several operational parameters such as the biomass composition, including the moisture content, the gasifying medium, the equivalence ratio and the operating temperature (Puig-Arnavat et al. 2010; Pereira et al. 2012). Key process parameters in biomass gasification are explained below:

Gasifying agent

Gasification requires the addition of a gasifying agent to rearrange the molecular structure of the biomass by converting the solid biomass feedstock into gases and liquids (Basu 2013c). Depending on the desired product gas composition, and hence in its intended end-use, the gasifying medium can be air, pure oxygen, steam or a mixture of them. Air is the most common and cheapest oxidant agent; however, its high nitrogen content lowers the heating value of the syngas, which can range between 4-6 MJ/Nm^3 (Neubauer 2013). Pure oxygen as a gasifying agent can increase the gas heating value (12-28 MJ/Nm^3) with the counter effect of increasing operating costs from the air separation process to obtain oxygen (Neubauer 2013). The partial combustion of the biomass with air or pure oxygen generates the thermal energy required for the biomass drying step, increases the biomass temperature and supplies the heat needed by the gasification endothermic gasification and compensates for heat losses (Basu 2013b; Puig-Arnavat et al. 2010).

Steam, as gasifying agent alone or as a combination with air or oxygen, can increase the hydrogen content in the gas and enhance the gas heating value to values between 12-14 MJ/Nm^3 (Neubauer 2013). Carbon dioxide is also a convenient option as an oxidant because it exists as a component in the syngas. However, the use of CO_2 or steam as gasifying agents requires an external heat supply to drive the endothermic reactions inside the gasifier unless a mixture of them with air or oxygen is used (Puig-Arnavat et al. 2010).

Equivalence ratio

The equivalence ratio is one of the most important and controllable operating parameters in a gasification process. It represents the ratio of the actual amount of air (or oxygen) to the amount of stoichiometric air (Basu 2013b), as equation 6 indicates:

$$\boldsymbol{ER = \frac{m_a}{m_{st}} = \frac{actual\ air\ amount}{stoquiometric\ air\ amount}} \qquad \text{Equation 6}$$

Where m_a refers to the amount of air, as a gasifying agent, required to gasify a unit mass of fuel and m_{st} refers to the theoretical air required for the complete combustion of the same unit of fuel (biomass).

Gasification processes, unlike combustion, require a deficient supply of air into the gasifier, with the ER ranging between 0.2 and 0.3 (Basu 2013b). The equivalence ratio strongly influences the performance of the gasifier and the quality and composition of the product gas (Basu 2013b).

For ER < 0.2, it is likely that incomplete gasification occurs, resulting in high char formation and producer gas with low heating values. However, an ER > 0.4 can trigger the formation of complete combustion products, CO_2 and H_2O, rather than the combustible components of the producer gas, CO and H_2; consequently reducing the gas heating value. Therefore, the importance to correctly determine the ER while designing the gasification process (Basu 2013b).

Gasifier Temperature

The gasifier temperature is a process parameter that greatly influences the producer gas yield and composition; therefore, the control over this variable is crucial to obtain a good quality product gas and good overall process efficiency. For lignocellulosic biomass gasification is important to reach minimum temperatures of 800-900 °C, to assure the adequate gasification of lignin. In a gasification process, the temperature increases through the oxidation (exothermic) reactions; therefore, higher temperatures demand higher amounts of oxygen. High gasification temperatures can enhance the yield of hydrogen and the gas flow; it can also help reducing tar formation (Pereira et al. 2012; Basu 2013b; Molino et al. 2016).

The gasification temperature requirements depend on the design of gasifiers; entrained flow gasifiers should operate at higher temperature ranges (1400-1700 °C) to melt the ash, but fluidised bed gasifiers have to operate within a range of 700-900 °C to prevent the bed material softening. Fixed-bed gasifiers operate at temperatures around 1000 ºC (Basu 2013b).

Gasification performance parameters

The conversion efficiency of a gasification system is commonly measured using two parameters: cold gas efficiency and hot gas efficiency.

Cold gas efficiency measures the potential energy output of the producer gas over the biomass energy input (Basu 2013b) as equation 7 indicates:

$$\boldsymbol{CGE = \frac{m_{pg} \cdot LHV_{pg}}{m_{bm} \cdot LHV_{bm}}} \quad \text{Equation 7}$$

where m_{pg} and LHV_{pg} are the mass and low-heating value of the product gas, and $\mathrm{m_{bm}}$ and LHV_{bm} are the mass and low-heating value of the biomass feed.

Hot gas efficiency measures, in addition to the energy output of the producer gas, the sensible heat carried by the hot gas (Basu 2013b):

$$\boldsymbol{HGE = \frac{m_{pg} \cdot LHV_{pg} + m_{pg} \cdot C_p \cdot (T_f - T_0)}{m_{bm} \cdot LHV_{bm}}} \quad \text{Equation 8}$$

where $\mathrm{T_f}$ is the gas temperature at the gasifier exit, $\mathrm{T_0}$ is the temperature of the fuel entering the gasifier and C_p is the heat capacity of the product gas.

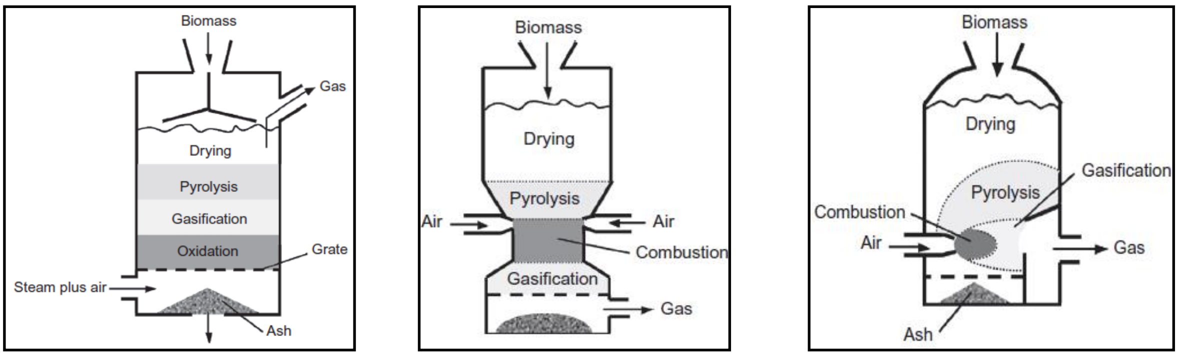
3.3.4 Types of biomass gasifiers

There are different types of gasifiers that can meet diverse applications (i.e. energy and/or chemicals/fuels production) across a range of small to large operating scales. Gasifiers are classified broadly depending on the following categories:

a) type of gasifying agent used in the process (air, oxygen or steam).
b) the mode of heat supply to the reactor: an auto-thermal gasifier is self-heated by the feedstock oxidation and allo-thermal if the energy required is supplied externally (Baruah and Baruah 2014).
c) the pressure used in the reactor (atmospheric or pressurised).
d) the interior reactor's design, contacting mode between the gas-solid material (biomass) phases.

The last category is very important since the interior configuration of the reactor determines how the gas and the biomass interact, this strongly influences the composition of the product gas and the performance of the gasifier (Basu 2013b). The most common configuration type of gasifiers are the followings:

Fixed bed gasifiers are the most common and low-cost design option for small-scale operations, yet produce a gas with a relatively low heating value (LHV: 4-6 MJ/Nm^3). Currently, large numbers of small-scale (10-500 kWth) fixed-bed biomass gasifiers are used around the world, especially for intermittent heat generation (Bauen et al. 2009). In fixed-bed gasifiers, the gasifying medium carries the biomass particles through the reactor, and the biomass is supported on a grate. In fixed-bed gasifiers, heat transfer and mixing is poor, which causes a non-uniform distribution of the fuel, temperature and gas composition inside the reactor. According to the direction of the airflow, they are further categorised as updraft, downdraft, and cross-draft gasifiers. Figure 8 shows an operation schematic of the three types of fixed-fed gasifiers.



a. Updraft gasifiers **b. Downdraft gasifiers** **c. Cross-draft gasifiers**

Figure 8. Operation schematics for the three types of fixed-bed gasifiers.
Adapted from (Basu 2013b)

- ***Updraft gasifiers*** are one of the simplest types of gasifiers with commercial use in small (e.g. cooking stoves) and large units. In this gasifier, the biomass is fed at the top of the gasifier and moves downwards, and the gasifying agent is supplied at the bottom of the reactor (grate), flowing upwards; therefore biomass and gasifying agent are in counter-current movement (Basu 2013b). This favours an efficient use of the combustion heat, yielding high gasification efficiencies (Cold Gas Efficiency (CGE): 40-60% and Hot Gas Efficiency (HGE): 90-95%), also the LHV of the producer gas spans between 5.0-6.0 MJ/Nm^3 (Ahrenfeldt, Bain, van de Beld, et al. 2005).

  The advantages of updraft gasifiers are their simple design, tolerance for higher moisture and ash content in the biomass, high-charcoal burn-out and internal heat exchange, also low sensitivity to load fluctuations. The drawbacks are high tar content in the product gas (30-150 g/Nm^3) and other pyrolysis products, making this type of gasifiers unsuitable for high-volatile fuels feedstock. Due to the high tar-content in the producer gas, these gasifiers are more fit to work couple to direct firing applications, such as boilers or furnaces with no cleaning required (Basu 2013b). Updraft gasifiers are generally used for direct firing in boilers or furnaces, which do not require prior gas cleaning for tar removal; the scales of operation range between 2-30 MW thermal input.

- ***Downdraft gasifiers*** are also a reliable, simple and low-cost technology used in small scale systems with ranges of applications between 10 kW – 1 MW of thermal input (Molino et al. 2016). In these gasifiers, the biomass feed and gasifying agent both move downwards; the biomass enters in the top of the gasifier, and the air (gasifying agent) is introduced at a height below the top (McKendry 2002c). The product gas exits at the lowest zone of the reactor, after reduction phase, passing through a hot-temperature zone of hot ash that helps to crack the tars (Jenkins 2014; Ahrenfeldt, Bain, van de Beld, et al. 2005).

  The main advantages of these gasifiers are the low rate of tar production (0.015 – 0.5 g/Nm^3) in the producer gas, resulting in a clean gas apt for applications in ICEs, and relatively high HGE: 85-90% (Ahrenfeldt, Bain, van de Beld, et al. 2005). The lower tar concentration also results in higher tolerance for biomass feedstock with high-volatiles contents, yielding higher carbon conversion rate and demanding shorter times for ignition (Molino et al. 2016; Basu 2013b).

  The main drawbacks are the lower energy content of the producer gas (4.5-5.0 MJ/Nm^3) due to higher exit temperatures (900-1000 ˚C) and higher ash and particulates content in the producer gas. They also have a higher sensitivity to the biomass characteristics, such as a lower-moisture content (below 25% wt.) and uniform particle size (4-10 cm) (Basu 2013b; Molino et al. 2016).

- ***Cross-flow gasifiers*** have common application in micro-scale units for the gasification of charcoal to generate shaft power (<10 kW_e) (Ahrenfeldt, Bain, van de Beld, et al. 2005). In this type of gasifiers, the fuel is fed at the top of the reactor, and the air is injected through a nozzle by the sidewall of the reactor. The product gas leaves the gasifier from the opposite side of the air supply. They have a small reaction zone, with a low thermal capacity that gives faster responses times (McKendry 2002c; Basu 2013b).

  The advantages of cross-draft gasifiers are the suitability to operate at very small-scale units, shorter start-up times (5-10 minutes) enabling good responses to load changes when coupled to engines; low tar-content product gas (0.01-0.1 g/Nm^3) and faster response times due to a small reaction zone with low thermal capacity (Basu 2013b; Ahrenfeldt, Bain, van de Beld, et al. 2005). The disadvantages of this design are the requirement of high-quality charcoal with a low-ash (0.5-1 % dry-ash basis) moisture content (10-20% wt.) and small particle feedstock size (5-20 mm). They also can reach high temperatures in the hearth zone which can lead to material problems (Basu 2013b; Ahrenfeldt, Bain, van de Beld, et al. 2005).

Fluidised bed gasifiers were developed, initially, for large-scale coal gasification and later on have been used for biomass gasification to overcome the drawbacks of fixed-bed gasifiers. These designs are advantageous within a wide range of operation scales (1-10 MW), with higher suitability for medium-size units (McKendry 2002c; Ahrenfeldt, Bain, van de Beld, et al. 2005). These gasifiers operate in a fluidisation condition where the gasifying agent is injected at appropriate velocities to bring a fluidised bed of granular solids into a semi-suspended position. The biomass is then injected into the bed, mixes with the sand (i.e. inert media) and starts decomposing into the combustible gas (Ahrenfeldt, Bain, van de Beld, et al. 2005; Basu 2013b; Jenkins 2014).

The forced movement of the solid material creates excellent mixing conditions, and a more uniform temperature distribution makes these gasifiers more tolerable to many feedstock and changes in fuel characteristics, hence reducing risks of biomass agglomeration. The product gas obtained has a medium tar-content (10 g/Nm^3) in comparison to other types of gasifiers and have a high concentration of small particles, requiring downstream cleaning devices (Basu 2013b; McKendry 2002c; Jenkins 2014). They are further categorized in bubbling fluidised bed gasifiers and circulating fluidised bed gasifiers.

- ***Bubbling fluidised bed gasifiers*** (BFB gasifiers) are the most robust, popular and commercial option of fluidised gasifiers for biomass gasification, particularly suitable for medium-scale units (see Figure 9 to the left). In BFBG, the biomass feed (requiring particles size <10 mm) is introduced into the bed materials and put into a fluidised state by the injection of the gasifying agent from the bottom. The biomass goes through pyrolysis in the hot-bed to form the char with the gaseous compounds, where the high molecular compounds (tar) are cracked by the contact with the hot-temperature bed (McKendry 2002c; Basu 2013b). These gasifiers have a clear distinction between the freeboard zone and the fluidised bed reaction zone (Ahrenfeldt, Bain, van de Beld, et al. 2005).

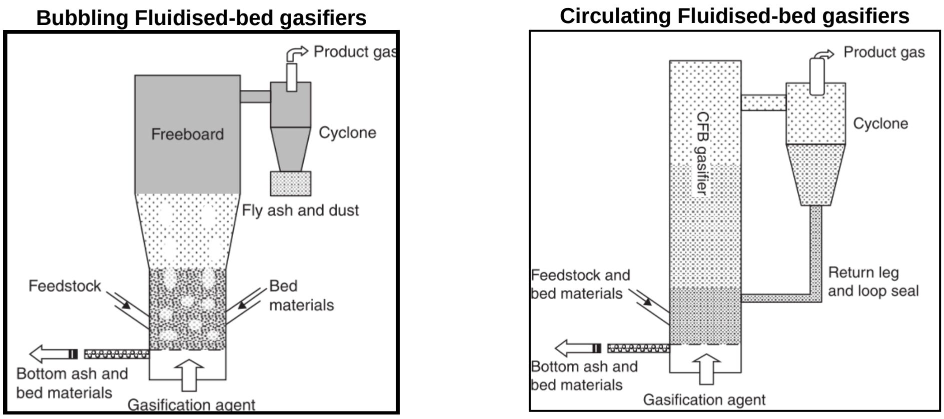


Figure 9. Schematics for the two types of fluidised-bed gasifiers (Neubauer 2013)

The BFB gasifiers main advantages are high mixing and gas-solid contact, good temperature control, good flexibility for load, process, and for handling fuels with different characteristics, moderate tar concentration in gas (< 1-3 g/Nm^3). The disadvantages are the loss of carbon in the ashes, the dragging of dust ashes and the costs in investment and maintenance (Molino et al. 2016).

- ***Circulating fluidised bed gasifiers*** (CFB gasifiers) are especially attractive for biomass gasification due to the long gas residence, being also suitable for fuels with high volatiles (Basu 2013b). CFBG comprise of a riser (reactor), a cyclone and a solid recycle device, as Figure 9 to the right shows. Here, the bed material circulates between the riser and the cyclone; the cyclone removes the ash and separates the bed material and char from the product gas, and finally, a loop seal returns the solid particles to the bottom of the gasifier (Basu 2013b; McKendry 2002c). The operation temperature inside the reactor ranges in the interval of 800-1000 °C (Basu 2013b).

CFBG differ from BFBG by the hydrodynamic behaviour inside the reactor, reaching higher fluidisation velocities (3.5 – 5.5 m/s) and having a non-distinct interface between the freeboard and the fluidised bed zone (Basu 2013c; Ahrenfeldt, Bain, van de Beld, et al. 2005). The main advantages of CFBG gasifiers are having a moderate tar production, higher carbon conversion, flexibility to load changes and good ability to scale-up. The main drawbacks are also the loss of carbon in the ashes, demanding size reduction and preparation of solid material, more complex and costly (i.e. investment and start-ups) technology and restricted solid-gas contact (Molino et al. 2016).

Entrained flow gasifiers: This type of gasifier is widely used for large-scale units (> 100 MW_{th}), with successful applications for coal and petroleum coke gasification. In entrained flow gasifiers, fine fuel particles or slurry fuel are pneumatically injected in a burner for mixing with the gasifying agent (i.e. oxygen or mixture of oxygen and steam), which is fed in co-current. The solid fuel and the gasifying agent form a dense cloud that flows through the gasifier. These gasifiers operation is characterised by high temperatures (> 1300-1600 ˚C), high pressures (26-6- bar), short residence times (~1 s) and high-gas flow velocities (Ahrenfeldt, Bain, van de Beld, et al. 2005; Basu 2013b; Neubauer 2013).

The major advantages of the entrained flow gasifiers are low tar and CO_2 concentration, high carbon conversion rate, high degree of feedstock conversion, good fuel flexibility and uniform temperature (Neubauer 2013; Molino et al. 2016). Yet, their application for biomass gasification has been very limited commercially due to their requirement of biomass feed finely pulverised (<0.15 mm) which is hard to obtain for fibrous materials like biomass. Other limitations of the EFG are low CH_4 concentration, complex operational control, high-level of sensible heat in the product gas (i.e. requiring extensive heat recovery), high-demand of oxidant requirements, short-life of system components and high costs of plant construction and maintenance (Molino et al. 2016; McKendry 2002c; Basu 2013b).

Plasma gasifiers entail the thermal disintegration (also known as plasma pyrolysis) of the carbonaceous material into compounds within an oxygen-deficient environment and at very high temperatures (> 10,000 °C). These gasifiers operate with a plasma gun that creates an intensive electric arc between two electrodes with an inert gas in between (Molino et al. 2016; Basu 2013b).

These gasifiers are highly fit for the gasification of municipal solid waste (MSW) and toxic organic waste due to the low sensibility of the biomass quality and the high temperatures in the reactor (2700 - 4500 ˚C). They are also very efficient in tar destruction and other harmful products, produce a gas with high H_2 and CO concentration, yielding a gas with high HV and have a high tolerance for biomass characteristics (e.g. particle size, moisture content) (Basu 2013b; Molino et al. 2016; Heidenreich and Foscolo 2015).

Since plasma gasification is a relatively new technology, it is commercially immature, resulting in high investment and operation costs. Other limitations are the refractory consumption, necessary auxiliary fuel to produce the high-temperature environment, high electricity consumption, and the issue of a non-continuous process (Basu 2013b; Molino et al. 2016; Heidenreich and Foscolo 2015).

3.3.5 Producer gas cleaning technologies

The selection of the producer gas cleaning system configuration primary depends on the level of contaminants of the gas and its end-use application (Laurence and Ashenafi 2012; Woolcock and Brown 2013; Hasler and Nussbaumer 1999). If the contaminants are not reduced within the gasifier (i.e. “primary” or “in-situ” clean up), downstream cleaning techniques have to be applied to meet the requirements of the end-use technology (Woolcock and Brown 2012). Gas clean-up technologies are mainly categorized by the process temperature ranges as hot gas clean-up systems, suitable for temperatures ranging between 400 °C – 1000 °C, cold gas clean-up for temperatures below 400 C and warm gas clean-up occurring at temperatures above the boiling point of water but below ammonium chloride condensation. Another aspect considered for this categorization is the condensation temperature of certain compounds (Woolcock and Brown 2013).

The selection of the producer gas cleaning system depends on the level and type of contaminants in the producer gas, as well as in the end-use application (Laurence and Ashenafi 2012; Woolcock and Brown 2013; Hasler and Nussbaumer 1999). For ICE applications, it is important that the producer gas meets the fuel quality requirements of particulates concentration (<0.05 g Nm-3) and tar content (<0.100 g Nm-3), to avoid severe engine operational problems (Hasler and Nussbaumer 1999).

3.3.6 Biomass gasification: experiments and process modelling

Understanding and evaluating the behaviour of thermochemical biomass conversion and hydrodynamics inside a gasification system is essential to attain good gasifier performance and end-gas compositions. Therefore, the design and optimisation of a gasification process, considering the biomass characteristics, gasifier configuration and operating conditions, requires conducting either experimentation or mathematical modelling and simulations.

Experiments are closer-to-reality demonstration procedures used to understand the physical and thermochemical phenomena inside a gasifier, gain insights into the process performance when varying parameters, and obtain reliable design data (Basu 2013c). However, experimentation can be expensive and time-consuming, since they are not easily adaptable to new process parameters, to find optimum operating conditions for a specific gasifier design and scalable to different equipment sizes (Baruah and Baruah 2014).

On the other hand, computational modelling approaches can be a useful tool to represent also the insights of a gasification process by using mathematical equations that represent the reaction kinetics and the thermodynamic and hydrodynamic phenomena. Biomass gasification modelling can provide good guidance when evaluating the effect of input process parameters, feedstock characteristics and different reactor configurations and sizes (Basu 2013c; Puig-Arnavat et al. 2010). Modelling and simulation can also help identify optimum operating conditions and risky operation zones, that otherwise could be hazardous when trying to identify them by experimentation (Basu 2013c).

A balanced combination of modelling-simulation with validation using experimental data is useful to obtain reliable data and replicable experience for gasification process design, scale-up and optimization. The most common approaches for modelling biomass gasification processes are the thermodynamic equilibrium model and the kinetic rate model. Among these approaches, there are computational tools, like, Aspen Plus and GProms, that can help through the modelling and simulation of the gasification process (Basu 2013c; Baruah and Baruah 2014; Puig-Arnavat et al. 2010; Patra and Sheth 2015).

Kinetic rate models

This model considers the kinetics mechanisms of the gasification reaction, and the hydrodynamics inside the reactor hence can provide detailed information on the biomass conversion in a gasification system. This approach can be highly accurate and allows better simulation of the experimental data where the residence time of gas and biomass is relatively short, and the operating temperature is low. It also provides for char reduction process description using experimental correlations (Puig-Arnavat et al. 2010). Nevertheless, the formulation is more complex, it is more computationally intensive, and the model parameters can restrict its applicability for some gasification systems (Puig-Arnavat et al. 2010; Baruah and Baruah 2014).

The kinetic model can predict the gas yield, gas composition and temperature profile inside a gasifier during a finite period of time or for a finite volume (in a flowing medium). In addition, the model can also estimate these parameters for a given operating condition and gasifier configuration, unlike the thermodynamic model that assumes reactants undergo a well-mixed reaction for an infinite time period (Baruah and Baruah 2014; Basu 2013c). This model involves parameters like the reaction rate, residence time of particles and reactor hydrodynamics (Basu 2013c).

Thermodynamic equilibrium models

This model is based on the chemical equilibrium state of a reacting system, which occurs when the entropy is maximised, the Gibbs free energy is minimized, and the maximum conversion of reactants is achieved (Puig-Arnavat et al. 2010). Equilibrium models are not dependent on the gasifier design and not restricted to specific operating conditions. Therefore are widely used for feasibility studies and preliminary estimations of the product gas yield and the influence of fuel and process parameters on the process performance (Baruah and Baruah 2014). Since the model assumes the system reaches a chemical equilibrium state, it calculates the maximum achievable yield of the gas (Basu 2013c).

The equilibrium model does not show enough accuracy for certain conditions, such as when low operating temperatures occurred, and chemical equilibrium is not attained (Puig-Arnavat et al. 2010). These limitations in the model can lead to underestimations of the carbon dioxide, methane, tar and char contents in the producer gas composition and to overestimations of H_2 and CO yield in the product gas, thus causing overestimations of the producer gas heating value. The equilibrium model also cannot predict the influence of hydrodynamic and geometric parameters on the process performance (Basu 2013c; Puig-Arnavat et al. 2010; Baruah and Baruah 2014).

The thermodynamic equilibrium approach has shown good results when modelling entrained flow and downdraft gasifiers if high reaction temperature and long gas residence times can be achieved in the reactors. For updraft and fluidised bed gasifiers, results are not accurate enough, and the gasification process has to be simulated with adapted equilibrium models or by detailed flow-rate models since it is necessary to have detailed information about the biomass devolatilization (Puig-Arnavat et al. 2010).

CHAPTER 4. METHODOLOGY

This chapter presents a detailed description of the methods applied to evaluate the technical and economic feasibility and potential environmental impacts of deploying small-scale gasification systems for power and heat generation using agricultural residues. The application of this methodology contributed to achieving the specific objectives of this research, which were defined in Chapter 1.3. Figure 10 shows how the specific objectives correlate to the methods used in this research. Thicker arrow lines symbolise a direct correlation of the objective with the specific method as the main procedure required to attain the objective. The thinner arrows designate an indirect correlation, where the method supports the achievement of the specific objective as an auxiliary tool. The purpose of using this multidisciplinary and complementary approach was to gain a comprehensive insight into drivers, trade-offs and limitations of deploying these bioenergy systems under rural contexts.

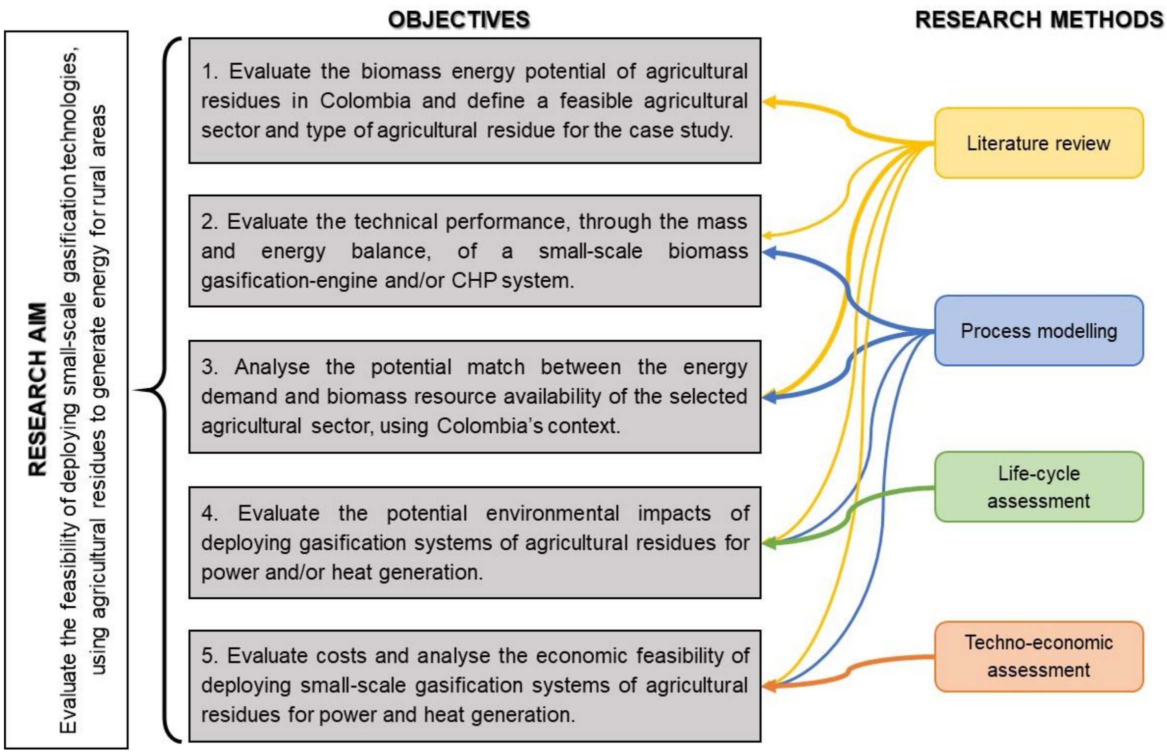


Figure 10. Correlation of objectives with the research methods

This chapter is structured in four sections. Section 4.1 explains how the agriculture residues resource assessment was conducted to select the agricultural residue for the case study. Section 4.2 presents information on the basic design of the gasification plant, the approach followed for the process modelling and the configuration set in *Aspen Plus* software to model the gasification plant. Section 4.3 introduces the lifecycle assessment method, used to evaluate the environmental impacts of the system. Firstly, the LCA framework and guidelines are explained; later, it is presented how the LCA method was applied in this research. Finally, section 4.4 describes the techno-economic assessment of the system.

4.1 Agricultural residues resource assessment: literature review based

A literature review framed on the bioenergy potential from agricultural residues in Colombia was conducted to attain the first objective of this thesis, aiming to evaluate and identify different alternatives of agricultural residues for the case study.

The revision covered significant studies on the biomass residues potential in Colombia, using as a baseline the *Atlas of Biomass residues energy potential in Colombia* (Escalante et al. 2011), as a comprehensive study on biomass residues potential commissioned by the Agency for Energy and Mining (UPME) in Colombia. This information was then, complemented with more literature by UPME (2015; 2003) and Gonzalez-Salazar, Morini, et al. (2014).

4.1.1 Review of the Atlas for the residual biomass energy potential in Colombia

The Atlas for the residual biomass energy potential in Colombia (Escalante et al. 2011) evaluates the theoretical energy potential of biomass residues, categorised in agricultural residues, animal wastes and municipal solid waste (MSW). The Atlas was developed based on a resource focused approach combining statistical analysis with a spatially explicit analysis methodology. It reports the resource availability and energy potential of indigenous biomass residues based on the geographical distribution of the resources per department of Colombia.

The data on the agricultural residues category for the biomass energy potential per year was ranked to select the agricultural residues with the highest energy potential (refer to chapter 2.4 for the rationale behind the selection of agricultural residues category). Table 2 was built to condense these data, including also the nature and amount of agri-residues per year; and information on the crops that generate these residues.

The agri-residues yielding the highest energy potential were examined further (refer to chapter 2.4.1) to curtail these options to those suggesting higher techno-economic feasibility for bioenergy applications and also requiring further research for their utilisation in Colombia. Finally, one type of agricultural residue was selected for the case study. The rationale behind this selection is presented in Section 5.1.

4.2 Basic design of gasification plant and process modelling approach

This section introduces the approach to attain the second and third objective, which aimed to evaluate the technical performance of the bioenergy system and analyse the balance between the energy demand and biomass resource availability in Colombia's rural context. The method presented in this sections is part of a peer-reviewed and published paper *"The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector"* by this author (Garcia-Freites et al. 2019) in the journal *Biomass Conversion and Biorefinery.*

4.2.1 Selection of gasifier and process design

Section 3.1 presented the justification for selecting gasification as a suitable technology for the conversion of agricultural residues to generate power and heat at small-scale applications in rural areas. Furthermore, the context of small-scale applications for bioenergy generation in rural areas also determines the gasifier design to fixed-bed gasifiers, commonly utilised for small-scale power and heat generation with capacities between 10 kW_{th} and 10 MW_{th} (Ruiz et al. 2013). Among the different fixed-bed gasifiers designs, the downdraft gasifier is selected as it features a simple design with well-proven performance and relatively low investment costs for small scale applications (Ruiz et al. 2013). Also, because of their internal configuration, downdraft gasifiers generate a producer gas with low tar content and average heating value suitable to be used as fuel gas in ICEs for electricity generation (Kirkels and Verbong 2011; Basu 2013b).

The process design and basic sizing of the downdraft gasifier were specified by determining these key input parameters and following guidelines for gasifiers process design in (Basu 2013b):

Thermal power output

An initial estimation of the desired thermal power output (Q) of the gasifier was made by setting the required net power output of the engine-generator set (P_{el}) and the electrical efficiency of the device (η_{el}), as equation 9 indicates.

$$\boldsymbol{Q} = \frac{\boldsymbol{P_{el}}}{\boldsymbol{\eta_{el}}}; \quad [\boldsymbol{kW_{th}}] \quad \text{Equation 9}$$

The net electrical power output of the whole biomass gasification-power was set from an iterative process when balancing the matching relation between the biomass supply and energy demand of the coffee farms in Colombia.

Biomass feed rate

The biomass feed rate (M_f) required to deliver the desired thermal power output (Q) is calculated with equation 10 (Basu 2013b), where $\boldsymbol{\eta_{gasif}}$ correspond to the gasifiers efficiency and LHV_{bm} to the biomass low heating value (on a dry-ash free basis). For downdraft gasifiers, a conversion efficiency of 70-75% is a good initial assumption, according to (Antonopoulos et al. 2012; Ruiz et al. 2013).

$$\boldsymbol{M_f = \frac{Q}{LHV_{bm} \times \eta_{gasif}}};\ \left[\frac{kg}{hr}\right] \quad \text{Equation 10}$$

Biomass composition and characteristics

The data on the coffee stems composition was sourced from the experimental work conducted in the Coffee Research Centre in Colombia by Oliveros-Tascón et al. (2017) and supported by another dataset reported by other scholars in Colombia (C. García et al. 2018). Table 5 shows the proximate and elemental analysis, and the chemical structure of the coffee stems biomass. Same literature sources also indicate that the desired particle size of the coffee-wood chips should be around 20 mm, following specifications of downdraft gasifier manufacturers. This data are inputs to the gasification model in *Aspen Plus* software.

Table 5. Chemical structure, proximate and ultimate analysis of coffee stems.
Source: (C. García et al. 2018)

Proximate analysis (%wt. dry basis)		**Elemental analysis** (%wt. dry basis)		**Chemical structure** (%wt. dry basis)	
Volatile matter	82.15	Carbon	48.35	Cellulose	40.4%
Ash	1.07	Hydrogen	5.93	Hemicellulose	34.01%
Fixed carbon	16.78	Oxygen	44.21	Lignin	10.13%
Moisture content (%wt.):	10	LHV_{daf} (MJ kg^{-1})	18	Ash	1.27%

*Nitrogen composition is determined by the difference in the elemental analysis

Gasifying agent and oxidant flow rate

Small-scale gasifiers are usually operated using air as the gasifying agent. The producer gas from this gasifiers has an LHV ranging between 4 – 7 MJ/m^3 that categorises it as a low-HV gas mixture; however, it is suitable as fuel for engine applications (Jenkins 2014; Neubauer 2013). Next, the equivalence ratio (ER) was set in 0.25, reported as the ER giving best yields for downdraft gasifiers (Basu 2013b); later in chapter 5.2.2, this parameter was evaluated in the sensitivity analysis.

Finally, the airflow rate was calculated using equation 11, where $\boldsymbol{M_f}$ is the biomass feed rate entering the gasifier and $\boldsymbol{m_{th}}$ is the stoichiometric amount of air:

$$M_{air,f} = m_{th} \times ER \times M_f; \quad \left[\frac{kg}{h}\right] \quad \text{Equation 11}$$

Table 6 collates the gasifier design parameters and average operating conditions described above, which are used as inputs for the process simulations. The expected thermal power output of the gasifier (100 kW_{th}) is set from examining the average electricity demand of a coffee farm and biomass availability. The biomass feed rate is determined from assuming a downdraft gasifier's efficiency of 75% that falls within the range for this type of gasifiers (Antonopoulos et al. 2012; Pereira et al. 2012).

Table 6. Gasifier design parameters and operating conditions

Design/operation parameters	Value
Gasifier thermal power output	100 kW_{th}
Gasifier's efficiency *(initial estimation)*	75%
Biomass feed rate	26 – 28 kg h^{-1}
Equivalence ratio (ER)	0.25-0.3
Air mass flow	42 kg hr^{-1}
Operating pressure	Atmospheric

4.2.3 Gasification modelling approach

Section 3.4 presented an overview of the current approaches used for modelling gasification. The selection of the thermodynamic equilibrium approach to model the gasifier was made based on the scope of this research which required high-level numbers that inform on the technical performance of the system. This approach is capable of predicting the maximum achievable gas yield and composition after gasification. It can also evaluate the influence of the biomass and process parameters on the gas yield and composition (Basu 2013c; Puig-Arnavat et al. 2010).

This method, yet has some limitations, as it does not consider the gasifier's geometry and hydrodynamics, and cannot predict tar formation. These limitations were addressed by firstly, understanding how the expected model outcomes and constraints of the modelling approach affect the purpose of this technical assessment. Certain limitations of this approach have less impact when predicting downdraft gasifiers behaviour. These gasifiers have poor mixing conditions, reaction temperatures between 1000-1400 °C and product gas output temperatures around 700-800 °C (Basu 2013b; Basu 2013c; Ruiz et al. 2013).

Secondly, certain measures were taken to acknowledge and mitigate the effect of the model constraints on the results, such as in the case of the restrictions on tar formation, which are presented in section 4.2.4. Furthermore, Section 4.5 discusses the methodological implications of this modelling approach to the simulation results.

General modelling assumptions

The assumptions considered for this process modelling are presented below and are consistent with other works on biomass gasification modelling; such as in (Antonopoulos et al. 2012; Vaezi et al. 2008; Shen et al. 2008; Begum et al. 2013; Beheshti et al. 2015; Nikoo and Mahinpey 2008; Ramzan et al. 2011; Doherty et al. 2010; Doherty et al. 2009; Doherty et al. 2013):

a) The thermodynamic equilibrium model is based on the minimisation of the Gibbs free energy approach to predict the gas composition and yield.
b) The gasification process is modelled assuming that after a long residences time, the system reaches a steady-state and reactants establish a chemical equilibrium (Buekens and Schoeters 1985).
c) The gasifier is modelled as operating at atmospheric pressure.
d) Biomass particles have a uniform size after chipping; and the average size remains constant during the gasification, based on the shrinking core model.
e) Tars are assumed as non-equilibrium products; hence, tar formation is not modelled due to the limitations of the thermodynamic equilibrium approach.
f) The biomass devolatilization phase (pyrolysis) occurs instantaneously and the main volatile gases produced are H_2, CO, CO_2, CH_4, and H_2O treated as ideal gases.
g) Ash in biomass is assumed to be inert, i.e. it does not participate in the chemical reactions.
h) Pressure drops in the unit operations are neglected (reactors and separators).

4.2.4 Simulation in *Aspen plus* software

The commercial modelling software *Aspen Plus V10* developed by Aspen Tech company was used to conduct the modelling and simulation of the biomass gasification-ICE plant, including the feedstock pre-treatment and downstream gas condition stages. *Aspen Plus* is a problem-oriented input programme that allows process design and simulation of the operation of biological, mechanical and chemical processes, involving energy and materials streams, in the form of solids, liquids and gases (Puig-Arnavat et al. 2010).

In the context of this research, the application of *Aspen Plus* with a thermodynamic equilibrium approach allowed to predict the system's mass and energy balances, and the composition of the producer gas and flue gas streams. It also allowed to examine the effect of the coffee stems characteristics and operating parameters on the producer gas composition and yield through the sensitivity analysis.

Aspen Plus model and simulation specifications

Modelling the biomass gasification plant also requires certain specifications in *Aspen Plus V10* to configure the simulation with different material streams, particularly with solids. The Aspen Tech support document for modelling solids (Aspen Technology Inc 2000) was used as a guideline, and supported by the work of Ramzan et al. (2011):

- Biomass and ash streams are modelled as non-conventional solids.
- Carbon is modelled as a pure and conventional solid.
- The working fluids were modelled as ideal gases; therefore, the IDEAL property method was chosen for the simulation.

Description of ASPEN Plus simulation model

Figure 11 shows the Aspen gasification process flow diagram. The model represents two core stages: the biomass preparation stage (i.e. coffee stems drying and chipping) and the gasification stage. The gas clean-up and cooling stages, together with the producer gas combustion for power generation are presented later in this section.

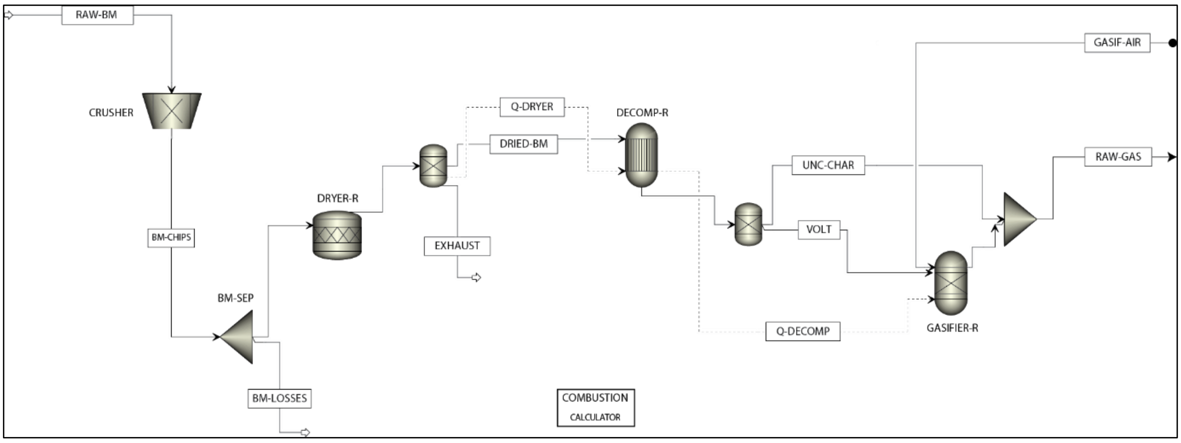


Figure 11. Aspen Plus process flowsheet of the biomass gasification system.

The biomass preparation stage starts with the coffee stems drying through sun-air drying exposure during one month to reduce the moisture contents from (63-70 % wt.) to (10-20 % wt.), as reported by Oliveros-Tascón et al. (2017). Natural drying of the biomass is possible due to the poor hygroscopic characteristics of the coffee stems and the weather conditions in the Colombian coffee regions, as Romo-Ortega et al. (Romo Ortega et al. 2011) indicate. Next, the coffee stems are cut in a wood chipper (approximate throughput of 0.75 ton/hr) to achieve an average uniform chip size of 2 cm, following specifications reported by Oliveros et al. (2017).

The gasification stage itself comprises three steps representing the main phases inside a real downdraft gasifier operation. Figure 12 schematises the simulation procedure followed by Aspen Plus for these stages.

Biomass drying stage: the biomass moisture content is reduced up to the level required for downdraft gasifiers (<10% MC) (Basu 2013b) using a stoichiometric-based reactor (RSTOIC unit block) and assuming that previously the coffee stems have been exposed to sun drying to reduce its moisture content from 25% wt. to 10-15% wt. (Oliveros-Tascón et al. 2017). A *FORTRAN* subroutine is used in this stage to determine the fractional conversion of biomass to water, by indicating the moisture content of the wet biomass stream and the desired MC of the dry-biomass stream. The stoichiometric reactor is modelled as isobaric (at atmospheric pressure) and adiabatic. After the drying reactor unit, a flash unit is used to separate the dry-biomass stream from the moisture removed.

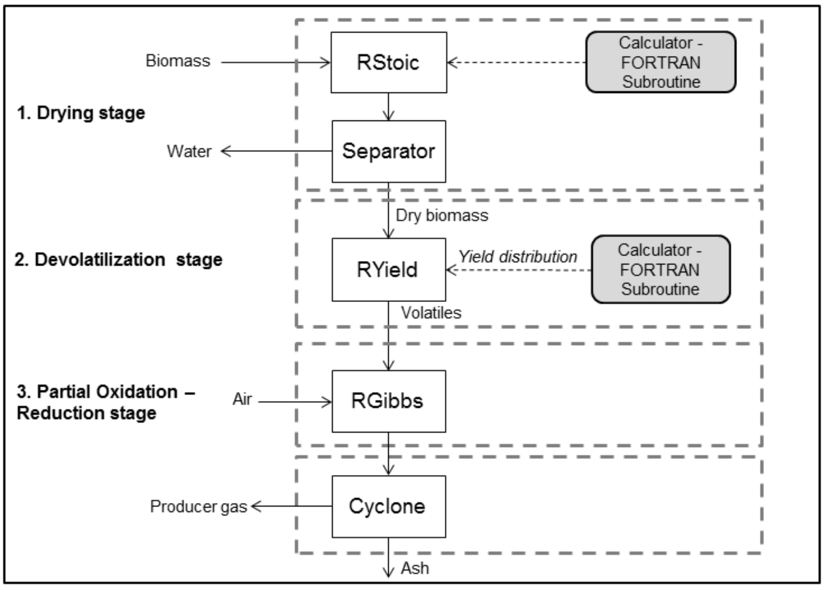


Figure 12. Aspen Plus simulation procedure for biomass gasification model.

Biomass decomposition (devolatilization): the dry-biomass stream, modelled as a non-conventional solid, is decomposed into its volatile components, with a reactor based on specific yields (RYIELD unit block). At this stage, it is assumed that 5% of the carbon mass fraction from the decomposed biomass stream is separated and then mixed back with the raw producer gas (Vera et al. 2013), to account for a portion of char not converted in the partial oxidation-gasification zone.

The biomass yield distribution into its volatiles components (i.e. carbon, hydrogen, nitrogen, oxygen and sulphur) is calculated with another FORTRAN subroutine, based on the biomass ultimate and proximate analysis. This subroutine gives the flexibility to change and evaluate different biomass composition.

Partial oxidation – Gasification: in the last stage, the partial combustion and gasification zone is modelled using a Gibbs reactor block (RGIBBS), which follows the Gibbs free energy minimisation approach. At this stage, air acting as the gasifying agent enters the reactor with the flow rate determined by the equivalence ratio specified in section 4.2.1.

Tar concentration in the producer gas

The presence of tar in the syngas is a significant problem of operability for many gasifiers systems. Therefore, certain measures have been proposed to minimise potential fouling of the downstream equipment due to tar concentration:

1. Selection of a downdraft gasifier: This technology produces a gas with low tar concentration (0.015-0.5 g Nm^{-3}), suitable for operating gasifiers coupled to internal combustion engines (Basu 2013b; Kirkels and Verbong 2011).
2. Preliminary design of the gas clean-up stage: this system can reduce the remaining tar and particle concentration in the producer gas. This configuration has proven to be reliable and highly efficient for small-scale fixed bed gasifiers (Hasler and Nussbaumer 1999; Woolcock and Brown 2013).
3. The preheating of the gasifying air to increase the temperature in the gasifier enhances the effectiveness of tar cracking, in addition to increasing the LHV of the producer gas (Raman et al. 2013)
4. Plan for cleaning and removal of tar deposits during daily shutdowns of the gasifier

4.2.5 Downstream stages of gasification plant: gas cleaning and power generation

For the completeness of the evaluation of the process performance of a real biomass gasification plant, the downstream gas conditioning (incl. cooling and cleaning) and producer gas combustion stages are modelled and simulated using *Aspen Plus V10 software.* Figure 13 shows the process flow diagram in Aspen Plus for the gas conditioning and coupling to the engine for power generation.

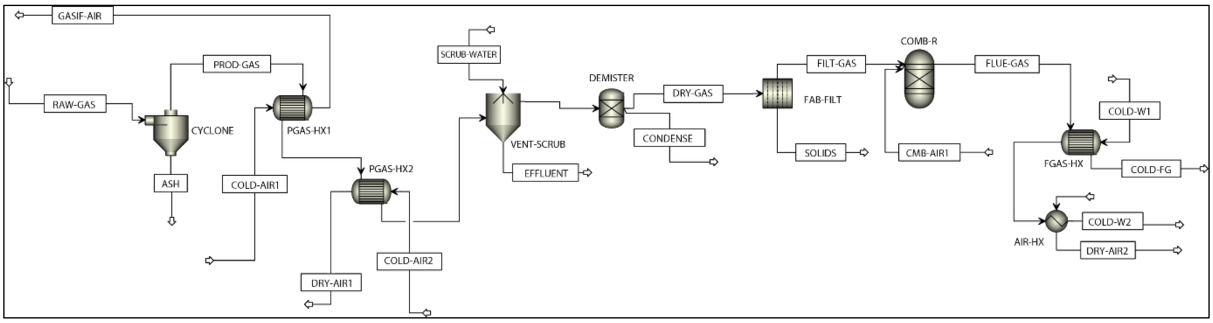


Figure 13. Process flow diagram of gas conditioning stage and coupling to ICE unit.

Description of gas clean-up stage

Section 3.3 reviewed the main gas clean-up technologies for biomass gasification applications. This process modelling adopted the cold gas clean-up configuration due to its suitability for small-scale applications and the characteristics of a producer gas from downdraft gasifiers. This producer gas can exhibit temperatures of ~400 °C (attainable after gas cooling) and low tar content concentrations (0.015-0.5 g/Nm^{-3}) (Heidenreich and Foscolo 2015; Ahrenfeldt, Bain, van de Beld, et al. 2005; Woolcock and Brown 2013). Cold gas clean-up systems have proven to be reliable and highly efficient for gasification systems, at the expense of thermal penalties from cooling the producer gas and increasing operation costs from an effluent treatment plant (Woolcock and Brown 2013).

The cold-gas clean-up configuration proposed in this research comprises a cyclone, *venturi* scrubber and a set of fabric filters, as illustrated in Figure 12. The producer gas exiting the gasifier at temperatures 651 °C enters the cyclone separator to remove particulates of d > 10 µm size with a removal efficiency of 85-95% (Sinnot 2005; Hasler and Nussbaumer 1999). The entrance diameter of the cyclone is calculated using the gas volumetric flow and an optimum gas inlet velocity of 15 m·s^{-1}. The other dimensions of the cyclone are determined as a function of this diameter, following the dimensions of Stairmand high-efficiency cyclones (Sinnot 2005).

After passing through the cooling stage, the producer gas enters the venturi scrubber where water is supplied into the venturi throat to capture smaller particulates (d > 0.5 µm) and tars. At this stage, the gas temperature is reduced to 40.4 ˚C. The water flow required as input into the scrubber is calculated using the gas volumetric flow and the optimum liquid-to-gas ratio (1 m^3 per 1000 m^3) for venturi scrubbers. The liquid effluent is treated in a water treatment plant; these facilities are also commonly required in coffee processing plants to treat other effluents generate during coffee washing. Finally, the producer gas enters a demister to remove the condensed water and then passes through a fabric bag filter that complements the gas cleaning by removing particulates of (d > 0.2 µm) and tar, before it enters the engine.

Table 7 collates the main design factors and process parameters of the cold gas clean-up system of the gasification plant. More details on the methods for sizing the gas cleaning components are found in Perry et al. (1997) and Sinnot (2005).

Table 7. Process parameters for cold gas clean-up system (d=particle diameter).

Plant unit	Design–Process parameters	Value
Cyclone separator	Gas volume flow	260 m^3/hr
	Optimum gas inlet velocity	15 m/s
	Entrance cyclone diameter	Dc = 0.218 m
	Removal efficiency	Particle separation: 85-95% (d > 10 µm)
		Tar separation: 60% (Hasler and Nussbaumer 1999)
Venturi water scrubber	Gas volume flow	95.7 m^3/hr
	Liquid-to-gas ratio	1 m^3 per 1000 m^3 *optimum design rate* (Sinnot 2005))
	Liquid volume flow	0.092 m^3 hr^{-1}
	T_{in} / T_{out} of producer gas	110 °C / 40 °C
	Removal efficiency	Particle separation: 99% (d > 0.5 µm)
		Tar reduction range: 50-90% (Hasler and Nussbaumer 1999)
Fabric filter	Operation Temperature	40 °C
	Removal efficiency	Particle separation: 99% (d > 0.2 µm) (Sinnot 2005)
		Tar reduction: 70%

Cooling stages of producer gas and flue gas

Gas cooling stages are used to reduce the temperature of the producer gas and flue gas in order to meet process requirements. The low-grade heat recovered from these stages can potentially supply the internal and/or external heat energy demands. Particularly for small-scale biomass applications, where the electrical efficiencies are low, a maximisation of on-site heat utilisation is essential to achieve higher energy efficiency and economic profitability (Fendt et al. 2012).

In this gasification-ICE system, as Figure 13 illustrates, the cooling stages consist of two consecutive gas-air heat exchangers to cool down the producer gas, and a second heat-exchanger to reduce the temperature of the flue gas, from the producer gas combustion. The first cooling stage reduces the temperature of the producer gas to meet temperature specifications of the gas clean-up equipment and gas engine. The first heat exchanger (PGAS-HX1) cools down the producer gas from 792 °C to 699 °C, and this sensible heat is used to preheat the gasifying air up to 250 °C. The effect of pre-heating the gasifying air is evaluated in the sensitivity analysis of the process modelling (Section 5.2.2).

The second heat exchanger (PGAS-HX2) continues decreasing the producer gas temperature to 120 °C. The recovered heat duty is used to heat up an airstream with a potential application in the coffee bean drying stage. The airflow rate is set to 31 m^3/min to obtain an air temperature between 48-50 °C; following optimum operating parameters in stationary coffee air-dryers (Roa-Mejía et al. 2000). Similar applications of gas-cooling systems in small-scale gasification plants were reviewed (Perez et al. 2015); hence, the shell-tube heat exchanger configuration could use stainless steel tubes materials.

The second cooling stage water cools the flue gas from the producer gas combustion with a concentric tubes heat exchanger (FGAS-HX) to a temperature of 120 °C. This step is required to meet environmental regulations regarding airborne emissions (EPA 2017) and prevent corrosive effects from condensation in the exhaust piping. The hot water is used in a second concentric tubes heat exchanger (AIR-HX) to heat up an airstream for the coffee drying process, following the parameters described above. A suitable material for these heat exchangers is steel, considering the water temperature could be maintained below the boiling point.

Both heat exchangers loops are simulated with *Aspen Plus* to estimate the maximum recoverable heat duty for each cooling stage. This heat exchanger configuration for downdraft gasifiers plants is supported on the work of Raman et al. (2013).

Internal Combustion Engine (ICE) sizing and producer gas combustion modelling

Small-scale internal combustion engines are a technical and economically feasible option for distributed energy generation. They can provide low capital costs, reliability, high operating efficiency, modularity and safety in comparison to other combustion technologies (Hagos et al. 2014). Producer gas with calorific values higher than 4 MJ/Nm^3 and low pollutant contents can be directly injected in ICE (Molino et al. 2016; Hagos et al. 2014).

The engine, however, will suffer a power derating, in the order of 20-30% of the power output (Perez et al. 2015), due to the characteristics of the biomass-based product gas. The power derating will depend on the fuel ratio and on the level of adaptions made to the engine (Indrawan et al. 2017). Therefore, this research accounts for the degrading of the producer gas engine performance, when calculating the net power output of the system. It is also acknowledged that spark-ignition engines currently designed to work with gasoline or diesel, require adaptations in the injection systems to be fuelled with 100% producer gas (Perez et al. 2015; Molino et al. 2016), yet further analysis of the technical performance of these engines were outside the scope of this research. The technical specifications of a four-cylinder internal combustion engine with a power rating of 25 kW are detailed in Appendix B.

The combustion phase of the engine is simulated with *Aspen Plus*, following a Gibbs minimization approach, to calculate the flue gas composition and temperature when the system reaches chemical and phase equilibrium. The outlet temperature of the exhaust gases sets the maximum thermal energy recovery from the flue gases. The mechanical system of the engine was not modelled; instead, an electrical efficiency of 30% is assumed to calculate the gross electrical power output of the system, accounting also for an additional 20% for the power derating.

4.2.6 Model validation and sensitivity analysis approach

This section describes the approach to validate the simulation results of the biomass gasification model with experimental data and the description of the sensitivity analysis conducted to evaluate the effect of key gasification parameters on the product gas composition and heating value.

Model validation with experimental data

The simulation results were validated with the experimental data reported by Oliveros-Tascón et al. (2017). The data (i.e. producer gas composition and yield) were obtained from pilot experiments conducted with a 20 kW_e commercial downdraft gasifier unit using coffee stems chips. This facility is located in Cenicafe, a national coffee research centre in Colombia. Other scholars in Colombia (García et al. 2017; C. García et al. 2018) have also presented experimental results from the gasification of coffee stems for different applications. A second dataset was also utilised with the experimental results reported by Garcia et al. (C. A. García et al. 2018).

For the validation procedure, the simulation in *Aspen Plus* reproduced a minimum of input conditions from the original experimental set-up, i.e. the fuel characteristics (biomass proximate and ultimate analysis) and the gasifier operating parameters. The output variables for the model validation were the producer gas composition, with its main components: H_2, CO, CO_2, CH_4, N_2 and H_2O, the gasification temperature and the gas yield (i.e.amount of gas produced per biomass fed into the system). From the product gas composition, the calorific value, the cold and hot gas efficiency were also determined and compared with the experimental data.

The predicted and experimental data were compared by calculating the absolute error and relative error (%) between each pair set of data, using equations 12 and 13:

$$\boldsymbol{Absolute\ error} = \boldsymbol{Exp, result} - \boldsymbol{Sim\ , result} \quad \text{Equation 12}$$

$$\textbf{Relative error}\ (\%) = \frac{|\textbf{absolute error}|}{\textbf{Exp result}} \times \mathbf{100} \quad \text{Equation 13}$$

where *Exp* is the value of the experimental results and *Sim* the value of the simulated result.

Sensitivity analysis

A sensitivity analysis was conducted to examine the effect of key gasification parameters on the producer gas composition and temperature at the exit of the gasifier, and subsequently on the gas LHV and the cold-gas efficiency, as a parameter of the gasification efficiency. The parameters were the biomass moisture content, the equivalence ratio (ER) and the air preheating temperature.

The moisture content (MC) is one of the most challenging biomass properties in the performance of thermo-chemical processes. The MC values were set between 10-60 %wt., typical of woody biomass compositions (Basu 2013a). The equivalence ratio (ER) also affects the gasifier performance by determining the gasification temperature and having a significant influence on the final gas heating value. The ER is varied within realistic conditions for gasification systems, between 0.1–0.5. Finally, the temperature of the gasifying air was also evaluated with the purpose of analyzing how the pre-heating of the air improves the gasification conversion efficiency by increasing the concentration of the combustible gases (CO and H_2), hence increasing the gas heating value (Doherty et al. 2009). The air preheating temperature ranges from 25 to 400 °C.

Finally, a model extrapolation was carried out to evaluate the capability of the model to predict effectively results for input data that fall outside the region of the baseline data set, by using the feedstock composition of other agricultural residues. In the case of non-linear behaviours from the model, then the one linear rule will be used for extrapolation of the model values outside the operating range (Roffel and Betlem 2006). In this stage, the model input parameters required further adjustment for a biomass feedstock with a different composition.

4.3 Methodology for Lifecycle Assessment

This section introduces the lifecycle assessment methodology followed to attain the third objective, aiming to evaluate the potential environmental impacts of deploying coffee stems gasification systems for power and heat generation. Overall, this section covers the LCA principles and framework and how these were applied in the context of this research.

4.3.1 LCA rationale in the research context

Evaluating the environmental performance of bioenergy systems is an essential component to realise the feasibility of these systems in a determined context. Therefore, the application of LCA has extended in the bioenergy field (McManus and Taylor 2017), as a useful and well-established modelling tool that determines the environmental impacts of the system's lifecycle.

The LCA component in the context of this research provided, besides the potential environmental impacts, valuable insights into drivers and trade-offs when comparing the bioenergy system's performance with a range of potential counterfactuals. Other scholars have also highlighted the applicability of LCA for researching the bioenergy development in Colombia. Gonzalez-Salazar et al. (2016) in the bioenergy technology roadmap for Colombia, suggests that further research is required focussing on LCA of GHG emissions associated with different bioenergy technologies. This LCA, however, goes beyond GHG emissions and their impact on climate change and examines other impact categories to gain a wider understanding of the environmental feasibility.

4.3.2 LCA methodology: framework and guidelines

LCA is a technique used to identify, quantify and evaluate existing environmental aspects, and potential environmental impacts that a product generates throughout the entire lifecycle, from raw material acquisition to final disposal (ISO 14040 2006). LCA application to a system can help identify opportunities for improving the environmental performance along the lifecycle, provide information to key stakeholders for decision making, select environmental performance indicators and for marketing purposes (ISO 14040 2006).

The LCA methodology has been internationally standardised by the International Organization for Standardization, through the standards ISO 14040 (Principles and framework of LCA) and the derivatives: ISO 14041, ISO 14042, ISO 14043 and ISO 14044. The LCA methodology comprises four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 14 shows a diagram of the LCA framework and how these stages are related between each other.

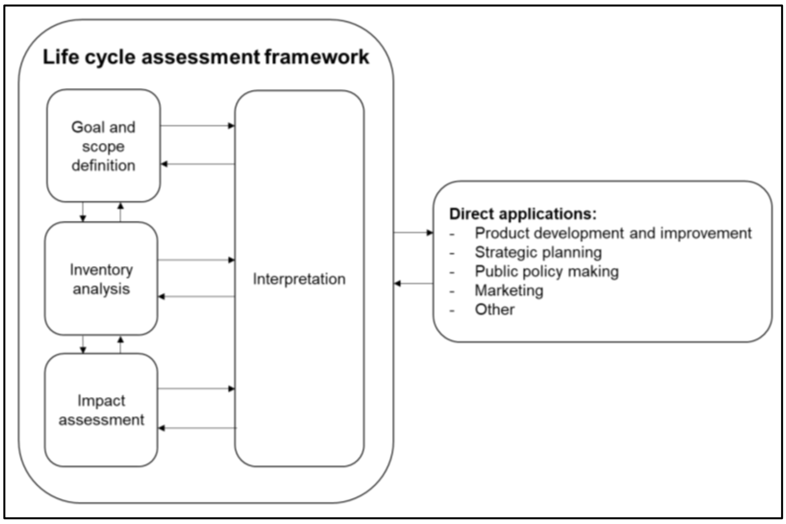


Figure 14. Stages of an LCA framework.

Goal and scope definition

It is the initial stage, where the goal is established, implying a clear and consistent definition of the intended application, audience, and rationale behind the LCA study (BSi and ISO 14044 2006). The definition of the scope entails describing the system and its functions, the functional unit (i.e. comparison basis), the boundaries of the system, and the time and geographical frame of the study (ISO 14040 2006). At this stage, the assumptions and limitations of the study are established, as well as, data quality requirements, the methodology for the lifecycle impact assessment and the allocation procedure, when necessary.

The **functional unit** is the quantified performance of a product system for use as a reference unit (ISO 14040 2006). It should be measurable and consistent with the objectives of the study (Patel et al. 2016; BSi and ISO 14044 2006). After selecting the functional unit, the reference flow is defined. This one relates to the quantified amount of product(s) required by the system or process to deliver the performance indicated by the functional unit. The **system boundary** delimits the unit processes included within the LCA study, and the inputs and outputs to and from the unit processes and their interrelationships, ideally using a process flow diagram. The main type of inputs and outputs of a system are flows of materials (raw and processed), energy and emissions. This stage should state the criteria to determine the system boundaries and the level of detail of the LCA.

The LCA system boundary of a bioenergy system generally encompasses four phases, as Figure 15 illustrates.

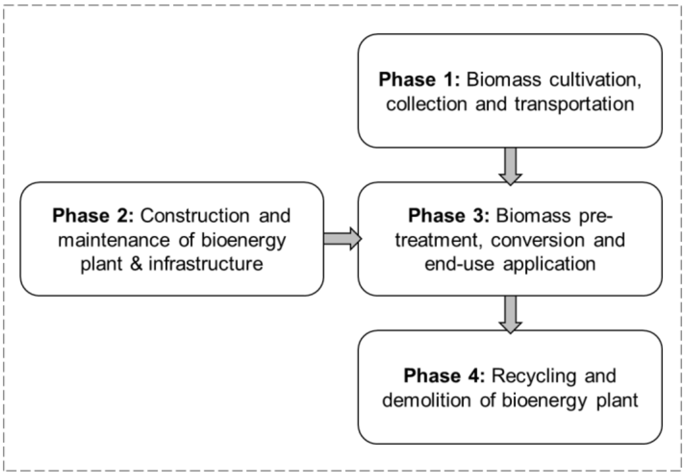


Figure 15. Generalised system boundaries of an LCA study to a bioenergy system
Modified from (Patel et al. 2016)

Lifecycle Inventory (LCI) analysis

It is the second LCA stage and involves the collection and calculation of the data required to quantify relevant inflows and outflows of the unit processes within the system boundary. At this stage, assumptions are made about the lack of data, and the reliability of the assumptions should be evaluated with a sensitivity analysis in the results interpretation phase. Also, in the LCI, the scope of the study is revised, particularly the system boundary at the light of further learning about the data requirements and limitations (ISO 14041 1998).

The **data collection** is the first step of the LCI phase and a resource-intensive task that requires a rigorous documentation process to enable an LCA study. The data is broadly classified as *inputs* in the form of energy, materials, ancillaries, and other physical inputs; *products*, *co-products*, and *waste*; *emissions* to air, water, and soil and *other environmental aspects*. Currently, there are several commercial software that can be used to assist in the data collection and processing, such as SimaPro, GHGenius, GREET (Greenhouse gases, Regulated Emissions and Energy use in Transportation), TEAM (Tools for Environmental Analysis and Management) and GaBi (Patel et al. 2016).

Then follows the **data calculation** involving the validation of the collected data and the correlation of this data to the unit processes and the reference flow of the functional unit. During this task, the documentation of the procedure and assumptions is also important, aiming to maintain the same procedure throughout the study for consistency (ISO 14040 2006; BSi and ISO 14044 2006).

Finally, when the system under study delivers more than one product, an **allocation procedure** has to be established and documented at this stage. The allocation of the collected data between the different products has to reflect the input-output relationships and their degree of contribution to the environmental impacts of the system. When several allocation methods are applicable, a sensitivity analysis should be conducted to evaluate the consequences of the decision on the results (ISO 14040 2006; ISO 14041 1998). The allocation procedure applied in this LCA is discussed in section 4.3.4.

Lifecycle Impact Assessment (LCIA)

In this stage, the magnitude and significance of the potential environmental impacts of the system are evaluated using the data from the LCI stage (ISO 14040 2006). Therefore, this involves associating the LCI data with specific environmental impact categories and indicators. This stage comprises three obligatory tasks: the selection of impact categories, category indicators, and characterisation models; classification and characterisation.

The **classification** step entails the assignment of the elementary flows from the LCI results to the selected impact categories considering the potential of the substances to cause different environmental problems (BSi and ISO 14044 2006; Goedkoop et al. 2016). Next, the **characterisation** step calculates the category indicator results. It involves the conversion of the inventory results, using characterisation factors, to common units and the aggregation of the converted results within the same impact category.

There are optional elements that can support the LCIA and simplify the interpretation of the results: The **normalisation** allows comparing the relative magnitude and significance of the impact category indicator, by dividing the category indicator results by reference value. Generally, the reference value refers to the number of emissions or discharges generated by a country or region, during a specific period (Goedkoop et al. 2016; ISO 14042 2000). In the **grouping** step, the impact categories are assigned into one or more sets; this could involve arranging the impact categories on a nominal basis or rank the impact categories in a given hierarchy. The **weighting** element consists of the conversion of the indicator results of different impact categories by assigning numerical factors (or weights) based on value choices (ISO 14042 2000). This step is very subjective to the selection of the value-choice and is not recommend in the ISO standards when the comparative results are disclosed to the public (Goedkoop et al. 2016).

Lifecycle Impact Assessment Methodologies

The lifecycle impact assessment methods (LCIAM) are environmental modelling-based tools used to interpret, classify and transform the lifecycle inventory results of a product or service into understandable and measurable environmental impacts. These methods are developed to comply with the basic structure of the LCIA phase, where the classification and characterisation steps are mandatories (BSi and ISO 14044 2006).

The lifecycle impact category methods are broadly categorised by their characterisation approach, as mid-point or end-point based approach methods. The end-point level methods (damaged-oriented approach) link the inventory results through a specific environmental mechanism to an endpoint category or area of protection (Goedkoop et al. 2016). This end-point approach can provide better information on the environmental relevance, at the expense of higher uncertainties on the results, as they involve more than one environmental mechanism (Huijbregts et al. 2017).

The mid-point level methods (problem-oriented approach) link the inventory results to an indicator somewhere in the middle of the cause-effect chain, before the end-point category (Goedkoop et al. 2016). Methods using a mid-point characterisation approach have a stronger relationship with the environmental flows, carrying less uncertainty, as the inventory results are closer to the environmental mechanism (Huijbregts et al. 2017).

Results interpretation

The final phase consists in the interpretation and discussion of the results from the LCI and LCIA stages while revising that findings are consistent and appropriate with the goal and scope, and with the limitations identified by the data quality assessment and sensitivity analysis (ISO 14043 2000). This phase consists of three main steps:

1. Identification of the significant issues of the LCI and LCIA phases: the purpose of this step is to organize the LCI and LCIA results to help to determine the significant issues of these phases, taking into account the defined goal and scope definition and the following results interpretation step.

2. Evaluation to examine the consistency, completeness and sensitivity of the study: this step aims to demonstrate and enhance the reliability of the methodology and results from the LCI and LCIA phases. Hence, a series of checks for completeness, sensitivity and consistency are conducted, also using the significant issues identified in the first step. This step complements the data quality analysis and the uncertainty analysis.

3. Presentation of the conclusions, recommendations and limitations of the study: the final step intends to establish conclusions, identify limitations and propose recommendations for the intended application of the LCA study, on a collectively and iteratively manner with the other steps (ISO 14043 2000).

4.3.3 Application of LCA methodology in this research

After introducing the LCA methodology, the following section presents the application of this method in the context of this research. However, the complete LCA development, including the four main stages, is covered in chapter 6.

LCA modelling framework

This LCA aims to answer the question: *"what environmental impacts can be attributed to the construction and operation of the coffee stems gasification system for power and heat generation?"* applying an attributional LCA. This perspective was the most adequate to answer similar questions for the baseline system (and counterfactuals), allowing both systems comparisons. Additionally, the attributional perspective supports the comparison between systems of equal functional units (Goedkoop et al. 2016). This is the case for the bioenergy system and counterfactuals, with the final purpose of calculating the net environmental impacts of the bioenergy scenario through a comparative LCIA.

This attributional perspective supported the assessment of multifunctional processes and provided a suitable approach for the lifecycle impact assessment. It also supported using average processes in the background data of the LCI, those that represent a global market, whether for producing raw materials or generating electricity (Hauschild et al. 2011).

An attributional framework offers two procedures to manage multifunctional systems, allocation or system expansion, the first one was chosen following the guidelines of ISO standards, and the selection is described in section 4.3.4. Additionally, a midpoint-level method was selected for the LCIA stage as it provides information about the environmental performance of a system with a higher level of scientific consensus (Goedkoop et al. 2016). As the mid-point approach models less environmental mechanisms, it carries on less uncertainty on the results method (Cherubini and Strømman 2011).

LCA Software

The description of the LCA stages showed that some of these tasks are resource and time-intensive, particularly in the LCI and LCIA that require data collection, processing, and analysis. Using an LCA software can facilitate this work; however, they can also raise issues on data uncertainty and black-box model limitations, which have to be considered. Most of the software packages are designed to help the user carry out the data inventory of the product and/or process, to then allocate the inflows and outflows of material, energy, emissions and disposals to a common basis or functional unit (Rice et al. 1997).

The features, products and services of LCA software can vary depending on the scope and intended customers, yet the overall advantages of using an LCA software are:

- Structured platform to represent the LCA phases, enabling compliance with the ISO standards.
- Assists data collection with comprehensive inbuilt databases for the more commonly used materials, processes, products and equipment
- Supports easier and more efficient processing and calculation of large amounts of data
- Facilitates using and comparing different LCIA methodologies
- Provides a graphical interface that enables results interpretation and the elaboration of reports

On the other hand, using LCA software has certain drawbacks. Some of these were identified in (McManus 2002) and complemented with the author's experience using an LCA software:

- Data in the inbuilt-databases can be connected to seemingly hidden data that is sometimes ignored by the LCA practitioner. This creates a *black-box* model issue as the user has none or minimum control of what happens between the inputs and outputs of the LCA.
- Issues with data quality and accuracy are also related to the *black-box* model issue since data could not be representative of the geographical and time-frame of the study. European and North American companies have developed the majority of this software, which has led to insufficient reliable data from countries outside these areas.
- The relative easiness and flexibility of conducting an LCA with software could potentially lead to inappropriate selection of the supporting methods and interpretation of the results. This could happen if the person lacks experience in LCA and has a poor understanding of the process or product.

After balancing the advantages and drawbacks of using an LCA software, and gathering insights of researchers on the helpfulness of using a software, this LCA was developed with the assistance of software. However, it was taken into consideration potential limitations that could arise, particularly when conducting an LCA on a bioenergy system in the context of the Colombian coffee sector.

Selection of LCA software

The selection of the LCA software was carried out after a revision of features, pros and cons of different software alternatives that have been used by scholars in the bioenergy research field. Among the different software options, SimaPro was selected to facilitate carrying out the

LCA. This software stands out among other options by featuring several advantages, such as a good interface for the graphical representation of the impact assessment phase, adaptability, easy to use, and a range of options for the LCIA methods. SimaPro was also identified as the most commonly used software package within the cluster of revised papers on LCA of bioenergy systems, supporting the selection of this modelling tool. Additionally, this software had a licence available for researchers at the Tyndall Centre for Climate Change Research of the University of Manchester.

SimaPro was used to assist in the data collection and calculation in the LCI stage and for the classification and characterisation tasks of the LCIA stage. The analyst and single-user SimaPro version 8.5 was used, having also available the databases from Ecoinvent, Agri-footprint, US Life Cycle Inventory database and Swiss Input/Output database, which are examined in the next section.

4.3.4 Approach to LCI: data collection and multifunctional systems

One of the most resource-demanding tasks in an LCA is the data collection. This data can be obtained from different sources: the regular operation of a process, during laboratory experiments, pilot tests, process modelling, databases, and scientific and grey literature.

The majority of the foreground data for this LCA, known as the specific data required to model the system (Goedkoop et al. 2016), was obtained from the mass and energy balances of the biomass gasification-CHP plant process simulation. The inventory was complemented with background data, comprising datasets for the production of generic materials, energy streams, transport, infrastructure and waste management (Goedkoop et al. 2016). For this research, the database *Ecoinvent* version 3.3, available in the SimaPro 8.5 package, was used to obtain the secondary data of the bioenergy and reference systems. The additional information was obtained, from literature, specifically from scientific and policy-related reports from Colombia to represent the geographical context of this study.

Ecoinvent is considered one of the most comprehensive and worldwide used lifecycle inventory background database. The main characteristics of this database (ETH Domain and Swiss Federal Offices 2018) are:

- Comprehensive datasets for the whole lifecycle of a product or service
- Datasets cover all relevant environmental flows
- Data is structured at a unit process[2] level, ensuring transparency over the supply chain.

[2] The unit process (UPR) is the smallest element considered in the lifecycle inventory analysis for which input and output data are quantified (ISO 14040 2006)

When the information in the Ecoinvent database did not represent the nature of a product with a particular geographical location, a new unit process (UPR) was created. A new UPR record was created in Simapro to represent the Colombian electricity mix by combining the shares of electricity generation by fuel sources. The “Electricity by fuel” data from *Ecoinvent* was used to create this input, and it is described in Appendix C.

Managing multifunctional systems in LCA using ISO guidelines

A multifunctional system can deliver more than one product and/or function, as the coffee stems-gasification CHP system. These systems are considered a methodological challenge in LCA, in principle, designed to evaluate individual product systems that deliver one primary function and its associated environmental impacts (Hauschild et al. 2011). To solve *multifunctionality* issues, the ISO 14044 standard (BSi and ISO 14044 2006) recommends a set of hierarchical steps to account for and evaluate the effect of a system’s multiple functions over potential environmental impacts. This ISO hierarchy was schematised by Hauschild et al. (2011) in a decision tree and is presented in Figure 16.

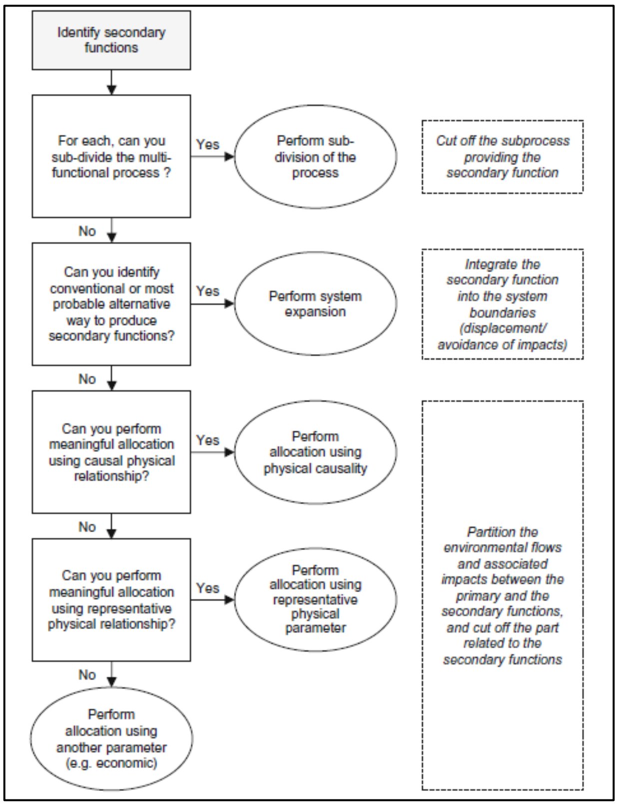


Figure 16. Decision tree to solve multifunctionality based on ISO hierarchy
Source: (Hauschild et al. 2011)

In the decision tree, the first option (*subdivision of unit process*) is to divide the multifunctional unit process into minor units, separate the production of the first product from the second one and exclude the subprocesses providing the additional functions from the product system.

This step is not feasible in many cases since it is very difficult to physically subdivide the unit processes of a system.

The second option (*system expansion*) consists of expanding the system to integrate the secondary function into the system boundaries, which is also equivalent to crediting for avoiding the production of secondary function with an alternative system. This approach is generally used when accounting for secondary function in a hotspot analysis when not comparing two alternative systems (Hauschild et al. 2011) and are more associated with consequential modelling (Goedkoop et al. 2016).

When system expansion is not possible, the options that follow entails the *allocation* of the environmental flows and associated impacts between the system products. According to ISO standards, the allocation should be performed, in order of preference, applying a physical causality, a representative physical parameter and finally using another parameter, such as an economic revenue (Goedkoop et al. 2016).

This ISO standard-based decision tree was used as a guideline to select the most suitable approach for managing the two energy outputs of the coffee stems gasification-CHP plant, considering the nature and context of this bioenergy system. This is later discussed in Section 6.1 in the goal and scope section of the LCA.

4.3.5 Lifecycle Impact Assessment

This section covers; first, a comprehensive LCIA of the coffee stems gasification ICE/CHP plant construction and operation (from a cradle-to-gate). Secondly, it encompasses a comparative- environmental impact assessment of the bioenergy scenario with baseline and potential counterfactual scenarios to evaluate net environmental impacts.

As part of the obligatory elements of an LCIA (ISO 14042 2000), the *classification* and *characterisation* steps are carried out to determine the category indicator results for the defined impact categories. These steps were followed for each bioenergy and reference systems under study.

The impact categories addressed in this LCIA are all relevant for an environmental sustainability assessment of a bioenergy system (Patel et al. 2016). The categories included were climate change; fossil fuel and metal depletion; particulate matter formation; photochemical oxidant formation; human toxicity; freshwater and terrestrial ecotoxicity; freshwater eutrophication and terrestrial acidification.

Other impact categories related to land-use, land transformation, ionizing radiation, marine eutrophication and marine ecotoxicity were outside the scope of this LCA study. These impact categories do not address environmental issues that have been caused directly by the construction and operation of the coffee stems gasification-ICE/CHP system (i.e. ionising radiation) or otherwise could have marginal influence over them. Since coffee stems are treated as agricultural residues, potential impacts on the direct use or transformation of land are not associated with this residue, nor environmental impacts related to the coffee cultivation. Furthermore, the geographical location of coffee farms in mountainous regions far from coastal areas, suggest that coffee residues local utilisation would not impact marine ecosystems.

Selection of lifecycle impact assessment method (LCIAM)

The selection of the LCIAM requires identifying the most relevant environmental issues associated with the product system (Goedkoop et al. 2016). Furthermore, the approach followed in conducting the lifecycle impact assessment guided the selection of the LCIAM, which for this case, was an LCA mid-point level method. The environmental assessment of the coffee stems gasification system and counterfactuals required a method with a comprehensive and updated set of impact categories to account for air, soil and water emissions; and resources depletion. Furthermore, considering the geographical scope of this LCA, a method with a global scale was more suitable for the nature of this assessment.

For the selection of the LCIAM, the above aspects were considered and the available methods in Simapro reviewed, considering their main advantages and limitations (Appendix E includes a table collating this information). A short-list was produced that included the most comprehensive and recently revised mid-point methods: *CML-IA (2016 version)*, *ReCIPE (version 2016)* and *ILCD 2011 Midpoint+*. Following this, the *CML-IA* method was ruled out since it excludes the particulate matter and land use impact categories, and has, instead, a European-based scale (Pre Sustainability 2016). Principally, the particulate matter category was essential for evaluating the bioenergy system against the counterfactual scenarios that displace traditional biomass practices, i.e. cookstoves and open-burnings.

The ReCIPE 2016 method developed in 2008 by the cooperation between RIVM[3], Radboud University Nijmegen, Leiden University and Pré Consultants (Huijbregts et al. 2017), was chosen over the *ILCD 2011 Midpoint+*. The ReCIPE method features a more recently updated methodology with the latest version released in 2016 and covers a wider range of characterisation factors. This method also provides the flexibility to interpret the lifecycle

[3] RIVM stands for National Institute for Public Health and the Environment in Dutch

impact assessment results under either a problem or a damage-oriented approach. The global scale feature of ReCIPE reinforced the selection of this method, having characterisation factors with studies representing a wider international context. Furthermore, similar LCA works on biomass (including wood-type residues and crop residues) gasification have used ReCIPE method for the impact assessment phase which supported the selection of this method (Adams and McManus 2014; Boschiero et al. 2016; González-García and Bacenetti 2019).

ReCIPE method

This method was conceived to integrate two LCIA methods, a damage-oriented approach method, Eco-Indicator 99 and a problem-oriented approach method, CML-IA. The latest version of the method was released in 2016. It comprises 18 midpoint impact categories that can be converted into three endpoint characterisation factors (i.e. Human health, Ecosystems and Resource scarcity), by multiplying the characterisation factor by a damage factor.

The ReCIPE also comprises in its structure a categorization that groups similar types of assumptions and value choices into three different perspectives, *Individualistic* (I), *Hierarchist* (H) and *Egalitarian* (E). This LCA uses the hierarchist (H) perspective, as the most accepted by scientific and policy guidelines with regard to the period and plausibility of impact mechanisms.

Characterisation factors in ReCIPE

The characterisation factors (CF) are used to convert the elementary flows of the LCI into individual impact category indicators results. The CFs are determined by the impact assessment method, and ReCIPE uses the equivalency factors dictated by the IPCC fifth assessment report (2013). Table 8 summarises and describes the impact categories covered in this LCA and the characterisation factors at the mid-point level (CFm) used by ReCIPE (Huijbregts et al. 2017), using a hierarchist perspective.

Table 8. Impact categories and characterisation factors at the midpoint level
Data from (Huijbregts et al. 2017; EPA 2016; Goedkoop et al. 2016)

Impact Category	Description	Characterisation factor	
Climate change	The CC category represents the heat-trapping capacity of GHGs in the atmosphere. Time Horizon: 100 years	*Global Warming Potential (GWP)I*[4]	CO_2: 1 kg $CO_{2,eq}$/kg
			CH_4: 34 kg $CO_{2,eq}$/kg
			N_2O: 298 kg $CO_{2,eq}$/kg
Fossil Resource Scarcity	The fossil depletion category captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil	*Fossil fuel potential (FFP):*	Crude oil: 1 $oil_{,eq}$/kg
			Natural gas: 0.84 kg $oil_{,eq}$/Nm^3
			Hard coal: 0.42 kg $oil_{,eq}$/kg
			Brown coal - peat: 0.22 kg $oil_{,eq}$/kg

Fine Particulate matter formation (PMF)	PMF category indicates the increase in $PM_{2.5}$ intake by population resulting in negative health impacts. Covers primary and secondary aerosols caused by air pollution.	*Particulate matter formation potential*	$PM_{2.5}$: 1 $PM_{2.5,eq}$/kg
			SO_2: 0.29 $PM_{2.5,eq}$/kg
			NO_X: 0.11 $PM_{2.5,eq}$/kg
			NH_3: 0.24 $PM_{2.5,eq}$/kg
Mineral Resource Scarcity	The Surplus Ore Potential expresses the average extra amount of ore to be produced in the future due to the extraction of 1 kg of a mineral resource.	*Surplus ore potential*	Copper: 1 kg $Cu_{,eq}$/kg
			Aluminium: 0.17 kg $Cu_{,eq}$/kg
			Nickel: 2.9 kg $Cu_{,eq}$/kg
			Manganese: 8.23 kg $Cu_{,eq}$/kg
			Chromium: 0.095 kg $Cu_{,eq}$/kg
			The CF_m for others mineral resources are included in the ReCIPE report (Huijbregts et al. 2017).
Photochemical Oxidant Formation (POF)	The POF potential determines the formation of reactive substances that cause harm to human health and vegetation.	*Photochemical oxidant formation*	NOx: 1 kg $NOx_{,eq}$/kg
			NMVOC: 0.18 kg $NOx_{,eq}$/kg
Human Toxicity	Toxicity categories account for the environmental persistence, accumulation in the human food chain, and toxicity of a chemical. Time Horizon: 100 years	*Human toxicity potential*	Refer to ReCIPE report (Huijbregts et al. 2017) for categorisation factors at midpoint level for toxicity categories.
Terrestrial ecotoxicity		*Terrestrial ecotoxicity. potential*	
Freshwater ecotoxicity		*Freshwater ecotoxicity potential*	
Freshwater Eutrophication (FE)	FE category examines the impacts caused by the excessive discharge of nutrients into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen	*Freshwater eutrophication potential*	P: 1 kg P_{eq} /kg
			PO_4^{3-}: 0.33 kg P_{eq}/kg
Terrestrial Acidification (TA)	TA potential records the acidifying effect of inorganic substances, such as SO_2, NOx, and NH_3, on the soil.	*Terrestrial acidification potential*	SO_2: 1 kg $SO_{2,eq}$/kg
			NO_X: 0.36 kg $SO_{2,eq}$/kg
			NH_3: 1.96 kg $SO_{2,eq}$/kg
Ozone Depletion (OZ)	The OZ potential quantifies the amount of ozone a substance can deplete relative to CFC-11 for a specific time horizon Time horizon: 100 years	*Ozone depletion potential*	CFC-11: 1 kg $CFC\text{-}11_{,eq}$/kg
			CFC-12: 0.59 kg $CFC\text{-}11_{,eq}$/kg
			CFC-113: 0.66 kg $CFC\text{-}11_{,eq}$/kg
			CFC-114: 0.27 kg $CFC\text{-}11_{,eq}$/kg
			CFC-115: 0.061 kg $CFC\text{-}11_{,eq}$/kg
			Halon 1301: 14.1 kg $CFC\text{-}11_{,eq}$/kg
			Halon-1301: 14.1 kg $CFC\text{-}11_{,eq}$/kg
			Halon-1211: 8.8 kg $CFC\text{-}11_{,eq}$/kg
			Halon-2402: 14.4 kg $CFC\text{-}11_{,eq}$/kg
			The midpoint characterisation factors for others ODS are included in the ReCIPE report (Huijbregts et al. 2017)

4.4 Methodology for Techno-economic Assessment

The techno-economic assessment (TEA) addresses the fifth objective of this research aiming to "*evaluate costs and analyse the economic feasibility of deploying small-scale gasification systems of agricultural residues for power and heat generation*".

Therefore this section presents the rationale and scope behind the techno-economic assessment for the coffee stems gasification-PO/CHP system. It also describes the approach followed to estimate the total costs of the bioenergy plant and the selected economic performance indicator.

4.4.1 Rationale and scope of the economic analysis

The TEA aimed to investigate through a suitable set of metrics the economic performance of the coffee stems gasification-PO/CHP plant and analyse the potential economic impacts of producing biomass-based power and low-grade heat at small-scale applications compared to existent systems. This assessment also examines the importance of different costs and operation factors that could potently support, or on the contrary, hinder the competitiveness of the system. Similarly, as with the LCA, experts consulted for a technology roadmap for Colombia recommended performing an economic analysis when deploying novel bioenergy technologies, under the specific Colombian context (Gonzalez-Salazar, Venturini, et al. 2014).

This TEA comprised, first, the estimation of the capital and operation costs of the small-scale gasification plant. The costs were evaluated at a study estimate level and also adjusted to the scale and geographical context of the coffee sector in Colombia. The basic design and scale of the plant's major equipment were sufficient to conduct a high-level costs estimation at a degree level of accuracy that ranges between ±30% (Sinnot 2005; Peters et al. 2003).

The Levelised Cost of Electricity (LCOE) was used as the economic performance metric to assess the economic feasibility of the bioenergy system compared to existent rural energy systems. This indicator was considered suitable given the nature of the system; a small-scale coffee stems gasification to supply the energy demand of coffee farms. Under this contexts, farmers are not expected to generate profits from the electricity and heat production, as no surplus of electricity feeds back to the centralised power system. Instead, coffee farmers and cooperatives acting as energy self-generators and investors could potentially benefit from energy bills savings.

The use of the LCOE allows simple and transparent analysis of the costing components influencing the unitary cost of energy generation (IRENA 2018). Additionally, it helps to compare the unitary cost of electricity delivered by the bioenergy system in contrast to the unitary costs of the current power generation systems in rural areas, whether off-grid diesel-based generation or on-grid generation. Others common discounting methods used on techno-economic assessments, such as the net present value and the internal rate of return were considered unsuitable for the aim of this economic appraisal. In principle, these other metrics are more focused on evaluating potential revenues from the energy generation, in the form of power or heat, which is not the case in this research.

4.4.2 Theoretical framework of the economic analysis

This economic analysis follows a bottom-up approach, with the structure illustrated in Figure 17. The structure of the bottom-up approach used in this techno-economic assessment that starts with a first-level cost estimation of the major process equipment. Then follows the calculation of the total capital costs that include the equipment costs, other fixed capital costs and the working capital costs. The second level of the analysis consists of annualising the capital costs and estimating the annual cost incurred in operation and maintenance of the plant, including the biomass costs. The third-level of the analysis comprises the calculation of the annual electricity generation, using the capacity factor of the plant. Finally, the LCOE is calculated using the annual costs calculated in step 2 and the annual electricity generation from step 3. A detailed explanation of each step is presented later in this chapter.

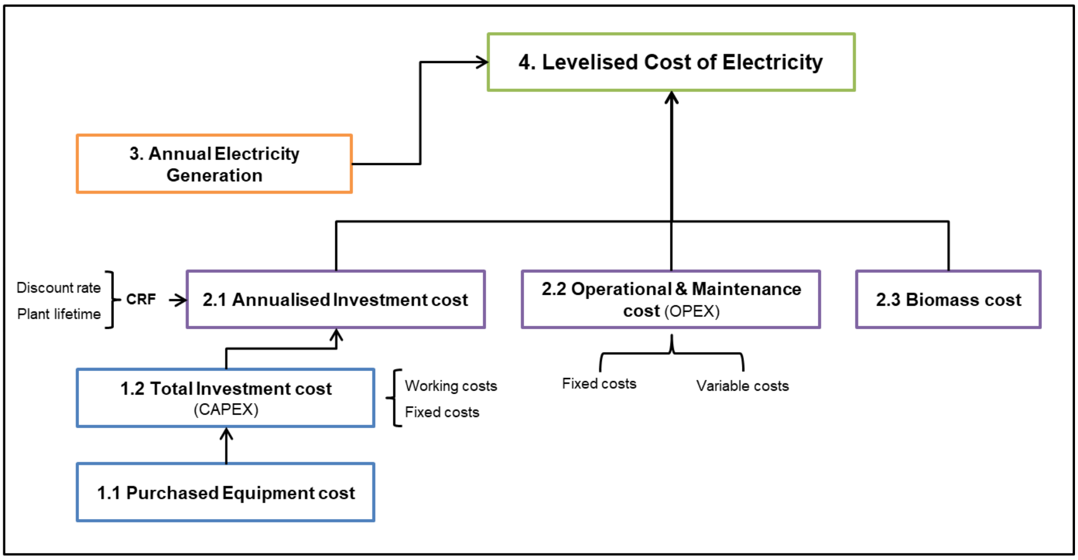


Figure 17. The structure of the bottom-up approach used in this techno-economic assessment

4.4.3 Estimation of the Total Capital Costs: Fixed Capital and Working Capital

The capital investment of a plant is the amount of money required, first, for designing, purchasing, building and installing the plant and the auxiliary facilities, and second, to operate the plant and its facilities (Peters et al. 2003). The capital costs are divided into fixed capital costs and working capital costs. The first one comprises the once-only sum of expenses required to have the plant ready for the start-up; they are also sub-divided into direct fixed cost and indirect fixed costs. The working capital costs are the extra capital, over and above the fixed capital, necessary to start-up and operate the plant until income is earned (Sinnot 2005). The constituent elements of the capital costs are described in the following sections.

Fixed Capital Costs

The fixed capital costs constitute the investment needed to design, construct, purchase and install the process equipment and infrastructure, including auxiliary facilities and utilities for the complete process operation of the plant (Towler and Sinnott 2013a).

Estimation of the Purchased Equipment Costs (PEC)

The purchase of the plant's equipment constitutes one of the major expenses in the capital costs of a plant, representing on average 15-40% of the fixed capital costs and are used as a baseline to estimate other fixed capital costs (Peters et al. 2003; Towler and Sinnott 2013a).

The equipment costs of the biomass gasification–power plant were estimated using catalogues of manufacturers of these technologies, together with the process flow diagram of the whole system that provided detail on the major equipment of the plant (section 4.2). In many cases, however, manufacturers commercialise integrated systems of biomass gasification and power generation units, including the downdraft gasifier, gas-cleaning unit, and power generation set under one cost. Different manufacturers were considered to grasp the overall cost of this technology and to take into consideration other key factors such as transportation costs, maintenance, technical support, and personnel training.

The final selection of the manufacturers and the corresponding equipment costs was made following the technical guidance provided by Dr Carlos Oliveros-Tascon in Colombia. He is the director on postharvest research in Cenicafe (Coffee Research Centre in Colombia), and principal investigator of an experimental pilot project on coffee stems gasification (Oliveros-Tascón et al. 2017). During the research visit held at the facilities of Cenicafe in June 2018, we exchanged knowledge on the potential and challenges of coffee residues utilisation and their conversion through bioenergy conversion through gasification in the coffee sector.

Concerning the equipment costs, Dr Oliveros underlined the experience they have had with All Power Labs, a company that manufactures biomass gasification-power generation platforms with experience in developing projects in the Global South (All Power Labs 2018). The equipment prices supplied by *All Power-Labs* for the downdraft gasifier-power generation set and *Koyote Agroindustries* for the wood chipper, were used as a reference for estimating the main equipment costs and reflect prices used in the Colombian coffee sector.

These prices are considered approximate figures for a TEA at a study estimate level but are accurate enough to evaluate the economic feasibility of this bioenergy system. Table 9 collects the main equipment costs and technical specifications. These prices are within the range of other values reported in the literature for biomass gasification plants of similar capacities (Perez et al. 2015; Fischer and Pigneri 2011; IEA 2015).

Table 9. Major purchased equipment costs of biomass gasification-power generation plant

Plant equipment	Equipment specification	Manufacturer	Equipment reference cost
Woodchipper	**Coyote CK4 chipper:** - Stems of maximum 10 cm in diameter - Motor Launtop diesel 20 HP	*Koyote Agroindustria*	US$ 6,500
Gasification-power generation plant	**PP30 Power Pallet:** includes downdraft gasifier (multistage heat recycling), gas cleaning unit, engine, and generator - Continuous Power Rating: 25 kW - Biomass consumption: 1 kg/kWh (dry biomass) - Max. continuous operation: 12 hours	*All Power Labs* (2018)	US$ 2,000/kW (specific cost)

For the cases when the cost of a piece of equipment of a particular size was not available, the accepted relation known as the sixth-tenth factor rule was used (Towler and Sinnott 2013a). Equation 12 correlates the size and cost of known equipment to similar equipment with different capacity. :

$$C_2 = C_1 \times \left(\frac{S_2}{S_1}\right)^n \quad \text{Equation 14}$$

Where C_2 is the cost of the new equipment of capacity S_2 and C_1 is the cost of similar equipment with capacity S_1. The exponent n is the incident factor indicating the economy of scale and varies depending on the type of chemical process (n: 0.5 -1). A good initial estimate for the incident factor is $n=0.6$, an average figure across the whole chemical engineering industry (Towler and Sinnott 2013a).

Finally, the total **purchased equipment costs** (PEC) was then calculated as the sum of the costs of all the main equipment of the plant:

$$PEC = C_{e,1} + C_{e,2} + \cdots + C_{e,n} \quad \text{Equation 15}$$

Estimation of Direct Fixed Costs (DFC)

The direct fixed capital costs comprise, besides the equipment cost, other expenses related to the equipment installation, construction, and conditioning of the plant. These other direct fixed costs were estimated using the *factorial method*, a commonly accepted approach for costs estimation at a *study estimate* (pre-design) level (Perez et al. 2015), using the main equipment's cost as a baseline (Sinnot 2005; Towler and Sinnott 2013b).

The *Factorial method* uses factors for estimating the physical plant costs and taking as a base the total purchased equipment costs (PEC). These cost factors derive from historical cost data of extensive industry experience and have been collated in different books on plant design and chemical engineering, e.g. (Smith 2005; Sinnot 2005; Peterson and Haase 2009; Masters 2004). Each cost component factor is presented as a span, to account for a variation that represents the scale, complexity and type of processing plant. The applicability of this method depends mainly on the reliability of the purchased equipment cost data and the degree of accuracy required from the cost estimation (Sinnot 2005).

Since the scale and rural geographical context of this bioenergy system are considered in this TEA, not all the components of the direct and indirect fixed capital costs are pertinent, those that apply in this context are described below:

- *Installation costs*

The installation of equipment involves costs for labour, foundations, supports, platforms, construction expenses, and other costs related to the erection of the equipment; and they can vary from 25%-55% of the PEC (Towler and Sinnott 2013a). This component is one of the main fixed costs of this small-scale plant and covers civil work related to building the foundations and air-ventilated small warehouse to place the gasifier-engine system. The lower-end value of 25% cost was used as the installation cost factor, considering the small-scale of the bioenergy system (Perez et al. 2015).

- *Instrumentation and Control costs*

This component covers the installation-labour costs, expenses for auxiliary equipment and materials required to instrument and control the plant. Total instrumentation cost depends on the amount of control required and may be equivalent to 6%-30% of the PEC (Towler and Sinnott 2013a). In this TEA, the quote of the gasification-power plant already includes an integrated control unit in the overall price (All Power Labs 2018), therefore a lower cost factor of 6% is considered, to account for additional costs.

- *Piping costs*

The piping component covers materials, piece of equipment and labour for the complete erection of the piping in the plant, and costs can range between 10% to 80% of the PEC (Towler and Sinnott 2013a). This cost factor largely depends on the type of material that the plant processes, where plants handling justs fluids derive in higher costs (Peters et al. 2003). In this research, the small-scale bioenergy plant processes both, biomass and fluids streams (i.e. water, gases and air), hence the figure of 10% is used, also considering that part of the piping is also included in the integrated cost of the gasification-power plant.

- *Electrical Installations*

The electrical installation component includes the power wiring, lighting and transformation service elements, and within this, the associated installation-labour and materials costs. This cost component generally ranges between 10-15% of the purchased equipment. In this TEA, a value of 10% PEC is considered to represent the costs of a small-scale bioenergy plant.

- *Cost components outside the scope of this TEA*

Other components of the direct fixed capital costs were discarded, as they are relevant for larger-scale processing plants that require more auxiliary infrastructure and equipment to operate than a small-scale gasification plant. These components are the *building and services costs* (i.e. costs for the erection of building connected to the main plant) and, *yard improvement* (i.e. costs for fencing, grading, roads, sidewalks and railroad sidings).

Service facilities costs (i.e. utilities for supplying steam, water, power, compressed air, and fuel) and *land costs* are also dismissed from this fixed-capital estimation. For the first one, it is assumed that the water supply is available for utilisation and no extra expenses are required. This is the general case in coffee farms which require water supply for irrigation systems and for the coffee processing plant. The land costs are also discarded under the assumption that plants could be installed in existent farms owned by coffee producers or cooperatives.

Once the costs factors are defined, the **direct fixed capital costs** are then calculated using equation 16:

$$\boldsymbol{DFC = PEC(1 + f_1 + \cdots + f_4)} \quad \text{Equation 16}$$

Where the factors f_1 to f_4 account for the other direct-fixed costs items, described above, in addition to the purchased equipment cost.

Indirect Fixed Capital Costs

The indirect fixed capital costs account for three main items: engineering and supervision, contractor's fee and contingencies. The cost items were also calculated using the factorial method; in this case, the baseline value is the direct fixed capital (DFC) cost.

Engineering and Supervision

The engineering and supervision component accounts for the costs of the activities related to the design and supervision of the procurement and plant construction. It is considered an indirect cost as it is not charged directly to equipment, material or labour costs. For this TEA, the engineering and supervision costs are estimated as 8% of the direct fixed costs, following guidelines from (Towler and Sinnott 2013a; Peters et al. 2003).

Contractor's Fee

This item corresponds to the wage paid to the contractor, and it is estimated to be span between 2% to 8% of the direct plant cost or 1.5% to 6% of the fixed capital investment (Peters et al. 2003). For this TEA, this component is included as the smaller fraction (2%) of the direct fixed costs of the plant, again considering the small-scale of the plant.

Contingencies

The contingencies costs compensate for unpredictable events during the plant's construction, such as weather events, errors in estimations and small design changes (Peters et al. 2003). Contingencies are estimated as 5% of the direct fixed costs (Towler and Sinnott 2013a).

Table 10 summarises the cost factors used to estimate the direct and indirect fixed capital costs of the small-scale gasification-power plant located in rural areas.

Table 10. Costs factors for the estimation of the direct and indirect fixed capital costs

Direct Fixed Capital Costs		
f_1	Installation costs	25% * PEC+
f_2	Instrumentation & Control	6% * PEC
f_3	Piping	10% * PEC
f_4	Electrical installations	10% * PEC
Indirect Fixed Capital Costs		
f_5	Design and Engineering	8%*DFC++
f_6	Contractor's fee	2%*DFC
f_7	Contingency	5%*DFC

+PEC: Purchased Equipment Cost
++DFC: Direct Fixed Cost

Finally, the **total fixed-capital costs** are calculated with equation 17:

$$\boldsymbol{Fixed\ capital} = \boldsymbol{DFC} \times (\mathbf{1} + \boldsymbol{f_5} + \boldsymbol{f_6} + \boldsymbol{f_7}) \quad \text{Equation 17}$$

Working Capital Costs

The working capital cost is the additional investment required to start operating the plant and generating revenues, or in this case, until electricity and heat are utilised externally. It covers raw materials for plant start-up, raw material and intermediate inventories, cost of transportation for materials and funds to cover payrolls and outstanding bills (Sinnot 2005; Smith 2016). Working capital is estimated as a percentage of the fixed capital costs, spanning between 5 – 20% (Sinnot 2005), using equation 17.

$$\boldsymbol{Working\ capital} = [\mathbf{5}\% - \mathbf{20}\%] \times (\boldsymbol{Fixed\ capital}) \quad \text{Equation 18}$$

This TEA uses the lower end (5%) as the expenses incurred in raw materials and intermediates are minor, considering the scale and context of this gasification-power/CHP system.

Lastly, the ***Total Capital Costs*** of the plant are calculated as the sum of the fixed and working capital costs, using equation 19:

$$\boldsymbol{Capital\ costs} = \boldsymbol{Fixed\ capital} + \boldsymbol{Working\ capital} \quad \text{Equation 19}$$

4.4.4 Annualizing the Total Capital Costs

Following the conceptual framework explained in section 4.5.2, the capital cost estimation is annualised by multiplying the capital costs by the *capital recovery factor* (CRF). The CRF is a ratio used to calculate the present value of a series of equal annual cash flows and incorporates two key parameters, the *discount rate* per year of the project and the *plant lifetime* (HOMER Pro 2019). The CRF is calculated using equation 20.

$$\boldsymbol{CRF} = \frac{\boldsymbol{i(1+i)^n}}{\boldsymbol{(1+i)^n - 1}}, \quad \boldsymbol{i = discount\ rate\ per\ year}, \ \boldsymbol{n = number\ of\ years} \quad \text{Equation 20}$$

Discount rate

The discount rate is the interest rate that could have been earned if the money would have been invested in a better alternative (Masters 2004). This rate allows discounting back to a common year the lifetime cost and electricity generation of the system (IRENA 2018). Although the scope of this economic assessment does not require to establish the capital investment sources for deploying these technologies, it is important to consider an initial discount rate that reflects the financing condition of the particular market of that technology. A discount rate of 10% was used as an initial estimation to calculate the CRF. This value is an accepted figure for economic appraisals of bioenergy power generation systems, also previously reported in (IRENA 2012; IEA 2015; Fischer and Pigneri 2011; Nouni et al. 2007; Gonzalez-Salazar, Venturini, et al. 2014). The influence of this parameter on the LCOE was later analysed through a sensitivity analysis, using a range of discount rates, including an 8% value used in Colombia for renewable energy generation projects(UPME 2015).

Plant lifetime

This parameter is indicative of the number of operating years of the plant. For this TEA, an assumption of a plant lifetime of 15 years was made as it is dictated by the lifetime of the energy generation unit (Arena et al. 2010). In this case, the power train unit is the internal combustion engine being the most expensive equipment to replace. This unit is affected by the tars, soot and other contaminants generated in the biomass gasifier, having considerable damaging effects on the adequate functioning of the gasifier and ICE (Naqvi et al. 2017). This lifetime figure is also a common value reported in other TEAs on gasification systems with similar operating scales (Abe et al. 2007; Arenas Castellanos 2009).

Higher lifetimes for this type of gasification plants are proven to be attainable with a proper maintenance program (Arena et al. 2010). A range of plant's lifetime values between 3-30 years was also evaluated in the sensitivity analysis, to illustrate the changing trend of the LCOE when the lifetime parameter varies.

Finally, the annualised capital costs of the coffee stems gasification-power plant was calculated using equation 21.

$$\boldsymbol{Annualized\ Capital\ Cost} = \boldsymbol{Capital\ cost} \times \boldsymbol{CRF}, \quad \text{Equation 21}$$

4.4.5 Estimation of the Operating and Maintenance costs

The operating and maintenance costs (O&M) are the expenses incurred to operate the plant and obtain the final product or service. They are usually reported on an annual basis and are divided into *fixed costs*, which are independent of the production rate and *variable costs* that depend on the amount of product generated (Sinnot 2005; Peters et al. 2003). Operating costs are estimated from the process flowsheet that indicates the materials, energy and other utilities service requirements to operate the plant. This TEA uses, both the mass and energy balances from the Aspen process modelling results and the fixed capital costs to estimate the operating costs.

Fixed Operating and Maintenance costs

The fixed O&M costs include maintenance, operating labour, supervision, plant overheads, capital charges, rates, insurance costs, royalties and licence fees (Towler and Sinnott 2013b). Similarly, as in the capital costs, the fixed operating cost components were examined to select those relevant for the O&M of a small-scale biomass gasification-power plant, supported by the information provided by Oliveros-Tascón (2018). The applicable items within the fixed O&M costs were the *Maintenance cost* and the *Operating labour.* The local taxes were excluded, as, within the context of this study case in the Colombian coffee sector, projects certified as using renewable energy technologies in Colombia are exempted of local and custom tax payments (Congreso de Colombia 2014).

Maintenance costs are estimated as a fraction (5-10%) of the fixed capital costs (Towler and Sinnott 2013b), using for this TEA the upper end of the range to account for the regular maintenance work required for a gasifier to clean-up tar and other contaminants.

The *operating labour cost* is estimated from the number of shifts and day personnel required to run the plant. Information of plants with similar scales suggested that the operation of this small-scale bioenergy plant requires a manning of one shift per day with one worker per shift. Therefore, the labour cost in this TEA is estimated using as an approximate the standard wage of a technician in Colombia (Ministerio del Trabajo 2018).

Variable Operating and Maintenance costs

The variable operating costs of a plant comprise the raw materials, miscellaneous operating materials, utilities and transportation costs (Smith 2016). The first three components are estimated using the mass and energy balances obtained from the process modelling (chapter 5.2) and local unitary prices of materials and utilities in Colombia at the present year.

Table 11 groups the applicable fixed and variable O&M costs components, with the values and/or considerations used for their estimation.

Table 11. Operating and Maintenance costs components for the biomass gasification-power plant

Operating and Maintenance costs	**Typical values and considerations**
Fixed costs items	
Maintenance	5 – 10% of fixed capital costs
Operating labour	From manning estimates
Variable costs items	
Raw materials: Diesel	Estimated using the fuel requirement for the wood chipping and the number of gasifier start-ups
Transport cost	Estimated using average road transportation costs within rural areas in Colombia

Miscellaneous materials	10% of maintenance costs
Utilities: Water and Electricity	Estimated using mass and energy balance from the process flowsheet. The Venturi scrubber consumes water in the gas-clean upstage. The electricity, whether from off-grid or on-grid sourced, is consumed at a low rate to cover the fraction of power that is not self-supplied by the plant. For both cases, tariffs of utilities in Colombia are used.

Similarly, as with the total capital costs, the total operation and maintenance costs are the sum of the fixed and variable O&M costs of the plant, using equation 22:

$$\boldsymbol{Operation\ and\ Maintenance\ costs} = \boldsymbol{Variable\ costs} + \boldsymbol{Fixed\ costs} \quad \text{Equation 22}$$

For this economic feasibility assessment at a study-estimate level, the end-of-life costs of the plant were not included, however, should be considered in more detailed economic estimates (Sinnot 2005; Peters et al. 2003).

4.4.6 Estimation of biomass costs

The biomass feedstock studied in this research are coffee crop residues obtain from the systematic tree pruning of the coffee trees. This activity is carried out periodically, regardless of the final fate of the coffee stems to maintain the coffee production yield in the plantations. Hence costs related to pruning, biomass transportation and labour are currently part of the overall costs of coffee harvesting (Arcila Pulgarín 2007).

Nevertheless, to also reflect the potential of this biomass to become an attractive solid fuel and the dynamics of the coffee sector, two scenarios were considered. One assumed null biomass costs when the coffee stems are utilised in situ at the farm to fuel the gasification-power plant; hence, just animal transportation is used. The other one considered a low biomass cost when coffee stems are collected and transported to near community-based coffee processing plants to supply the feedstock demands from the gasification-CHP plant. This cost covers labour expenses related to collection activities and transportation. Additional expenses, for example, to fuel the coffee stems chipping are included in the operating costs of the system.

4.4.7 Calculation of the Levelised Cost of Electricity

The Levelised Cost of Electricity represents the ratio between the lifetime cost of the plant divided by the lifetime power generation; both discounted to a common year (IRENA 2018).

The LCOE was established as the cost metric used to measure the unitary electricity cost and compare how economically feasible power generation with this bioenergy system could be compared to current (on/off-grid) power generation systems in the coffee sector. The LCOE calculation is the last stage of this bottom-up economic assessment, which required the estimation of the capital, operational and fuel costs on an annual basis, using equation 23 from (Fischer and Pigneri 2011).

$$\boldsymbol{LCOE}\ [\$/\boldsymbol{kWh}] = \frac{\boldsymbol{Annualized\ CAPEX+OPEX+Fuel\ costs}}{\boldsymbol{Annual\ electricity\ generation}} \quad \text{Equation 23}$$

The annual electricity generation is calculated as the product of the rated power of the plant, the maximum number of operating hours per year and the capacity factor of the plant.

$$\boldsymbol{Annual\ electricity\ generation}\ [\boldsymbol{kWh/year}] = Rated\ power\ \ [kW] \times 8760\ hr \times Capacity\ factor$$

Then, the capacity utilisation factor of a power generation plant is defined as the ratio of the actual power output of the plant divided by the maximum power output of that plant over the same period (Masters 2004). The effect of the capacity factor on the LCOE of the plant is also examined further in the sensitivity analysis of the economic analysis.

Assumptions for the calculation of the Levelised Cost of Electricity

For the calculation of the LCOE, certain assumptions were made, which are consistent with the LCOE estimation of other power generation technologies (IRENA 2018; IEA 2015).

- The discount rate (r) is stable and does not vary during the lifetime of this project.
- The power (generation) output of the plant, at the assumed capacity factor, does not vary during the lifetime of this project.
- Decommissioning and waste management costs are not included in the LCOE calculation
- The LCOE of the bioenergy system does not include power distribution and transmission costs; hence, for a consistent comparison, the diesel-based generation system does not include these costs either.
- In the Colombian context, a national carbon tax is implemented just in the transportation sector; hence, this does not apply for the power generation sector and is not included in the LCOE estimation.

4.4.8 Sensitivity analysis for the Levelised Cost of Electricity

The sensitivity analysis assessed the influence of economic and plant operation-related parameters on the estimation of the LCOE by changing these parameters values over a fixed range. A base case was set to represent the “most probable scenario” in the Colombian coffee sector. Next, these parameters were varied one at a time within the same percentage level of variation, -100% to 100%, where 0% refers to the base case. The parameters were the discount rate, the lifetime of the plant, the capacity factor, the purchased equipment costs, the direct and indirect factors determining the capital costs and the operation and maintenance costs factors. The results of the sensitivity analysis of the levelised cost of electricity are presented in Chapter 7.2.

4.5 Methodological limitations and implications

This section discusses significant strengths and limitations of the methods applied and how their combined use allows a multidisciplinary and comprehensive insight into this research topic.

4.5.1 Implications of the thermodynamic equilibrium modelling approach

The process modelling method applied was developed following a review of the approaches used to evaluate the performance of a gasification system (Section 3.4). This approach was designed to allow an assessment of the technical performance of the gasification system. Under the scope of this research, the level of detail required for this feasibility assessment allowed for estimations of gas composition, mass and energy flows to assess the system’s performance. The limitations of a thermodynamic equilibrium approach such as that applied within this research do not considers in the modelling the gasifier’s geometry, the hydrodynamics, and tar formation.

These potential limitations were addressed by, firstly, understanding the purpose of conducting a high-level technical feasibility assessment of the gasification system and the outcomes from a thermodynamic equilibrium modelling. About this, the selected approach gave the flexibility to evaluate the effect of biomass properties, operating conditions and system’s scale-up, on the gas composition and yield and hence on the gasification’s efficiency. Secondly, as downdraft gasifiers exhibit poor mixing and heat transfer and produce relatively low tar concentration, the limitations of the thermodynamic equilibrium modelling did not significantly affect the prediction of the gasifier’s behaviour.

Finally, a valuable overall insight into the technical performance of the whole gasification system was obtained where results were supported by the model validation with experimental data. For future work focused on progressing to a detailed design of the gasification-CHP system, more advanced modelling and further validation could be required to refine the results from the whole gasification-CHP system model.

4.5.2 Implications of using a lifecycle assessment approach

LCA method is an analytical approach widely applied to investigate the potential environmental impacts of bioenergy systems. The applied LCA framework provided a step by step analytical approach, where through modelling each lifecycle enabled further assessment of different bioenergy systems scenarios and their counterfactuals in the context of the coffee sector in Colombia.

Since the scope from an LCA does not incorporate localised impacts but global and regional impacts (McManus 2002), this could have implications on the LCA outputs. For the interpretation of results, it is important to consider that the LCA outputs do not reflect specific environmental impacts in Colombia. Instead, the benchmarking of different scenarios (bioenergy and counterfactuals) on a lifecycle impact assessment level intended to reflect the dynamics of rural contexts in Colombia. Results should be interpreted, taking this into account.

Further actions were also taken to contextualise these results. Most of the foreground data of the LCI was taken from the mass and energy balance of the process modelling phase; therefore, they represent the coffee stems properties and process parameters of a small-scale gasification system. Also, when necessary, new datasets were created to characterise specific features of Colombia’s energy system, such as the grid power mix (Section 6.2), but generic datasets were used when national-level information was not available. A similar approach was followed when collecting the lifecycle inventory data of the baseline system and counterfactuals. When sensible data was not available to allow an equitable comparison between bioenergy and counterfactual scenarios, certain environmental impact categories were omitted as this would lead to high uncertainty in the results.

Another outstanding issue when conducting this LCA came with the lifecycle impact assessment (LCIA) stage, at this point, it was necessary to select an LCIA method that could address the goal and scope of this LCA. Concerning this, although the selection of ReCIPE method was analysed following certain criteria and supported by similar studies (indicated in Section 4.4.4), the results obtained using this method enclose uncertainty that is difficult to mitigate.

LCAs studies that have focused on advanced bioenergy technologies, such as gasification, remain relatively low compared to more mature technologies which have derived into data scarcity to model full lifecycle of these bioenergy systems. In this research, the data used to model the construction, dismantling and recycling stages of the gasification plant was a particular issue. This led to a reassessment of the initial LCA scope and system's boundary for a cradle-to-gate LCA that allowed equitable comparisons with baseline and counterfactuals systems. A clear opportunity for future work is then to promote data reporting and collection of the direct and indirect-related activities of these bioenergy systems which could support more comprehensive LCAs.

4.5.3. Implications of using LCOE to evaluate the economic feasibility

The use of LCOE as the economic metric contributed to a comprehensive but simple analysis of the costs of this technology's deployment in rural contexts, and how it compares with those from more mature power generation technologies deployed in the coffee sector.

The utilisation of the LCOE metric to compare renewable and conventional power generation systems could be misleading, in certain cases, as the LCOE does not reflect the nature of the renewable sources. For example, if it is a variable renewable energy (VRE) source, then the electricity delivered has different characteristics from an electricity vector of a conventional power plant. VRE depends strongly on time and location (i.e. weather patterns), whereas the conventional power generation systems are considered dispatchable. The LCOE also does not include grid integration costs (i.e. distribution, transmission networks, among others) which could be significant depending on the amount of penetration of the VREs.

The issues presented above, yet, do not significantly affect the utilisation of the LCOE in this economic assessment, as the gasification-CHP system has distinctive features which differentiate it from VREs. First, bioenergy systems are considered dispatchable power generation plants, provided there is planning between the biomass supply and the energy demand of the sector. The second feature is the small-scale power generation capacity of this system, aiming to supply local energy demands. Therefore, it is not necessary to incorporate costs for grid interconnections, and this would not impact the LCOE of this small-scale gasification system, and its comparison with diesel-power generation systems.

CHAPTER 5. TECHNICAL ASSESSMENT OF COFFEE STEMS GASIFICATION-CHP SYSTEM

This chapter presents the results of the technical assessment on the biomass gasification-CHP system, using the process modelling approach on this system and the selected agricultural residue as the biomass feedstock. Additionally, it introduces the selection and justification of the agricultural residue and sector for the case study.

The chapter comprises three sections. Section 5.1 describes the case study framed in Colombia's context: the selection of the agricultural residues and associated sector. Using the feedstock selected for the case study, section 5.2 presents and discusses the results of the process modelling of the biomass gasification for power (and heat) generation system. Finally, section 5.3 analyses the balance between biomass availability and energy demand of coffee farms in Colombia to inform suitable operating scales for the systems.

5.1 Selection of agricultural residue for the Colombian case study

The literature review that focused on examining the biomass energy potential from agricultural residues in Colombia (Chapter 2.4) gave a general overview of the current uses of these residues and their agricultural context. This review allowed identifying prospective opportunities and hurdles for the application of agri-residues in bioenergy systems.

After revising and filtering different options, using the approach indicated in chapter 4.1, the coffee stems were chosen as the feedstock for the case study. The rationale behind this selection is based on the research aim, the properties of this agri-residue, and the characteristics of the coffee sector itself.

- Research on the energy potential of coffee stems has been minor in Colombia and other coffee-producing countries, compared to other coffee residues, like husks and pulp. Evidence of this is the scarce literature on the utilisation of these residues for energy conversion purposes.

- The socio-economic characteristics of the coffee sector in Colombia, where approximately 91% of coffee production concentrates on small and medium farms require energy access solutions for small-scale applications. This context sits with the aim of this research on assessing the feasibility of bioenergy technologies integration at small scale applications in rural areas, as are the ones that are lagging in agricultural development with less technical, financial and policy-related support in Colombia.

- Different from other agricultural sectors in the country, like the sugarcane and palm oil industry, the coffee sector is structured on small and medium-scale landholders that could potentially receive wider socio-economic and environmental benefits from the implementation of such bioenergy systems.

- The coffee sector in Colombia has a well-structured organisation with a National Coffee Federation; cooperatives that represent farmers' interests; institutions that regulate the coffee market and finance agricultural projects and a national centre on coffee research (CENICAFE). This context could enable more effective and impactful research, with more reliable information to support it.

- The coffee stems are an untapped biomass resource in rural areas, mostly used inefficiently as fuelwood in rural cookstoves. This residue has suitable characteristics for thermochemical conversions, like gasification: a high-lignocellulosic content, a heating value ranging between 17.5 - 18 MJ/kg and a low-ash content compared to other coffee residues.

- Finally, the coffee agro-industries in many others low and middle-income countries in the Global South, with similar socio-economic dynamics as in Colombia, could potentially benefit from the findings and recommendations of this research.

Table 12 presents other agricultural residues with potential for bioenergy conversion in the agricultural sector in Colombia, that could prompt future research. The different biomass resources are linked with the bioenergy technologies alternatives, the potential scales of operation, and the energy end-product demanded by each sector.

Table 12. Alternative of agricultural residues with potential for bioenergy conversion in Colombia

Biomass	Bioenergy technology and potential scale of operation	Energy products
Sugarcane leaves (FR)	Combustion or gasification at medium-large scale applications The energy demand of the sugar/ethanol production plants could inform the scale of operation Potential to export the surplus electricity to the grid	Electricity and low-pressure steam for the sugar or ethanol processing stages
Rice husk (AR)	Combustion or gasification at small-medium scale applications Energy demand and production capacity of rice mills could inform the scale of operation Potential for electricity generation to supply just local demands.	Electricity and process heat for rice processing stages
Coffee husk (AR)	Combustion or gasification at small-medium scale applications Energy demand and production capacity of coffee processing plants could inform the scale of operation Potential for electricity generation to supply just local demands.	Electricity and process heat to dry the coffee grain and coffee seed.

5.1.2 Description of the case study and coffee sector in Colombia

The coffee sector in Colombia has coffee farms of small, medium and large-scale sizes representing different coffee production capacities and socio-economic realities (FNC 2014). Table 13 shows the main features of different coffee farmers in Colombia.

Table 13. Coffee farmers and cultivated areas distribution in Colombia

Coffee farms	Coffee farmers		Coffee cultivated areas		Farm extension	
	Population	*Share (%)*	*Hectares*	*Share (%)*	*Hectares*	*Share (%)*
Small-holder (< 1 ha) *non-unionised*	274,000	50%	156,000	16%	813,000	26%
Small-holder (1–5 ha) *unionised*	254,000	46%	533,000	56%	1,723,000	55%
Medium-holder (5.1 – 10 ha)	18,000	3%	117,000	12%	310,000	10%
Large-holder (> 10 ha) *Business setting*	6,000	1%	143,000	15%	281,000	9%
Total	**552,000**		**949,000**		**3,127,000**	

Small coffee farmers have coffee cultivations below 5 hectares of land and represent the largest share (96%) of coffee production in Colombia. Depending on the level of income, they sell the coffee cherries in their rawest form or transform them into beans using handicraft equipment that include sun-air drying facilities (FNC 2014; Roa-Mejía et al. 2000). A fraction of small farmers and, occasionally also medium farmers, are organised in cooperatives to collect and process their coffee cherries at community coffee processing plants to improve the cost-efficiency of the of their coffee production chain.

Large-scale coffee farmers are the smallest fraction in the coffee sector (1%); however, their farms have a business/company setting, resulting in higher incomes to the farmers. (FNC 2017). Different from small and medium scale farms, large landholders and their families do not run their farms directly but rather are usually managed by others generating rural employment. These farms have higher capital investment and highly technified processing plants that require a combination of natural and mechanical coffee drying for larger coffee productions (Roa-Mejía et al. 2000).

The dynamics of the coffee sector also entail different electricity and heat demands from the coffee farms and processing plants. Therefore to represent these different contexts, this research evaluated two coffee stems gasification systems. Both have the same power generation capacity but differentiate from the energy outputs, one delivers power only, and the other one generates power and recovers the heat duty of the system.

Coffee gasification-ICE system for power generation

This system comprises the biomass preparation stage, requiring the coffee stems chipping and sun-drying to reduce moisture content, the coffee wood chips gasification and gas conditioning stage, and finally, the power generation stage, using the fuel gas in the ICE. This gasification-ICE system could deliver 25 kWe of nominal capacity and meet the electricity demand of small and medium-sized coffee farms, covering the energy requirements of farming activities and household appliances. This system does not recover the low-grade heat from the gas cooling stages for external applications as there is no heat demand for mechanical coffee drying.

Coffee stems gasification-CHP system for power and heat generation

The second system is similar; the main difference consists in the additional heat recovery unit to supply part of the heat demand for external applications, such as coffee drying. This gasification-CHP system could deliver 25 kWe of electricity and 40 kWth of thermal power to meet the energy demands of large coffee farms or of community coffee processing plants. These plants operate during the coffee harvesting periods, i.e. six to eight months per year.

5.2 Process modelling of coffee stems gasification-power system

This section presents the results of the process modelling and simulation of the small-scale gasification-PO/CHP system, using the coffee stems as feedstock and the validation of theses results against experimental data. The mass and energy balances of the system were used to evaluate potential heat recovery pathways and the biomass energy conversion efficiency of the whole system.

The results presented in this section were peer-reviewed and published in the Springer Journal *Biomass Conversion and Biorefinery* in the paper *"The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector"* by the author of this thesis (Garcia-Freites et al. 2019) and supervisors.

5.2.1 Producer gas composition - gas yield and model validation

The simulation of the coffee stems gasification model in *Aspen Plus V10* predicted the main thermodynamic process variables, including temperatures, flow rates and compositions of gas streams in the process. For the technical assessment, the most valuable outputs of this model are the producer gas composition, yield and heating value, guiding the evaluation of the suitability of the producer gas as a fuel for ICEs.

The gas composition predicted by the Aspen plus model and the experimental data for the model validation are presented in Table 14. The simulation results for the producer gas composition, LHV and gas yield were compared against two experimental studies, as section 4.2.6 indicates. The datasets are those reported by Oliveros-Tascón et al. (2017), referred to it as *'Exp data 1',* and by Garcia et al. (C. A. García et al. 2018), referred to is as *'Exp data 2'*.

Table 14. Validation of Aspen simulation results with experimental data

Gas species	**Producer gas parameters:** Predicted - Exp. data 1			**Producer gas parameters:** Predicted - Exp. data 2		
	Predicted data 1 (mole %)	Exp. data 1 (mole %)	Percentage error 1	Predicted data 2 (mole %)	Exp. data 2 (mole %)	Percentage error 2
Hydrogen	20.4%	19.9%	2.5%	22.3	19.53	14.3%
Carbon monoxide	19.8%	19%	4.1%	18.8	16.32	15.1%
Carbon dioxide	11.5%	10%	15%	13.8	13.77	0.03%
Methane	0.65%	3%	78.4%	1.2	3.42	65.7%
Nitrogen	41%	n/a	-	43.4	46.49	6.7%
$LHV_{d.b.}$	4.9 MJ/m^3	5.6 MJ/m^3	12.3%	4.7 MJ/kg	4 MJ/kg	13.8%
Gas yield	2.54 kg gas/ kg BM	2.12 kg gas/ kg BM	20%	2.52 kg gas/ kg BM	2.84 kg gas/ kg BM	11.1%

d.b.: dry basis
n/a: Not available

The model validation with both sets of experimental data shows good agreement with the simulation results for the mole fractions of H_2, CO, CO_2, and N_2 components, and the producer gas yield and LHV. Nonetheless, the methane (CH_4) mole fraction is under-predicted by the simulation resulting in a high percentage error, for both cases.

The methane composition is usually under-predicted when a gasification system is modelled following a thermodynamic equilibrium approach. As theory specifies, the *methanation* reaction, described by the equation ($C + 2H_2 \leftrightarrow CH_4$), tends to deviate from chemical equilibrium at high temperatures (above 800 °C), as is the case of this gasification model (Barman et al. 2012).

On balance, since the H_2 and CO composition are the main combustible components in the producer and are slightly over-predicted in the simulations, the low heating value is not deleteriously affected by the lower CH_4 concentration. As a result, the low heating value of gas yields an average percentage error of 13%, acceptable for this modelling work.

5.2.2 Sensitivity analysis

After the model validation, the expected results of the sensitivity analysis showed the predictive capabilities of the model, by evaluating the effect of key gasification parameters on the gas composition, temperature, heating value and cold-gas efficiency. Section 4.2.6 in chapter 4 explains the approach followed in conducting this sensitivity analysis.

Effect of biomass moisture content

Figure 18 illustrates the effect of the coffee stems moisture content (MC) on the gas composition and gasification temperature profile.

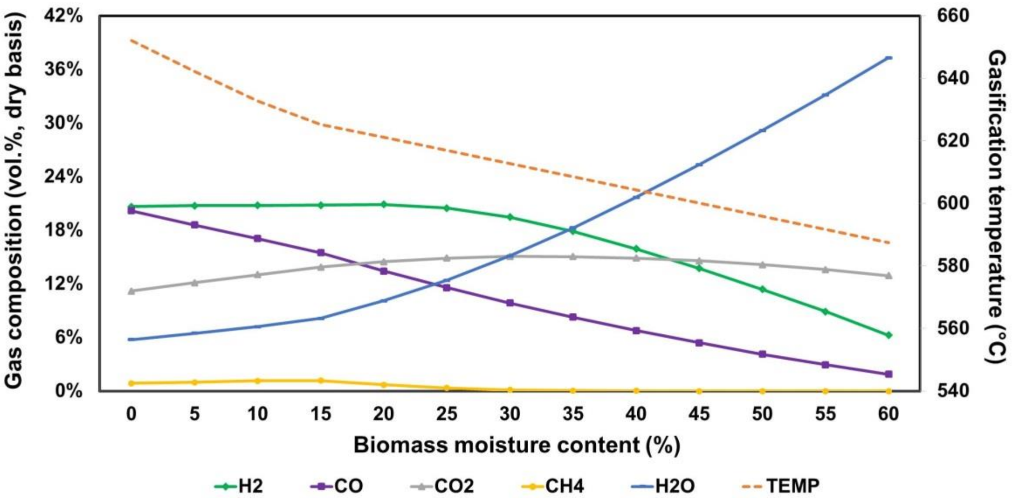


Figure 18. Effect of biomass moisture content on the producer gas composition and temperature

The H_2O concentration in the producer gas increases steadily over the biomass moisture content range. The excess of H_2O demands more energy to evaporate the moisture in the biomass, plunging the gasification temperature. A decline in the temperature favours the reverse direction of the endothermic water-gas reaction ($C + H_2O \leftrightarrow CO + H_2$) and the forward direction of the exothermic CO shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$). This results in a sharp drop in the CO concentration and a slight decrease in H_2 concentration for MC values above 25%. On the contrary, the CO_2 mole fraction increases gradually up to an MC of 35%, after it stabilises. The methane concentration is very small and slowly decreases with higher moisture contents.

Figure 19 presents the overall effect of the moisture content on the gas LHV and the cold gas efficiency. The decreasing concentration of H_2 and CO and rising mole fraction of H_2O in the producer gas lowers the gas LHV, which consequently affects the gasifier performance, measured by the CGE of the gasifier. This confirms the importance of controlling the moisture content of the biomass, which for downdraft gasifiers should not exceed 25% wt. (Basu 2013b;

Ahrenfeldt, Bain, van de Beld, et al. 2005); more specifically keeping MC ranges between 10-20 %wt leads to a better gasification performance (Basu 2013c).

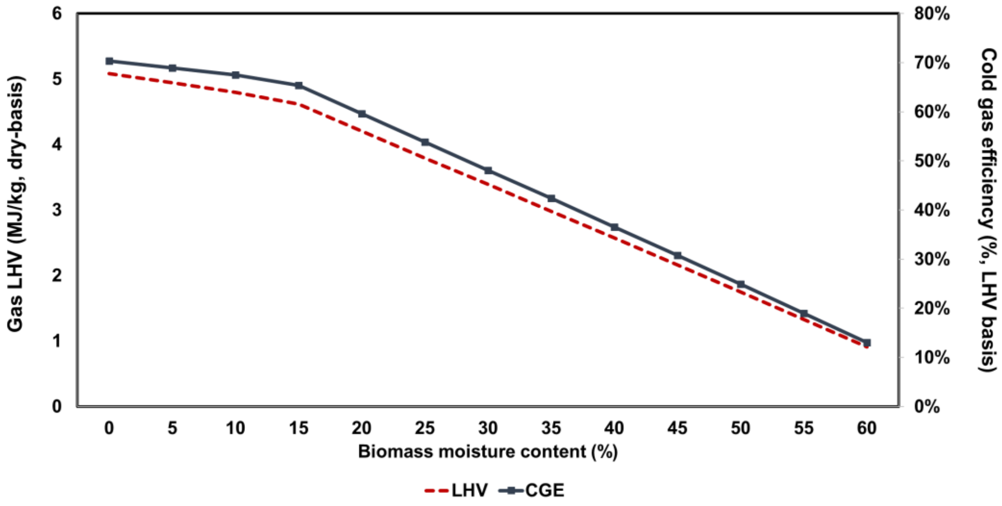


Figure 19. Effect of biomass moisture content on the producer gas LHV and CGE

Effect of the equivalence ratio

In auto-thermal gasifiers, as the one modelled in this work, the gasification temperature is controlled with the amount of air supplied to the gasifier (equivalence ratio – ER). Hence, Figure 20 illustrates the effect of the ER on the gas composition and temperature profile.

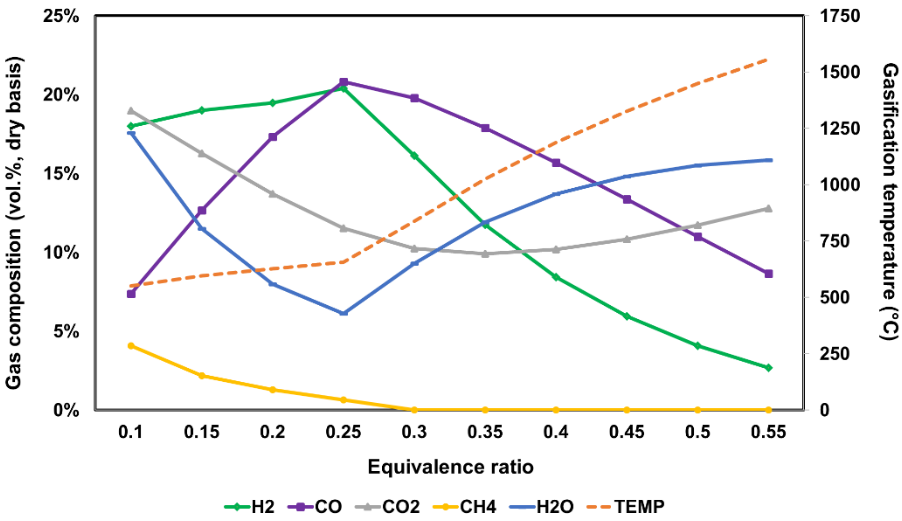


Figure 20. Effect of equivalence ratio on the producer gas composition and temperature

As the ER increases, the gasification temperature rises favouring the products of the endothermic water-gas reaction $(C + H_2O \leftrightarrow CO + H_2)$. Therefore, the CO mole fraction escalates, whereas the H_2 mole fraction rises more gradually, both reaching peak values at ER=0.25. At this equivalence ratio, downdraft gasifiers are expected to give the best yield (Basu 2013b), as the trends of the CO and H_2 mole fractions show.

In contrast, the CO_2 and H_2O mole fractions drop until ER values of 0.35 and 0.25, respectively; after this, they start rising gradually. As more O_2 is available in the gasifier and the char (C) in the biomass has been consumed, the CO and H_2 start reacting with the oxygen, producing the combustion products CO_2 and H_2O. The CH_4 mole fraction decreases until almost zero, due to *methanation* reaction tending towards more reactants than products when the temperature rises.

The variation of the N_2 mole fraction is not plotted in this graph, as for the modelling purposes is considered an inert gas. The N_2 composition in the producer gas increased from 29% to 60%, over the ER range from 0.1 to 0.55. Other minor components in the gas, such as NOx and H_2S, were not included in the sensitivity analysis as the model predicted just traces of them.

The variation in the concentration of the combustible components, CO, H_2 and CH_4, directly affects the gas low heating value, and consequently the conversion efficiency of the system. Figure 21 shows that as ER increases from 0.1 to 0.25, the gas LHV rises gradually, reaches a peak when the CO and H_2 mole fractions are in their maximum values, and then falls rapidly as the concentrations of CO and H_2 drop. Consequently, the cold-gas efficiency (CGE) follows a similar trend, where the highest CGE yields at an ER value of 0.25.

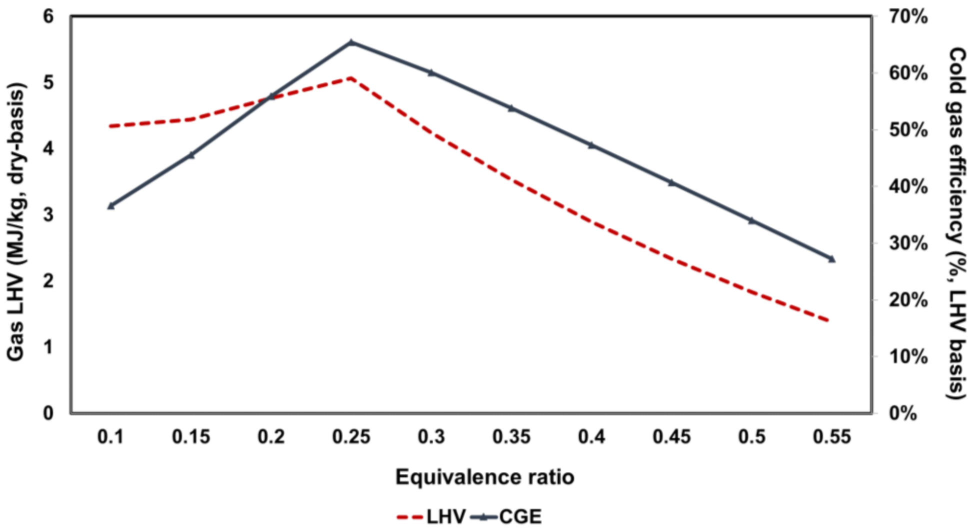


Figure 21. Effect of equivalence ratio on the producer gas LHV and CGE

Effect of preheating the gasifying air

Air entering the gasifier as a gasifying agent at temperatures higher than ambient temperatures (> 25°C) can improve the gasification conversion efficiency. Figure 22 shows how as the air temperature increases the H_2 and CO mole fractions augment, resulting in a higher gas LHV. Opposed to this, the CO_2 and H_2O mole fractions decrease. The CH_4 mole fraction remains almost constant across the whole range. This behaviour is caused by an increase in the gasification temperature due to the higher sensible heat of the airstream, as the gasifying medium.

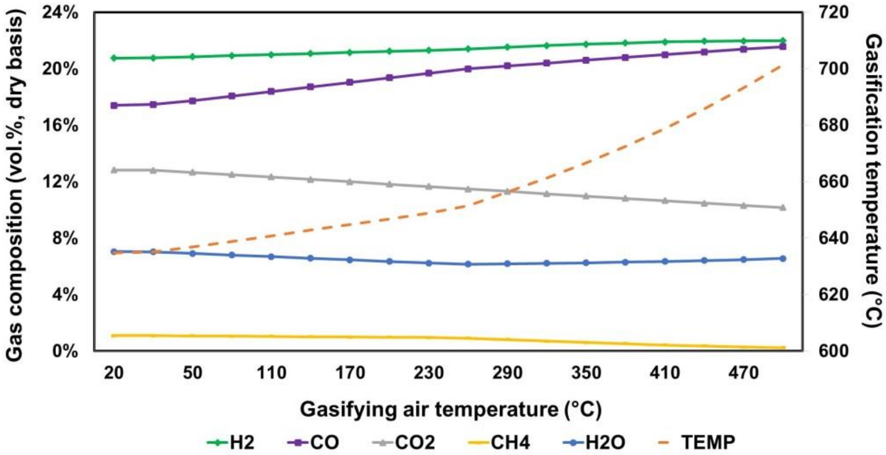


Figure 22. Effect of gasifying air temperature on producer gas composition and temperature

The higher concentration of the main combustible components, CO and H_2, in the producer gas induces an increase of the gas LHV, which improves the biomass to gas conversion efficiency, measured by the CGE, Figure 23 shows. It is also important to highlight that rising the air temperature above 260 °C causes a marginal increase in the low-heating value. Therefore, the benefits of preheating the gasifying air have to be pondered against the costs of implementing heating equipment, whether using an external heat source or an internal heat recovery unit.

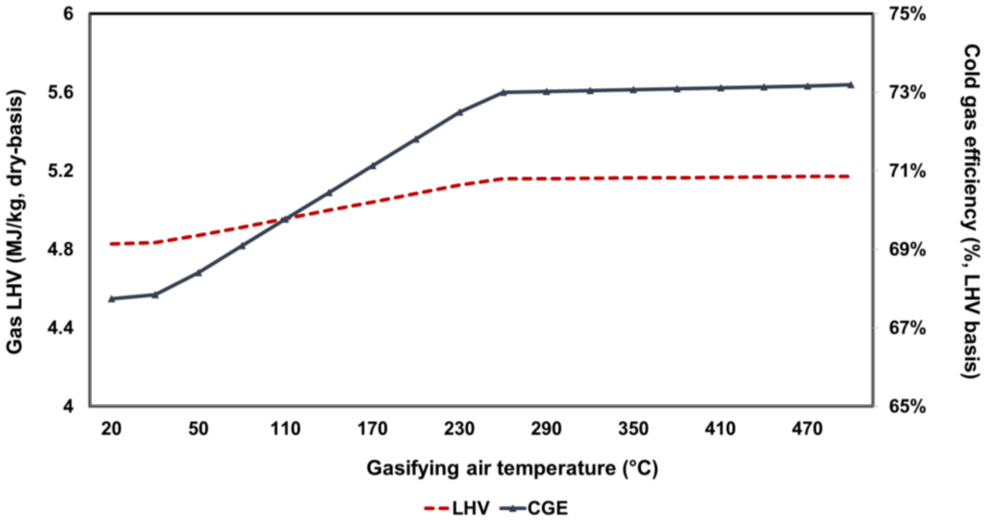


Figure 23. Effect of gasifying air temperature on gas LHV and CGE

The trends followed by the profiles of the producer gas composition, temperature, low heating value and cold-gasification efficiency, showed the expected behaviour, in accordance to the gasification modelling theory and previous studies, such as in Ramzan et al. (2011); Zainal et al. (2001); Doherty et al. (2009), Yao et al. (2018) and Altafini et al. (2003).

Understanding the effect that these gasification parameters have on the gasification temperature, producer gas composition, and then on the LHV and CGE is important to understanding if a practical implementation of this gasification system is feasible. The control over certain biomass properties (moisture content) and key operating parameters on optimum design values can significantly improve the gasifier performance and conversion efficiency of the whole system. The potential benefits of these measures should be pondered against an expected increase in costs when implementing the gasification system.

5.2.3 Technical performance of coffee stems gasification model

The model validation and sensitivity analysis showed that the model could predict the maximum gas yields and composition from the coffee stems gasification. Then, Table 15 reports the main output parameters of the model to determine and analyse the gasifier and the whole system's performance.

Table 15. Performance parameters of the downdraft gasifier-gas engine system

Gasifier-ICE system performance parameters	
Clean producer gas flow	85 $Nm^3 h^{-1}$ (64 kg h^{-1})
Gas yield	2.46 kg gas per kg of biomass
Producer gas calorific value	5.6 MJ Nm^{-3} (5.3 MJ kg^{-1})
Cold Gas Efficiency (CGE)	70.6%
Hot Gas Efficiency (HGE)	87.2%
Net electricity output	20.4 kW_e
Low-grade heat recovery	40.4 kW_{th}
Cogeneration system efficiency	45.6 %

For the baseline setting, the simulation results indicate that the downdraft gasifier fed with 28 kg h^{-1} of coffee stems can generate a producer gas fit as fuel for ICE and CHPs applications. It meets minimum standards of specific energy content in fuel gas, with LHV > 4 MJ/Nm^3 as reported by Molino et al. (2016). The gasification performance parameters, CGE (70.6%) and HGE (87.2%) show good gasification efficiency. Both values are within characteristic ranges for downdraft gasifiers, 60-80% for the CGE (Heidenreich and Foscolo 2015; Susastriawan et al. 2017; Pereira et al. 2012) and 85-90% for the HGE (Basu 2013b). The HGE is expected to be higher than the CGE as the first one includes, in addition to the chemical energy, the sensible heat of the hot producer gas.

The fuel properties predicted by the gasification model suggest that the coffee stems-based producer gas has good potential as a fuel for small-scale engine applications. Therefore, using the producer gas to fuel an ICE/CHP-generator set could generate 25 kW_e of gross electricity, assuming an electrical efficiency of 25%, as explained in chapter 4.2.5.

Additionally, a maximum of 40.4 kW_{th} of thermal power output could be recovered from the whole gasification-ICE system after deploying heat recovering units from producer gas and flue gas cooling stages. The following section (5.2.4) analyses the heat recovery pathways to obtain the low-grade heat vectors and their potential application in the coffee sector.

5.2.4 Heat recovery pathways

The two heat exchangers stages, one to cool down the producer gas, and the other for cooling the flue gas before exhaustion, were simulated in *Aspen Plus* following the configuration described in chapter 4.2.5. Table 16 collates the results from the simulation of the heat recovery units, including outlet temperatures from the different streams, flow rates and heat duties.

Table 16. Basic parameters of heat recovery stages

Heat recovery stage 1					
Heat exchanger 1: (PGAS-HX1)	*Producer gas*	*Gasifying air*	Heat exchanger 2: (PGAS-HX2)	*Producer gas*	*Drying air*
T_{in}	792.3 °C	25 °C	T_{in}	699.5 °C	25 °C
T_{out}	699.5 °C	250 °C	T_{out}	120 °C	50.6 °C
Mass flow	68. kg h^{-1}	42 kg h^{-1}	Mass flow	68.7 kg h^{-1}	2165.6 kg h^{-1} (flow rate: 34 m^3/min)
Maximum heat duty: 2.69 kW			***Maximum heat duty: 15.6 kW***		
Heat recovery stage 2					
Heat exchanger 3: (FGAS-HX)	*Flue gas*	*Water*	Heat exchanger 4: (AIR-HX)	*Hot water*	*Drying-air*
T_{in}	600 °C	25 °C	T_{in}	91 °C	25 °C
T_{out}	120 °C	91 °C	T_{out}	28 °C	50 °C
Mass flow	529.8 kg h^{-1}	280 kg h^{-1}	Mass flow	280 kg h^{-1}	3134.3 kg h^{-1} (flow rate: 47 m^3/min)
Maximum heat duty: 23.21 kW			***Maximum heat duty: 22.12 kW***		

For the baseline setting, the maximum recoverable heat duty from the gas cooling stages is 40.4 kW_{th}, yielding a thermal power output efficiency of 30.3% for the whole system (i.e.

biomass to heat conversion). This sensible heat could be used to supply the thermal power demand of the system and external heat demand of a coffee processing plant.

The heat duty recovered from the *PGAS-HX1* (2.69 kW) could be utilised to heat the gasifying air up to approximately 250 °C. This could result in an increase in the LHV of the producer gas from 4.7 MJ kg^{-1} to 5.3 MJ kg^{-1}, as Figure 23 illustrated for the sensitivity analysis of this parameter. Another application is for the pre-drying the biomass when natural drying mechanisms are not sufficient to reduce the moisture content. The heat recovered from the *PGAS-HX2* could be used externally, to supply part of the process heat demand during mechanical coffee drying.

The second heat recovery stage cools down the flue gases to 120 °C to meet environmental regulations (using *FGAS-HX*) and could potentially generate 23 kW_{th} of thermal power. This second heat exchanger (*AIR-HX*) recover this heat duty by heating another air stream that could also be used for the coffee drying step. A higher thermal energy vector could be attainable in this stage because of a higher mass flow rate of the flue gases.

Since potential applications of these heat duties are for mechanical coffee drying, the air was heated to reach temperatures around 50 °C, as the guidelines of Cenicafe in Roa-Mejia et al. (2000) indicate for mechanical coffee drying. As this step largely influences the final characteristics of the coffee bean, it is important to maintain uniform drying process to achieve a standard grain moisture content (10-12 %wt.) (Roa-Mejía et al. 2000). The optimum conditions of air temperature (48-52 °C) and airflow rate (66 m^3 min^{-1} per ton of coffee for static layers dryers) conditions (Roa-Mejía et al. 2000) could be achieved by combining both recovered heat duties.

These numbers represent maximum recoverable heat duties that in a real-life operation are limited by the efficiency of the heat exchangers and coffee driers, and also by the capacity factor of the plant and the capital available for investment.

5.2.5 Mass balance

Table 17 presents the mass balance of the system; the input and output flows are presented for the biomass gasification and producer gas combustion stages. For the baseline case, it can be inferred that a biomass feed rate of 28 kg/hr of coffee wood chips (compensating for biomass losses from chipping) could generate 20 kW_e of net power output. After removing ash, char and other particulates in the gas clean-up stage, this produces 63.8 kg/hr of clean producer gas for final injection into the ICE.

Table 17. Biomass gasification- ICE system mass balance

Net electricity output: 20 kWe	
<u>BIOMASS GASIFIER</u> *(includes biomass chipping and gas clean-up)*	
Input:	
Coffee tree stems (MC: 8.7 % wt.)	28 kg/hr
Air (gasifying agent)	42 kg/hr
Output:	
Clean producer gas	63.8 kg/hr
Ash (out from cyclone + filter)	0.26 kg/hr
Char (out from cyclone + filter)	1.15 kg/hr
Condensate (out from condenser)	3.38 kg/hr
INTERNAL COMBUSTION ENGINE *(combustion process modelling)*	
Input	
Producer gas	63.8 kg/hr
Air (oxidant agent for combustion)	86.14 kg/hr
Output	
Flue gas	149.95 kg/hr

The gas yield, another key parameter indicative of the gasifier performance, results in 2.5 kg of producer gas per kg coffee stems falling within the values of 2.84 and 2.12 reported by Garcia et al. (2018 a) and Oliveros-Tascón et al. (2017), respectively. Similarly, the parameter relating biomass-to-electricity generation for this biomass gasifier-ICE system results in 1.12 kg of coffee stems chips per 1 kWh of electricity. This number is also in accordance with the experimental result of Oliveros et al. (2017) indicating an average supply of 1.25 kg of coffee wood chips to generate one kWh of electricity. Both parameters, the first representing the yield of the gasifier and second the yield of the whole system, supported the model predictive capabilities and the good performance of the gasification system.

5.2.6 Energy balance

The energy flows of the coffee stems gasification-CHP system are represented in a Sankey diagram (Figure 24) to illustrate how the biomass energy transforms into useful heat and power outputs, but also where are the main energy losses of the system. In the first stage, the intrinsic chemical energy of the biomass is converted through the gasification process into the energy carried by the clean and cooled producer gas, with a 71% overall efficiency. Another fraction is recovered from the producer gas sensible heat in the form of thermal power (13.7%)

in the gas cooling stage. The energy losses in the gasifier and gas clean-up stage account for almost 15% of the biomass energy input.

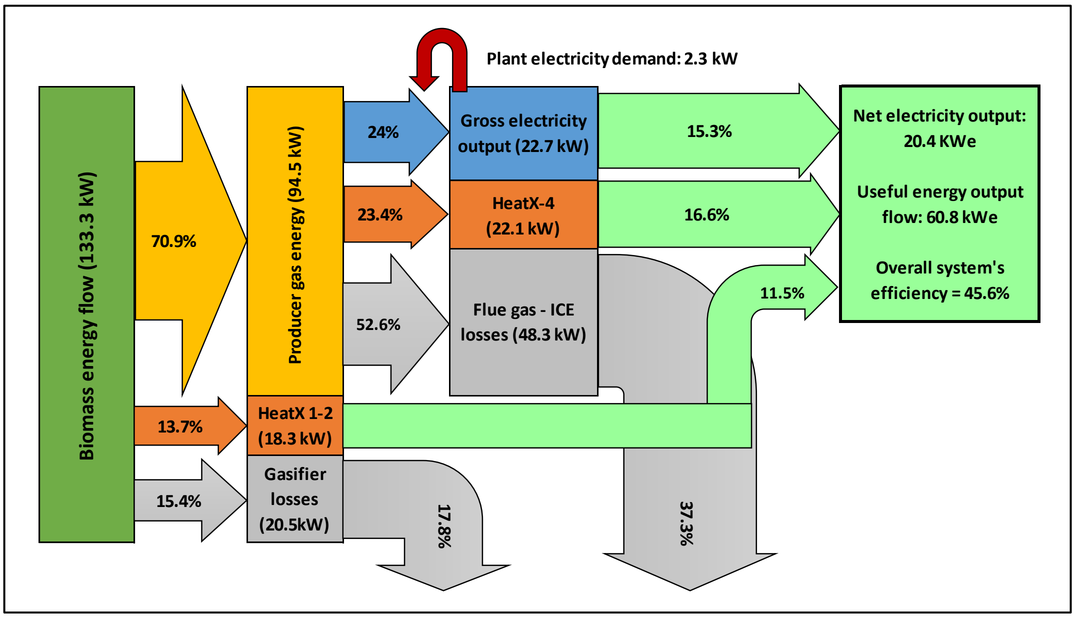


Figure 24. Energy flow balance (Sankey chart) of the biomass gasifier-ICE system

In the second stage, the energy of the producer gas transforms into electricity in the ICE-generator set with an electrical efficiency of 24%; a fraction (10%) of the gross electrical output provides the internal power demand of the plant resulting in a net power output of 20 kW_e. In addition, part of the sensible heat from the hot flue gases is recovered in the second stage of heat exchangers. The thermal energy losses deriving from the powertrain section, i.e. CHP-generation set and the flue gases, accounting for 52.6% of the producer gas energy input.

Overall, the whole system's energy conversion efficiency, combining electrical and thermal power outputs, results in 45.6%. The recovery and integration of the low-grade heat to external applications, such as for the coffee drying stage, significantly enhance the overall performance of the system, that otherwise would result in lower conversion efficiency, for power only generation 15.3%. Also, the cogeneration efficiency number (45.6%) obtained for this small-scale bioenergy systems agrees with other numbers reported on gasification of agricultural residues studies, as indicated in Vera et al. (2013), Perez et al. (2015) and Baratieri et al. (2009).

Furthermore, considering the significant thermal energy that the producer gas carries within, this gas could also be applied for direct utilisation in boilers for on-site heat production. Even though this energy pathway is not studied here, it is pertinent to highlight the versatility of the producer gas as a fuel for small-scale bioenergy applications in rural areas.

5.3 Biomass supply and energy demand of the coffee sector

The technical performance results indicate that these systems implementation could be technically feasible, having the potential to supply power and heat demands of coffee farms and coffee processing plants. Yet, for this to start materializing, the match between the biomass resource availability and the farm's energy demand has to be considered.

During the coffee harvesting periods in Colombia, the operation of the 100 kW_{th} gasifier-CHP system during 4380 hours per year (capacity factor of 50%) could produce annually 87,600 kWh of electricity generation and a maximum thermal power output of 157,200 kWh[5]. On the feedstock side, the gasifier would require 122 t per year of coffee wood chips to operate.

These numbers from the energy supply and biomass demand of the gasification system could suit the energy requirement and biomass availability of large coffee farms in Colombia. Electricity consumption in these farms is on average 2,700 kWh per month (Arenas Castellanos 2009); therefore, the system could potentially supply the demand of two farms. This demand includes the power requirements of the farm household and the coffee processing plant.

On the other side, the coffee stems availability per year in these farms could reach up to 180[6] t/year of dry-coffee wood. This figure represents the biomass portion (50%) that can be removed sustainably from the plantations and losses during biomass preparation (Romo Ortega et al. 2011). This biomass quantity is higher than the system's resource demand; however, their availability is constrained by each farms management systems and their coffee plantations age (i.e. trees pruning after 4 to 6 years of cultivation (Arcila Pulgarín 2007)). This implies that the combined biomass collection of at least two farms could be required, as well as storing facilities in the farms to facilitate sustained feedstock availability and protect the coffee wood from rain and prevent decomposition.

The heat recovered from the gas cooling stages could be used to supply part of the thermal power demand in the coffee drying stages of the processing chain. The heat duty over a year could dry up to 56 t of washed coffee beans that after drying become into 34 t of dry-coffee per year for market trading.

[5] This maximum net thermal power output does not include the plant's internal heat demand.

[6] Equivalence: 1 kg of coffee cherries yield of average 0.6 kg of coffee stems

Alternatively, this power and heat generation could also supply the power demand of a community-based coffee processing plant, requiring on average 25 kW of power capacity to operate one coffee processing line.

Direct application to small scale farms (~1-5 ha of cultivated land) would be less viable as it would require the integration of several small farms to guarantee a regular biomass feedstock supply. Instead, small-farm holders could beneficiate of the bioenergy supply to community-based coffee processing plants or implement smaller gasification systems.

5.4 Key findings of technical assessment

The results presented in this chapter contributed to the evaluation of the potential, and technical feasibility of gasifying coffee stems to produce electricity and low-grade heat. The composition, yield and LHV of the producer gas suggest that the gas has a valuable energy content and could be used as fuel for ICE and CHP applications. Other parameters also indicate the good gasification performance, with a cold-gas efficiency of 70.6% and hot-gas efficiency of 87.2%.

A downdraft gasifier with a thermal capacity of 100 kWth and coupled to ICE or CHP-generation could generate approximately 20 kW_e of net electricity. The heat recovery from the gas cooling stages could be used to supply the heat demand during coffee drying and enhance the biomass conversion efficiency of the systems and its applicability in the coffee sector.

For applications in the coffee sector, the analysis showed that at suitable operating scales the system could meet the demand of large farms or community coffee processing plants, and in balance, these farms could have the biomass availability required to run the gasifier. For smaller farms, smaller gasification systems would be required due to lower electricity demand, probably not demanding process heat, and also less coffee stems available due to the smaller size of the coffee plantations.

Relevant findings emerge from the results of this research which could help to realise a feasible implementation of this coffee residues gasification system:

1. Recovering and integrating the low-grade heat is key to increase the (cogeneration) process efficiency; its potential application within the coffee processing chain also enhances the relevance of this bioenergy system for the rural coffee sector.
2. Managing certain biomass and gasifier operating parameters, such as the biomass MC, equivalence ratio and gasifying air temperature, over an optimum range for fixed-

bed gasifiers can enhance the gas LHV. This impacts positively the gasifier performance and the whole system's efficiency.

3. Balancing the biomass supply and the energy demand at coffee farms level is a vital factor to determine the scale of operation and feasibility of using these coffee residues in small-scale gasification systems for power and heat generation.

Overall, these results were conductive to reach the specific objectives two and three of this research (Chapter 1.3). They also contributed to the research aim providing overall insights into the technical performance of the system and how its deployment in the coffee sector could balance the energy demand and agri-residues availability. In addition, the outcomes of the process modelling, particularly the mass and energy balances and basic design of the gasification plant also functioned as inputs to the lifecycle assessment and techno-economic assessment stages of this research.

CHAPTER 6. LIFECYCLE ASSESSMENT OF COFFEE STEMS GASIFICATION FOR POWER AND HEAT GENERATION

This chapter presents the LCA of the coffee stems gasification system for power and heat generation, and the results contribute to attaining the fourth objective on evaluating potential environmental impacts associated to these systems deployment in rural areas. The chapter contains relevant and original findings that inform on the environmental feasibility of using locally available agri-residues in small-scale bioenergy systems to generate decentralised energy. They also highlight the importance of examining counterfactuals to identify wider benefits and trade-offs related to the implementation of these systems.

The chapter structure follows the framework of an LCA according to ISO standard 14040 (2006): LCA goal and scope in section 6.1, lifecycle inventory (LCI) in section 6.2, lifecycle impact assessment (LCIA) in section 6.3 and the interpretation of results in section 6.4.

6.1 Goal and scope of LCA

The goal of this LCA is to assess the potential environmental impacts of deploying small-scale gasification systems of coffee residues for power and heat generation, using the Colombian coffee sector as a case study. Within this goal, the intended outcomes of this LCA were, first, identifying the stages that generate the largest environmental burden over the system's lifecycle horizon and propose alternatives for mitigation. Second, to evaluate the net environmental impacts of the bioenergy system, by comparing it with a baseline system and other counterfactuals that represent practices of the Colombian coffee sector. The results on the net impacts also contribute to analysing synergies and trade-offs of deploying this bioenergy system in rural contexts.

The LCA results are expected to be of interest to academics and stakeholders involved in the coffee sector (i.e. farmers, trading companies, cooperatives and government authorities) in Colombia and other coffee-producing countries. This approach and general findings could serve as insights to stakeholders of other agricultural supply chains with bioenergy potential.

6.1.1 Product system

The first stage is the coffee stems pruning, collection, chipping and natural drying to obtain the dry coffee wood chips as a solid fuel. The second stage is the gasification of the wood chips to generate the producer gas, and following gas cleaning and cooling. Finally, the third stage is the producer gas fuelling into the ICE for the generation of power (and heat for the CHP system only), and subsequent cooling and filtering of flue gases after combustion.

The bioenergy system, delivering power and heat, was compared against different counterfactuals. These represent current coffee stems uses in rural areas, i.e. fuelwood in cookstoves for cooking, direct-combustion in industrial stoves for heat, or disposed of in open-burnings. The most common application was defined as the baseline case. Additionally, several counterfactuals were defined as potential scenarios that could also occur within the coffee sector if the bioenergy system would not be deployed. Section 6.1.5 describes each of these systems in detail.

6.1.2 Functional unit

The main utility of the CSG-ICE system is the generation of power for coffee farms household and farming productive activities, alternatively, when the heat is recovered, the main utilities of the CSG-CHP system are power and heat generation. The power vector attends the same purposes indicated above, and the heat vector supplies the thermal power demand for coffee beans drying. Both systems could also have the implicit function to serve as an agri-residues management alternative.

The functional unit of the coffee stems gasification for power generation system is the generation of 1 kWh (3.6 MJ) of electrical power. For the alternative system, that recovers the low-grade heat for external applications, the functional unit is 1 kWh of energy produced, as two energy vectors are obtained. For this case, an allocation approach was used to assign the system's environmental impacts between both energy vectors (section 6.1.4).

These functional units were compatible when comparing the bioenergy system with the baseline and counterfactuals, serving the purpose for the calculation and analysis of the net environmental impacts of the bioenergy system. An alternative functional unit of 1 kg of raw biomass was used when examining the bioenergy system application over the coffee stems open-burning practice, as the latter one does not generate measurable energy vectors.

6.1.3 Systems boundary

The boundary of this system comprises the inlet and outlet flows of materials, energy, emissions and use of infrastructure and equipment to operate the system. Figure 25 illustrates the system boundary with the main stages of the coffee stems gasification-CHP plant, which broadly includes the construction and operation phase of the plant.

Plan construction

This phase encompasses the manufacturing of construction materials, installation and civil work required to set-up the infrastructure of the biomass gasification-CHP plant. This phase is included in the LCA to inform of the required inputs of materials and energy consumption, and subsequent release of airborne, soil and water emissions during the plant construction.

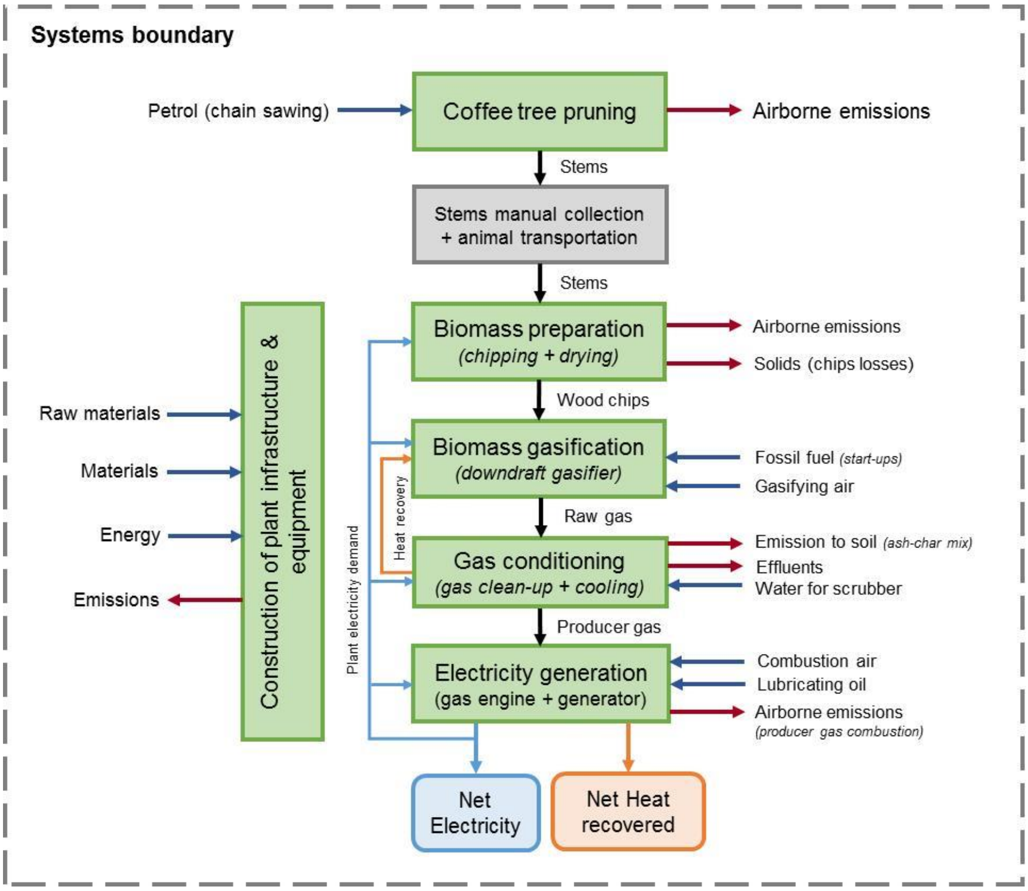


Figure 25. System boundary for the biomass gasification-CHP plant

Plant operation

This phase comprises three main stages of the biomass gasifier-ICE/CHP plant. The first stage is the biomass collection and pre-treatment, the second stage covers the biomass gasification and gas conditioning, and the third stage consists of the producer gas energy conversion into power and heat (recovery). This phase covers inputs related to energy and material (raw and processed) flows, including fossil fuels required for auxiliary services. The outputs consist of emissions to air, water and soil and waste treatment, as well as the two energy vectors produced by the system. A detailed description of all the sub-stages of the plant operation phase is included in section 4.2.

Phases outside the system boundary

The coffee cultivation and harvesting stages are outside this system's boundary since the coffee stems are treates as crop residues with low, if not none, economic value. Therefore, allocating the environmental burden of these stages on the coffee stems utilisation would not reflect its current economic value in this sector. The activity of coffee tree pruning, yet, is inside the system boundary as a required step to obtain this biomass.

The plant dismantling and materials recycling/disposal phase is also not included within the system boundary, in general there is a lack of information in the LCA literature related to this phase (Patel et al. 2016). Furthermore, in Colombia, the final fate of construction materials could be subject to high data uncertainties associated with different circumstances in rural contexts. On one side, waste management systems are very rudimentary, especially in rural areas; therefore, there are no inventories on the consumption of materials and energy and emissions releases generated during waste disposal activities. On the other side, people in poor rural areas are regarded as highly inventive (FNC 2014); hence, recyclable materials, such as metals, could be potentially reused elsewhere but in informal applications.

Additionally, the few existent LCA studies including this stages concluded that construction and dismantling stages have almost negligible environmental impacts compared to operating and biomass production phases (Carpentieri et al. 2005; Thornley, Upham, et al. 2009) which supports this decision.

6.1.4 Evaluating the net lifecycle impact assessment

This LCA also aimed to assess the net environmental impacts of the bioenergy system over a baseline and other potential counterfactuals by calculating net reductions or increments of the selected impacts categories. This assessment examined different scenarios that could develop in the coffee sector, for the bioenergy system and counterfactuals.

Definition of the bioenergy scenarios

The bioenergy scenario, besides comprising the coffee stems gasification-ICE system for power only or CHP generation, includes the alternative activities that could potentially substitute the current uses of this biomass, i.e. cooking, direct-combustion or open-burning.

For the cases that replace coffee stems used in rural cookstoves (baseline scenario), the bioenergy scenario includes an alternatively cooking fuel to make it comparable with the counterfactuals. Considering the context in the rural coffee sector in Colombia, this scenario accounts for the current mix of cooking fuels used in rural areas of Colombia, using data from the Department for National Statistics (*DANE in Spanish)* (DANE 2017). The data is presented in Table 18 and lists the fuels with their share in the mix of rural cooking fuels. The fuels selected as potential replacements for coffee stems cookstoves are LPG, natural gas and electricity, having the highest share in the mix. For the third one, the assumption is that the bioenergy system could supply the power demand of the electrical cookstove.

Table 18. Current mix of cooking fuels in Colombian rural areas
Source: (DANE 2017)

Fuel	No. Rural households[7]	Share in the mix of cooking fuels
LPG	1,600	53.1%
Firewood	877	29.1%
Natural Gas	473	15.7%
Electricity	40	1.3%
Mineral coal	21	0.7%
Kerosene	4	0.1%

For the cases that replace the coffee stems direct-combustion for process heat generation the heat vector from the bioenergy system could potentially replace it, and for the case of coffee stems open-burning practices no energy vector needs replacement.

Definition of the counterfactual scenarios

Different counterfactuals are evaluated in this LCA to reflect the dynamic interactions and complexities of rural areas. The counterfactual scenarios comprise the baseline system and other potential counterfactuals representing current practices with coffee stems and rural power and heat generation systems in the coffee farms.

Baseline: Coffee stems burning in traditional cookstoves

The use of coffee stems as firewood in traditional brick-cookstoves is the most common use of this biomass in the rural coffee sector (Rodríguez Valencia and Zambrano Franco 2010); hence this practice is part of the baseline system. Firewood is the second most common cooking fuel in rural areas (DANE 2017) followed by LPG, as Table 18 indicates. The energy efficiency of traditional firewood cookstoves is generally very low (10-15% thermal efficiency) and generates high levels of airborne emissions and other contaminants; however (EPA 2016), the specific efficiency values depend on the design of the cookstoves.

Counterfactual 1: Coffee stems direct combustion for coffee bean drying

[7] Data on the number of household derives from the representative sample taken from the Colombian Quality of Life Survey by (DANE 2017)

Farmers with coffee processing plants within their farms use available coffee residues, such as husks from milling coffee beans and coffee stems as solid fuels for the coffee bean drying (Oliveros Tascón et al. 2009; Álvarez-Hernandez and Martinez-Tovar 2007). Semi-industrial stoves are fuelled with coffee wood, and husk and the heat generated is used to heat the airstream in the drying chambers (Cenicafe 2013).

The coffee stems direct-combustion process with application in the coffee drying stage is modelled in *Aspen Plus* using the combustion efficiency reported in (Cenicafe 2013) and obtaining the mass and energy balances of this system and the composition of the flue-gas emissions. For this scenario, the useful heat output from the coffee stems direct-combustion is matched to the heat recovered in the coffee stems gasification.

<u>Counterfactual 2: Coffee stems open-burning</u>

Open-burnings to dispose of coffee stems in rural areas have become less frequent, yet it can sometimes occur in coffee farms; therefore, this LCA also includes this practice. Data was collected from secondary sources to use generic numbers of air emissions from open-burning activities using a similar wood composition, as specific data for emissions generated from coffee stems open-burnings does not exist for Colombia or any other coffee producer country. For this scenario, the functional unit for both systems is presented in mass units (1 kg of biomass) as open-burnings can not deliver measurable energy products.

The energy systems, described below, complement the counterfactuals scenarios; ensuring that the bioenergy, baseline and counterfactual scenarios are comparable and deliver the same energy products or use the same amount of biomass (open-burnings case):

<u>Power generation in rural areas (part of the baseline system)</u>

In the rural areas of Colombia, electricity can be supplied by off-grid diesel-based generators or the power grid, depending on the location of the coffee farm. The first one is the most common case in isolated rural areas and is part of the baseline system. However, to reflect the reality of other rural areas in Colombia; an alternative set of counterfactuals scenarios also consider the impact of replacing the grid-electricity generation.

<u>Heat generation for coffee drying in rural areas (part of the baseline system)</u>

The use of fossil fuels to generate (process) heat is a common practice when carrying out mechanical drying within a coffee processing plant in the Colombian coffee sector (Roa-Mejía et al. 2000). This activity complements the baseline scenario when the coffee residues are not used for heat generation. This LCA considers the most common fossil fuel alternatives for coffee drying, i.e. mineral coal and diesel.

Scenario development for the comparative lifecycle impact assessment

More than 14 scenarios are considered for the net lifecycle impact assessment. These scenarios comprise realistic combinations of the bioenergy and counterfactual scenarios that can individually deliver equivalent energy outputs, with different conversion efficiencies, resources consumption and emissions discharges. Table 19 presents a matrix that illustrates all of the comparative cases between the bioenergy and counterfactual scenarios.

Table 19. Combination of bioenergy and counterfactual scenarios

Cases A	BIOENERGY SCENARIO			COUNTERFACTUAL SCENARIO			
	Bio-electricity (1 kWh)	**Bio-Heat** *coffee drying* (1.56 kWh)	**Heat for cooking** *(Alternative fuels)* (0.97 kWh)	**Electricity** (1 kWh)	**Heat for cooking** (0.97 kWh)	**Heat for coffee drying** (1.56 kWh)	**Open-burning** (No heat output)
A1	100% Bio-electricity	-	LPG cookstove	Diesel-Electricity	Coffee stems - cookstove	-	-
A2	100% Bio-electricity	-	Natural gas-cookstove	Diesel-Electricity	Coffee stems - cookstove	-	-
A3	100% Bio-electricity	-	Electrical stove	Diesel-Electricity	Coffee stems - cookstove	-	-
A4	71% Bio-electricity	29% Bio-heat	LPG cookstove	Diesel-Electricity	Coffee stems - cookstove	Hard coal coke - stove	-
A5	71% Bio-electricity	29% Bio-heat	LPG cookstove	Diesel-Electricity	Coffee stems - cookstove	Light fuel oil - 10 kW stove	-
A6	100% Bio-electricity	-	LPG cookstove	Grid-Electricity	Coffee stems - cookstove	-	-
A7	100% Bio-electricity	-	Natural gas cookstove	Grid-Electricity	Coffee stems - cookstove	-	-
A8	100% Bio-electricity	-	Electrical stove	Grid-Electricity	Coffee stems - cookstove	-	-
A9	71% Bio-electricity	29% Low-grade heat	LPG cookstove	Grid-Electricity	Coffee stems - cookstove	Hard coal coke - stove	-
A10	71% Bio-electricity	29% Low-grade heat	LPG cookstove	Grid-Electricity	Coffee stems - cookstove	Light fuel oil - 10 kW stove	-

Cases B	BIOENERGY SCENARIO			COUNTERFACTUAL SCENARIO			
	Electricity (1 kWh)	**Heat for coffee drying** (1.56 kWh)	**Heat for cooking** (0.97 kWh)	**Electricity** (1 kWh)	**Cooking fuel**	**Heat for coffee drying** (1.56 kWh)	**Open-burning**
B1	71% Bio-electricity	29% Low-grade heat	-	Diesel-Electricity	-	Coffee stems combustion - Furnace	-
B2	71% Bio-electricity	29% Low-grade heat	-	Grid-Electricity	-	Coffee stems combustion - Furnace	-

Cases C	BIOENERGY SCENARIO			COUNTERFACTUAL SCENARIO			
	Electricity (1 kWh)	**Heat for coffee drying** (1.56 kWh)	**Heat for cooking** (0.97 kWh)	**Electricity** (1 kWh)	**Cooking fuel**	**Heat for coffee drying** (1.56 kWh)	**Open-burning**
C1	100% Bio-electricity	-	-	Diesel-Electricity	-		Coffee stems open-burning
C2	100% Bio-electricity	-	-	Grid-Electricity	-		Coffee stems open-burning

Cases A	Comparison of the bioenergy system (incl. alternative cooking fuel) with counterfactuals that relate to coffee stems use in cookstoves, off/on-grid electricity and fossil-fuel base heat generation
Cases B	Comparison of the bioenergy system with counterfactuals that relate to coffee stems direct-combustion for heat generation (coffee drying) and off/on-grid electricity
Cases C	Comparison of the bioenergy system with counterfactuals that relate to coffee stems disposal in open-burning and off/on-grid electricity

Figure 26 exemplifies, using the case A1, the procedure followed to calculate the net environmental impact of the bioenergy scenario for a specific impact category. It also illustrates the calculation of the corresponding percentage reduction or increment of the impact categorie indicator as a result of the bioenergy system deployment.

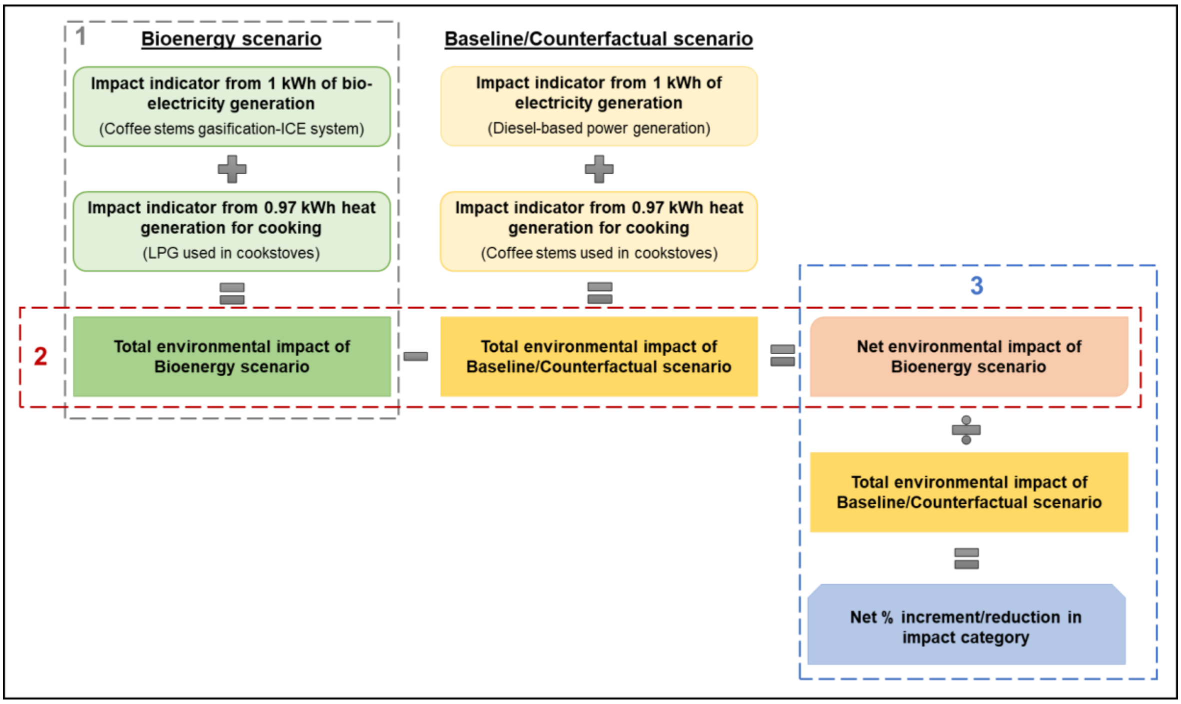


Figure 26. Procedure to calculate the net environmental impacts of the bioenergy system

Step 1 (grey dashed box): The total environmental impact of each scenario is obtained from adding the contribution of each system to the impact category. For example, for the bioenergy scenario, it is the sum of the climate change indicator from 1 kWh of bio-electricity generation and the climate change indicator from 0.97 kWh of heat generation (using LPG cookstoves). This procedure was repeated for each impact category considered in this LCIA.

Step 2 (red dashed box): The net environmental impacts of the bioenergy scenario are calculated as the difference between the total environmental impact of the bioenergy scenario and counterfactual scenario.

Step 3 (blue dashed box): Finally, the percentage increment and/or reduction on the impact category is the ratio between the net environmental impact of the bioenergy scenario over the environmental impact of the baseline/counterfactual scenario.

6.2 Lifecycle Inventory

For this stage, the system boundary defined in the LCA goal and scope determined the unit processes (activities) that were included in this inventory. This section also contains a description of the data gathered for the activities related to the baseline and counterfactual scenarios, used to calculate the net environmental impacts of the bioenergy scenarios. Information on how the data was collected and further analysed to use in this LCI was presented in chapter 4.3.

6.2.1 Lifecycle inventory for coffee stems gasification-CHP plant

Inventory for plant construction

This inventory comprises the inputs of materials, transportation and energy required to manufacture the equipment and build the infrastructure of the plant; and the outputs from emissions associated with these activities in addition to the waste treatment of materials. The raw data is obtained from the *Ecoinvent* database using two unit processes, a synthetic gas plant that is scaled-down to model the downdraft gasifier unit, and a heat and power cogeneration unit to model the power train of the bioenergy system.

The dataset of the infrastructure process of the synthetic gas plant is based on a generic fixed-bed gasifier plant with a thermal power output of 5 MW_{th}, and the capacity to gasify 32 t/day of wood chips and produce 80,000 Nm^3/day of syngas. The gasification unit process also includes the biomass pre-treatment stage and downstream gas conditioning. The inventory for the synthetic gas plant construction and CHP unit is presented in Appendix C.

The data used for the inventory of the plant construction are generic numbers that represent a technology but not the context of an existing gasification-CHP plant in Colombia. These figures, however, can provide a good record of materials consumption and emissions releases since gasification technologies are imported from overseas, generally from the USA (All Power Labs 2018). This LCI considered this fact when setting the unit process of the plant infrastructure specifying that for example the electricity and heat requirements to build the plant came from the USA electricity mix.

Later, to represent the fraction of the plant's infrastructure (PI) required to deliver the functional unit, 1 kWh of electricity, the inventory for the unit processes were scaled down to meet the operating hours, the service lifetime and smaller capacity of this bioenergy system. For the gasification plant, the equivalence 1 Nm^3 of syngas: 9.12×10^{-9} plant's unit from the LCI of the *'synthetic gas, from wood, at fixed gasifier'* unit process in Ecoinvent was utilised as a reference value. This number was adjusted using the linear correlation below from (Sinnot 2005) to fit the utilisation fraction of the infrastructure to a plant of lower syngas production capacity. The same procedure was applied to scale the utilisation of the CHP unit infrastructure. These numbers are included in Table 20 within the plant's operation LCI.

$$\%\,\boldsymbol{Infrst, small\ scale} = \%\,\boldsymbol{Infrst, large\ scale} \times \frac{\boldsymbol{Thermal\ capacity, small\ scale\ plant}}{\boldsymbol{Thermal\ capacity, large\ scale\ plant}} \quad \text{Equation 24}$$

Inventory for plant operation

Most of the inventory of the activities comprising the operation of the coffee stems gasification-CHP plant was collected using the mass and energy balance and gas composition from the *Aspen Plus* process modelling (refer to chapter 5.2). Detailed information on the characteristics and functionality of the main equipment, i.e. wood chipper, gasifier, gas clean-up equipment and heat recovery units, were presented elsewhere in chapter 4.2. The data collection was complemented using the Ecoinvent database when requiring information on generic processes, e.g. Diesel fuel burned in electric generation set.

Other activities of the plant's operation, such as the coffee stems transportation with animal-powered transport, and the coffee stems sun-air drying, are not included within the inventory. They don't have associated consumption of materials and energy and emissions releases.

Table 20 summarises the inputs and outputs of this lifecycle inventory and data observations for each unit process comprising the plant operation and utilisation of infrastructure and equipment.

Table 20. LCI for coffee stems gasification-CHP plant operation (FU:1 kWh of electricity)

Unit process	Amount	Unit	Observations
Product			
Bio-electricity	1	kWh	
Inputs from nature and technosphere			
Wood, hard, standing *(material from nature)*	1.5	kg	This input represents the coffee stems feed required for gasification, and covers for potential losses in the chipping and handling stages. A typical wood feedstock unit process from *Ecoinvent* database was used.
Stems chain-sawing *(material from technosphere)*	0.5	min	This input data specifies an approximate time the chainsaw is operated to obtain the raw biomass, using a unit process from *Ecoinvent* database. Context: coffee farmers generally use a petrol chainsaw to cut the stems and branches of a coffee tree.
Coffee stems chipping *(material from technosphere)*	1.2	kg	A stationary electric chipper can be used to model the wood chipping process of the coffee stems to the particle size required by the downdraft gasifier. An *Ecoinvent* database unit process is used, specifying the wood chips amount required at the outlet of the chipper and fed into the gasifier. Context: this chipper was selected as the system does not require mobile chipper and can, instead, self-generate the power required by the auxiliary equipment. This assumption was assessed later in the sensitivity analysis by evaluating the impact of utilising a diesel-based terrain chipper.
Water (gas scrubbing) *(material from technosphere)*	1.6×10^{-2}	kg	This number specifies the make-up water flow required to compensate for the water fraction that is purged in the venturi scrubber after gas cleaning. This figure was obtained from *Ecoinvent,* and a tap-water unit process with a global source specification from *Ecoinvent* was used as input.
Lubricating oil	1.3×10^{-5}	kg	The unit process is taken from the *Ecoinvent* database
Heat (gasifier start-ups) *(energy from techno-sphere)*	6.2×10^{-3}	MJ	The data input represents the amount of heat generation in a Diesel pre-burner, using a generic *Ecoinvent* unit-process (small-scale heat production with diesel/light fuel oil in a 10 kW burner). Context: Gasifiers needs to be pre-heated to start operation. The time of the start-up depends on the gasifier design; downdraft gasifiers have start-up times between 15 to 30 minutes. Diesel is the most likely available fossil fuel in rural areas; hence, this one is used instead of natural gas, to represent the start-up process.
Auxiliary power supply	0.01	kWh	This number represents the input of external electricity that supplies the plant's power demand during start-ups. Two different inputs of electricity source were used (and examined in the sensitivity analysis), power from a diesel generation and power from the national grid. The diesel generator is a generic unit process from *Ecoinvent* database, and for the grid electricity production, a new unit process was set in *Simapro* to represent the typical grid electricity mix in Colombia, using the unit processes for electricity by fuel in *Ecoinvent*. Details on how this unit process was set are presented in Appendix C (Table 38). Context: a small fraction of the plant's power demand is supplied externally by a diesel generator or by the power grid, depending on the location and size of the coffee farm. For this LCA, a 10% fraction (Oliveros Tascón et al. 2009) of the plant's power demand is assumed derives from an external source.

Use of gasification plant	3.3×10^{-9}	p	These figures represent the fraction of the plant's infrastructure and equipment (gasifier +CHP unit) required to generate 1 kWh of electricity (functional unit). The inventory for the plant's infrastructure was presented elsewhere in Table 36 and Table 37 in Appendix C. The unit processes were scaled down to meet the operating hours, the service lifetime and smaller capacity of this bioenergy system.
Use of CHP unit	9.9×10^{-8}	p	
Outputs			
Flue gas air emission *(from producer gas combustion)*	$CO_{2,Bio}$: 1.76	kg	The flue gas composition and yield after the combustion of the producer gas in the ICE/CHP unit were obtained from the process modelling results
	$CO_{,Bio}$: 0.028	kg	
	$CH_{4,Bio}$: 1.93×10^{-18}	kg	
	H_2O: 0.24	kg	
	N_2: 4.45	kg	
	NOx: 3.94×10^{-5}	kg	
	N_2O: 4.26×10^{-7}	kg	
Ash-char mix *(from gasifier)*	0.015	kg	Due to limitations of the process modelling approach, the data for the ash-char mix do not represent specifically the solids collected in the cyclone after the coffee stems gasification. Instead, figures from the *Phillys2* database for an ash composition of woody biomass. The detailed composition of the ash-char mix is presented in Appendix C. It was assumed that these ash-char solids mix are used for landfarming, considering the added-value of the nutrients within the mix. Due to the uncertainties with the final fate, different scenarios were examined in the sensitivity analysis.
Wastewater treatment	1.6×10^{-5}	m^3	This output represents the effluent discharged after the gas clean-up from the *venturi* gas scrubber. The effluent rate per kWh was obtained from the process modelling, yet the typical composition is taken from the *Ecoinvent* database. Context: Coffee farms generally have small water treatment facilities required to treat effluents during coffee processing; hence, it was assumed that the wastewater from the gasification plant could potentially be treated before being discharged to sewage.

This unit process represents the heat for domestic cooking using as an alternative fuel, LPG. This unit process is part of the bioenergy scenarios evaluated in the LCA, labelled as **cases A1** and **A4** in Table 28 and **cases C1-C4** in Table 29. This LCI was built using data reported in (EPA 2016) and complemented with the *Ecoinvent database V3.3* to account for the inputs and outputs associated with the production of the LPG.

Table 21. LCI of heat production for domestic cooking using LPG.
Functional unit: 0.97 kWh – Source: (EPA 2016) and Ecoinvent database V3.3

Unit process	Amount	Unit
Product		
Heat from LPG; traditional gas stove; at consumer *LPG cookstove thermal efficiency: 45%*	0.97	kWh
Inputs from nature and technosphere		
LPG, at consumer *(material from technosphere)*	0.155	kg
Outputs: emissions and waste treatment		
Emissions to air from the combustion of LPG in a domestic cookstove *(Flue gas yield and composition are taken from the database of US Environmental Protection Agency (EPA 2016))*	CO_2: 0.484	kg
	CO: 3.46x10-4	kg
	CH_4: 7.96x10-5	kg
	NMVOC: 5.19x10-4	kg
	NOx: 5.19x10-4	kg
	Particulates: (< 2.5 μm): 8.65x10-5	kg

6.2.2 Lifecycle inventory for baseline system and counterfactuals

The LCI for the counterfactuals, including baseline system, also required data collection from the *Ecoinvent* database, scientific and grey literature. For a transparent comparison between bioenergy and counterfactuals scenarios, data was adjusted to account for the lower energy efficiency of the devices in the counterfactuals resulting in higher material requirement.

The use of infrastructure for the baseline system and counterfactuals was not included due to lack of data availability; therefore, when comparing both systems impact category indicators, the use of the gasification-CHP infrastructure was excluded for consistency purposes. For the cases where the data related to the agricultural activities/processes do not represent information from Colombia, data from countries with similar rural socio-economic context were used. Table 22, Table 23 and Table 24 present the LCI for the baseline system. The LCI for the other counterfactuals, representing cases C (coffee stems direct-combustion for coffee drying) and cases D (coffee stems open-burning), were included in Appendix D.

Table 22. LCI for heat production in rural cookstoves (using coffee stems) – Functional unit: 0.97 kWh
Source: *Ecoinvent* Database V3.3

Unit process	Amount	Unit
Product		
Heat from rural cookstove	0.97	kWh
Inputs from nature and technosphere		
Wood, hard, standing (material from nature) *The input represents the coffee stems feed requirement to produce heat for domestic cooking. A hardwood feedstock unit process from Ecoinvent database was used.*	1.47	Kg
Chainsawing, delimbing, NE-NC/RNA *(US LCI database)* *The unit process specifies the chainsaw operation time to obtain the coffee stems. The data includes the diesel consumption, hydraulic oils and general lubricant required for the hydraulic systems and moving parts of the equipment.*	1.03	Min
Outputs: emissions and waste treatment		

Emissions to air from the combustion of coffee stems in domestic cookstoves *(Flue gas yield and composition are taken from (EPA 2016))*	$CO_{2,\ BIO}$: 2.497	kg
	$CO_{,BIO}$: 0.127	kg
	$CH_{4,BIO}$: 0.008	kg
	NMVOC: 0.135	kg
	SO_2: 5.89×10^{-4}	kg
	NOx: 0.0014	kg
	N_2O: 1.62×10^{-4}	kg
	PM (> 2.5 um, < 10 um): 0.016	kg
Wood ash mixture *Data for ash composition of woody biomass with similar proximate and ultimate composition to the coffee stems were used taken from Phillys2 database. Wood ash yield was taken from* (EPA 2016)	0.055	kg

Table 23. LCI for electricity production with a Diesel generating set

Functional unit: 1 kWh – Source: *Ecoinvent Database V3.3*

Unit process	Amount	Unit
Product		
Electricity (diesel-based generation)	1	kWh
Inputs from nature and technosphere		
Diesel *(material from nature)*	0.237	kg
Lubricating oil *(material from technosphere)*	0.000684	kg
Outputs: emissions and waste treatment		
Emissions to air from the combustion of Diesel burned in generating set (Flue gas yield and composition are taken from *Ecoinvent Database V3.3*)	CO_2: 0.7484	kg
	CO: 0.0684	kg
	CH_4: 1.71×10^{-6}	kg
	NMVOC: 0.00093	kg

	SO_2: 6.16x10^{-4}	kg
	NOx: 0.01404	kg
	N_2O: 6.12x10^{-4}	kg
	Particulates: (< 2.5 µm): 0.00174	kg
	Mercury: 4.7x10^{-9}	kg
	Cadmiun: 2.4x10^{-9}	kg
	Chromiun: 1.2x10^{-8}	kg
	Copper: 4.1x10^{-7}	kg
	Nickel: 6.05x10^{-8}	kg
	Zinc: 8.6x10^{-7}	kg
Waste mineral oil {RoW}	1.56x10^{-4}	kg

*RoW: Rest of the World

Table 24. LCI of heat generation production from hard coal coke combustion in industrial stove/furnace
Functional unit: 1.6 kWh - Source: Ecoinvent database V 3.3

UNIT PROCESS	AMOUNT	UNIT
Product		
Process heat (Coke furnace)	1.6	kWh
Inputs of material and energy from nature and technosphere		
Coke *(material from nature)* *This input represents the fuel feed required to generate 1.6 kWh of heat in an industrial stove/furnace (accounting for heat losses). The unit process is taken from the Ecoinvent database V3.3*	0.4	kg
Outputs: emissions and waste treatment		
Emissions to air from coke combustion in an industrial stove – *(Composition and yield of flue gas is taken from Ecoinvent database V3.3.)*	CO_2: 0.21	kg
	CO: 0.019	kg

	CH_4: $5.94x10^{-6}$	kg
	NMVOC: $2.97x10^{-7}$	kg
	SO_2: $1.72x10^{-4}$	kg
	NOx: $2.39\ x10^{-5}$	kg
	N_2O: $5.83x10^{-7}$	kg
	PM (> 2.5 µm and <10 µm): $3.97x10^{-6}$	Kg
	PM (< 2.5 µm):$1.99x10^{-6}$	Kg
	Mercury: $1.31x10^{-9}$	Kg
	Cadmiun: $6.67x10^{-10}$	Kg
	Chromiun: $3.33x10^{-9}$	Kg
	Copper: $1.14x10^{-7}$	Kg
	Nickel: $1.68x10^{-8}$	Kg
	Zinc: $2.39x10^{-7}$	Kg
Coal ash	0.0016	Kg

6.2.3 Biogenic carbon accounting

The coffee stems as biomass resource stores biogenic carbon as part of the photosynthesis process, where plants sequester CO_2 from the atmosphere (Harris et al. 2018). If the biomass is later combusted, as in this bioenergy system, the CO_2 is emitted back to the atmosphere, resulting in a net-zero addition of CO_2 to the atmosphere, i.e. *carbon neutrality* (Basu 2013d). This carbon neutrality is continuously challenged and should be examined for different bioenergy systems, and based on changes in the soil carbon stock and carbon storage capacities of long-rotation trees or wood products (Wiloso et al. 2016; Cherubini et al. 2011). For example, forestry systems that grow for decades have a long time lag between the CO_2 sequestration and its release back to the atmosphere, different from annual crops (Röder et al. 2019; Adams et al. 2013).

This LCA acknowledges the issue on biogenic carbon accounting, yet, considers that the biogenic CO_2 generated from the producer gas combustion has a net-zero GWP impact. This assumption is supported on the nature of this agricultural residue obtained after a short biomass turn-over time, i.e. trees pruned after growing periods of 4-6 years (Arcila Pulgarín 2007) and following guidelines of the IPCC methodology. The GWP impact associated with the emission of biogenic carbon in the form of CH_4 is included since CH_4 is not removed from the atmosphere and has a stronger GWP compared to CO_2 when applying the IPCC 100a LCIA method (IPCC 2013). The same applies to the emissions of biogenic carbon in the form of CO; however, this gas is short-lived in the atmosphere and can quickly transform into other forms (Wiloso et al. 2016)

6.2.4 Allocation procedure

The LCA methodology in section 4.3.4 presented an overview of the hierarchical steps that ISO 14044 set out as a guideline to manage multifunctional systems when conducting an LCA. The decision tree in Figure 16 was followed, and the subdivision of unit processes step discarded as it is not physically feasible to divide the unit processes of the gasification plant into smaller units. The system expansion step was possible, yet not useful when comparing the environmental impacts of two systems, the bioenergy and baseline systems.

The next step indicated an allocation method; however, as different allocation alternatives seemed potentially applicable to this bioenergy system, a sensitivity analysis was performed to examine the impact of the allocation method on the results. The partitioning factors for each allocation approach are summarised in Table 25, and the results of sensitivity analysis are presented later in section 6.4.

Table 25. Specific values and partitioning coefficients for the different allocations

Co-products	Exergy allocation			Energy allocation		Economic allocation	
	Exergy production (kWh-exergy)	η_C	αi (%)	Energy production (kWh-energy)	αi (%)	Cost of coffee drying ($/kg coffee)	αi (%)
Electricity	100,740	1	71%	100,740	37%	0.35	16%
Heat	42,048	0.24	29%	175,200	63%	2	84%

The exergy allocation is based on the exergy content of the electricity and heat vectors. These were determined by multiplying the annual electricity and heat production by the corresponding Carnot factors (η_C), as described by Njakou Djomo et al. (2013). The $\eta_{C,el}$ for electricity is 1 and, the one for heat $\eta_{C,th} = 0.24$ was determined using equation 25; assuming an ambient temperature of $T_a = 298\ K$ and a steam temperature of $T_s = 393\ K$. Finally, the partitioning coefficients were calculated as fractions of the exergy-based content for electricity and heat.

$$\boldsymbol{\eta_{C,th} = \frac{T_s - T_a}{T_s}} \quad \text{Equation 25}$$

The energy allocation was easier to calculate, as the partitioning factors correspond to the fractions of annual electricity and heat production from the total energy production of the system. In this case, both vectors are treated as having the same potential to do work, as indicated in (Boschiero et al. 2016).

For the economic allocation, the average costs structure for the coffee drying process (fuel for heating: 84% and electricity: 16%) proposed by Duque-Orrego (2001) was used. These values allowed to establish partitioning coefficients, making them comparable but also reflecting the economic value of the energy products within the context of the coffee sector.

6.3 Results of Lifecycle Impact Assessment

This section presents the main results of the lifecycle impact assessment phase using the inventory detailed above, and the LCIA approach described in section 4.5.4. The first set of results comprises the LCIA of the coffee stems gasification-power only and CHP generation systems. The second set presents the comparative LCIA between the bioenergy and counterfactual scenarios to calculate the net environmental impacts.

6.3.1 LCIA of the coffee stems gasification-ICE system

The LCIA for the coffee stems gasification-power/CHP plant comprised the results from the classification (implicit task) and characterisation of the inventory data. The results identified the processes causing the greatest impact over the environmental impact categories, as well as the effect of the major inventory stressors.

Data characterisation

Table 26 collates the characterisation results for the coffee stems gasification-power plant to generate 1 kWh of electricity, using the method *ReCiPe* midpoint–Hierarchical. This data characterisation initially considers just the power vector, assuming that the heat is not recovered and emitted as waste heat. Then, section 6.3.2 analyses the influence of different allocation methods (for the power and heat vectors) on the data characterisation.

Table 26. Characterised data for the production of 1 kWh of electricity

Impact category	**Midpoint results** *(Functional unit: 1 kWh of electricity)*	
	Total	**Unit**
Climate change (CC)	0.0165	kg CO_2,eq
Fossil Depletion (Fo-Dep)	0.0053	kg oil,eq
Particulate matter (PM)	8.58 $\times 10^{-5}$	kg PM10,eq
Metal Depletion (Me-Dep)	0.0014	kg Fe,eq
Photochemical Oxidant Formation (POF)	0.0015	kg NMVOC
Human Toxicity (Hu-Tox)	0.033	kg 1,4-DB eq.
Terrestrial ecotoxicity (Te-Ecotox)	4.3$\times 10^{-5}$	kg 1,4-DB eq.
Freshwater ecotoxicity (FW-Ecotox)	1.2 $\times 10^{-4}$	kg 1,4-DB eq.
Freshwater Eutrophication (FW-Eu)	1.1 $\times 10^{-4}$	kg P eq.
Terrestrial Acidification (Te-Acidf)	1.7 $\times 10^{-4}$	kg SO_2 eq.
Ozone Depletion (Oz-Dep)	2.05 $\times 10^{-9}$	kg CFC-11 eq

Figure 27 complements the results showed above by illustrating the characterised data disaggregated by the sub-stages of this bioenergy system to produce 1 kWh of electricity. The results are discussed below for each impact category and using the information presented by both, Table 26 and Figure 27.

▪ ***Climate change***

The climate change impact category is mostly affected by the greenhouse gas (GHGs) emissions associated to the operation stage of the coffee stems gasification-power system, accounting for 83% of the total impact category indicator for climate change (0.0165 kg CO_2 eq).

The following activities related to feedstock preparation and plant's operation have the highest contribution to this impact category:

- The off-grid electricity generation (from diesel generators) that supplies 10% of the plant's auxiliary power demand contributes with 57% of the climate change impact indicator

(0.0094 kg CO_2, eq/kWh). The remaining 90% of the plant's power consumption is self-generated by the gasification-power plant

- The coffee trees pruning with a petrol-fuelled chainsaw emits 0.0029 kg CO_2 eq/kWh and contributes 18% to this impact category.
- The combustion of diesel in a pre-burner for the gasifier start-ups (base case: 50 start-ups/year) releases $6\text{x}10^{-4}$ kg CO_2 eq/kWh, contributing with 3.6% to the impact category.
- The indirect emissions from the coffee wood chipping (0.000546 kg CO_2 eq/kWh) using a stationary electric chipper follow with a 3.3% share in this impact category. The electricity required to run the wood chipper is part of the auxiliary power demand of the plant and is supplied by the same gasification-ICE plant.

On the other hand, the emissions related to the construction of the gasifier unit (0.0018 kg CO_2,eq) and ICE/CHP unit (0.0010 kg CO_2 eq) together account for 17% of the total climate change potential. Within these two stages, the highest GHG emissions are released during the activities from burning coal for heat generation, the diesel-burning in building machines and the production of reinforcing steel.

The GHG emissions from the flue gases produced during the producer gas combustion have a marginal influence of less than 1% on this impact category. The impact indicator for this category sums 0.00013 kg CO_2 eq per kWh resulting from the emissions of nitrous oxide (N_2O) and biogenic methane (CH_4), as biogenic CO_2 is not accounted for in this impact category.

The major stressor of climate change for this system is carbon dioxide (CO_2), accounting for 94.4% of the total climate change impact indicator. These CO_2 emissions are generated from the combustion of fossil fuels (i.e. diesel, gasoline and coal) in different activities/processes during the operation and construction stages of the plant. The emissions of methane (CH_4: 0.00042 CO_2 eq) and nitrous oxide (N_2O: 0.00042 CO_2 eq) contribute with 2.6% and 2.2%, respectively to this impact category. CH_4 and N_2O emissions are also related to fossil fuel combustion when generating a fraction of the auxiliar power and during the plant construction.

▪ ***Fossil fuels depletion***

The impact category indicator for fossil fuel depletion sums 0.0053 kg of oil,eq. The activities that contribute to this category are the diesel-based auxiliar power generation (60%), the coffee trees pruning (21%), the plant's construction (12.5%), the heat generation for gasifier start-ups, with the associated diesel-burning (3.8%) and the wood chipping (2.2%). The trends of fossil fuel consumption across the different plant's activities correlate with the results for the climate change potential since the GHGs emissions result from the combustion of these fuels.

The main fossil fuels consumed during the plant operation activities are diesel for the generation of auxiliary power and heat for the start-ups, and petrol for the coffee plants chain-sawing; both fuels account to 84.5% the impact indicator. There is also some consumption of hard coal (8.4%) and natural gas (5.4%) related to processes during the plant construction, diesel-burning for auxiliary power generation and coffee wood chipping.

- ***Particulate matter formation (PMF)***

The total particulate matter released during the plant operation is $8.6x10^{-5}$ kg PM_{10} eq. The activities that contribute to this category are mainly the diesel-burning during the auxiliary power generation (64%); the trees chain-sawing (12%), the plant's construction (11%), and the NOx emissions from the producer gas combustion (10%).

The airborne emissions that contribute to the PM formation are mostly nitrogen oxides-NO_x (62%), particulates <2.5 um-$PM_{2.5}$ (26%), sulphur dioxide-SO_2 (7.6%) and particulates with diameter between 2.5-10 um-$PM_{2.5\text{-}10}$ (4%).

- ***Photochemical oxidant formation (POF)***

The POF indicator for this plant's construction and operation is equivalent to 0.0015 kg of Non-methane volatiles organic compound (NMVOC). The emissions from the producer gas combustion have the largest contribution (84.9%) to the formation of photochemical oxidants during the operation of the gasification-ICE plant operation. The emissions from the combustion of diesel in the power generation set and of petrol in the chainsaw follow, with contributions to the POF of 10.6% and 3.4%, respectively.

The precursor substances having a large impact on the formation of photochemical oxidants that later transform into ozone are carbon monoxide (CO) from the producer gas combustion with the highest share, 82% (0.0013 kg NMVOC), followed by nitrogen oxides (NOx) with 15% share ($2.4x10^{-4}$ kg NMVOC); most of them released during diesel (power generator) and petrol (coffee trees chainsawing) combustion.

- ***Freshwater eutrophication***

Freshwater eutrophication (FW-EU) is caused by releases of phosphorus (P)-containing substances into water and soil, leading to a rise in the nutrient levels of freshwater bodies. The P emissions to the soil during the wood ash-char landfarming contributing 98% of the FW-EU impact indicator (0.00011 kg P_{eq}). Other activities associated to the plant's construction, diesel-based power generation and the wood chipping have minimal contributions and together sum up the remaining 2% of the FW-EU potential, mainly with phosphate and phosphorus emissions to water.

- ***Terrestrial acidification***

The airborne emissions from many activities, mostly within the plant's operation phase, contribute to an increase in the soil's acidity, and consequently to the terrestrial acidification (Te-Acid) potential. The activities causing the largest impact on this category are the diesel-based auxiliary power generation (59%), the coffee trees chain-sawing (17%), the producer gas combustion (13%) and plant construction (10%). The major stressors contributing to this impact indicator are the NOx (79%), SO_2 (19%) and SO (2%) air emissions.

- ***Metal depletion***

An amount of 0.0014 kg of $Fe_{,eq}$ of metal resources are depleted in the lifecycle of the plant, with the consumption dominated by the construction of the gasifier and CHP unit, accounting for 66.8% of metal depletion. The manufacturing of the stationary chipper and the operation and manufacturing of the diesel engine each contributes with 21.4% and 10.7%, respectively, to the metal depletion indicator. The highest consumed metals in these activities are iron with 41% ($5.9x10^{-4}$ kg Fe eq), manganese with 20% ($2.7x10^{-4}$ kg Fe eq), chromium with 11% ($1.5x10^{-4}$ kg Fe eq), nickel with 4% ($5.8x10^{-5}$ kg Fe eq) and different copper alloys used for the production of low-alloyed steel, together contributing to 19% of metal depletion.

Toxicity categories: Human toxicity - Terrestrial ecotoxicity - Freshwater ecotoxicity

These toxicity categories evaluate the impact of the environmental persistence, accumulation in the human food chain and toxicity of chemicals emitted to the soil, water and air (Huijbregts et al. 2017).

Human toxicity (Hu-Tox) is affected mainly by the soil emissions during the disposal of the ash-char mix through landfarming, accounting for 85% of the total chemical emissions (0.033 kg 1,4 DB,eq). The coffee trees chain-sawing process and activities related to the plant's construction have associated chemicals discharges with smaller contributions, each accounting with 5.6% and 5.3% to Hu-Tox potential. The main stressors in this category are the soil emissions of Cadmium (47%), Zinc (26%), Manganese (10%) from the ash-char landfarming, and waterborne emissions of Barium (6%) and Manganese (5%).

Terrestrial ecotoxicity (Te-Ecotox) is similar, as with the human toxicity category, influenced by the soil emissions from the activity of ash-char mixture landfarming. This activity contributes with almost 99% of the Te-Ecotox impact indicator ($4.3x10^{-5}$ kg 1,4 DB,eq) with discharges to soil from different substances, such as Zinc (50%), Copper (26%), Vanadium (9%), Cobalt (7%) and Nickel (3%), Mercury (1%) and Chromium (1%).

Unlike the two previous impact categories, different activities from the plant construction and operation stages contribute to the Freshwater eco-toxicity (FW-Ecotox) category, with an indicator of 1.2×10^{-4} kg 1,4-DB,eq. In order of contribution, the activities with the strongest influence are the gasification-ICE/CHP plant construction (45%), the diesel-based auxiliary power generation (24%), the coffee trees chain-sawing (13%), the coffee wood chipping (10%) and the ash landfarming (6.8%). Multiple chemical discharges to water contribute to the FW-Ecotox, with Copper (32%), Nickel (21%), Barium (10%) Manganese (9%) and Zinc (5%) accounting for the largest contribution to this category.

Ozone depletion

The stratospheric ozone depletion is caused by the emissions of ozone-depleting substances (ODS) that cause a decrease in the atmospheric total ozone, which ultimately lead to human health damage. The chemicals containing ODS have chlorine and bromine groups that interact with ozone and have a persistent fate (Huijbregts et al. 2017).

The indicator for the ozone depletion impact category sums 2.05×10^{-9} kg CFC-11 eq for the operation of this bioenergy system. The activities contributing to this impact category are, as expected, related to the use of fuels deriving from crude oil, such as the diesel-based auxiliary electricity generation and the construction of the plant’s infrastructure, producing 82% and 13% of the ozone depletion impact category. The major stressors contributing to this category are the Bromotrifluoro-methane (or Halon 1301) and the Bromochlorodifluoro- Methane (or Halon 1211), chemicals used as fire suppression agents during the production of crude oil (Guest et al. 2011).

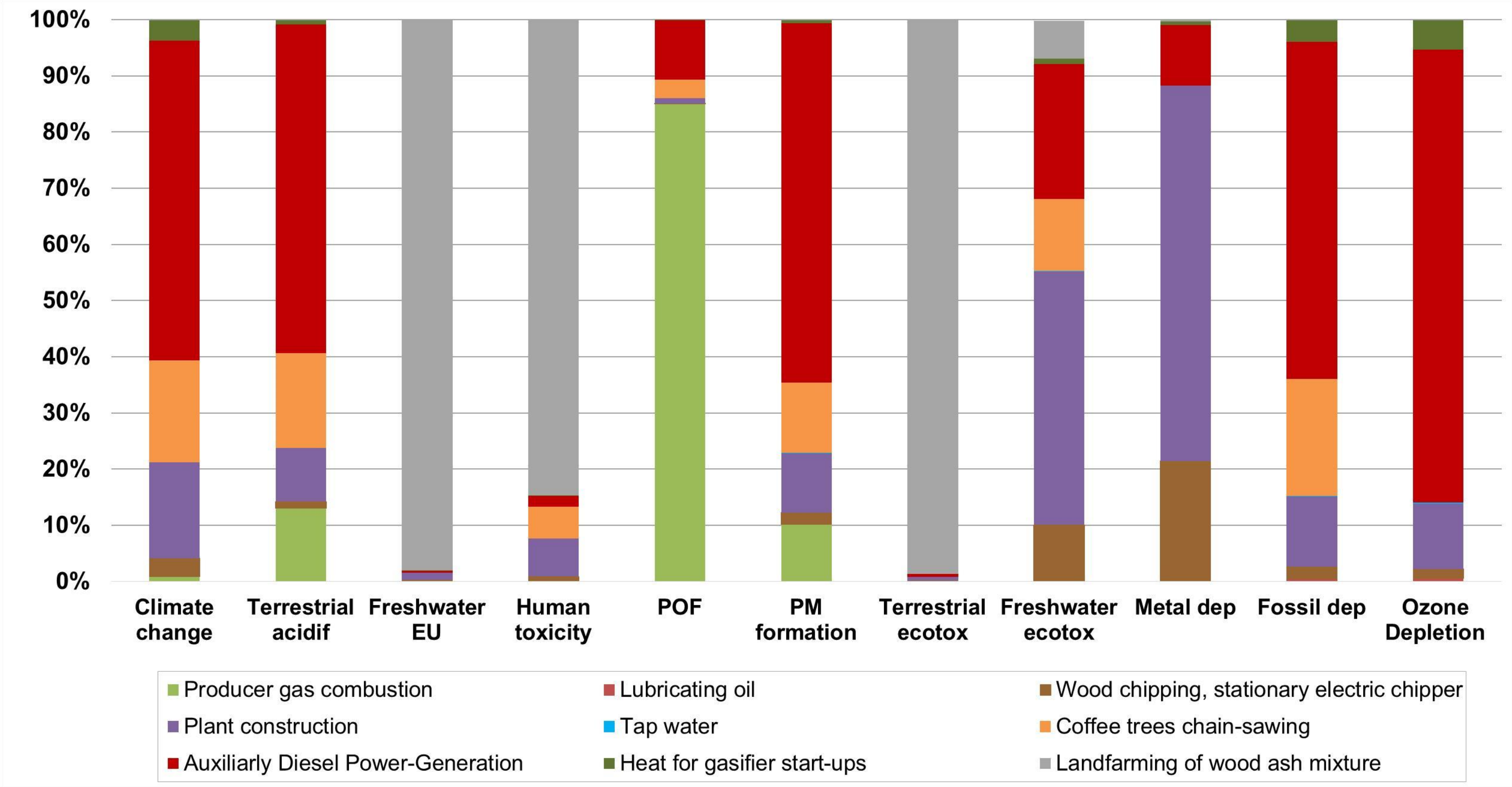


Figure 27. Characterised data for coffee stems gasification-power plant Operation and construction – ReCIPE Midpoint (H)

6.3.2 Impact allocation: Sensitivity analysis

After allocating 100% of the impact indicators to the production of electricity, this section examines the allocation of the impacts categories between the electricity and heat vectors. Different allocation methods were examined using the approach described in chapter 4.3.4.

Table 25 presents the characterised results for the same impact categories assessed above using an exergy, energy and economic allocation methods. As the numbers show, the impact indicators from the same vector (e.g. 1 kWh of electricity) can vary by one order of magnitude between different allocation methods. For the electricity vector, for example, the climate change impact indicator can range between 1.17 $x10^{-2}$ kg $CO_{2,eq}$ per $kWh_{,el}$ (exergy allocation) to 2.60 $x10^{-3}$ kg $CO_{2,eq}$ per $kWh_{,el}$ (economic allocation). Similarly, this occurs across many other impact categories.

Table 27. Comparison of allocation approaches for the production of electricity and heat

Impact Category	**Unit**	***Exergy***		***Energy***		***Economic***	
		Electricity (71%)	Heat (29%)	Electricity (37%)	Heat (63%)	Electricity (16%)	Heat (84%)
Climate change	kg $CO_{2,eq}$	1.17 $x10^{-2}$	$2.7x10^{-3}$	6.04 $x10^{-3}$	$6.18x10^{-3}$	$2.60x10^{-3}$	$8.20x10^{-3}$
Terrestrial acidification	kg $SO_{2,eq}$	$1.21x10^{-4}$	$3.0x10^{-5}$	6.24 $x10^{-5}$	$6.39x10^{-5}$	$2.69x10^{-5}$	$8.47x10^{-5}$
Freshwater eutrophication	kg $P_{,eq}$	$8.09x10^{-5}$	$2.0x10^{-5}$	4.19 $x10^{-5}$	$4.28x10^{-5}$	1.81 $x10^{-5}$	$5.68x10^{-5}$
Human toxicity	kg 1,4-$DB_{,eq}$	2.32 $x10^{-2}$	5.7 $x10^{-3}$	1.20 $x10^{-2}$	$1.23x10^{-2}$	5.17 $x10^{-3}$	$1.63x10^{-2}$
Photochemical oxidant formation	kg NMVOC	1.10 $x10^{-3}$	$2.7x10^{-4}$	5.68 $x10^{-4}$	$5.81x10^{-4}$	2.45 $x10^{-4}$	$7.71x10^{-4}$
Particulate matter formation	kg $PM10_{,eq}$	$6.1x10^{-5}$	$1.5x10^{-5}$	3.13 $x10^{-5}$	$3.20x10^{-5}$	1.35 $x10^{-5}$	$4.25x10^{-5}$
Terrestrial ecotoxicity	kg 1,4-$DB_{,eq}$	$3.1x10^{-5}$	$7.5x10^{-6}$	1.59 $x10^{-5}$	$1.62x10^{-4}$	6.84 $x10^{-6}$	$2.15x10^{-5}$
Freshwater ecotoxicity	kg 1,4-$DB_{,eq}$	$8.4x10^{-5}$	$2.1x10^{-5}$	4.35 $x10^{-5}$	$4.45x10^{-5}$	1.88 $x10^{-5}$	$5.91x10^{-5}$
Metal depletion	kg $Fe_{,eq}$	$1.0x10^{-3}$	$2.5x10^{-4}$	5.17 $x10^{-4}$	$5.29x10^{-4}$	2.23 $x10^{-4}$	$7.01x10^{-4}$
Fossil depletion	kg $oil_{,eq}$	$3.8x10^{-3}$	$9.2x10^{-4}$	1.94 $x10^{-3}$	$1.99x10^{-3}$	8.38 $x10^{-4}$	$2.64x10^{-3}$

Figure 28 illustrates better the variation of the characterised results across the different allocation methods using the impact category indicator for climate change. This figure confirms that the numbers above, allocating an environmental impact between the electricity and power vectors using different methods can yield significantly different results. No allocation is also an alternative for the LCA of CHP systems, assuming the functional unit is a combination of the energy products fractions by reflecting the ratio 1:1.7 ratio of electricity to heat for the coffee stems gasification-CHP system.

The LCA goal and scope guide the selection of the most appropriate allocation method (Adams 2011), where alternatives should be placed within the context of this research.

Considering this and the guidelines provided by the ISO standards, an exergy allocation approach was used in this case, in the absence of an allocation parameter that reflects a physical causality. For this gasification-CHP plant that delivers power and low-grade heat, applying an exergy allocation reflects better the higher work potential (availability) of electricity overheat. The concept of exergy from the second law of thermodynamics illustrates this, indicating that heat, a form of disorganised energy, has less available energy than work, a form of organised energy used to produce the electrical power (Cengel and Boles 2011).

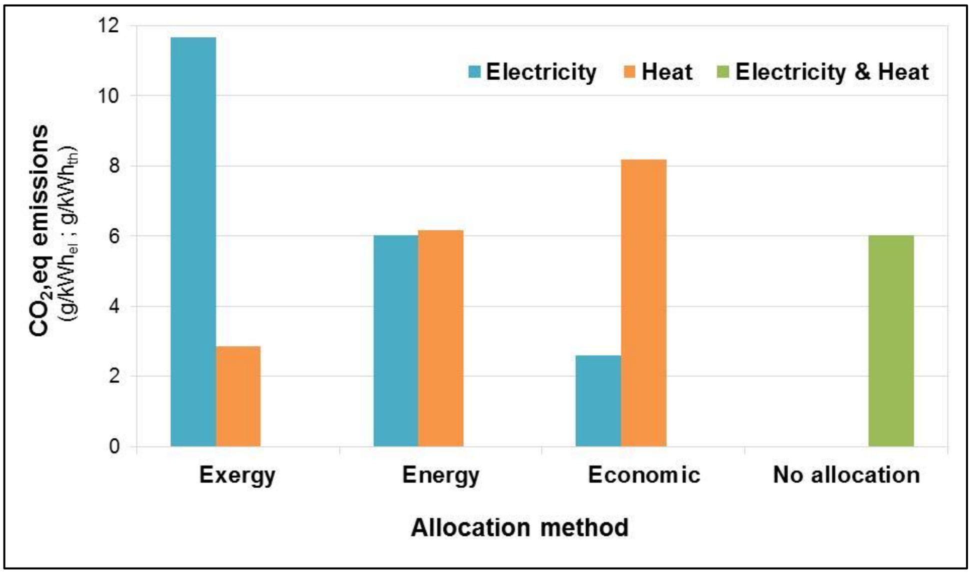


Figure 28. Climate change characterised results for impact allocation methods

To the contrary, the energy-based allocation assumes that both energy products have an equivalent potential (Hauschild et al. 2011). Also, the issue with the economic-based allocation is that the partitioning factors could vary with the price of the utilities in the market, all having different prices. It is the case in the coffee sector, where the electricity in coffee farms could come from the grid or Diesel power generation; similarly, with heat generation for the coffee processing where different fuels are utilised. An exergy allocation, instead, can provide a uniform basis when all utilities are energy services (Jana and De 2016). The no-allocation option for the power and heat vectors was not useful to compare the environmental impacts of the bioenergy system against counterfactuals and calculate the net environmental impacts.

6.3.3 Comparative LCIA of bioenergy and counterfactual scenarios

This section presents the LCIA results of the net environmental impacts of the bioenergy system by comparing bioenergy and counterfactual scenarios detailed in Table 15. The results represent the reductions or increments on the environmental impacts that could result from deploying the bioenergy system and replacing the counterfactuals. They were analysed in two sets; the first one presents the bioenergy scenarios for power only generation with their corresponding counterfactuals (Table 28); the second one presents the bioenergy scenarios producing power and heat and their related counterfactuals (Table 29).

A colour-based grading was given to the net percentage reductions or increments numbers across all the impact categories. The purpose of this colour differentiation was to attain a high-level understanding of the net reductions and increments across all the environmental impact indicators for the different cases.

Net environmental impacts from coffee stems gasification for power generation

The results in Table 28 are additionally classified into group A assessing the net impacts of replacing the coffee stems application in cookstoves and group B evaluating net impacts from replacing coffee stems open-burning. Key findings of this comparative LCIA are presented below:

<u>Results of group A: Replacement of the coffee stems application in cookstoves</u>

- The type of electricity that could be replaced by the bioelectricity vector has a significant impact on the net impact of the bioenergy system. Replacing the on-grid electricity vector could result in net increases in climate change, freshwater ecotoxicity, fossil fuel, metal and ozone depletion impact categories. Since the power system in Colombia has a large share of hydropower generation (>70%) and low consumption of fossil fuels, this derives into a power grid with a relatively low carbon footprint. This implies that trade-offs would need to be considered, to balance environmental benefits against limitations.
- The substitution of diesel-power generation by the bio-power vector could result in net reductions across most of the life-cyle impact categories, including climate change, fossil fuel depletion and particulate matter formation. Subsequently, this could translate into many environmental benefits, compared to the outcomes when replacing grid-based power, but independent from the use of the alternative cooking fuels.
- The selection of the alternative cooking fuel mode to replace the traditional biomass cookstoves has less influence on the net environmental impacts of the bioenergy scenarios. However, opting for electric stoves (powered by the bioenergy system) could

Table 28. Net environmental impacts from coffee stems gasification for power generation

Cases	Bioenergy / Counterfactual scenarios	Climate Change	Fo-Dep	Metal-Dep	PM form.	POF	Te-Acidfic.	FWater-EU	Te-Ecotox.	FW-Ecotox.	Human-Tox	Ozone-Dep
Cases A: Evaluation of displacement of traditional coffee wood cookstoves practices for bioelectricity generation												
A1	B: 100% Bio-Power + LPG Cookstove C: Diesel power + CS Cookstove	-48%	-36%	-75%	-98%	-92%	-89%	-78%	-76%	-78%	-76%	-34%
A2	B: 100% BioElectr + NG Cookstove C: Diesel Power + CS Cookstove	-48.6%	-51%	-73%	-97%	-94%	-87%	-73%	-72%	-25%	-61%	-77.5%
A3	B: 100% BioElectr + Elect Cookstove C: Diesel Electr + CS Cookstove	-86%	-85%	24%	-98%	-73%	-93%	-44%	364%	-54%	-34%	-86.2%
A4	B: 100% BioElectr + LPG Cookstove C: Grid Electr + CS Cookstove	68%	642%	116%	-97%	-85%	-26%	-77%	-81%	12%	-69%	5608%
A5	B: 100% BioElectr + NG Cookstove C: Grid Electr + CS Cookstove	66%	475%	136%	-96%	-88%	-11%	-72%	-78%	284%	-50%	1842%
A6	B: 100% BioElectr + Elect Cookstove C: Grid Electr + CS Cookstove	-56%	73%	950%	-98%	-52%	-58%	-41%	264%	131%	-15%	1093%
Cases B: Displacement of coffee stems open-burning practices												
B1	B: 100% BioElectr C: Diesel Electr + CS Open-burning	-98.4%	-98.3%	-91%	-99.5%	-95%	-98.6%	ND	ND	-96%	ND	-98.8%
B2	B: 100% BioElectr + Elect Cook C: Grid Electr + CS Open-burning	-93%	-79%	-20%	-99%	-90%	-94%	ND	ND	-76%	ND	7.7%

-50%	Net reductions (high positive effects) ≤ -50% in the impact category indicator, when comparing the bioenergy system with the counterfactuals
-50%	Net reductions (average positive effects) between -50% and 0% in the impact category indicator, when comparing the bioenergy system with the counterfactuals
50%	Net increments (highly negative effects) ≥ 50% in the impact category indicator, when comparing the bioenergy system with the counterfactuals
50%	Net increments (average negative effects) between 0% and 50% in the impact category indicator, when comparing the bioenergy system with the counterfactuals

- produce higher reductions in the climate change, fossil fuel depletion and terrestrial acidification potentials compared to the other fossil fuel-based cookstoves. On the other hand, this could cause increments on the metal depletion and terrestrial ecotoxicity categories. Higher consumption of metal resources and soil emissions from the ash mixture landfarming could be expected when utilising the bio-electricity vector to power the electric stoves.

Results of group B: Replacement of the coffee stems open-burning practices

- The abatement of coffee stems open-burnings by their utilisation in biomass gasification-power systems could result in high net reductions in all the impact categories, when diesel electricity is also replaced. This could potentially lead to a reduction in environmental and health impacts, particularly those tackling local air pollution problems as a result of less particulate matter formation.

- For these cases clustered under group B, the type of electricity substituted by the bio-power has a marginal influence over the impact categories. However, for the particular case B2, replacing the reference scenario could result in low net increments in ozone depletion (-7%). The reason for this lies in the slightly higher utilisation of crude-oil based fossil fuels (e.g. diesel) required to operate the coffee stems gasification-CHP plant, hence, an increase in ozone-depleting substances (ODS) compared to lower ODS emission from the grid-electricity generation and the open-burning of the coffee stems.

- For the freshwater eutrophication, human and terrestrial ecotoxicity categories, there is no conclusive data that could inform on the potential environmental impacts of implementing the bioenergy system over biomass open-burnings. Although the LCIA of the coffee stems gasification-power system (section 6.3.1) showed that soil emissions from ash-char landfarming contribute largely (>80%) in these categories, there is no inventory data reported on soil emissions from open-burnings for this type of biomass. Therefore the systems were not comparable for these impact categories.

Net environmental impacts from coffee stems gasification for power and heat generation

Table 29 collates the results for the comparative LCIA of the coffee stems gasification for power and heat generation system-CHP system and the related counterfactuals scenarios. For the bioenergy system producing two energy outputs, the environmental impacts were apportioned between the power and heat products using an exergy-based allocation, as explained in section 6.2.4.

Table 29. Net environmental impacts from coffee stems gasification for power and heat generation

Cases	Bioenergy / Counterfactual scenarios	Climate Change	Fossil fuel Dep	Metal Dep	PM form.	POF	Te-acidific.	Freshwater EU	Te-ecotox.	Freshwater ecotox.	Human tox	Ozone-Dep
Cases C: Displacement of coffee wood cookstoves practices for coffee wood bioelectricity and bioheat generation												
C1	**B:** 71%BioElectr+29%BioHeat+LPG Cook **C:** Diesel Electr + Coal heat + CS Cook	-72%	-56%	-82%	-98%	-93%	-92%	-86%	-80%	-90%	-89%	-44%
C2	**B:** 71%BioElectr+29%BioHeat+LPG Cook **C:** Diesel Electr + Diesel heat + CS Cook	-55%	-46%	-77%	-97%	-92%	-89%	-80%	-78%	-79%	-78%	-45%
C3	**B:** 71%BioElectr+29%BioHeat+LPG Cook **C:** Grid Electr + Coal heat + CS Cook	-56%	18%	-47%	-97%	-88%	-81%	-85%	-84%	-85%	-87%	240%
C4	**B:** 71%BioElectr+29%BioHeat+LPG Cook **C:** Grid Electr + Diesel heat + CS Cook	11%	129%	27%	-97%	-86%	-41%	-79%	-83%	-14%	-71%	216%
Cases D: Displacement of coffee wood combustion in industrial stoves (coffee bean drying) for coffee wood bioelectricity and bioheat generation												
D1	**B:** 71% BioElectr + 29% BioHeat **C:** Diesel Electr + CS combust (drying)	-98.4%	-98.5%	-93%	-98.7%	-92%	-98.5%	15.6%	-29.3%	-97.1%	-66.4%	-99%
D2	**B:** 71% BioElectr + 29% BioHeat **C:** Grid Electr + CS combust (drying)	-91%	-85%	-74.5%	-89.8%	-31%	-84.4%	56.3%	-66.4%	-87.7%	-31.9%	-67.4%

-50%	Net reductions (high positive effects) ≤ -50% in the impact category indicator, when comparing the bioenergy system with the counterfactuals
-50%	Net reductions (average positive effects) between -50% and 0% in the impact category indicator, when comparing the bioenergy system with the counterfactuals
50%	Net increments (highly negative effects) ≥ 50% in the impact category indicator, when comparing the bioenergy system with the counterfactuals
50%	Net increments (average negative effects) between 0% and 50% in the impact category indicator, when comparing the bioenergy system with the counterfactuals

The results are classified in group C that assesses net impacts from replacing coffee stems cookstoves and group D evaluating the net impacts of replacing the direct-combustion of coffee stems to generate heat for coffee drying.

Results of group C: Replacement of the coffee stems application in cookstoves

- The heat recovery and integration for coffee drying could enhance the overall environmental performance of the bioenergy system over the current baseline systems. These derive from fewer emissions and resources depletion that translates into higher net reduction across many impacts categories after replacing another fossil-based heat vector.

- The effect of the type of power generation that could be replaced, whether off or on-grid, is less influential when including the bio-heat vector. For example, comparing the case C3 (Table 29) with case A4 (Table 28) shows that heat integrating the bioheat vector could significantly improve the system's performance, resulting in net reductions in the climate change, metal depletion and freshwater ecotoxicity impact categories, instead of net increments. These results are obtained despite the fact that in the reference scenario the grid electricity is used.

- The type of fossil-based heat that is substituted by the bioheat vector has a considerable impact on the bioenergy system performance across many impact categories (i.e. climate change, fossil fuel and metal depletion, terrestrial acidification and freshwater ecotoxicity). As expected, since coal combustion causes higher emissions of GHGs and other pollutants, the displacement of coal-based heat (cases C1 and C3) could result in higher net reductions across these categories than the substitution of diesel-based heat (C2 and C4).

Results of group D: Replacement of the coffee stems direct-combustion for heat generation

- The scenarios evaluating the substitution of coffee stems combustion for process heat generation show that the coffee stems gasification-CHP system could be a more environmentally feasible process for energy cogeneration. Across most of the selected impact categories, the implementation of the bioenergy-CHP system could result in high net reductions in air, water and soil emissions, and lower resources depletion. This trend is representative for both; off-grid and on-grid power generation cases.
- The freshwater eutrophication impact category increased because of higher water discharges of P-containing substances from the bioelectricity vector, with respect to the reference system.

6.4 Results Interpretation

The final phase of the LCA comprises the interpretation and discussion of findings from the LCI and LCIA phases. A sensitivity analysis is included here to examine the influence of several parameters associated with the plant's construction and operation on the LCA results. Finally, recommendations were presented to enhance the feasibility of the bioenergy system, from an environmental perspective. Limitations identified along this LCA were also discussed.

6.4.1 Key findings: LCIA of the coffee stems gasification-CHP system

After examining the characterised data for the construction and operation of the coffee stems-gasification-power plant, the following key findings stand out from this LCIA phase:

- The activities related to the plant's operation have a significant environmental impact over the lifecycle of the system, contributing to most of the impact categories. The utilisation and burning of fossil fuels for upstream operation activities (i.e. coffee stems pruning, wood chipping and gasifier start-ups) cause the largest burden on many environmental impact categories.

- The plant construction activities have a significant influence over fewer impact categories, such as the metal depletion impact category (67%) and freshwater ecotoxicity category (45%).

- The emissions from the producer gas combustion in the ICE/CHP have a negligible impact (0.8%) over the climate change impact category. The CO_2 gas, the GHG with the highest concentration in the flue gas stream, has a biogenic origin and in ReCIPE is accounted as having zero global warming impact (GWP). The biogenic CH_4 concentration is very low; therefore, its contribution to the climate change category is marginal; in this case, ReCIPE method accounts its GWP. The non-GHG emissions from this flue gas, CO and NO_x, have a significant effect over other impact categories, such as in the photochemical oxidant formation (85%), particulate matter formation (10%), and terrestrial acidification (13%).

- The utilisation of the ash-char mixture for landfarming, as a waste treatment alternative, could have a large impact on the freshwater eutrophication, human toxicity and terrestrial ecotoxicity categories. However, since this ash composition was taken from secondary data (ECN Phyllis database), the results could carry on data uncertainty and not accurately represent the composition of the real ash stream from coffee stems. The impact of this activity over other potential waste treatment alternatives is analysed as a sensitivity case in the section below.

- The associated emissions from diesel-burning in the power generation set to supply a fraction of the plant's auxiliary electricity have a major contribution to several environmental impact categories, i.e. climate change, fossil fuel depletion, PM formation and terrestrial acidification. Different results could be attainable for different fractions of power supply to the plant, or for when the plant has accessible power-grid connections, that could support part of the auxiliary electricity. These other cases are further examined in the sensitivity analysis in the section below.

- The emissions from the coffee trees pruning with petrol chainsaws also have a significant contribution to the same impact categories indicated above, but at a lower level than the emissions from the diesel-based power generation.

6.4.2 Key findings: Comparative LCIA of bioenergy - counterfactual scenarios

The following bullet points highlight the key findings of the comparative LCIA between the bioenergy and counterfactual scenarios:

- For cases when the bioenergy systems replace diesel generation, emission reductions on air, water, and soil could be achieved, and resources depletion could lower. These results in net positive environmental impacts across all impact categories. Specifically, the electricity generation through the biomass gasification-CHP system could derive in a total net reduction of 49% in GHG emissions and up to 90% less particulate matter formation, when diesel power generation is displaced.

- In contrast, negative impacts on climate change, fossil, and metal depletion are obtained when the bioenergy system replaces, grid power; which in Colombia has a high share of hydropower generation. In this case, implementing the coffee stems gasification-CHP can result in increments of up to 65% in GHG emissions.

- The influence other counterfactuals exploring different coffee stems utilisation routes for cooking, and process heating showed that the gasification of coffee stems for power and heat generation could lead to positive environmental impacts.

- The bioenergy system benchmark against a suite of counterfactuals to calculate the net environmental impacts highlights the importance of investigating the impact of different counterfactual scenarios. This task allowed to identify benefits, but more importantly, trade-offs that should be addressed to achieve the desired environmental sustainability of the bioenergy system.

6.4.3 Sensitivity analysis

A sensitivity analysis was carried out to identify the parameters having the largest influence on the environmental impact categories. The LCIA results of the biomass gasification-power plant (section 6.3.1) provided an indication of which were those parameters associated with different activities of the plant operation. Different cases were defined, each one with a base case that represented the most probable scenario; next, each parameter was changed individually to analyse the relative effects of that parameter over the base case results.

Table 30 describes the sensitivity cases, indicating the base case, the sensitivity figures and the percentage variation from the base case and the main impact categories affected.

Initially, all the impact categories were included in the sensitivity analysis; then after analysing the results, they were screened to highlight the impact categories that were most affected by each parameter. Also, some cases were not possible to be assessed due to lack of data, such as the impact of different wood ash composition. Key findings drawn from this sensitivity analysis are summarised below:

- Changing the *source of auxiliary power generation* (case A), from diesel-based electricity to grid-electricity reduces fossil fuel consumption by (-55%). Consequently, this decreases the climate change potential (-49%), particulate matter formation (-63%) and terrestrial acidification (-56%) impact categories.

- Similarly, as above, lower *consumption of the auxiliary (Diesel) power generation* (case B1) decreases fossil fuel depletion, climate change, particulate matter formation and terrestrial acidification. On the contrary, higher utilisation of the external (Diesel) power generation (case B2), increases all these impact categories.

- Switching from an electric wood chipper to a diesel one (when grid-power is not available as an auxiliary source) increases the fossil fuel consumption, as well as the climate change and metal depletion potential. These increments are less significant than the ones caused by the parameters in case A and B.

- In the context of the rural coffee sector in Colombia, farmers alternatively use *machetes* to prune the coffee trees. The utilisation of this cutting tool does not consume fuel or generate emissions (case D); hence, it could reduce the fossil fuel depletion, climate change, terrestrial acidification, freshwater eutrophication and PM formation. Selecting one cutting tool over the other, yet, is not a straightforward decision since using machetes entails a labour-intensive and time-consuming task. This is not discussed further as the analysis of these social aspects were outside the scope of this LCA.

- The number of start-ups in a fixed period directly affects the amount of fuel consumed in gasifier pre-burner, in this case, Diesel. More starts-ups increase, as expected, the fossil fuel depletion, climate change, freshwater eutrophication and terrestrial acidification; the opposite happens when the numbers of stars-ups decrease. The selection of this parameter is closely related to the capacity factor of the plant, which, in turn, is influenced by the energy demand to the bioenergy plant.

- The numbers of operating hours of the plant also affect the capacity factor. Higher capacity factors (case F1) yield a reduction in the metal resource depletion (-15%) and freshwater ecotoxicity categories (-9%), as the plant's infrastructure is utilised more efficiently to deliver the same amount of energy. The opposite happens if the plant's capacity factor decreases (case F2). The numbers indicate, however, that the positive effect of achieving a high plant's capacity factor could be marginal, compared to the other cases, but this effect also combines with one of fewer gasifier start-ups.

- The final fate of the ash-char mixture could have a substantial effect on specific impact categories. The base case corresponds to the ash mixture landfarming to reincorporate the nutrients into the soil, representing a possible scenario in this rural context. However, if instead a different residues management is given to this by-product and is disposed of in a landfill, it could lead to a sharp increase in the freshwater-ecotoxicity (+1176%) and human toxicity categories (+398%). At the same time, but with a minor effect, it would decrease the impact on the terrestrial ecotoxicity (-99%) and freshwater-eutrophication (-97%).

Table 30. Sensitivity analysis for the LCA of the coffee stems gasification-CHP plant

Case ID	Sensitivity case	Base case	Sensitivity	Change from base-case	Main Impact Categories affected
A	Type of auxiliary power generation *(10% of plant's power demand)*	Diesel-based power generation	Grid-power	Different method	PMF (-63%); TeA (-56%); FoDp (-55%); CC (-49%);
B1	Fraction of auxiliary power generation *(diesel-based power)*	10%	20% (0.02 kWh)	+100%	PMF (+64%%); FoDp (+60%); TeA (+59%); CC (+58%); WaDp (38%);
B2			5% (0.005 kWh)	-100%	PMF (-32%); FoDp (-30%); TeA (-29%); CC (-28%); WaDp (-19%);
C	Coffee wood chipping	Electric	Diesel	Different method	FoDp (+15%); CC (+15%); MeDp (-10%)
D	Tree pruning	Chain-sawing	No chain-sawing *(manual pruning with machete)*	Different method	Fo-Dep (-21%); CC (-18%); TeA (-17%); FwE (-13%); PMF (-12%)
E	Gasifier start-ups *(related to operating hours)*	1 per week *(50 weeks – 15 min pre-burning)*	5 times per week	400%	Fo-Dep (+19%); CC (+18%); WaDp (+12%); FwE (+5%); TeA (+4%)
F	Operating hours *(related to plant's infrastructure)*	5256 (CF: 60%)	2628 (CF: 30%)	-50%	MeDp (+44%); FW-Ecotox (+28%); Wa-Dep (+25%)
			7884 (CF: 90%)	+50%	Me-Dep (-15%); FW-Ecotox (-9%); Wa-Dep (-8%)
G	Utilisation/Disposal of coffee wood ash mixture	Ash mixture landfarming	Ash mixture to sanitary landfill	Different method	FW-Ecotox (+1176%); Hu-Tox (+398%); Te-Ecotox (-99%); FW-Eu (-97%)

6.4.4 Improvement potential and recommendations

This LCA has underlined opportunities to enhance the environmental performance of this type of bioenergy systems in the context of rural areas, and also to expand on the data collection to improve LCA application in future research in bioenergy:

- In terms of climate change and fossil fuel depletion, there is potential to reduce the (indirect) GHG emissions and fossil fuel consumption from the plant's operation activities. The sensitivity analysis showed that limiting the utilisation of diesel-power generation and other upstream activities consuming fossil fuels (stems pruning and chipping, and gasifier start-ups) could potentially reduce these impact categories. The utilisation of electric machinery (e.g. electric wood chipper) could help to achieve this, whenever the power requirement is self-supplied by the gasification plant.
- Increasing the operating hours of the plant is recommended to reduce the environmental burden of the plant construction stage, maximise the benefits of utilising the bio-electricity and bio-heat vectors, and lower the consumption of fossil fuels and its associated impacts. These outcomes result as an increase in the plant's capacity factor and a reduction in the number of the start-ups of the gasifier. This could have wider positive impacts by increasing the process efficiency and the economic competitiveness of the bioenergy vectors.
- The end of life stage of the system, i.e. plant dismantling and potential recycling of materials was outside the system boundary, as not enough data is still available that could represent the potential environmental impacts of this stage. It is recommended that ongoing and future projects on biomass gasification carry on systematic data collection along the plant's lifecycle to enable more comprehensive LCA studies.
- The final fate of the ash-char mixture from the biomass gasification could have a significant impact on environmental issues, such as the freshwater eutrophication and toxicity-related impact categories. Therefore it is pertinent to characterise the ash composition which depends on the biomass feedstock (i.e. coffee stems) and operating conditions in the gasifier. This could better inform on whether the components of the ash stream could be used or not as nutrients to enrichen the soil for crops cultivation.

CHAPTER 7. ECONOMIC ASSESSMENT OF SMALL-SCALE COFFEE STEMS GASIFICATION-CHP

This chapter presents the results of the techno-economic assessment for the small-scale gasification-power/CHP system, obtained from the cost estimation and calculation of the levelised cost of electricity for this system. These outcomes contributed to achieving the research aim and the sixth objective of this research by analysing the estimated costs of the gasification system and its economic feasibility.

This chapter is structured into four sections. Section 7.1 presents the results of the study level-estimation of the capital, operation and maintenance costs of the gasification-power plant. Section 7.2 discusses the sensitivity analysis for the LCOE of this bioenergy plant, followed by section 7.3 that calculates and compares the LCOE of the gasification-power plant with the LCOE of the diesel-based generation system. Section 7.4 presents the LCOE of the coffee stems gasification system, when the heat recovery is included.

7.1 Costs estimation of the biomass gasification – power only system

7.1.1 Capital costs

Table 31 presents the results of the capital costs (CAPEX) of the coffee stems gasification-power system, disaggregating them in direct, indirect and working capital cost components. As indicated in Section 4.4, the main purchased equipment cost (PEC) was used as the baseline to calculate the other capital costs. The unitary cost of the combined gasification-power train unit was fixed as $ 2,000/kW using price quoted by manufacturers (All Power Labs 2018). This value was spanned between ($1,400/kW - $2,600/kW) to display, first the degree of accuracy of a study-level estimate, fluctuating between ± 30% of the reference value and, second, the range of the market prices for this type of gasification technologies.

Therefore, using the mean unitary cost ($ 2,000/kW) and the lower and upper limits of this value, the other CAPEX components for the system were also calculated and presented in Table 31 The percentages (%) in the last column represent the share of each cost component to the CAPEX of this gasification system. As it is expected, the purchased equipment cost has the highest share (59%) in the cost structure; suggesting it is a critical component in the CAPEX estimation. The value of this share is also within the range (40 – 60 %) reported in the literature by Towler and Sinnot (2013a) and Peter et al. (2003).

Other direct fixed costs components have also significant contributions to the CAPEX of the system at this level of operating scale, such as is the case of the installation costs (10%), and the combined contribution of the piping and electrical installation costs (8%). In real-life applications, these costs could be affected by the geographical location in rural areas, raising issues of access to construction materials and equipment, and a qualified workforce. The instrumentation and control cost component has a low contribution to the CAPEX since the gasification system has an integrated control system.

Table 31. Capital costs estimation of the biomass gasifier-power generation system

CAPITAL COST COMPONENTS				**Costs shares**
1. Direct Fixed Capital Cost (Direct FCC)				
1.1 Purchased Equipment Cost (PEC) (Gasifier-ICE unitary cost)	$ 41,500 ($ 1,400/kW)	$ 56,500 ($ 2,000/kW)	$ 71,500 ($ 2,600/kW)	61%
1.2 Other Direct Fixed Capital Cost segments				
f_1: Installation cost	$ 7,262.5	$ 14,125	$ 23,237.5	11%
f_2: Piping	$ 2,905	$ 5,650	$ 9,295	4%
f_3: Electrical Installations	$ 2,905	$ 5,650	$ 9,295	4%
f_4: Instrumentation & Control	$ 1,452.5	$ 2,825	$ 4,647.5	2%
Total DFC Cost	**$ 56,025**	**$ 84,750**	**$ 117,975**	$\sum \%\boldsymbol{DFC} = \mathbf{83\%}$
2. Indirect Fixed Capital (Indirect FCC) Cost segments				
2.1 Engineering and supervision	$ 4,482	$ 6780	$ 9438	6%
2.2 Contractor's fee	$ 1,121	$ 1695	$ 2359.5	2%
2.3 Contingencies	$ 2,801	$ 4238	$ 5898.8	4%
Total IFC costs	**$ 8,404**	**$ 12,713**	**$ 17,696.3**	$\sum \%\boldsymbol{IFC} = 12\%$
Fixed Capital Cost (FCC) DFC + IFC costs	**$ 64,429**	**$ 97,463**	**$ 135,671**	**95%**
3. Working Capital Cost (WCC)	**$ 3,221**	**$ 4,873**	**6,784**	**5%**
4. TOTAL CAPEX ESTIMATES (Fixed + Working Capital costs)	**$ 67,650**	**$ 102,336** (Reference value)	**$ 142,455**	**100%**

Among the indirect fixed capital costs, the engineering and supervision cost is the most relevant item contributing to 6% of the capital costs. This cost component could be crucial for adequate and more detailed design and engineering of the plant. The breakdown of these fixed capital costs also agrees with the one reported by the IRENA (2012).

Given the nature of this bioenergy system, the working capital cost represents a smaller portion (5%) of the CAPEX in comparison to other production plants, generally accounting between 10–20% of the fixed capital costs (Sinnot 2005). For a small-scale biomass gasification plant for cogeneration purposes, it is not necessary to maintain inventories of large quantities of raw materials and stocks of end-products. Hence it is plausible to estimate working capital costs with a low share in the capital costs structure.

7.1.2 Operating and maintenance costs of biomass gasification-power system

The operation and maintenance costs (OPEX) of the biomass gasification-power system are detailed in Table 32. As described in Section 4.4, some of the components of the OPEX are calculated as a fraction of the fixed capital costs, using a study (factor) estimate approach. The estimate of maintenance cost is 10% of the fixed capital costs, and subsequently, the variable miscellaneous costs are 10% of the maintenance costs. For this reason, the final values of the OPEX range within $13,982 - $19,674 per year, accounting for a degree of accuracy between ± 20% for study-level estimations.

The fixed operating costs, which do not change with production rate, dominate with an 87% share of the annual OPEX; where the maintenance costs constitute more than half of the OPEX (58%). This is consistent with the real operation of biomass gasifiers that require continuous inspections of the gasifier, the gas clean-up unit, and the gas engine, to avoid downstream fouling from to tar clogging. Regular maintenance could increase the lifetime of the plant, and this practice could have positives repercussions, including on the LCOE, as it is discussed later in the sensitivity analysis.

Table 32. Estimation of Operating costs of biomass gasifier-power generation unit

1. Fixed Operation Costs (FOC)				**Cost components share in OPEX**
1.1 Maintenance (10% of FCC)	$ 7,159	$ 9,746	$ 12,334	58%
1.2 Operating labour (one operator per shift)	$ 4,839	$ 4,839	4,839	29%
Annual FOC	**$ 11,997**	**$ 14,585**	**$ 17,172**	$\sum \%\boldsymbol{FOC} = \mathbf{87\%}$
2. Variable Operation Costs (VOC)				
2.1 Miscellaneous (10% Maintenance)	$ 716	$ 975	$ 1,233	6%
2.2 Diesel fuel (wood chipping)	$ 836	$ 836	$ 836	5%
2.3 Diesel fuel (gasifier start-ups)	$ 23	$ 23	$ 23	0.1%
2.4 Electricity (Auxiliary supply)	$ 409	$ 409	$ 409	2%

Annual VOC	**$ 1,984**	**$ 2,243**	**$ 2,502**	$\sum \%\boldsymbol{VOC} = \mathbf{13\%}$
3. Biomass costs	**NA**	**NA**	**NA**	
ANNUAL OPEX (Fixed + Variable Operation Costs)	**$ 13,982**	**$ 16,921** (Reference value)	**$ 19,674**	**100%**

The variable operation costs constitute the expenses that depend on the amount of power generated in the plant. They contribute 14% of the OPEX, and specifically the costs of the miscellaneous expenses and the Diesel fuel consumption for the mobile wood-chipper, together account for 11% of the OPEX. The other variable operating costs, i.e. the fuel costs for the gasifier's start-ups and the auxiliary electricity supply to the plant have a small contribution to the OPEX; however, both values depend on the capacity factor of the plant.

The biomass costs are assumed negligible when the gasification system delivers power only, assuming that the coffee stems are collected in the farms and used in situ. Hence transport and labour (collection) costs are considered negligible. This is not the case when the system operates in large-scale farms and community coffee process plants, requiring higher biomass resources, this is discussed in section 7.4.

7.2 Sensitivity analysis: LCOE of coffee stems gasification-power only

This sensitivity analysis evaluates the influence of costing and operational parameters on the levelised costs of electricity for this coffee stems gasification-power generation system. Details on the approach used to calculate the LCOE and perform this sensitivity analysis are described in section 4.5.5 and 4.5.6, respectively.

Figure 29 illustrates how and to what extent these parameters influence the behaviours of the LCOE over a fixed range of variation, ± 100%. Some parameters were not varied within the same interval, as this would result in negative values for the capacity factor, which does not have a logical meaning in this analysis.

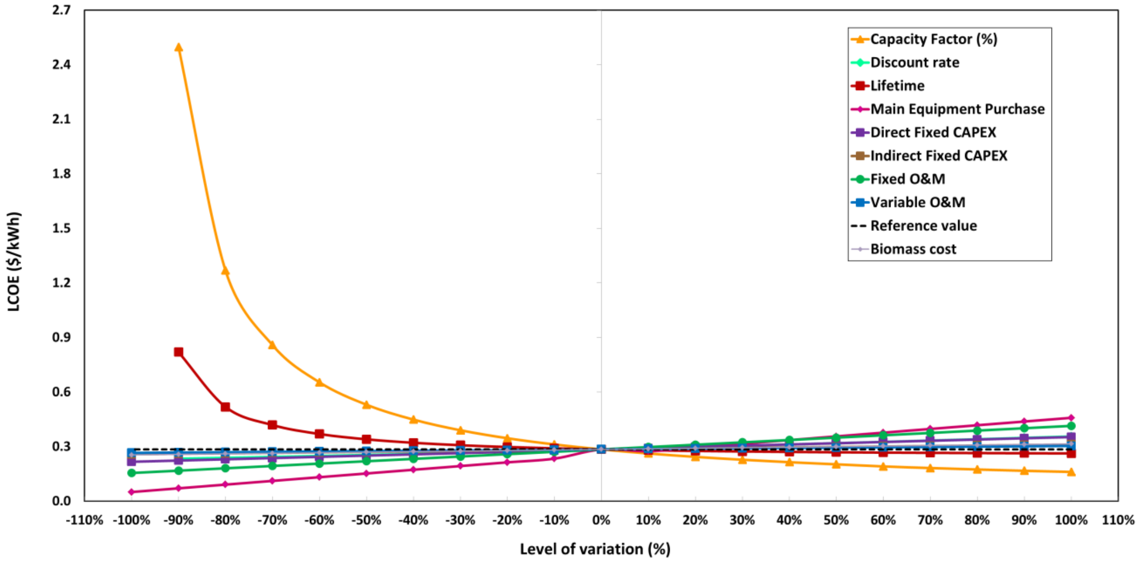


Figure 29. Sensitivity analysis for LCOE of biomass gasification CHP system

7.2.1 Effect of the capacity factor

The ***capacity factor*** **(CF)** has a strong influence on the LCOE. Figure 29 shows that as the capacity factor increases the LCOE (orange line) decreases; with a more noticeable variation for capacity factors below the reference value. In this case, the level of variation of the CF: -90% - 100 % over the reference value translates into a variation of the LCOE between 7% - 140%. Values over 90% would not be feasible in the real operation of a power generation device; therefore, this range is used with the sole purpose of illustrating the major influence of the CF over the LCOE. Additionally, the power load that could serve this gasifier is not constant over the day, yet, this sensitivity analysis assumed a constant power load to investigate the effect of the capacity factor.

Therefore, it is desirable to have a plant with a high capacity utilisation factor in order to minimise the LCOE. The factors that could determine the CF of this plant relate closely to how the biomass supply and energy demand match at the coffee (rural) sector level. It also guides the design and sizing of the plant to supply specific energy demands and prevents undermining the power generation capacity of the biomass gasification-power plant.

The power output of the small-scale gasifier-power system is also limited by the maximum hours of continuous operation before a routine maintenance cycle is required. Hence, a potentially feasible capacity factor for a 25 kW_e gasification-power only system implemented in rural areas could range between 55-75%.

7.2.2 Effect of plant lifetime and discount rate

The lifetime of the plant and the discount rate, the two parameters defining the capital recovery factor, have opposite effects on the LCOE trend.

The **lifetime of the plant** has an inverse relation with the LCOE; a longer lifetime of the plant reduces the LCOE (red line) of the system, yet this effect is more noticeable over shorter lifetimes (< 15 years), whereas for higher numbers the influence is lower. Therefore, the impact on the LCOE of incrementing the lifetime of the plant beyond 15 years would be less significant than the negative effect of a lifetime lower than six years. The expected lifetime of gasification systems ranges between 10-20 years (Fischer and Pigneri 2011; Nouni et al. 2007; Arena et al. 2010; Abe et al. 2007), although these figures are subject to adequate operation and maintenance schemes of the plant.

On the other hand, the **discount rate** has a directly proportional relation over the LCOE (blue line). Nevertheless, varying the discount rate over (1-20%) range has overall a negligible effect on the LCOE, as shown in Figure 29.

7.2.3 Effect of capital and operation cost components

All the cost components associated with the construction and operation of the gasification-power plant have a directly proportional effect on the LCOE, although with different levels of magnitude. These components are mentioned below by order of influence on the LCOE:

- The ***main purchased equipment*** is the cost component with the greatest effect on the LCOE trend (magenta line). This fact was anticipated from being the component with the highest cost share in the CAPEX, influencing the fixed and working capital costs of the plant.

- The variation of the ***fixed operational cost*** (green line), which accounts for the maintenance and labour costs of the plant, has a lower effect on the LCOE figure in comparison to the main equipment costs. The prioritisation of this cost element on the regular operation of the system could extend the lifetime of the plant. This has shown to have an adverse impact, as for shorter lifetimes, the LCOE increases.

- Next, on the level of impact follows the other ***direct fixed capital cost*** (purple line) with a marginal effect over the LCOE. This behaviour relates to minor participation of this component on the CAPEX, due to smaller installation requirements for a small-scale bioenergy system.

- The ***indirect fixed capital costs*** (brown line) and the ***variable operation and maintenance costs*** (blue line) have a negligible impact over the LCOE. The low share of these components on the CAPEX and OPEX of this small-scale plant support this outcome and results in overall low costs for the fuel (diesel) and utilities demanded by the plant.

- The ***biomass cost*** has a marginal influence on the LCOE, as expected from an agricultural residue with a current low value in the coffee supply chain.

The trends followed by the LCOE when varying the selected cost and operating parameters are characteristic to power generation devices, not just of this bioenergy system. However, the degree of influence of these parameters is representative of small-scale bioenergy systems implemented in rural areas, as Nouni et al. also highlights (2007). Certain features of this system, such as the low energy demand, the small scale of the system, the low (or negligible) costs of the biomass, and the geographic and economic context of the coffee sector could largely influence the effect of the evaluated parameters on the LCOE. The parameters with the greater impact on the LCOE of this small-scale gasification-power system are the capacity factor, the plant lifetime and the cost of the main equipment, and as such should be examined in more depth in detailed cost evaluations. Considering the influence of the capacity factor on the LCOE, this parameter was considered a variable when comparing the LCOE of the bioenergy and diesel-based power generation system.

7.3 LCOE of coffee stems gasification-power system

This section presents the results of the levelised cost of electricity (LCOE) calculation for the small-scale gasification-power system, following the bottom-up cost estimation approach for this TEA (Section 4.4). Since the capital and annual operation costs of the plant could fluctuate up to ±30% from the reference value for a study-level estimation, Table 33 collects the LCOE values of this system accounting for the CAPEX and OPEX variations. The assumptions behind the plant lifetime, discount rate and capacity factors values are described elsewhere, in Section 4.4. The items shaded in light grey are the direct inputs to calculate the LCOE; the others are the indirect numbers for the calculation of the annualised capital investment and the annual electricity generation.

Table 33. LCOE range for the coffee stems gasification-power plant

Calculation of LCOE	Lower end	Reference value	Upper end
Annualized Capital Investment	**$ 9,882.5**	**$ 13,454.4**	**$ 17,026.4**
Total Capital Costs	*$ 75,167*	*$ 102,336*	*$ 129,504*
Plant Lifetime	*15 years*	*15 years*	*15 years*
Discount rate	*10%*	*10%*	*10%*

Capital Recovery Factor	*0.13*	*0.13*	*0.13*
Total Operational Costs	**$ 13,982**	**$ 16,828**	**$ 19,674**
Annual Electricity Generation	**126,932 kWh/year**	**126,932 kWh/year**	**126,932 kWh/year**
Capacity factor	70%	70%	70%
Maximum Electricity Generation	181,332 kWh/year	181,332 kWh/year	181,332 kWh/year
Levelised Cost of Electricity	**0.19 USD/kWh**	**0.24 USD/kWh** *(Reference value)*	**0.29 USD/kWh**

The plant's capacity factor was 70%; at this operating scale, it is expected that coffee farms require a continuous power generation and that the biomass supply closely matches the energy demand of the farm throughout a year. The LCOE could fluctuate between 0.19 and 0.29 USD/kWh (±20%), corresponding to the lower and upper end of the CAPEX and OPEX of the plant, as the other parameters remain invariable.

Furthermore, to account for the strong sensitivity of the LCOE to the capacity factor; Table 34 presents the LCOE range considering plausible fluctuations of this plant's capacity factor over a year (55 – 75%). The reference values of the OPEX and CAPEX of this system are used for a conservative evaluation.

Table 34. LCOE range of the small-scale gasification-power system for CF range 55%-75%

Lifetime	**Discounted rate**	**Annualized CAPEX** (US$/year)	**Annual OPEX** ($/year)	**Capacity factor**	**LCOE** ($/kWh)
15 years	10%	$ 13,454 (44%)	$ 16,828 (56%)	**55% - 75%** Reference: 70%	**0.22 - 0.33** (CF:75% -55%)
CRF: 0.13					

The levelised cost of electricity of the small-scale coffee stems-gasifier-power only system is estimated within the range of **0.22 - 0.33 USD/kWh** for a plant's capacity factor between 55% – 75%. This capacity factor span represents the annual power generation of the plant under different scenarios of electricity demand in small and medium coffee farms.

The capacity factor of biomass power generation plants could span between 85%-95% (IRENA 2018); however, capacity factors of small-scale bioenergy systems in rural areas, is constrained by the low electricity demand and availability of agricultural residues. Capacity factors below 20% are consistent with the power demand of farms with low daytime electricity consumption (< 10 kWh/month), mostly requiring electricity for household activities during night-time hours (Abe et al. 2007). This is common for small farmers that cultivate and harvest coffee but do not carry out the coffee processing in their farms. On the contrary, capacity factors above 55% reflect the power demand of farms that carry out farming and coffee processing activities within the farm, consuming more electricity in the daytime hours. Therefore, the location of the system in a decentralised, remote rural village and the daily electricity demand of the coffee farm are two key aspects that determine the capacity factor of such power generation systems.

The LCOE for this small-scale bioenergy plant is set as 0.24 USD/kWh for a capacity factor of 70% (reference value) that represents a foreseeable scenario of the electricity demand-supply relation in small and medium coffee farms. The LCOE value was compared against the range of LCOE reported in different cost analysis for specific bioenergy technologies. This value falls within the range reported by the IRENA: 0.12 – 0.28 USD/kWh for gasifier-CHP technologies. On the other hand, it falls outside the LCOE span reported by Lazard (2017) for biomass direct power generation system: 0.055–0.114 USD/kWh; this is expected for more mature technologies. Direct comparisons of the LCOE of gasification systems, however, is a complex task due to the number of assumptions and parameters involved in its calculation.

LCOE: coffee stems gasification-power vs Diesel power generation

The LCOE of the coffee stems gasification-power system was compared against the LCOE of diesel-power generator and plotted for different capacity factor in Figure 30. The purpose of comparing these values was to evaluate whether power generation through this bioenergy system could be economically competitive in rural contexts. It was assumed that both systems have the same power generation capacity and operate under similar conditions.

Figure 30 also presents, for both LCOE values, the contribution of the capital, operation and fuel costs to the levelised cost of electricity. For the bioenergy system, the annualised capital costs and the annual operational costs have similar contributions to the LCOE value across the entire capacity factor span. For the diesel-power generation system, the fuel (Diesel) cost has a strong influence on the LCOE.

Contrary to the bioenergy system, the capital and operation cost components of the diesel system decrease sharply as the capacity factor increases. Also, the contribution of operating costs to the LCOE is marginal in comparison to the bioenergy system. This is consistent with more mature power generation technologies that require simpler operation and maintenance tasks. Fischer and Pigneri (2011) report a similar breakdown of the levelised cost of electricity for biomass gasification and diesel-based power generation systems.

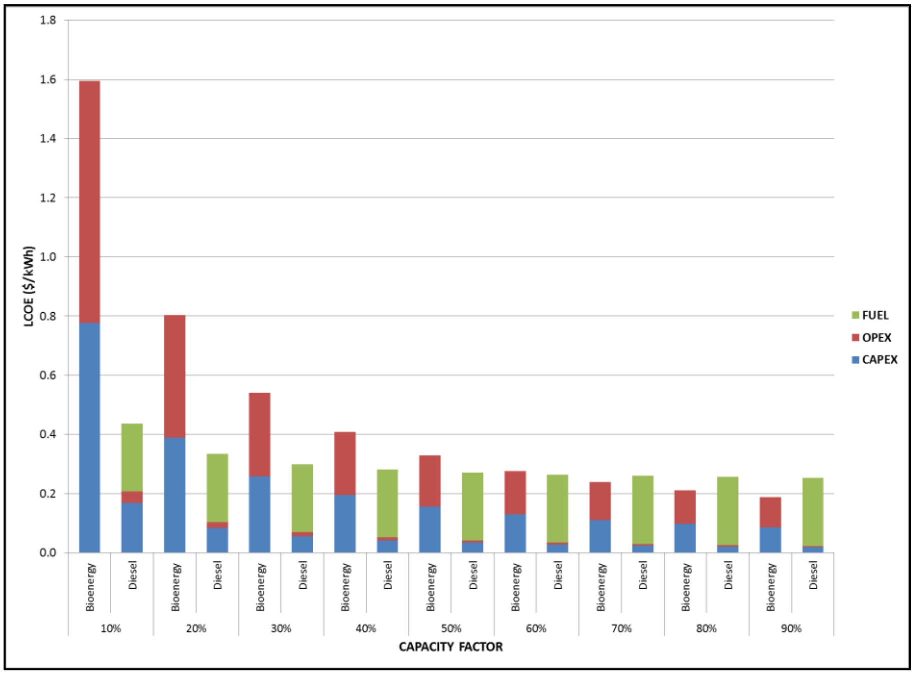


Figure 30. Costs distribution of LCOE of bioenergy and Diesel-based system

Figure 31 provides further insight into the economic feasibility of the gasification-power system illustrating how the capacity factor has a strong effect on the LCOE, and, subsequently, on the economic competitiveness of the system in rural areas.

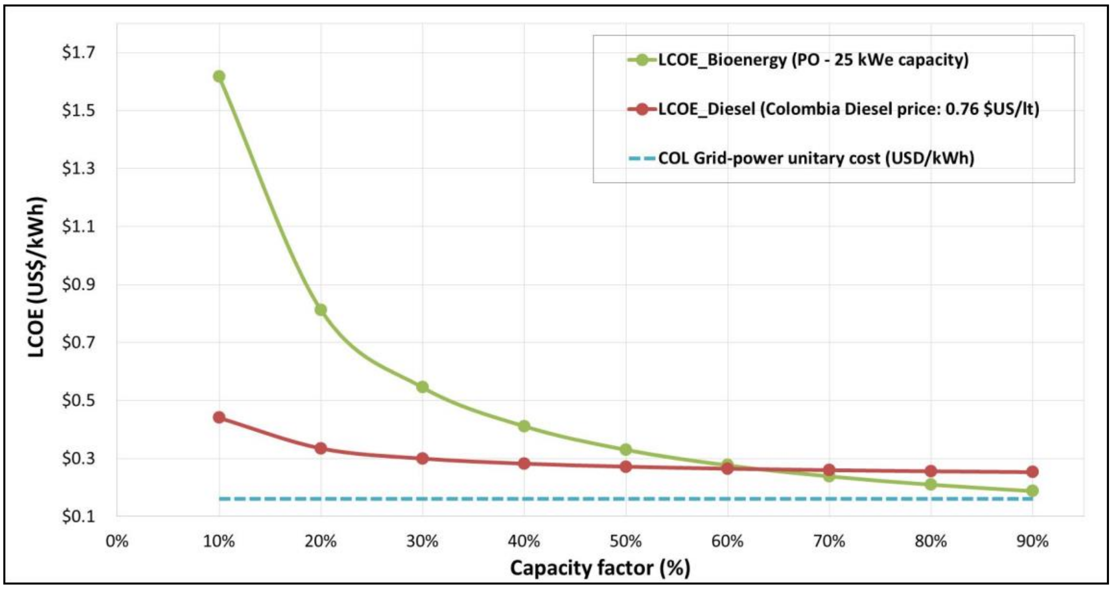


Figure 31. LCOE comparison of coffee stems gasification-power system vs Diesel power system

The LCOE of the gasification and diesel systems were plotted across the capacity factors range, including the customer's tariff of grid electricity. This value, however, is not directly affected by the capacity factor.

The LCOE profiles indicate that for capacity factors above 60%, the LCOE of the gasification-power plant levels with the LCOE of a diesel generation system when the fuel price is 0.76 USD/litter[8]. As crude oil exporters, Colombia has relatively low diesel price compared to other countries, e.g. UK: 1.49 USD/litter[9] and world average: 0.82 USD/litter.

Capacity factors higher than 50% are considered high for small-scale distributed generation systems due to low electricity demands in rural villages. However, coffee farms that also have farming activities (i.e. coffee processing plants) demand more daytime electricity, increasing the utilisation of the plant and the capacity factor (Rodríguez Valencia 2011). Higher utilisation of the gasification system results in lower unitary power generation costs making the system more economically attractive to coffee farmers.

Figure 31 also shows that the LCOE of the gasification system cannot match the tariffs of grid-based electricity under any utilisation capacity factor. This suggests that, under current conditions, implementing this bioenergy system could not be economically competitive in rural areas with grid-connection.

Additional measures could potentially improve the economic feasibility of the bioenergy system. Direct actions on the technology could involve accounting for additional cost savings from the heat recovery and costs reductions to the main purchased equipment. Indirect actions could entail, for example, a shift of current subsidies to diesel power generation in isolated rural areas, to incentivise distributed generation with agricultural residues.

For early commercial bioenergy technologies, like gasification, there is potential for cost technology reductions in the long term; however, reductions in the short term could still be marginal (IRENA 2018). Economic implications from the low-grade bio-heat integration into the system's feasibility are discussed in the next section.

7.4 LCOE of the coffee stems gasification-CHP system

The results in this section evaluated the levelised costs of electricity for the alternative coffee stems gasification systems that generate power and recovers the low-grade heat. This system of similar capacity incorporates a heat recovery unit that integrates the low-grade heat vector to applications within the coffee processing chain, such as coffee drying.

[8] Average Diesel price for a coffee region in Colombia: https://www.minenergia.gov.co/precios-ano-2019

[9] https://data.worldbank.org/indicator/EP.PMP.DESL.CD

The same costing factors and assumptions applied for the previous LCOE calculation as it is still a small-scale (downdraft) gasifier in the context of the rural coffee sector. This system, however, has differentiating factors when estimating its LCOE: i. the biomass costs are included at this operating scale, ii. the system has a lower utilisation capacity factor, as a result of the heat demand at specific periods, iii. The fossil fuel savings as a potential economic benefit from heat integration is accounted for as a heat-credit in the LCOE calculation.

7.4.1 Including biomass costs in the LCOE

The operation of the coffee stems gasification-CHP system farms in rural areas would demand more biomass resources that could entail costs associated with the feedstock collection and transport. However, setting a price to this type of biomass is difficult, as the current domestic utilisation of this residue in the coffee farms has resulted in informal and scarce data on the costs related to the coffee stems collection and transportation (including labour). This economic assessment uses an average figure that connects the costs of pruning coffee trees per hectare with the amount of dry wood obtained from these trees, *i.e. $ 0.052–0.072 USD per pruned tree → $ 0.016-0.022 USD/kg of dry-coffee wood*. In Colombia, this cost is usually paid by the National Coffee Federation (FNC in Spanish) to coffee farmers to incentivise the systematic renovations of coffee trees. The range of the biomass cost is also consistent with the agricultural residues costs ($ 0.02-0.05 USD/tonne) reported in (IRENA 2018; IRENA 2012).

Figure 32 illustrates again the distribution of costs in the LCOE, now including the biomass costs for the gasification system.

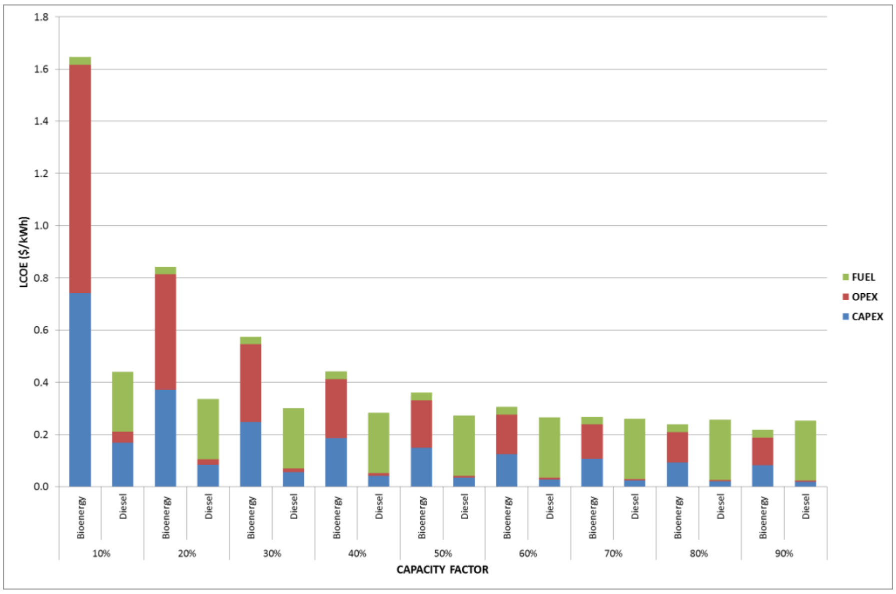


Figure 32. Costs distribution of LCOE of bioenergy (including biomass costs) and Diesel-power system

It is noticeable that the biomass cost, as the fuel of the system, has a marginal cost compared to the high fuel costs for the Diesel system.

7.4.2 Influence of lower capacity factor in the LCOE

The energy demand-biomass supply balance of the coffee stems gasification-CHP system differs from the power-only system in the energy vectors that produce and their final users. For the CHP case, the low-grade heat is used to supply part of the thermal energy demand of the coffee drying stage, and it could have applications in large scale farms and community coffee processing plants.

The recovery of the low-grade heat for the coffee drying stage, although it could increase the process conversion efficiency; it poses a restriction on the capacity factor of the system. For this case, the external heat demand from the coffee processing plant occurs during specific periods of the year, i.e. coffee harvest and processing periods. This could reduce the number of operating hours of the gasification plant and diminish the capacity factor interval where the plant could effectively operate. Therefore, since the heat demand changes along the year, with high peaks occurring after coffee harvest seasons, the system has a lower range of capacity utilisation factor (30%-60%).

Table 35 presents the cost estimates, and the LCOE range that results from a capacity factor span characteristic of the coffee stems gasification-CHP system. The LCOE presented here does not include the heat credit mechanisms, as this is evaluated in the next section.

Table 35. LCOE range of the small-scale gasification-CHP system for CF range 30%-60%

Lifetime	**Discounted rate**	**CAPEX** (USD/year)	**OPEX** (USD/year)	**Biomass costs** (USD/year)	**Capacity factor**	**LCOE** ($/kWh)
15 years	10%	$ 13,454	$ 16,474	$ 2,980	**30% - 60%** *Reference: 50%*	**0.58 – 0.31** *Reference: 0.36*

7.4.3 Effect of heat credit on the LCOE of the bioenergy system

The utilisation of the bio-heat in the coffee processing chain (i.e. drying stage) could represent extra fuel cost savings to coffee farmers. Therefore, to evaluate the potential economic benefits of the heat vector integration, a fixed heat price was set and represents the fuel (diesel) costs avoided from drying an equivalent amount of coffee beans.

This heat credit (-0.086 $US/kWh) is subtracted from the LCOE, as an added-value of this bioenergy-CHP system, but also as a fuel cost that farmers could avoid when deploying these systems in large coffee farms or community coffee processing plant. This heat credit varies with the type of fossil fuel used in the drying ovens, being Diesel the most expensive option among other fuels, such as coal and propane (Roa-Mejía et al. 2000).

Figure 33 illustrates the influence of the heat credit on the LCOE of the coffee stems gasification-CHP system, and how it compares with the LCOE with no heat credit, the LCOE for diesel-power generation and grid- electricity custom's tariff for different capacity factors.

The integration of the recovered heat vector in the coffee processing chain, and subsequently, the incorporation of the heat credit reduces the system's LCOE. For plant capacity factors above 50%, the $LCOE_{Bioenergy}$ with heat credit matches the $LCOE_{Diesel}$. Differently, the LCOE that does not account for the heat credit balances the Diesel generation costs for capacity factors above 70%. High capacity factors could be difficult to achieve when the bio-heat vector is also integrated into the coffee processing chain, as explained above.

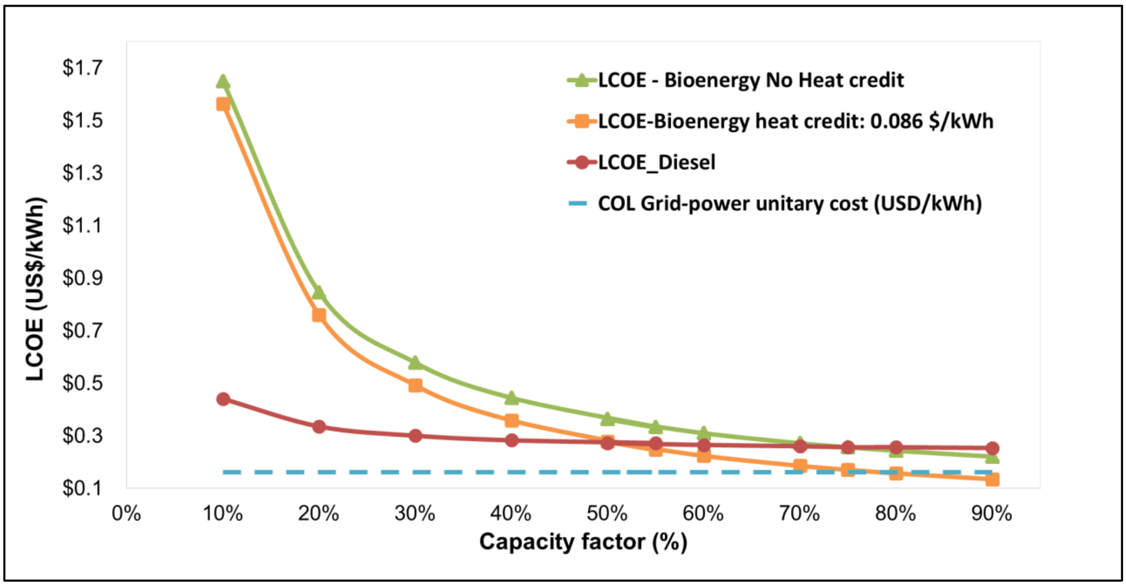


Figure 33. LCOE of coffee stems gasification CHP system vs LCOE Diesel generation system

The results suggest that accounting for the heat credit in the LCOE could enhance the economic competitiveness of power generation with the gasification-CHP system. Furthermore, including this heat credit reduces the LCOE to values that could potentially equalise the cost of grid-electricity for coffee farmers, although, at very high capacity factors.

This heat credit mechanism could positively impact the economic feasibility of these systems, together with high capacity factors. The heat credit application, more specifically, improves the flexibility of the system, allowing operations when the heat demand is concentrated in specific periods of the year. It could also expand its applicability in rural coffee areas with grid-interconnection, providing opportunities to boost energy security and independence to centralised power generation.

7.5 Key findings of the techno-economic assessment

This chapter presented the results of the techno-economic analysis of the coffee stems gasification system for power and heat generation in the context of the Colombian coffee sector. The outcomes of this analysis provided with costs estimations for this technology and help determine its economic feasibility.

The capital and operating costs of the coffee stems gasification-CHP plant contribute similarly to the plant's total costs. The costs of the main equipment are the most significant cost components, mostly due to the early deployment of this technology in the market. Biomass costs, however, have a marginal share in the total costs, since the feedstock are low-cost agricultural residues use in situ/close to the point of collection.

The sensitivity analysis indicated how cost and operation-related parameters influenced differently the levelised costs of electricity, as the economic metric of this analysis. The capacity factor showed it has the greatest effect on the LCOE, with an inverse relation. Other parameters, such as the lifetime of the plant, the main equipment costs and fixed operating costs, also have a significant effect on the LCOE.

The LCOE was calculated for two cases. The first one accounted for the coffee stems gasification system for power only generation, representing the energy demand of small and medium coffee farms. The second one was a similar system that also supplied power and heat to large coffee farms and coffee processing plants.

Relevant findings from this LCOE-based assessment are summarised below and contribute to boosting the economic competitiveness of the system, and the feasibility for its implementation:

1. Attaining high capacity factors for the coffee stems gasification PO/CHP systems is crucial to significantly reduce the LCOE of this bioenergy system and level this cost with the LCOE for diesel power generation. This closely intertwines with the energy demand of the coffee farms, their socio-economic contexts and coffee processing capacities.
2. Integrating the bio-heat vector during the coffee processing plant permits the incorporation of a heat credit in the LCOE that represents fuel costs savings during the coffee drying stage. This heat credit reduces the LCOE of the gasification system, making this system cost-competitive with diesel-power generation at lower capacity factors. It also

allows matching the customer's tariffs for grid-electricity, which is not possible when the heat credit is not included.

CHAPTER 8. MULTIDIMENSIONAL FRAMEWORK TO ASSESS BIOENERGY FEASIBILITY AND CORRELATIONS TO SDGs

Deploying technologies, whether mature or emergent, require a comprehensive assessment that goes beyond the technical feasibility and evaluates wider sustainability implications. After analysing the results from the technical, environmental and economic assessments, Chapter 8 integrates these findings and discuss pivotal drivers and trade-offs that could help to attain feasible bioenergy systems in rural contexts. These key outcomes were aligned to relevant Sustainable Development Goals to identify wider co-benefits to sustainable development that could be achieved with this system's deployment in rural areas.

8.1 A multidimensional framework to assess bioenergy feasibility

The outcomes from the technical, economic and environmental assessments underlined several pivotal drivers and trade-offs to these bioenergy systems deployment in rural areas. Many of these factors interconnect across the three studied dimensions becoming in relevant synergies that could guide and foster the feasibility and sustainability of these systems. Furthermore, the introductory chapter highlighted the prominent role that the sustainable deployment of bioenergy could play to achieve the 2030 Agenda for Sustainable Development. Therefore, a multidimensional framework was developed to integrate these pivotal factors and correlate them to the SDGs to capture these findings, reflect upon the linkages with the SDGs, and extract high-level inferences.

Figure 34 illustrates this framework which comprises four dimensions. The first dimension relates to the resource availability and the process modelling outcomes, highlighting technical performance-related drivers. The second dimension links to the identified lifecycle environmental impacts, underlining potential drivers and trade-offs from replacing current practices. The third dimension relates to the economic assessment and emphasises conditions, where the bioenergy system could be economically feasible. Finally, the fourth dimension examined high-level societal implications that derive from the analysis of the biomass supply-energy demand balance in the rural coffee sector and the other dimensions.

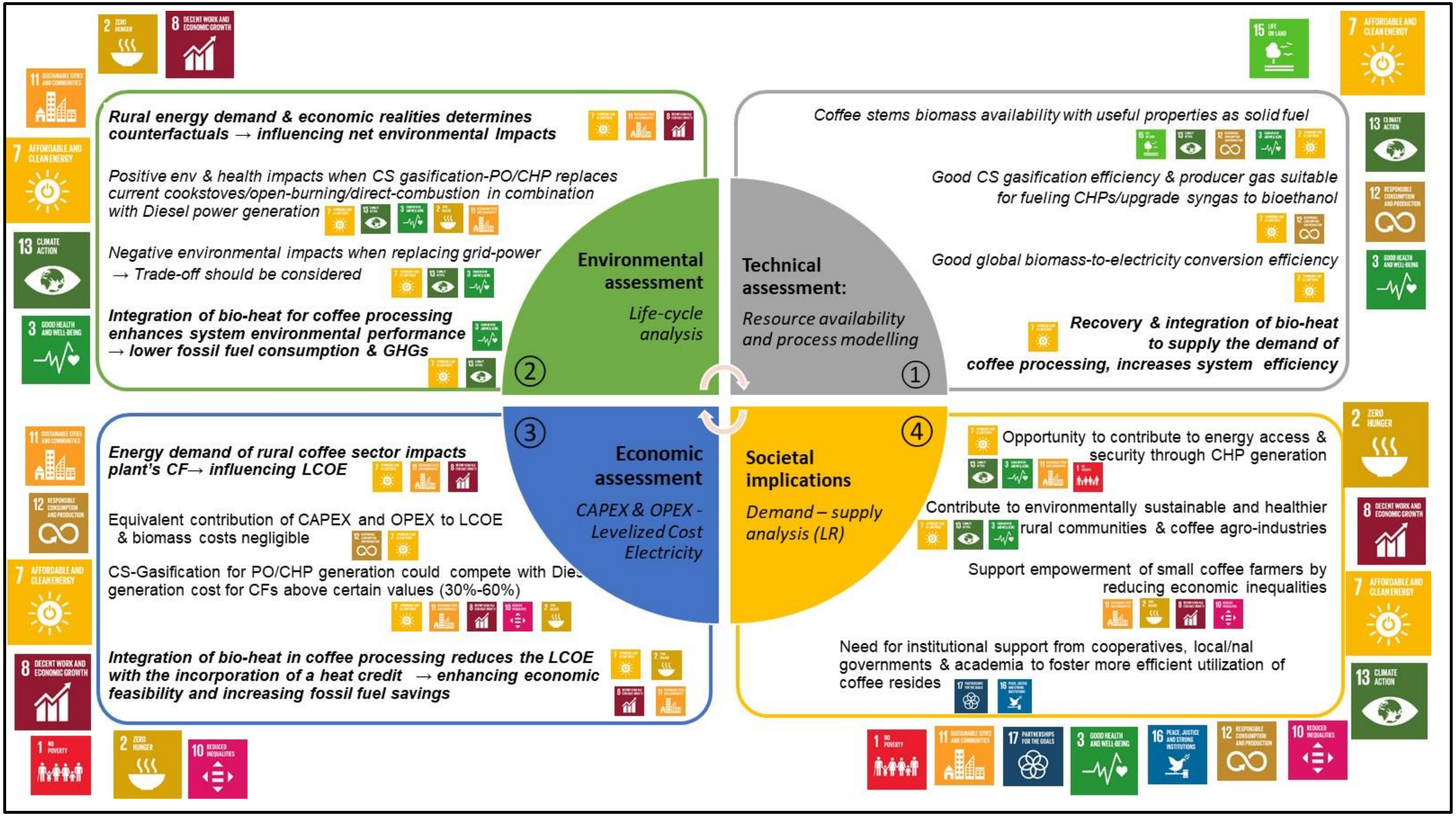


Figure 34. Multidimensional framework of synergies and trade-offs of bioenergy and their correlation to the SDGs

8.2 Recognising synergies in bioenergy generation using agri-residues

The framework highlights the synergies that interconnect across the different dimensions, by enhancing or hindering the feasibility from deploying these systems:

- **The balance between biomass availability and energy demand at a coffee farm-local level is key to determine the scale and characteristics of the bioenergy system**. This balance influences the technical, environmental and economic performance, and consequently the potential feasibility of the system.

- **The integration of the bio-heat vector to supply the heat demand of the coffee processing chain improves the overall performance and feasibility of the system.** It enhances the biomass conversion efficiency of the system producing two useful energy outputs from one biomass input. It also increases the net positive environmental impacts as a result of less consumption of fossil fuels. Finally, it could make the bioelectricity more costs competitive to the diesel power generation and grid-electricity, with a heat credit that represents fuel savings from heat generation in the coffee sector.

- **The capacity factor of the plant is another determinant feature to the feasibility of this system.** Higher capacity factors result in lower levelised costs of electricity for the bioenergy system, balancing with the electricity costs from diesel generators for certain CF values. Additionally, higher capacity factors lead to fewer plant start-ups which reduce fossil fuels burnings and consequently decrease associated emissions and operation costs.

- **An analysis of the counterfactuals in the rural sector allows identifying drivers and trade-offs to the deployment of bioenergy systems**
  The scattered location of coffee farms in Colombia and the different socio-economic realities of these farmers suggest that there are multiple contexts within the same coffee sector. Hence, many counterfactuals arise, and they should be examined against the proposed bioenergy system to determine where the benefits and trade-offs lie from a technical, environmental and economic perspective. The counterfactuals particularly influence the net environmental impacts and economic feasibility of the bioenergy system relative to the baseline system.

8.3 Linking drivers and trade-offs of this bioenergy system to SDGs

This framework also correlated the key drivers of these bioenergy systems deployment to the 2030 Agenda for Sustainable Development, showing how this bioenergy system could align and support the achievement of specific SDGs targets. Over 11 SDGs were linked to the identified pivotal drivers for these systems' deployment. Certain SDGs come across multiple times, suggesting a strong two-way driving correlation between them, which was visually denoted in the framework with larger icons. It is worthwhile highlighting the following aspects about these relevant SDGs and their targets:

SDG 7 - Clean and affordable energy

→ *Target 7.1: Ensure universal access to affordable, reliable and modern energy services*

→ *Target 7.2: Increase the share of renewable energy in the global energy mix substantially*

The SDG 7 shows strong connections with the key drivers across all dimensions, acting as, both, a rationale for and beneficiary from the implementation of these systems. Specifically, targets 7.1 and 7.2 could be supported by the system's technical viability (i.e. adequate gasification and cogeneration efficiencies), the potential environmental benefits (i.e. reduction in emissions and resources depletion) and economic competitiveness (i.e. fuel costs savings for power and heat generation).

SDG 13 Climate action

→ *Target 13.2: Integrate climate change measures into national policies, strategies and planning*

The SDG 13 is also prominent within the framework and is a primary driver to promote the sustainable deployment of renewable energies for distributed generation. The environmental benefits that this system could generate, particularly, for GHG emissions reductions, evidence the potential of agricultural residues to deliver low-carbon energy at suitable operating scales. This type of bioenergy conversion could be highly relevant and impactful in developing countries where these resources are locally available and could be used more efficiently, tackling polluting rural practices.

SDG 3 - Good Health and Wellbeing

→ *Target 3.9: <u>Reduce the number of deaths and illnesses</u> from hazardous chemicals and <u>air, water and soil pollution and contamination</u>*

The rationale and contribution to support this goal derive from the extended health benefits that could results by reducing local air pollution, as a consequence of less particulate matter formation and reductions in the human toxicity potential. This could be achieved by replacing the current uses of this biomass in cookstoves and disposal in open-field burnings.

SDG 8 – Decent work and economic growth

→ *Target 8.2: Achieve higher levels of economic productivity through <u>diversification, technological upgrading and innovation</u>, including through a focus on <u>high-value-added and labour-intensive sectors</u>*

→ *Target 8.3: Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalisation and growth of micro-, small- and medium-sized enterprises*

Self-cogeneration in these bioenergy systems could meet the energy demand of coffee farms in rural areas. It could also support the development of community coffee processing plants, which are generally formed by small coffee farmers. The capability of the gasification-CHP system to recover and integrate the heat into the coffee productive chain increases the economic feasibility, making it more attractive to investment from coffee farmers and cooperatives. The correlation between the potential economic benefits and SDG-8 also evidence the need for more effective and practical national level-policies that support distributed self-cogeneration using renewable resources at small-scales.

SDG 2 – Zero Hunger

→ *Target 2.3: Double the agricultural productivity and incomes of small-scale food producers…, through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment*

→ *Target 2.4: "... implement resilient agricultural practices that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality."*

The implementation of the small-scale bioenergy systems in the rural coffee sector could improve the incomes of coffee farmers; reducing fuel costs and adding value to the coffee supply chain through the utilisation of local residues. This could be translated into more sustainable agricultural and rural practices that avoid highly polluting activities, such as open-burnings and cooking in traditional rural cookstoves.

SDG 10 – Reduce inequalities

Target 10.1: By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average

Target 10.2: By 2030, empower and promote the social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or another status

Target 10.4: Adopt policies, especially fiscal, wage and social protection policies, and progressively achieve greater equality

The identified outcomes of potential environmental benefits and better economics (savings in fuels and/or electricity costs) could open to new opportunities for coffee farms in terms of income and livelihood.

Correlations with other Sustainable Development Goals:

The potential benefits that could result from these bioenergy systems could have more indirect correlations with other SDGs, and these are briefly listed below:

SDG 11: Sustainable cities and communities	***11.A*** *Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning*
SDG 12: Responsible consumption and production	***12.2*** *Achieve sustainable management and efficient use of natural resources* ***12.5*** *Substantially reduce waste generation through prevention, reduction, recycling and reuse* ***12.A*** *Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production*
SDG 15: Life on land	***15.1*** *Ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements*
	15.2 *Promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally*
	15.A *Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems*
SDG 16: Peace, justice and strong institutions	***16.4*** *By 2030, significantly reduce illicit financial and arms flows, strengthen the recovery and return of stolen assets and combat all forms of organised crime*
	16.7 *Ensure responsive, inclusive, participatory and representative decision-making at all levels*
	16.8 *Broaden and strengthen the participation of developing countries in the institutions of global governance*
	16.B *Promote and enforce non-discriminatory laws and policies for sustainable development*
SDG 17: Partnership for the goals	***17.7*** *Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms* ***17.9*** *Enhance international support for implementing effective and targeted capacity-building in developing countries to support national plans to implement all the sustainable development goals* ***17.14*** *Enhance policy coherence for sustainable development* ***17.16*** *Enhance the global partnership for sustainable development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support the achievement of the sustainable development goals in all countries, in particular developing countries*

Overall, this framework emphasises a complementarity around the drivers and needs for these bioenergy systems to reach feasibility. The technical and environmental dimensions reflect untapped agricultural residues with potential for a more energy-efficient and sustainable utilisation; but considering, in certain cases, environmental trade-offs. On the other side, the economic and societal dimensions suggest that for these systems to be feasible and sustainable in rural areas, they should meet energy demands or improve energy security conditions, be economically competitive and provide wider societal benefits. These four dimensions complement each other, and their relevant drivers could impact a whole range of farmers and agro-industries.

This multidimensional framework could open new opportunities to interdisciplinary research on the role of bioenergy to achieve the Sustainable Development Goals, with high relevance to developing countries. This framework, as a starting point, has the potential to be reinforced with a quantitative approach that analyses, through a set of indexes, the correlative nature between drivers and challenges on each dimension and the SDGs.

8.4 Key findings of the multidimensional framework

This chapter presented the integration of the main findings of this research under a multidimensional framework to prompted the discussion on pivotal drivers and trade-offs of these bioenergy systems. Relevant synergies also emerged across the studied dimensions that should be considered when implementing such systems. They relate to the importance of balancing the biomass availability and the energy demand in context-specific agriculture sectors. It also emphasises the usefulness of harnessing the biomass energy conversion by implementing heat recovery pathways in the system, and of maximising the utilisation of the systems (plant's capacity factor) to enhance its costs competitiveness.

Furthermore, through an analysis of the 2030 Sustainable Development Goals Agenda, strong two-way driving correlations were identified between these drivers and many SDGs across all the dimensions. The deployment of these bioenergy systems using agri-residues could potentially promote wider social co-benefits in rural areas. It could strongly contribute to affordable clean energy (SDG-7), support climate change mitigation (SDG-13), ensure good health and well-being (SDG-3). Additionally, it could promote sustainable agriculture (SDG-2), reduce inequalities among rural communities (SDG-10) and foster sustainable and inclusive economic growth in developing countries (SDG-8).

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarises the main findings, conclusions, and recommendations from this research. Section 9.1 provides an overview of the key findings and contributions of this research and how they address the objectives presented in Chapter 1. Section 9.2 offers general recommendations and some more specific points for stakeholders in the policy sector and social organisations. Section 9.3 outlines opportunities for future research and Section 9.4 highlights the originality of this research, its contributions to the body of knowledge and how its main outputs have been disseminated. Finally, section 9.5 closes this thesis with the concluding remarks.

9.1 Overview of the key findings and contributions

Deploying bioenergy technologies sourced from agricultural residues could contribute to rural energy access and security, reduce the environmental impacts of fossil-based energy generation, and provide wider socio-economic benefits to farmers. This research, through a comprehensive and integrated assessment, has attained the *overall aim* of evaluating the feasibility of small-scale gasification systems to generate power and heat for rural areas using indigenous agricultural residues.

This research followed a multidisciplinary approach that combined technical, economic and environmental assessments on a case study in the Colombian coffee sector. The research outcomes provided insights into synergies and trade-offs to tap agri-residues for bioenergy generation at small-scale applications. Wider societal implications were underlined by correlating pivotal drivers to the Sustainable Development Goals. An overview of the key findings and how they relate to the research objectives is presented below.

Objective 1: *Evaluate the biomass energy potential of agricultural residues in Colombia and define a feasible agricultural sector and type of agricultural residue for the case study.*

The review on the biomass potential of agricultural residues in Chapter 2.4 highlighted the diverse and vast amount of resources in Colombia, over other residues. Alternatives of agricultural residues were examined, analysing the resource availability, the biomass characteristics and the context of the agricultural sector. Chapter 4.1 outlined the approach followed for this analysis and Chapter 5.1 presented the selection and justification of coffee stems, and hence the coffee sector, as the case study of this research.

The rationale behind selecting the coffee sector and this agricultural residue lies in several arguments (Chapter 5.1). From the biomass resource perspective, most of this residue remains untapped in inefficient and polluting rural practices, such as rural cookstoves and open-burnings. This biomass also has suitable characteristics of solid fuels for conversion through gasification, such as high lignocellulosic content, higher heating value and lower ash content compared to other coffee residues.

From the coffee sector perspective, the coffee cultivation in Colombia, concentrated in small and medium farms, could benefit from improved energy security conditions in farms and agro-industries. This characteristic suggests that the implementation of these systems could result in wider socio-economic and environmental benefits to all range of coffee farmers, but particularly to small and medium land-holders. In addition, the well-structured organisation of the coffee sector in Colombia could enable more effective and impactful research that could potentially translate into real applications. Finally, the fact that almost 90%[10] of coffee production takes place in developing countries, many of them facing clean energy access-problems, allowed this research to expand and investigate potential bioenergy pathways that could enhance rural energy access and reduce the carbon intensity of rural coffee supply chains.

Objective 2: *Evaluate the technical performance of a small-scale bioenergy system and identify key parameters to enhance the system's performance*

Chapter 3 sets the theoretical framework of relevant biomass and bioenergy concepts, with specific interest on gasification, the technology selected to assess in this research. Chapter 4.2 introduced the thermodynamic equilibrium approach and the *Aspen Plus* software, as a suitable method to estimate mass and energy balances of the gasification process, and evaluate its process performance. Finally, Chapter 5 presented the process simulation results and their validation with experimental data. It also provided a high-level discussion on the system's technical performance and examined the balance between the energy demand and biomass supply of the sector.

The technical results indicated that the system could be technically feasible. The coffee stems gasification generates a producer gas with a low-heating value (5.6 MJ/Nm^3) that could meet minimum standards for engine applications. Also, the performance parameters, cold-gas efficiency (CGE: 71%) and hot-gas efficiency (HGE: 87%) suggest an acceptable gasification efficiency. These values matched with figures of other downdraft gasifiers, reporting figures between 60%-80% for the CGE and 85%-90% for the HGE. The simulation results were

[10] http://www.ico.org/profiles_e.asp

validated against experimental data and showing overall, an adequate agreement. This also indicated that the gasification model was capable of predicting gas composition and yield.

The results also indicated that when coupled to a gas engine, the downdraft gasifier with a thermal capacity of 100 kWth could generate 20 kWe of net electrical power and recover 40 kWth of thermal power output. The recovered heat could be used to supply the part of the external heat demand for coffee drying. The integration of the heat vector to the coffee processing chain increases the system's efficiency ($\eta_{cogen} = 45.6\%$) and its applicability in farms and community coffee processing plants.

Objective 3. *Analyse the potential match between the energy demand and biomass resource availability of the selected agricultural sector, using Colombia's context.*

The mass and energy balances from the process modelling guided the analysis of the balance between the biomass availability and energy demand of coffee farms in Colombia (Chapter 5.3). The analysis indicates that deploying small-scale gasification-CHP systems could meet the energy demand of diverse coffee farms.

From the energy demand side, a plant with the capacity to deliver 20 kW_e of net electricity could meet the average power requirements of two to three large coffee farms. The low-grade heat recovered from the plant could supply the thermal power demand for coffee drying, generating 23–34 t/year of dried-coffee (for capacity factors: 30% - 50%). The bio-heat vector could substitute heat generation with fossil fuels by covering for energy requirements to dry 19%-28% of the annual coffee production in large-scale farms (~120 t/year of dried-parchment coffee).

From the biomass supply side, one large farm could have the coffee stems availability (180 tons/year [11]) to match the coffee stems demand of the gasification plant. However, the nature of this feedstock requires a combination of the biomass supply from two or three farms to guarantee regular biomass feed into the plant.

For *small and medium coffee farmers*, the utilisation of the power and heat could be more feasible when implementing the system in community coffee processing plants. In this case, the same gasification-CHP plant could generate the electricity demand of the processing plant and contribute to the heat demand. The final net electricity and heat outputs depend on the

[11] This figure considers that approximately 50% of total residues can be removed sustainably to avoid soil degradation (Romo Ortega et al. 2011)

plant's capacity factor. For farms with productive systems, this demand is affected by the coffee harvesting periods in Colombia, which occurs twice a year.

The coffee stems gasification in situ in small and medium farms requires a scale-down of the system's capacity (< 20 kWe). However, heat recovery could be less feasible due to high investments costs against low coffee annual production, and more extended use of natural coffee drying. At this scale, the systems could supply a daily power demand for household and farming activities, resulting in higher capacity factor.

Objective 4. *Evaluate the potential environmental impacts of deploying gasification systems of agricultural residues for power only and CHP generation.*

The evaluation of the environmental impacts was conducted using a lifecycle assessment on the coffee stems gasification system for power and heat generation. Chapter 5.3 detailed the methodology for this LCA, following the framework indicated by the ISO standards. Then, Chapter 6 presented the LCA development.

The results of the LCA showed that the operation phase of this system has a significant impact on environmental performance compared to the construction phase. Fossil fuel burning in the plant's upstream operation activities resulted in the largest contributors to many impact categories. Therefore, alternatives to minimise or replace fossil fuels utilisation could reduce the environmental burden on impact categories, such as climate change, fossil fuel depletion and land acidification (chapter 6.3.1).

The evaluation of the net environmental impacts of the bioenergy system, using a baseline and counterfactuals as benchmarks, showed that a wide range of results that depended strongly on the socio-economic context of the coffee sector.

The comparison with baseline showed that replacing the use of coffee stems in rural cookstoves and the diesel-based power generation for bio-electricity generation could result in net reductions on climate change and other impact categories. However, replacing the grid-power could result in a higher climate change potential, fossil fuel and metal depletion, as the power grid in Colombia has a low-carbon intensity with a high share of hydropower generation (Chapter 6.3.2).

The selection of the alternative cooking fuel source has a lower influence on the net impacts of the bioenergy system. The selection of electric stoves (fuelled with bio-power vector) over fossil fuel cookstoves produces higher positive effects over the climate change and fossil depletion impact categories. However, social acceptability and adaptation of electrical cookstoves in the existing infrastructure might raise other challenges that need to be examined further (Chapter 6.3.2).

Avoiding coffee stems open-burnings could result in an impactful and sustainable residue management solution that additionally delivers energy in rural areas. The bioenergy system could generate net positive environmental impacts across all categories. Particularly, net reductions in particulate matter formation could potentially reduce local air pollution and improve the health of rural communities (Chapter 6.3.2).

The bio-heat integration in the coffee drying stage could yield higher net positive environmental impacts compared to power only, by replacing heat generation with fossil fuels in the coffee processing chain (Chapter 6.3.2). The substitution of direct-combustion of coffee stems by their gasification for cogeneration could also produce net positive effects over many impact categories. This suggests that coffee stems gasification could be more environmentally sustainable, providing the flexibility to deliver power and heat outputs for small-scale applications (Chapter 6.3.2).

In general, the extent of the net environmental impacts produced by the coffee stems gasification-power/CHP depends strongly on the current practices that are displaced. These counterfactuals are determined by the energy demand and economic context of the coffee sector.

Objective 5. *Evaluate costs and analyse the economic profitability of deploying small-scale gasification systems of agricultural residues for power and heat generation.*

The economic assessment consisted of a *study-level* estimation of the capital and operational costs of the small-scale gasification-CHP plant, and calculation of the levelised cost of electricity to analyse the economic feasibility of the system. Section 4.4 presented the scope of this economic assessment.

The results presented in Chapter 7 showed that the capital and operational costs of the plant have similar contributions to the LCOE of the plant. Whereas, the biomass cost, due to its nature as an agricultural residue, has a low cost (or even negligible) and a marginal influence in the LCOE.

The sensitivity analysis for the LCOE underlined the influence of the cost and operating parameters. The capacity factor (CF) has the strongest influence on the LCOE. It is determined by the time the plant operates over a period, and subsequently by the energy demand of the coffee farm. Therefore, when the gasification plant generates power only, it could have a higher CF (55% - 75%) than when delivering power and heat (35%-60%). The former meets the annual power demand of coffee farms for household and farming activities, but the latter depends on the heat demand for coffee drying, occurring twice a year after harvest periods. The plant's lifetime, main equipment and fixed operation cost have also notable influence on the LCOE.

The LCOE of the gasification-power plant could match the LCOE of diesel-power generation for capacity factors above 60%. This suggests that under these conditions, the power generation with the gasification system could potentially be cost-competitive with diesel generation.

For the gasification-CHP plant, the LCOE of the bioenergy system could match the LCOE of the diesel generation for capacity factors higher than 50%. However, this system could operate between a limited capacity factor range that supplies lower heat demands over a year. On the other hand, the utilisation of this heat vector enables a heat credit that accounts for the avoided fossil fuel consumption, which could be discounted from the LCOE. This showed to significantly improve the economic feasibility of the gasification-CHP system at lower capacity factors. The relatively low Diesel price in Colombia and more mature technologies for diesel-power generation represent a barrier to the deployment of this form of distributed generation.

This LCOE-based comparison also pointed out that the bioenergy system can not match the grid electricity tariffs in Colombian rural areas under any capacity factor. Nevertheless, for the coffee stems gasification-CHP system, the LCOE could equalise these tariffs, for capacity factors over 60% and when the heat credit is applied. The high share of hydropower generation in the country, together with the regulated domestic tariffs and subsidies to rural areas derives into low prices of grid-electricity. This is another hurdle to distributed generation, which in cases, of poor reliability in the grid could help improve the energy security of rural areas.

9.2 Recommendations

This section presents recommendations that prompted from the research findings, and that could contribute towards achieving the feasibility and sustainability of small-scale bioenergy systems. These recommendations are also potentially transferable knowledge to other contexts where bioenergy could play a key role in the sustainable development of rural areas:

- ✓ ***Assess the feasibility of bioenergy systems using a multi-dimensional approach to maximise benefits, identify trade-offs and mitigate challenges***

Evaluating and potentiating synergies across different dimensions could enhance local benefits from deploying these bioenergy systems. In this research, the heat integration to the coffee processing chain enhances the conversion efficiency; augments the environmental benefits (e.g. higher emissions reductions) and improves the system's economic viability. This synergy could also expand to wider social co-benefits, by increasing the applicability of these systems in rural areas and promoting sustainable economic growth in the coffee sector.

- ✓ ***Understand and balance energy demands and biomass availability in rural contexts to determine operating scales and increasing the capacity factor.***

  Identifying the energy requirements and availability of coffee residues in farms showed that the demand and supply could balance differently in coffee farms. Large farms and community coffee processing plants could benefit from both power and heat vectors; however, small farms could require constant power input. The scales of the farms, their location, and whether they include coffee processing plants determines the type of energy demand. Subsequently, this influences the plant's power capacity and the utilisation capacity factor.

- ✓ ***Evaluate the impact of counterfactuals to identify environmental trade-offs and limitations and guide decision-making***

  Evaluating the net environmental impacts of power and heat generation from coffee stems gasification system by comparing bioenergy, and counterfactuals scenarios underline many potential benefits. However, in certain cases, those that replaced grid electricity resulted in negative effects, with higher GHG emissions and fossil fuel consumption. These trade-offs should be examined on whether continuing with existing practices, consider different alternatives or offset negative effects with wider socio-economic benefits to farmers. The local community needs and national/local policies and agendas could also help prioritise and guide on pathways to follow.

- ✓ ***Integrate the 2030 Agenda for Sustainable Development and the SDGs when conducting integrated feasibility assessments of bioenergy systems.***

  The SDGs are an important platform to guide countries to take action on urgent global challenges and achieve sustainable development. Therefore, correlating relevant SDGs with key drivers of these bioenergy systems resulted in a useful tool to identify wider socio-economic benefits and support to the achievement of SDGs.

As the results of this study evidenced, a real distributed generation alternative in rural areas require ***policymakers and government actors*** to work on the following objectives:

- ✓ Establish a national bioenergy roadmap or agenda that could steer future research and prioritise financial efforts on those bioenergy pathways that are relevant for the country's sustainable development.
- ✓ Set targets for the deployment of sustainable bioenergy systems at a regional level, incentivising the utilisation of indigenous residues and waste to supply local energy demands, and additionally the displacement of traditional biomass uses.
- ✓ Transform subsidies for diesel-power generation in rural areas to financial mechanisms that could stimulate distributed generation using renewable energies, such as the coffee stem gasification plant for power and heat generation.
- ✓ Expand the current financial and tax incentives to different mechanisms that can directly beneficiate micro/small-power and heat generation to supply only local energy demands (no feed-into the grid).

Furthermore, ***social organisations***, such as coffee cooperatives and coffee federations, could also contribute to the following plans:

- ✓ Continue the deployment of community coffee processing plants, as they could be adequate spaces for the implementation of small-scale coffee stems gasification systems harnessing the power and heat vectors. Additionally, they also support the economic growth of small coffee farmers.
- ✓ Promote education and training on sustainable development to farmers to enhance the feasibility of rural productive activities and integrate their views and needs during project planning and development.

9.3 Future work

This research has opened the window to future work across different disciplines and areas of research; these ideas are described below:

- ***Assessing the bioenergy potential of coffee residues in other countries***

  Most of the coffee producer countries (90%) are categorised as low and middle-income countries, many of them with no access to clean energy in rural areas. This circumstance poses an opportunity to evaluate how coffee residues could contribute to supply energy demands through the deployment of small-scale bioenergy systems in coffee farms. Although this research was framed in the coffee sector in Colombia, the comprehensive and multidimensional approach developed here is transferable to other coffee producer countries. Other coffee sectors have similar conditions like the one in Colombia, where coffee cultivation is concentrated in small farmers that depend on coffee trading for their subsistence. This is a greater motivation to conduct further research in this area. In general, this approach could also be expanded and serve as a baseline to explore bioenergy pathways in other agricultural sectors of developing countries, facing greater urgency to work towards achieving the SDGs.

Exploring bioenergy pathways to deliver rural distributed generation using other agricultural residues in Colombia

The review of the agricultural residues bioenergy potential in Colombia revealed that these resources are significant and much of its potential remains untapped. Therefore, future research could focus on exploring the possible use of these residues for energy production. Agri-residues from maize and rice production and crop residues from sugar cane plantations also have significant bioenergy potential to supply power and heat demands in these sectors. For this future research, the multidimensional framework could also be used as a baseline to assess the feasibility of other bioenergy pathways with the use of agri-residues.

Analysing the biomass supply-energy demand balance using a higher geographical resolution

The analysis of the balance between energy demand and the biomass availability was conducted at a country-level. However, this balance could vary across different regions, depending on the geographical location of the coffee farms and the level of rural and agricultural development. Therefore, to bring closer the applications of these systems, further research could analyse the demand-supply balance with a higher geographical resolution on a regional level. This could allow the identification of potential farms or rural communities where these systems could be implemented.

In-depth assessment of the social dimension from deploying bioenergy systems in rural areas

The connection of the pivotal drivers for the bioenergy systems deployment with the *SDGs* allowed identifying wider societal benefits to farmers. This framework has opened the possibilities for future research to explore in-depth socio-economic implications, including the role of farmers, social organisations and public institutions to reach feasible deployment of these bioenergy systems.

Additionally, this framework could serve as a baseline for further research focused on using quantitative approaches to assess the impact of bioenergy development on SDGs achievement for specific case studies. Following the line of action, for example of different energy poverty metrics, a set of indexes could be developed to measure and monitor progress generated by these bioenergy systems across different SDGs.

9.4 Originality and research impact

The conversion of agri-residues in gasification systems to supply rural energy demands can lead to environmental and socio-economic benefits to rural communities. However, the deployment of these technologies could fail if its feasibility and sustainability are not assessed adequately. For overcoming these challenges, minimise risks and identify potential benefits of these systems, it is essential to conduct integrated assessments that analyse their synergies and trade-offs in local contexts. Not considering this integrated approaches derives into a lack of wider understanding of the feasibility and sustainability of bioenergy systems, hampering the deployment of these technologies.

This research identified key drivers and wider societal implications that could foster the sustainable deployment of bioenergy systems in rural areas. Drivers that were common across all dimensions were recognised as synergies that could motivate actions to enhance the feasibility of these systems. On the other hand, the identified trade-offs and limitations advise on facts that should be considered to avoid unsuccessful implementation of the systems.

The multidimensional framework is a novel perspective that integrates key drivers and identifies correlations between bioenergy and the SDGs. It allows for exploring benefits beyond cleaner energy production, identifying wider impacts that support sustainable agriculture. This framework is a valuable tool that can be replicated in other cases.

The modelling of the coffee stems gasification system expanded the knowledge on the technical feasibility of low carbon energy generation in coffee supply chains at the relevant operating scales. The analysis of the potential balance between the biomass availability and the energy requirements in coffee farms contributed to raising awareness of renewable indigenous resources. This outcome was published in the journal *Biomass Conversion and Refinery* and presented to academics and industry stakeholders on different occasions. The presentation in the *International Workshop: Advances in Cleaner Production*-IWACP (Colombia, 2018) was meritorious of a distinction for best presentation.

The LCA work to evaluate the net environmental impacts from generating power and heat through the gasification of coffee stems is part of the novelty and originality of this work. The novelty of this LCA lies in the benchmark framework developed to compare bioenergy and counterfactual scenarios that reflect the dynamics of the socio-economic realities in the coffee sector. These outcomes emphasise the importance of identifying environmental benefits, but also trade-offs from the bioenergy conversion of agri-residues in rural areas. These results were presented at the European Biomass Conference and Exhibition in 2019 and at a plenary session “Cleaner Production for Achieving the SDGs”, as a keynote speaker in the IWACP

2018. Furthermore, a paper presenting the LCA results is to be submitted to a special edition of the peer-reviewed journal *Biomass and Bioenergy*.

Outside the academia, insights from this research were disseminated in outreach activities in the UK and overseas. The novelty and impact of these results have also been instrumental for contributing to workshops and meetings, e.g. Newton-Fund workshop on Sustainable Biomass Processing and Conversion in Peru and the research visit to the Coffee Research Centre in Colombia with academics and farmers.

9.5 Concluding remarks

This thesis has assessed the feasibility of deploying small-scale gasification systems to convert coffee residues into power and heat for rural areas. This research followed a comprehensive approach that integrates the technical, environmental and economic dimensions of the system, using a case study in the Colombian coffee sector. These results can be interpreted as a feasibility assessment of technical performance, the potential environmental impacts and economic viability of this system in rural contexts. Results indicated that the coffee residues gasification-CHP systems could be feasible when synergies are potentiated, by maximising advantages on the conversion efficiency, environmental benefits and economic competitiveness. However, when trade-offs to the system's deployment are identified, they should be analysed in the light of wider socio-economic benefits or consider different pathways.

This research also contributed to understanding how bioenergy from agricultural residues could contribute to tackling sustainability challenges in developing countries. The multidimensional framework highlighted potential co-benefits to rural communities related to contributing to energy access, health improvement, sustainable agriculture, reduction of inequalities in rural areas and economic growth.

In conclusion, this research supports the overarching argument that bioenergy technologies, such as gasification, have the potential to deliver energy demands in rural areas while tapping the utilisation of agricultural residues. Overcoming barriers to these systems deployment is still challenging, especially in rural contexts where traditional biomass uses predominate. Yet, the synergies identified across the technical, environmental and economic dimensions could help to attain the system's feasibility and sustainability. Furthermore, wider societal co-benefits to rural communities could also be realised, as suggests the strong correlation between bioenergy development and the Sustainable Development Goals.

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APPENDIX A: Publications and event participation during PhD

A.1. Paper publications

The following journal papers were written and published during the PhD programme:

3. **Garcia-Freites, S.**, Welfle, A., Lea-Langton, A., Gilbert, P., Thornley, P. (2019). The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector. *Biomass Conversion and Biorefinery*, pp.1–16. Available from: https://doi.org/10.1007/s13399-019-00480-8

Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-019-00480-8

ORIGINAL ARTICLE

Check for updates

The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector

Samira Garcia-Freites[1] · Andrew Welfle[1] · Amanda Lea-Langton[1] · Paul Gilbert[1,2] · Patricia Thornley[1,3]

Received: 24 April 2019 / Revised: 1 July 2019 / Accepted: 15 July 2019

Abstract
The coffee industry constitutes an important part of the global economy. Developing countries produce over 90% of world coffee production, generating incomes for around 25 million smallholder farmers. The scale of this industry poses a challenge with the generation of residues along with the coffee cultivation and processing chain. Coffee stems, obtained after pruning of coffee trees, are one of those abundant and untapped resources in the coffee supply chain. Their high lignocellulosic content, the low calorific value ranging between 17.5 and 18 MJ kg^{-1} and the low ash content make them a suitable solid fuel for thermochemical conversion, such as gasification. This research evaluates the feasibility of using these residues in small-scale downdraft gasifiers coupled to internal combustion engines for power and low-grade heat generation, using process modelling and the Colombian coffee sector as a case study. The producer gas properties (5.6 MJ Nm^{-3}) and the gasifier's performance characteristics suggest that this gas could be utilized for power generation. A cogeneration system efficiency of 45.6% could be attainable when the system's low-grade heat is recovered for external applications, like in the coffee drying stage. An analysis of the energy demand and coffee stems availability within the Colombian coffee sector shows that the biomass production level in medium- to large-scale coffee farms is well matched to their energy demands, offering particularly attractive opportunities to deploy this bioenergy system. This work assesses the feasibility of providing coffee stem–sourced low-carbon energy for global coffee production at relevant operating scales in rural areas.

Keywords Gasification · Coffee residues · Process modelling · Power and heat generation · Coffee sector · Energy demand

Abbreviations

CHP	Combined heat and power
CGE	Cold gas efficiency
daf	Dry ash-free composition
d.b.	Dry-basis composition
ER	Equivalence ratio
HGE	Hot gas efficiency
ICE	Internal combustion engine
LI	Low income
LMI	Low-middle income
LHV	Low heating value
MC	Moisture content
UMI	Upper-middle income

Paul Gilbert and Patricia Thornley this work was done while having affiliation to the University of Manchester.

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1 Introduction

1.1 International context of coffee production

Coffee is an important global commodity, with a market that has shown significant resilience in a world with a changing agricultural economy, where coffee production has grown 3.5% per year since 2008, faster than 2.5% overall growth in agriculture [1]. The majority of coffee consumption occurs in industrialized countries, yet over 90% of world coffee production takes place in low- and middle-income countries [2, 3] and around 120 million people depend on coffee farming and

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Springer

4. Gough C., **Garcia-Freites S.**, Jones C., Mander S., Moore B., Pereira C., Röder M., Vaughan N., Welfle A. (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5ºC. *Global Sustainability* 1 (e5): pp. 1-9. https://doi.org/10.1017/sus.2018.3


Global Sustainability

cambridge.org/sus

Research Article

Cite this article: Gough C, Garcia-Freites S, Jones C, Mander S, Moore B, Pereira C, Röder M, Vaughan N, Welfle A (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Global Sustainability* **1**, e5, 1–9. https://doi.org/10.1017/sus.2018.3

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Keywords:
energy; policies; politics and governance

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Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C

Clair Gough[1], Samira Garcia-Freites[1], Christopher Jones[1], Sarah Mander[1], Brendan Moore[2], Cristina Pereira[2], Mirjam Röder[1], Naomi Vaughan[2] and Andrew Welfle[1]

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Non-technical summary

Biomass energy with carbon capture and storage (BECCS) is represented in many integrated assessment models as a keystone technology in delivering the Paris Agreement on climate change. This paper explores six key challenges in relation to large scale BECCS deployment and considers ways to address these challenges. Research needs to consider how BECCS fits in the context of other mitigation approaches, how it can be accommodated within existing policy drivers and goals, identify where it fits within the wider socioeconomic landscape, and ensure that genuine net negative emissions can be delivered on a global scale.

Technical summary

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement sets a goal of limiting the global temperature increase to "well below 2°C" and to pursue "efforts to limit the temperature increase to 1.5°C". Most emission pathways that are compatible with these goals are heavily reliant on negative emissions technologies (NETs), especially biomass energy with carbon capture and storage (BECCS), at a global scale to remove CO_2 from the atmosphere. The use of negative emissions in climate mitigation introduces a complex variety of technologies whose desirability, effectiveness and viability remain highly uncertain. This paper explores six key policy and governance challenges associated with BECCS, suggesting ways in which research could address some of these challenges: 1) How does BECCS fit with carbon budgets? 2) How negative is BECCS? 3) Can BECCS be delivered at sufficient scale? 4) Can sufficient biomass be provided sustainably? 5) How does BECCS fit into the policy context? 6) How does BECCS fit with climate agreements? Consideration of these challenges highlights the importance of a whole systems approach to assessing the use of BECCS and its potential as a keystone technology to deliver negative emissions.

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement sets a goal of limiting the global temperature increase to "well below 2°C" and to pursue "efforts to limit the temperature increase to 1.5°C" [1]. Most emission pathways that are compatible with these goals are heavily reliant on negative emissions technologies (NETs), especially biomass energy with carbon capture and storage (BECCS) at a global scale [2,3] to remove CO_2 from the atmosphere. However, the use of NETs in climate change mitigation introduces a variety of technologies whose desirability, effectiveness and viability remain highly uncertain.

BECCS is an emerging technology that combines large-scale biomass energy applications (including electricity generation) with the capture and storage of CO_2. In the case of BECCS, the negative emissions concept is based on the principle that, since CO_2 is absorbed from the atmosphere during the growth cycle of biomass feedstocks, if the CO_2 produced during combustion of biomass energy is captured and stored indefinitely, removal of CO_2 from the atmosphere can be achieved [4]. There are other suggested approaches for negative emissions such as afforestation, direct capture of CO_2 from the air with geological storage and enhanced weathering, but BECCS is by far the most prominent of these options in climate change mitigation scenarios. This paper explores the policy and governance challenges specific to achieving negative emissions through BECCS [2,5].

Achieving the goals of the UNFCCC Paris Agreement is dependent on tight limits to cumulative emissions of CO_2 (and other greenhouse gases) in order to stabilize their atmospheric concentration. At current emission rates, the cumulative global emissions, and consequently atmospheric CO_2 concentration, continue to rise and the remaining emission 'budget'

Paper under preparation:

Environmental synergies and trade-offs associated with bioenergy from agro-residues in the Global South: a case study of the Colombian coffee sector. Submission to the Journal Biomass and Bioenergy, Special issue: Modern bioenergy approaches in international development (October 2019)

A.2. Oral presentations and posters

The following table lists the oral and posters presentations that were done during the PhD programme in academic conferences and workshops.

Presentation title	Event	Role
Environmental trade-offs associated with bioenergy from agro-residues in sub-tropical regions: a case study of the Colombian coffee sector	*27th European Biomass Conference* Lisbon, Portugal - May 2019	Poster presenter
Cleaner Energy Production to Support Sustainable Agriculture in the Global South	*7th International Workshop: Advances in Cleaner Production* Barranquilla, Colombia - June 2018	Keynote speaker in plenary session
The Potential for Gasification of Coffee Stems to Provide Bioenergy for the Coffee Sector	*7th International Workshop: Advances in Cleaner Production* Barranquilla, Colombia. June 2018	Oral presenter ***Best Presentation Award***
Evaluating the potential of coffee stems gasification systems to generate low-carbon energy in rural areas	*Sustainable Biomass Processing and Conversion – Newton Fund Workshop* Piura, Peru – June 2018	Oral presenter
Evaluation of coffee stems gasification potential for power generation through ICEs: A case study in the Colombian coffee sector	MACE PGR Conference – University of Manchester Manchester, UK – March 2018	Oral presenter
Exploring biomass energy potential from agricultural residues in Colombia and the feasibility of its conversion in small-scale gasification systems	*International Bioenergy Conference* Manchester, UK – March 2017	Poster presenter
A biomass resource and technology assessment for Colombian agricultural residues	*Manchester Energy PhD Conference* Manchester, UK – February 2017	Oral presenter
Is it feasible to use agricultural residues in Colombia for biomass gasification?: Dilemmas versus realities	*Tyndall PhD Conference* Norwich, UK - April 2016	Oral presenter

Participation in other notable academic and outreach activities for training and capacity building**:**

Activity	Event
IEA-GHG International Interdisciplinary CCS Summer School	International CCS Knowledge Centre Canada - July 2017
Manchester Energy Summer School	The University of Manchester UK, 2016
Training course on gCCS software (GPROMS)	The University of Sheffield. Sheffield UK, 2016
Graduate Teaching Assistant Training	The University of Manchester UK, 2016

Poster presentation at International Bioenergy Conference - UK – March 2017:

MANCHESTER 1824 The University of Manchester — Gobernación del Atlántico — TyndallManchester Climate Change Research

Exploring biomass energy potential from agricultural residues in Colombia and the feasibility of its conversion in small-scale gasification systems

Samira Garcia Freites - Prof. Patricia Thornley - Dr Paul Gilbert

Tyndall Centre for Climate Change Research, The University of Manchester, United Kingdom

Introduction

Biomass energy potential from agri-residues in Colombia, estimated at ~400 PJ/year, remains mostly untapped and in some cases is converted on traditional inefficient processes for cooking or heating purposes.

Numerous rural areas in Colombia where these crop residues are available demand large amounts of electricity and heat (e.g. for farming and households activities), which could be potentially supplied using bioenergy. Extended research has been conducted worldwide in this direction, however previous studies cannot always be applied straightforward to some specific countries.

Aim of research

This work explores the biomass resource potential of agri-residues in Colombia and the feasibility of using gasification technology by evaluating the influence of certain process parameters on the product gas composition, heating value and process conversion efficiency of the system.

Research approaches:

Process modelling – simulation + Life-cycle assessment + Techno-economic assessment

Agricultural residues energy potential in Colombia

Crop	Crop prod. [t/yr]	Type of residue	Type of residue source	Amount of residue [t/yr][1]	Energy potential [TJ/yr][1]
Sugar cane	2,615,521	Leafs	Field residue	8,525,718	41,707.2
		Bagasse	**Agroind residue**	**7,008,873**	**76,871.6**
Raw Sugar cane	1,514,878	Leafs	Field residue	5,680,790	62,305.6
		Bagasse	Agroind residue	3,832,640	18,749
Coffee	942,327	**Stems**	**Field residue**	**2,849,596**	**38,561.5**
		Pulp	Agroind residue	2,008,192	7,206.2
		Husk	Agroind Residue	193,460	3338.6
Rice	2,463,689	Straw	Field residue	5,789,669	20,699.4
		Husk	Agroind Residue	492,738	7,136.5
Corn	1,368,536	Stover	Field residue	1,278,213	12,569

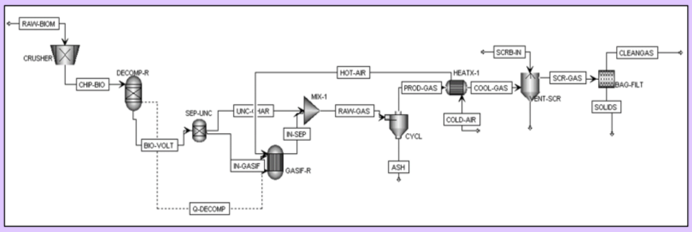
Sugarcane bagasse:

- Solid fuel for cogeneration plants in a well-stablished industry (237 MW installed capacity by 2015).
- Planned expansion of installed capacity with more ethanol distilleries and SC cultivation areas.
- Opportunity to increase conversion efficiency of the process with alternative conversion technologies.

Coffee crop residues (stems):

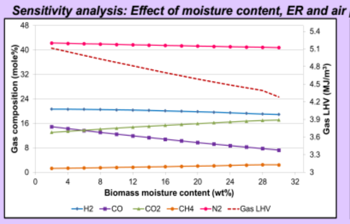
- Higher calorific value (19.75 MJ/kg) compared to other coffee residues and by-products[2].
- Suitable residues for thermochemical conversion processes – high lignocellulosic content[3].
- Demand of process heat for coffee drying and electricity for coffee grain processing
- High biomass availability (0.6 kg of coffee stems obtained from processing 1 kg of cherry coffee).

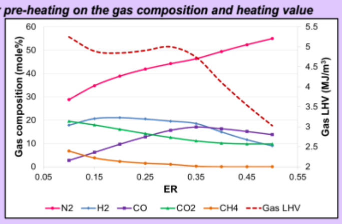
Small-scale biomass gasification system

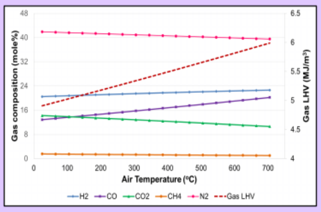


Gasification parameters		Feedstock: Coffee stems
Input data	Feed size (chips)	1-2 cm
	Feed rate	147.14 kg/hr
	HHV fuel (d.b)	19.26 MJ/kg
	Thermal capacity	500 kWth
	Equivalence ratio	0.25 (A/F=1.44)
	Moisture content	8.7%
Assumptions	Gasifier efficiency	75%
Output data	Product gas flow rate	485.5 m^3/hr
	Product gas LHV (d.b.)	5.8 MJ/Nm^3
	Gas outlet temperature	650 ºC
	Cold gas efficiency	71.5%
	Hot gas efficiency	85.25%
	Electrical energy output	200 kWe (n_e=38%)

Sensitivity analysis: Effect of moisture content, ER and air pre-heating on the gas composition and heating value







Conclusions

- The small-scale coffee stems gasification model was able to predict the gas composition and gasifier performance under a range of operating parameters with good agreement to results in [3].
- Coffee stems have a high biomass energy potential to produce electricity and heat process through small-scale gasification systems (Gas LHV: 4-6 MJ/Nm^3). Economic and environmental aspects need to be further evaluated to determine the sustainability and feasibility of this biomass energy conversion at small scale applications.
- Moisture content in biomass decreases CO% significantly and to a lesser extent H2% in the product gas; consequently degrading the gas heating value.
- An ER increase (>0.3) decreases the H_2, CO and CH_4 content in the product gas; hence decreasing steadily the gas HV. The optimum ER is in the range of 0.2-0.3, depending on the air temperature.
- The air (as oxidant agent) preheating influences the production of more combustible components (H_2 and CO) in the product gas; improving also the gas heating value and the overall gasifier performance. The air temperature increase will be limited to the heat recovery in the gasification system or to the feasibility of an external heat source.

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References

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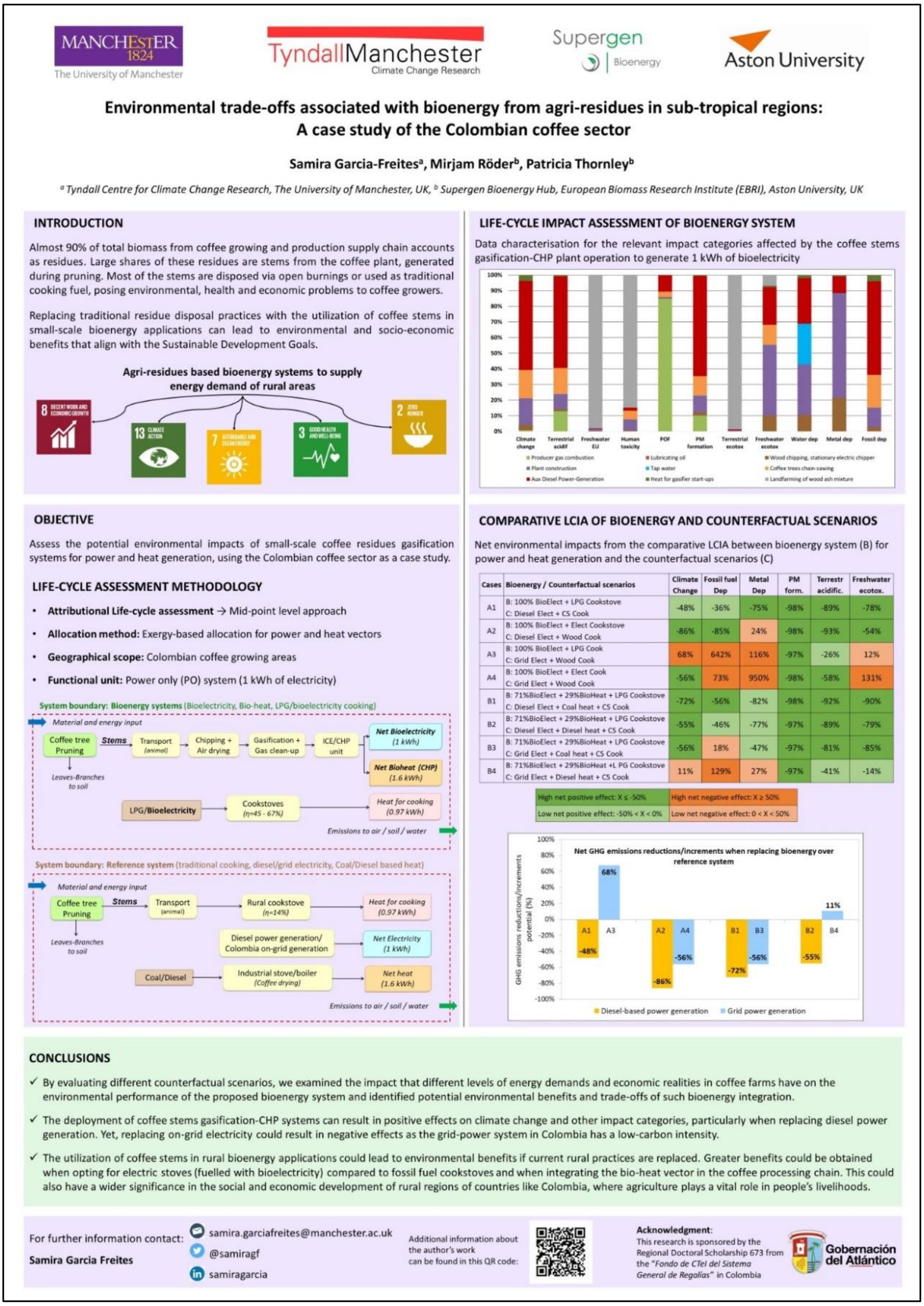
[2] Rodríguez Valencia, N. & Zambrano Franco, D., 2010. Los subproductos del café: fuente de energía renovable, Manizales. Available at: http://biblioteca.cenicafe.org/bitstream/10778/351/1/avt0393.pdf.
[3] Garcia CA, et al., Techno-economic and energetic assessment of hydrogen production through gasification in the Colombian context: Coffee Cut-Stems case, International Journal of Hydrogen Energy (2007).

Poster presentation at European Biomass Conference - Portugal – May 2019:



APPENDIX B. SUPPORTING DATA FOR TECHNICAL ASSESSMENT

TECHNICAL SPECIFICATIONS OF DOWNDRAFT GASIFIER – ALL POWER LABS

Source: (All Power Labs 2018)

ALL POWER LABS
Carbon Negative Power & Products

POWER PALLET - PP30

RENEWABLE

ON-DEMAND

POWER

The new **Power Pallet** PP30 25 kW genset is a renewable power solution that is a sensible answer to a critical need for distributed low-carbon energy. With standard grid-paralleling functionality, Combined Heat & Power, engine enclosure, and emissions control, the new PP30 meets the needs of modern, demanding power standards.

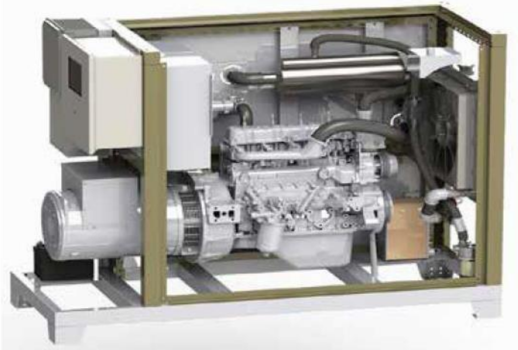
APL's unique patented multi-stage gasification architecture, in combination with our innovative gasifier-engine thermal integration, electronic control system and waste-heat recycling, gives the Power Pallet unprecedented biomass fuel flexibility and efficiency.

The Power Pallet uses agricultural and forestry waste materials that can be readily sourced very near the point of generation. It is compact and portable, easily transported to where the fuel is and where the power is needed. Unlike diesel fuel or gasoline, this fuel is often available at little or no cost, and most importantly, depending on feedstock selection and use details, the Power Pallet is capable of carbon-negative operation.

FUEL COST COMPARISON (VARIES by REGION)	
Diesel/LPG	\$0.25 - \$0.75/kWh
Gasoline	\$0.25 - \$0.75/kWh
Gasified Biomass	***\$0.00 - \$0.06/kWh***

PERFORMANCE	
Electrical Power: Continuous: On-grid with CHP:	25 kW@60 Hz / 22 kW@50 Hz 27 kW@60 Hz / 24 kW@50 Hz
Sound Level @ 7 meters:	75 dB(A)
Biomass Consumption:	1.0 kg/kWh (dry basis)
Run Time per Hopper Fill: Approximate @ 250 kg/m³ Fuel Density	5 kW: 12 hrs 10 kW: 6 hrs 15 kW: 4 hrs
Max. Continuous Operation:	>16 hours
Start Up Time:	10-15 minutes
COMBINED HEAT & POWER (CHP)	
Electrical Efficiency:	~23% (woody biomass, LHV) ~28% (syngas)
Electrical+Thermal Efficiency: Gasifier HX+Engine Cooling+Exhaust HX:	>65% (biomass) >80% (syngas) (3 stage)
CHP Heat Output: 3 stage: (without Exhaust HX) 2 stage:	2.0 kWth per 1 kWe 1.5 kWth per 1 Kwe
Engine Coolant: Working Fluid: Temperature Range:	Up to 50% PEG 75-95°C (165-205°F)
Customer-side CHP: Loop Temp. Minimum Flow Rate @ 50 kWth: Minimum Heat Delivery: Plumbing Connection:	75-90°C (165-195°F) 2.2 m³/hr (9.5 GPM) 0 kWth (native radiator backup) 1.5 inch sanitary fitting
GRID TIE / PARALLELING	
Controller:	DeepSea DSE8610 MKII
OPERATING CONDITIONS	
Ambient Temperature:	5-40°C/40-100°F
Ambient Relative Humidity:	5-95%
Installed Footprint:	1.78 x 1.42 x 2.24 meters 75 x 56 x 88 inches
Site Requirements: Outdoor: Enclosed or Poorly Ventilated:	1.75 m Overhead Clearance Well-ventilated, Level Pad, Covered from Rain and Direct Sun Forced Convection Hood Over Flare
SHIPPING	
Dimensions: Main Crate: Hopper Crate:	185 x 145 x 140 cm / 73 x 57 x 55 in. 83 x 83 x 114 cm / 33 x 33 x 45 in.
Weight: Main Crate: Hopper Crate:	1130 kg / 2500 lbs. 91 kg / 200 lbs.
GAS FILTRATION	
Dry Filtration System: HX Temp Control:	Cyclone+Bag House Gang Clean-in-place Shaker System Prevents Tar and H_2O Condensation
Gas Cooling Pre-filtration:	Engine Coolant HX Controls to 80-100°C HX In-situ Cleanable

All specifications are subject to change without notice



ALL Power Labs

APL is the global leader in small-scale gasification technology. We make biomass-fueled power generators that are ready for everyday work, to serve real-world, distributed-energy needs. Our compact gasifiers are now at work in over thirty countries, and support research at more than fifty universities around the world.

Our APL team is an unusual combination of hands-on fabricators and university-trained scientists and engineers. The result is a powerful combination of technical ability and physical know-how for developing innovative energy solutions.

We are deeply committed to supporting and developing biomass energy conversion by curating and disseminating comprehensive information and data on gasification science and technology—online, in work-shops, and free open house events.

Our facility is in Berkeley, CA. Please contact us to arrange a visit the next time you are in the Bay Area. We would love to show you around.

WARRANTY

ALL Power Labs products are covered by a 100% money back guarantee. If you buy something & find yourself unimpressed with the value of the product or company, we'll refund all your money (minus shipping costs) within 30 days of delivery. APL directly warrants all parts we manufacture (i.e. gasifiers, electronics, & related components) for two years or 4000 hours, & passes along the OEM warranty for parts we source & configure into our end products (e.g. engines & genheads). See **http://allpowerlabs.com/products/warranty** for full details.

GAS-MAKING SYSTEM	
Gasifier Type:	APL v5.x Patented Multistage Heat Recycling Downdraft
Materials:	304/310/321 SS / Mild Steel
Hearth:	Coated Ceramic
Char-Ash Removal:	Automated Auger to 16 hour batch vessel
Fuel Feed:	Automated: Hopper to Reactor
Hopper Capacity:	333 liters (88 gallons)
Hopper Filling: Batch: Automatic:	Manual while operating Continuous Feed Gate (optional)
Control System:	On-Board Automation
Flare: Clean Swirl Combustor	Auto Ignitor / Manual Mixture
ENGINE	
Type:	Ashok Leyland: Hino-Toyota Design
Displacement:	4.0 liter
Cylinder Configuration:	Inline 4 cylinder
Compression Ratio:	12:1
RPM:	1500 @50 Hz, 1800@60 Hz
Valve Configuration:	Overhead, Pushrod
Engine Block:	Cast Iron: Industrial Diesel Based Cylinders Lined for In-frame Rebuild
Pistons:	Aluminum Alloy: Center Dished Ring-trench Inserts Prevent Sticking
Cylinder Head: Circumferal Squish Combustion	Cast Iron Crossflow w/ Hardened Exhaust Inserts
Ignition:	Electronic: ECU Controlled
Lube Oil Capacity:	8 liters (8.5 quarts)
Coolant Capacity:	15 liters (16 quarts)
Auto Shutdown:	Low Oil Pressure High Coolant Temperature
System voltage:	12 VDC
Charging System: AC Genhead	Switch-mode Charger
System Voltage:	12 VDC
Recommended Battery:	Grp 24 Marine: 75Ah, 880 CCA
Auxilliary Components: ECU Controlled 12 VDC	Cooling Fans Water Pump
Auxillary Parasitic Load	850 Watt, 300 Watt w/o Radiator
Speed Control: Elect. Gov.	Woodward L-Series
Automated Mixture Control	Bosch Wide-Band O^2 Sensor
GENERATOR	
Type:	Marathon 284CSL1542, 12 wire
AVR:	DSE A106 MK II
Available Voltages:	120-277, 240-480 VAC
Available 3Φ Topologies:	Series or Parallel, Delta or Star
Total Harmonic Distortion:	<5%
Efficiency:	92%
Motor Surge Starting Cap:	>300%
Maximum Step-load	50% of Rated Power

All specifications are subject to change without notice

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APPENDIX C. SUPPORTING DATA FOR LCI OF BIOMASS GASIFICATION

This appendix presents supporting lifecycle inventory data that was required to model the construction and operation of the small-scale coffee stems gasification system.

Plant Construction

Table 36 and Table 37 shows the dataset for the construction of the *synthetic gas plant* and *heat and power cogeneration unit* taken from the Ecoinvent database (ETH Domain and Swiss Federal Offices 2018). The dataset includes the inputs from technosphere of materials and energy for manufacturing the infrastructure and constructing the plant site. The emissions to air, soil and water-related to the material extraction and energy inputs are included within these unit processes.

Table 36. Dataset of unit process for *Synthetic gas plant.*
Source: (Ecoinvent Centre 2007)

UNIT PROCESS	AMOUNT	UNIT
Product		
Infrastructure of synthetic gas plant	1	unit
Inputs from technosphere		
Concrete, normal, at plant	$3.6x10^2$	m^3
Diesel, burned in building machine	$1.1x10^6$	MJ
Electricity, medium voltage {US}, at grid	$6.0x10^4$	kWh
Aluminium, production mix, at plant	$7.2x10^2$	kg
Copper, at regional storage	$1.8x10^3$	kg
Reinforcing steel, at plant	$5.4x10^4$	kg
Steel, low-alloyed, at plant	$1.8x10^4$	kg
Heat, light fuel oil, at industrial furnace 1 MW	$1.1x10^6$	kg
Transport, freight, rail	$4.4x10^4$	tkm
Transport, lorry 28t	$2.1x10^4$	tkm
Emissions		
Heat, waste	$2.16x10^5$	MJ

Table 37. Unit process dataset for the Heat and Power cogeneration unit, 50 kW electrical
Source: (Ecoinvent Centre 2007)

UNIT PROCESS	AMOUNT	UNIT
Product		
Infrastructure of Heat and Power cogeneration unit	1	unit
Inputs from technosphere		
Gas motor, 206 kW, market for	0.333	p
Construction work, CHP unit, 160 kW electrical	0.414	p
Air input/output unit, CHP unit, 160 kW electrical	0.414	p
Start-up, CHP unit, 160 kW electrical	0.414	p
Energy requirement for assembly of CHP unit, 160 kW	0.414	p

Plant Operation

Table 38 shows the mix of grid-electricity generation in Colombia, using the XM (2019) platform to determine the share of each fuel on the mix. This information was used to create a new unit process in Simapro to represent the grid electricity mix of Colombia. Data for electricity generation by fuel was taken from the *Ecoinvent* database (2007).

Table 38. Data used for modelling the environmental impacts of Colombia electricity production
Source: (XM 2019)

Inputs from technosphere	%	Notes
Hydropower, reservoir, at tropical region	86%	Global average production
Natural gas, at combined cycle power plant	8%	Global average production
Natural gas, at conventional power plant	1%	Global average production
Coal, at power plant	4%	Global average production
Bagasse, cogeneration at power plant	1%	Brazil average production
Total	**100%**	

Table 39. Average composition of ash from wood
Source: (ECN - TCN 2019)

Element	mg/kg db
Organic Carbon	12
Sulphur	9.2
Silicon	82.6
Calcium	284
Magnesium	32.1
Potassium	54.5
Phosphorous	9.8
Aluminium	20.8
Iron	22.8
Copper	0.163
Zinc	1.66
Nickel	0.0552
Chromium	0.195
Lead	0.065
Manganese	20
Mercury	0.0001

APPENDIX D. LIFECYCLE INVENTORIES FOR COUNTERFACTUAL SCENARIOS

Lifecycle inventories of alternative electricity generation in the Colombian coffee sector

This unit process represents the alternative off-grid electricity generation system using a diesel generator. This unit process is part of the bioenergy scenarios evaluated in the LCA, labelled as **cases A1**-**A3** and **B1** in Table 28, and **C1** and **D1-D2** in Table 29. This LCI was built using a generic unit process reported in the *Ecoinvent database V3.3* (ETH Domain and Swiss Federal Offices 2018).

Table 40. LCI for electricity production with a Diesel generating set
Functional unit: 1 kWh – Source: *Ecoinvent Database V3.3*

Unit process	Amount	Unit
Product		
Electricity (diesel-based generation)	1	kWh
Inputs from nature and technosphere		
Diesel *(material from nature)*	0.237	kg
Lubricating oil *(material from technosphere)*	0.000684	kg
Outputs: emissions and waste treatment		
Emissions to air from the combustion of Diesel burned in generating set (Flue gas yield and composition are taken from *Ecoinvent Database V3.3*)	CO_2: 0.7484	kg
	CO: 0.0684	kg
	CH_4: $1.71x10^{-6}$	kg
	NMVOC: 0.00093	kg
	SO_2: $6.16x10^{-4}$	kg
	NOx: 0.01404	kg
	N_2O: $6.12x10^{-4}$	kg

	Particulates: (< 2.5 µm): 0.00174	kg
	Mercury: $4.7x10^{-9}$	kg
	Cadmiun: $2.4x10^{-9}$	kg
	Chromiun: $1.2x10^{-8}$	kg
	Copper: $4.1x10^{-7}$	kg
	Nickel: $6.05x10^{-8}$	kg
	Zinc: $8.6x10^{-7}$	kg
Waste mineral oil {RoW}	$1.56x10^{-4}$	kg

*RoW: Rest of the World

This unit process represents grid electricity generation (with the associated material and energy inputs and emissions) from the mix of fuels used in Colombia. The share of each fuel in the grid electricity mix (e.g. hydropower, natural gas, coal and bagasse-based cogeneration) was indicated in Table 38.

This unit process is part of the all of the counterfactual scenarios evaluated in the LCA, labelled as **cases A4-A6** and **B2** in Table 28 **C2** and **D2-D4** in Table 29. The data source for the unit processes for the electricity by fuel is Ecoinvent database (ETH Domain and Swiss Federal Offices 2018).

Table 41. LCI for Electricity generation from the Colombian power grid mix – Functional unit: 1 kWh

T

UNIT PROCESS	AMOUNT	UNIT
Product		
Electricity, production mix from Colombian power grid	1	kWh
Inputs from technosphere: electricity and heat		
Electricity, high voltage electricity production, hydro, reservoir, tropical region	0.86	kWh

Electricity, high voltage electricity production, natural gas, combined cycle power plant	0.08	kWh
Electricity, high voltage electricity production, natural gas, conventional power plant	0.01	kWh
Electricity, high voltage electricity production, hard coal	0.04	kWh
Electricity, high voltage cane sugar production with ethanol by-product	0.01	kWh
Outputs: emissions and waste treatment		
The air, water and soil emissions, and waste treatment outputs associated to each form of electricity generation are included in each of the unit process included as inputs to technosphere for electricity generation.		

Lifecycle inventory of alternative heat generation for coffee drying in the Colombian coffee sector

The lifecycle inventories presented below represent the current heat generation processes used to dry coffee beans in the Colombian coffee sector, as an alternative to coffee stems direct combustion. This unit process represents the process heat generation with an industrial stove/furnace fuelled with hard coal coke to dry coffee beans in the coffee processing plants in Colombia. This unit process is part of the counterfactual scenarios labelled as **cases C1** and **C3** in Table 29. The data source for this unit processes is Ecoinvent database V3.3 (ETH Domain and Swiss Federal Offices 2018).

Table 42. LCI of heat generation production from hard coal coke combustion in industrial stove/furnace
Functional unit: 1.6 kWh **-** Source: (ETH Domain and Swiss Federal Offices 2018).

UNIT PROCESS	AMOUNT	UNIT
Product		
Process heat (Coke furnace)	1.6	kWh
Inputs of material and energy from nature and technosphere		

Coke *(material from nature)* *This input represents the fuel feed required to generate 1.6 kWh of heat in an industrial stove/furnace (accounting for heat losses). The unit process is taken from the Ecoinvent database V3.3*	0.4	kg
Outputs: emissions and waste treatment		
Emissions to air from coke combustion in an industrial stove – *(Composition and yield of flue gas is taken from Ecoinvent database V3.3.)*	CO_2: 0.21	kg
	CO: 0.019	kg
	CH_4: $5.94x10^{-6}$	kg
	NMVOC: $2.97x10^{-7}$	kg
	SO_2: $1.72x10^{-4}$	kg
	NOx: $2.39\ x10^{-5}$	kg
	N_2O: $5.83x10^{-7}$	kg
	PM (> 2.5 μm and <10 μm): $3.97x10^{-6}$	Kg
	PM (< 2.5 μm):$1.99x10^{-6}$	Kg
	Mercury: $1.31x10^{-9}$	Kg
	Cadmiun: $6.67x10^{-10}$	Kg
	Chromiun: $3.33x10^{-9}$	Kg
	Copper: $1.14x10^{-7}$	Kg
	Nickel: $1.68x10^{-8}$	Kg
	Zinc: $2.39x10^{-7}$	Kg
Coal ash	0.0016	Kg

This unit process represents the process heat generation with a diesel-fuelled cogeneration unit used to dry coffee beans in the coffee processing plants in Colombia. This unit process is part of the first group of counterfactual scenarios labelled as **cases C2** and **C4** in Table 29. The data source for this unit processes is the Ecoinvent database (ETH Domain and Swiss Federal Offices 2018).

Table 43. LCI of heat generation from diesel combustion in CHP unit

Functional unit: 1.6 kWh - Source: (ETH Domain and Swiss Federal Offices 2018)

UNIT PROCESS	AMOUNT	UNIT
Product		
Heat production, diesel direct-combustion in heat and power co-generation unit	1. 6	kWh
Inputs of material and fuels from technosphere		
Diesel, market for *This input represents the fuel feed required to generate 1.6 kWh of heat in a cogeneration unit (accounting for heat losses). The unit process is taken from the Ecoinvent database V3.3*	0.047	Kg
Lubricating oil {GLO}| market for	1.34 x10^{-5}	Kg
Outputs: emissions and waste treatment		
Emissions to air from combustion of diesel in CHP unit *(Composition and yield of flue gas is taken from Ecoinvent database V3.3.)*	CO_2: 0.145	Kg
	CO: 3.0x10^{-4}	Kg
	CH_4: 2.4x10^{-5}	Kg
	NMVOC: 1.0x10^{-4}	Kg
	SO_2: 1.0x10^{-4}	Kg
	NOx: 1.4x10^{-4}	Kg
	N_2O: 1.0x10^{-5}	Kg
	PM <2.5 um: 2.0x10^{-6}	Kg
	Ammonia: 2.0x10^{-6}	kg
	Platinum: 2.0x10^{-11}	kg
Waste mineral oil | market for waste mineral oil	1.34x10^{-4}	kg

Lifecycle inventory of coffee stems practices: coffee stems burning in cookstoves, coffee stems combustion for coffee drying and coffee stems open-burnings in the Colombian coffee sector

This unit process represents the process heat generation from the direct combustion of coffee stems in an industrial furnace and/or stove to dry coffee beans in the coffee processing plants in Colombia. This unit process is part of the second group of counterfactual scenarios labelled as **cases B1** and **B2** in Table 28. The data source for this unit processes was obtained from the Aspen Plus process modelling and complemented with the Ecoinvent (ETH Domain and Swiss Federal Offices 2018) and US LCI database.

Table 44. LCI for heat production in rural cookstoves (using coffee stems) – Functional unit: 1 MJ
Source: *Ecoinvent* Database

Unit process	Amount	Unit
Product		
Heat from rural cookstove	0.97	kWh
Inputs from nature and technosphere		
Wood, hard, standing (material from nature) *The input represents the coffee stems feed requirement to produce heat for domestic cooking. A hardwood feedstock unit process from Ecoinvent database was used.*	1.47	Kg
Chainsawing, delimbing, NE-NC/RNA (*US LCI database)* *The unit process specifies the chainsaw operation time to obtain the coffee stems. The data includes the diesel consumption, hydraulic oils and general lubricant required for the hydraulic systems and moving parts of the equipment.*	1.03	Min
Outputs: emissions and waste treatment		
Emissions to air from the combustion of coffee stems in domestic cookstoves *(Flue gas yield and composition are taken from (EPA 2016)*)	$CO_{2,\ BIO}$: 2.497	kg
	$CO_{,BIO}$: 0.127	kg
	$CH_{4,BIO}$: 0.008	kg
	NMVOC: 0.135	kg

	SO_2: 5.89x10^{-4}	kg
	NOx: 0.0014	kg
	N_2O: 1.62x10^{-4}	kg
	PM (> 2.5 um, < 10 um): 0.016	kg
Wood ash mixture *Data for ash composition of woody biomass with similar proximate and ultimate composition to the coffee stems were used taken from Phillys2 database. Wood ash yield was taken from* (EPA 2016)	0.055	kg

Table 45. LCI for Heat generation from coffee stems direct-combustion in industrial furnace (drying of coffee beans) – Functional unit: 1.56 kWh

Unit process	Amount	Unit
Product		
Heat production, coffee stems direct-combustion in industrial stove/furnace	1.56	kWh
Inputs of material and energy from nature and technosphere		
<u>Wood, hard, standing</u> *The input represents the coffee stems feed requirement for combustion to produce heat for coffee drying. A hard wood feedstock unit process from Ecoinvent database was used.*	0.432	kg
<u>Chainsawing, delimbing, NE-NC/RNA (</u>*US LCI database)* *The unit process specifies the chainsaw operation time to obtain the coffee stems. The data includes the diesel consumption, hydraulic oils and general lubricant required for the hydraulic systems and moving parts of the equipment.*	0.086	min
Outputs: emissions and waste treatment		
<u>Emissions to air from coffee stems-combustion flue gas</u> *The flue gas composition and yield from the combustion of coffee stems in furnaces and/or industrial stoves was obtained from an Aspen Plus process modelling*	$CO_{2,BIO}$: 0.786	kg
	$CO_{,BIO}$: 0.012	kg
	$CH_{4,BIO}$: 1.2 x10^{-4}	kg
	NMVOC: 2.8x10^{-4}	kg
	SO_2: 2x10^{-5}	kg
	NOx: 6.4x10^{-4}	kg
	N_2O: 3.2x10^{-5}	kg

	PM <2.5 um: 3.6×10^{-4}	kg
	PM > 2.5 um, < 10 um: 2.0×10^{-5}	kg
Wood ash mixture, landfarming *The composition of the wood ash mixture was taken from the ECN - Phillys2 database (*Table 39 *of Appendix D) using representative numbers for woody biomass with similar proximate and ultimate composition as the coffee stems.*	0.00449	kg

This unit process characterises the emissions associated with the open-burnings of coffee stems. Currently, this is a less frequent practice in coffee farms, however, it still represents a rural practice in Colombia and was considered as part of the third counterfactual scenario, labelled as **cases C1** and **C2** in Table 29. The airborne emissions from the coffee stems combustion in open-burning was taken from Springsteen et al. (2011) and the unit processes for the inputs of hardwood feedstock and chainsawing were sourced from the Ecoinvent database (ETH Domain and Swiss Federal Offices 2018) and US LCI database.

Note: This LCI collates the data using a mass-based functional unit since open-burnings cannot deliver measurable energy products.

Table 46. LCI for Wood open-burning practice in rural areas – Functional unit: 1 kg

Unit process	Amount	Unit
Product		
Woody residues *(for open-burnings)*	1	kg
Inputs of material and energy from nature and technosphere		
Wood, hard, standing *(material from nature)* *The input represents the coffee stems feed requirement for combustion to produce heat for coffee drying. A hardwood feedstock unit process from Ecoinvent database was used.*	1	kg
Chainsawing, delimbing, NE-NC/RNA (*US LCI database)* *The unit process specifies the chainsaw operation time to obtain the coffee stems. The data includes the diesel consumption, hydraulic oils and general lubricant required for the hydraulic systems and moving parts of the equipment*	0.2	min
Outputs: emissions and waste treatment		
Flue gas composition	$CO_{2,BIO}$: 1.83	kg
	$CO_{,BIO}$: 0.063	kg

This is the direct flue gas composition and yield from the combustion of the woody biomass in open-burnings. Data is taken from (Springsteen et al. 2011).	$CH_{4,BIO}$: 0.003	kg
	NMVOC: 0.005	kg
	NOx: 0.003	kg
	PM (< 10 um): 0.0065	kg

APPENDIX E. SUPPORTING INFORMATION FOR LIFECYCLE IMPACT ASSESSMENT METHOD

The mains advantages and limitations of different lifecycle impact assessment methods included in Simapro 8.5 were considered to guide the method selection. Other methods, not included in the revision, are used to assess a single impact category or to conduct a water footprint assessment. These methods cannot assist in achieving the aim of this LCA study.

Table 47. Main features of lifecycle impact assessment methods

Impact Assessment Method *(Approach / Origin)*	**Advantages**	**Limitations**
CML-IA (2016 version) *(Mid-point/European)*	- Most of the geographic indicators have a global scale - A recently updated version of the characterisation factors of the LCIAM.	- Excludes particulate matter, land use and resource depletion categories - No weighting or addition steps
Impact 2002+ *(Mid-point and End-point/European)*	- Combines problem and damage oriented approaches - Provides characterisation factors for 1500 different LCI-results	- Excludes particulate matter category - No recently updated methodology
Eco-Indicator 99 *(End-point/European)*	- A comprehensive set of impact factors and categories - Groups similar types of assumptions and choices into different perspectives	- Outdated impact assessment methodology
ReCIPE (2016 version) *(Mid-point and End-point/Global)*	- Combines midpoint and endpoint impact categories - Groups similar types of assumptions and choices into different perspectives - A comprehensive and updated set of mid-point impact categories - Classified in SimaPro as a global method	- Normalisation and Weighting factors for ReCiPe 2016 not published yet.
EDIP 2003 *(Mid-point/European)*	- Includes exposure in the characterisation modelling of the main non-global impact categories - A comprehensive and updated set of mid-point impact categories	- Not recently updated methodology - Excludes particulate matter and land use categories -No differentiation in the resources depletion category
Ecological Scarcity 2013 *(End-point/European)*	- Measures impact of pollutant emissions and resource consumption using eco-points (i.e. eco-factors) - A comprehensive set of impact categories:	- Weighting task in the LCIA is biased towards the Swiss Environmental Policy
ILCD 2011 Midpoint + *(Mid-point/European)*	- A comprehensive and updated set of mid-point impact categories	- No recently updated methodology
IPCC 2013 *(Mid-point/European)*	- The method was developed by the IPCC, listing climate change factors with a timeframe of 20 and 100 years. - Comprehensive assessment of Climate change impact category	- Excludes other impact categories different from climate change Normalisation and weighting are not a part of this method.

APPENDIX F. DATA OF LIFECYCLE IMPACT ASSESSMENT ON COUNTERFACTUAL SCENARIOS

The tables presented in this appendix contain the characterisation results of the bioenergy and counterfactual scenarios, using the LCIA method *ReCiPe* midpoint–Hierarchical. The total indicators for each of the assessed environmental impact categories and the equivalent functional units of the bioenergy system and counterfactuals allowed their comparison and following calculation of the net environmental impact of the bioenergy system.

Table 48. Net Environmental Impacts of Case A1: Bio-Electricity + Heat from LPG cookstove vs Diesel Electricity + Heat from Coffee stems cookstoves

Impact Category	Units	Bio-Elect (1 kWh)	Heat LPG-Cookst[12] (0.97 kWh)	Total Impact indicators	Diesel-Elect (1 kWh)	Heat CS[13] -cookst[12] (0.97 kWh)	Total Impact indicators	Net Env-Impact	Net % change Env-Impact
CC	kg CO2 eq	1.7E-02	5.9E-01	6.1E-01	9.4E-01	2.3E-01	1.2E+00	-5.6E-01	-48%
Te - Acid	kg SO2 eq	1.7E-04	1.2E-03	1.4E-03	1.0E-02	1.5E-03	1.1E-02	-1.0E-02	-88%
FW - EU	kg P eq	1.1E-04	1.2E-05	1.3E-04	4.4E-05	5.4E-04	5.9E-04	-4.6E-04	-78%
Hu - Tox	kg 1,4-DB eq	3.3E-02	1.6E-02	4.9E-02	6.2E-02	1.4E-01	2.0E-01	-1.5E-01	-76%
POF	kg NMVOC	1.6E-03	1.7E-03	3.2E-03	1.6E-02	2.1E-02	3.7E-02	-3.4E-02	-91%
PMF	kg PM10 eq	8.6E-05	4.8E-04	5.7E-04	5.5E-03	1.6E-02	2.2E-02	-2.1E-02	-97%
Te – Ecot	kg 1,4-DB eq	4.3E-05	1.1E-05	5.5E-05	2.3E-05	2.1E-04	2.3E-04	-1.8E-04	-76%
FW - Ecot	kg 1,4-DB eq	1.2E-04	5.5E-04	6.7E-04	2.9E-03	9.2E-05	3.0E-03	-2.3E-03	-77%
Me-Dep	kg Fe eq	1.4E-03	2.4E-03	3.9E-03	1.5E-02	1.1E-05	1.5E-02	-1.1E-02	-74%
Fossil-Dep	kg oil eq	5.3E-03	2.0E-01	2.1E-01	3.2E-01	3.9E-03	3.2E-01	-1.1E-01	-36%
Oz-Dep	kg CFC-11 eq	2.1E-09	1.1E-07	1.1E-07	1.7E-07	1.1E-11	1.7E-07	-5.7E-08	-34%

[12] Cookst: Cookstove
[13] CS: Coffee stems

Table 49. Net Environmental Impacts of Case A4: Bio-Electricity + LPG cookstove vs Grid Electricity + Coffee stems cookstove

Impact Category	Units	Bio-Elect (1 kWh)	Heat LPG-Cookst (0.97 kWh)	Total impact indicators	Grid-Elect (1 kWh)	Heat CS Cookst (0.97 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.7E-02	5.9E-01	6.1E-01	1.3E-01	2.3E-01	3.6E-01	2.5E-01	68%
Te-Acid	kg SO2 eq	1.7E-04	1.2E-03	1.4E-03	3.6E-04	1.5E-03	1.8E-03	-4.9E-04	-26%
FW - EU	kg P eq	1.1E-04	1.2E-05	1.3E-04	2.0E-05	5.4E-04	5.6E-04	-4.4E-04	-77%
Hu-Tox	kg 1,4-DB eq	3.3E-02	1.6E-02	4.9E-02	1.6E-02	1.4E-01	1.6E-01	-1.1E-01	-69%
POF	kg NMVOC	1.6E-03	1.7E-03	3.2E-03	2.2E-04	2.1E-02	2.1E-02	-1.8E-02	-85%
PMF	kg PM10 eq	8.6E-05	4.8E-04	5.7E-04	1.2E-04	1.6E-02	1.7E-02	-1.6E-02	-97%
Te-Ecotox	kg 1,4-DB eq	4.3E-05	1.1E-05	5.5E-05	8.6E-05	2.1E-04	2.9E-04	-2.4E-04	-81%
FW-Ecotox	kg 1,4-DB eq	1.2E-04	5.5E-04	6.7E-04	4.8E-04	9.2E-05	5.7E-04	9.8E-05	17%
Me-Dep	kg Fe eq	1.4E-03	2.4E-03	3.9E-03	1.8E-03	1.1E-05	1.8E-03	2.1E-03	116%
Fossil-Dep	kg oil eq	5.3E-03	2.0E-01	2.1E-01	2.4E-02	3.9E-03	2.8E-02	1.8E-01	642%
Oz-Dep	kg CFC-11 eq	2.1E-09	1.1E-07	1.1E-07	1.9E-09	1.1E-11	2.0E-09	1.1E-07	5608%

Table 50. Net Environmental Impacts of Case A5: Bio-Electricity + Natural Gas cookstove vs Grid Electricity + Coffee stems cookstove

Impact Category	Units	Bio-Elect (1 kWh)	Heat NG-Cookst (0.97 kWh)	Total impact indicators	Grid-Elect (1 kWh)	Heat CS Cookst (0.97 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.7E-02	5.9E-01	6.0E-01	1.3E-01	2.3E-01	3.6E-01	2E-01	66%
Te - Acid	kg SO2 eq	1.7E-04	1.5E-03	1.6E-03	3.6E-04	1.5E-03	1.8E-03	-2E-04	-11%
FW - EU	kg P eq	1.1E-04	4.4E-05	1.6E-04	2.0E-05	5.4E-04	5.6E-04	-4E-04	-72%
Hu - Tox	kg 1,4-DB eq	3.3E-02	4.6E-02	7.9E-02	1.6E-02	1.4E-01	1.6E-01	-8E-02	-50%
POF	kg NMVOC	1.6E-03	8.9E-04	2.4E-03	2.2E-04	2.1E-02	2.1E-02	-2E-02	-88%
PMF	kg PM10 eq	8.6E-05	5.4E-04	6.3E-04	1.2E-04	1.6E-02	1.7E-02	-2E-02	-96%
Te - Ecotox	kg 1,4-DB eq	4.3E-05	2.1E-05	6.4E-05	8.6E-05	2.1E-04	2.9E-04	-2E-04	-78%
FW - Ecotox	kg 1,4-DB eq	1.2E-04	2.1E-03	2.2E-03	4.8E-04	9.2E-05	5.7E-04	2E-03	289%
Me-Dep	kg Fe eq	1.4E-03	2.8E-03	4.2E-03	1.8E-03	1.1E-05	1.8E-03	2E-03	136%
Fossil-Dep	kg oil eq	5.3E-03	1.6E-01	1.6E-01	2.4E-02	3.9E-03	2.8E-02	1E-01	475%
Oz-Dep	kg CFC-11 eq	2.1E-09	3.6E-08	3.8E-08	1.9E-09	1.1E-11	2.0E-09	4E-08	1842%

Table 51. Net Environmental Impacts of Case A6: Bio-Electricity + Electric cookstove vs Grid Electricity + Coffee stems cookstove

Impact Category	Units	Bio-Elect (1 kWh)	Heat Elec Cookst (0.97 kWh)	Total impact indicators	Grid-Elect (1 kWh)	Heat CS Cookst (0.97 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.7E-02	1.4E-01	1.6E-01	1.3E-01	2.3E-01	3.6E-01	-2.0E-01	-56%
Te - Acid	kg SO2 eq	1.7E-04	6.0E-04	7.7E-04	1.5E-03	1.8E-03	1.5E-03	-1.1E-03	-58%
FW - EU	kg P eq	1.1E-04	2.2E-04	3.3E-04	5.4E-04	5.6E-04	5.4E-04	-2.3E-04	-41%
Hu - Tox	kg 1,4-DB eq	3.3E-02	1.0E-01	1.3E-01	1.4E-01	1.6E-01	1.4E-01	-2.2E-02	-14%
POF	kg NMVOC	1.6E-03	8.7E-03	1.0E-02	2.1E-02	2.1E-02	2.1E-02	-1.1E-02	-52%
PMF	kg PM10 eq	8.6E-05	2.9E-04	3.8E-04	1.6E-02	1.7E-02	1.6E-02	-1.6E-02	-98%
Te – Ecot	kg 1,4-DB eq	4.3E-05	1.0E-03	1.1E-03	2.1E-04	2.9E-04	2.1E-04	7.7E-04	264%
FW - Ecot	kg 1,4-DB eq	1.2E-04	1.2E-03	1.4E-03	9.2E-05	5.7E-04	9.2E-05	7.8E-04	136%
Me-Dep	kg Fe eq	1.4E-03	1.7E-02	1.9E-02	1.8E-03	1.1E-05	1.8E-03	1.7E-02	949.8%
Fossil-Dep	kg Fe eq	5.3E-03	4.3E-02	4.9E-02	2.4E-02	3.9E-03	2.8E-02	2.1E-02	73.3%
Oz-Dep	kg oil eq	2.1E-09	2.1E-08	2.3E-08	1.9E-09	1.1E-11	2.0E-09	2.1E-08	1093%

Table 52. Net Environmental Impacts of Case B1: Bio-Electricity vs Diesel Electricity + Coffee stems open-burnings

Impact Category	Units	Bio-Elect (1 kWh)	Total impact indicators	Diesel-Elect (1 kWh)	CS open-burnings	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.7E-02	1.7E-02	9.4E-01	1.0E-01	1.0E+00	-1.0E+00	-98%
Te - Acid	kg SO2 eq	1.7E-04	1.7E-04	1.0E-02	2.5E-03	1.2E-02	-1.2E-02	-99%
FW - EU	kg P eq	1.1E-04	1.1E-04	4.4E-05	0.0E+00	4.4E-05	7.1E-05	163%
Hu - Tox	kg 1,4-DB eq	3.3E-02	3.3E-02	6.2E-02	1.9E-03	6.4E-02	-3.1E-02	-48%
POF	kg NMVOC	1.6E-03	1.6E-03	1.6E-02	1.6E-02	3.2E-02	-3.1E-02	-95%
PMF	kg PM10 eq	8.6E-05	8.6E-05	5.5E-03	1.1E-02	1.6E-02	-1.6E-02	-99%
Te – Ecot	kg 1,4-DB eq	4.3E-05	4.3E-05	2.3E-05	7.6E-09	2.3E-05	2.0E-05	87%
FW - Ecot	kg 1,4-DB eq	1.2E-04	1.2E-04	2.9E-03	1.5E-05	2.9E-03	-2.8E-03	-96%
Me-Dep	kg Fe eq	1.4E-03	1.4E-03	1.5E-02	0.0E+00	1.5E-02	-1.4E-02	-91%
Fossil-Dep	kg oil eq	5.3E-03	5.3E-03	3.2E-01	1.1E-03	3.2E-01	-3.2E-01	-98%
Oz-Dep	kg CFC-11 eq	2.1E-09	2.1E-09	1.7E-07	1.4E-13	1.7E-07	-1.7E-07	-99%

Table 53. Net Environmental Impacts of Case B2: Bio-Electricity vs Grid Electricity + Coffee stems open-burnings

Impact Category	Units	Bio-Elect (1 kWh)	Total impact indicators	Grid-Elect (1 kWh)	CS open-burnings	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.7E-02	1.7E-02	1.3E-01	1.0E-01	2.3E-01	-2.2E-01	-93%
Te - Acid	kg SO2 eq	1.7E-04	1.7E-04	3.6E-04	2.5E-03	2.9E-03	-2.7E-03	-94%
FW - EU	kg P eq	1.1E-04	1.1E-04	2.0E-05	0.0E+00	2.0E-05	9.5E-05	484%
Hu - Tox	kg 1,4-DB eq	3.3E-02	3.3E-02	1.6E-02	1.9E-03	1.8E-02	1.5E-02	84%
POF	kg NMVOC	1.6E-03	1.6E-03	2.2E-04	1.6E-02	1.6E-02	-1.5E-02	-90%
PMF	kg PM10 eq	8.6E-05	8.6E-05	1.2E-04	1.1E-02	1.1E-02	-1.1E-02	-99%
Te – Ecot	kg 1,4-DB eq	4.3E-05	4.3E-05	8.6E-05	7.6E-09	8.6E-05	-4.3E-05	-50%
FW - Ecot	kg 1,4-DB eq	1.2E-04	1.2E-04	4.8E-04	1.5E-05	5.0E-04	-3.8E-04	-76%
Me-Dep	kg Fe eq	1.4E-03	1.4E-03	1.8E-03	0.0E+00	1.8E-03	-3.6E-04	-20%
Fossil-Dep	kg oil eq	5.3E-03	5.3E-03	2.4E-02	1.1E-03	2.5E-02	-2.0E-02	-79%
Oz-Dep	kg CFC-11 eq	2.1E-09	2.1E-09	1.9E-09	1.4E-13	1.9E-09	1.5E-10	7.7%

Table 54. Net Environmental Impacts of Case C1: Bio-Electricity + Bio-Heat + LPG cookst vs Diesel Electricity + Heat-Coal (for coffee drying) + CS cookst

Impact Category	Units	Bio-Elect (1 kWh)	Bio-heat (1.56 kWh)	Heat LPG-Cookst (0.97 kWh)	Total impact indicators	Diesel-Elect (1 kWh)	Heat-Coal (1.56 kWh)	Heat CS Cookst (0.96 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.2E-02	3.0E-03	5.9E-01	6.1E-01	9.4E-01	1.0	2.3E-01	2.2	-1.6E	-72%
Te - Acid	kg SO2 eq	1.3E-04	3.1E-05	1.2E-03	1.3E-03	1.0E-02	5.1E-03	1.5E-03	1.7E-02	-1.5E-02	-92%
FW - EU	kg P eq	8.6E-05	2.1E-05	1.2E-05	1.2E-04	4.4E-05	2.4E-04	5.4E-04	8.2E-04	-7.1E-04	-86%
Hu - Tox	kg 1,4-DB eq	2.5E-02	5.9E-03	1.6E-02	4.6E-02	6.2E-02	2.0E-01	1.4E-01	4.1E-01	-3.6E-01	-89%
POF	kg NMVOC	1.2E-03	2.8E-04	1.7E-03	3.1E-03	1.6E-02	5.2E-03	2.1E-02	4.3E-02	-4.0E-02	-93%
PMF	kg PM10 eq	6.4E-05	1.5E-05	4.8E-04	5.6E-04	5.5E-03	2.2E-03	1.6E-02	2.4E-02	-2.3E-02	-98%
Te – Ecot	kg 1,4-DB eq	3.3E-05	7.8E-06	1.1E-05	5.2E-05	2.3E-05	2.5E-05	2.1E-04	2.6E-04	-2.0E-04	-80%
FW - Ecot	kg 1,4-DB eq	8.9E-05	2.1E-05	5.5E-04	6.6E-04	2.9E-03	3.9E-03	9.2E-05	6.8E-03	-6.2E-03	-90%
Me-Dep	kg Fe eq	1.1E-03	2.5E-04	2.4E-03	3.8E-03	1.5E-02	5.3E-03	1.1E-05	2.0E-02	-1.7E-02	-82%
Fo-Dep	kg oil eq	4.0E-03	9.6E-04	2.0E-01	2.1E-01	3.2E-01	1.5E-01	3.9E-03	4.7E-01	-2.6E-01	-56%
Oz-Dep	kg CFC-11eq	1.6E-09	3.8E-10	1.1E-07	1.1E-07	1.7E-07	3.1E-08	1.1E-11	2.0E-07	-8.8E-08	-44%

Table 55. Net Environmental Impacts of Case C2: Bio-Electricity + Bio-Heat + LPG cookst vs Diesel Electricity + Diesel- Heat (drying) + Coffee stems cookst

Impact Category	Units	Bio-Elect (1 kWh)	Bio-heat (1.56 kWh)	Heat LPG-Cookst (0.97 kWh)	Total impact indicators	Diesel-Elect (1 kWh)	Heat-Diesel (1.56 kWh)	Heat CS Cookst (0.96 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.2E-02	3.0E-03	5.9E-01	6.1E-01	9.4E-01	1.8E-01	2.3E-01	1.4E+00	-7.5E-01	-55%
Te - Acid	kg SO2 eq	1.3E-04	3.1E-05	1.2E-03	1.3E-03	1.0E-02	4.6E-04	1.5E-03	1.2E-02	-1.1E-02	-89%
FW - EU	kg P eq	8.6E-05	2.1E-05	1.2E-05	1.2E-04	4.4E-05	4.3E-06	5.4E-04	5.9E-04	-4.7E-04	-80%
Hu - Tox	kg 1,4-DB eq	2.5E-02	5.9E-03	1.6E-02	4.6E-02	6.2E-02	6.1E-03	1.4E-01	2.1E-01	-1.6E-01	-78%
POF	kg NMVOC	1.2E-03	2.8E-04	1.7E-03	3.1E-03	1.6E-02	4.4E-04	2.1E-02	3.8E-02	-3.5E-02	-92%
PMF	kg PM10 eq	6.4E-05	1.5E-05	4.8E-04	5.6E-04	5.5E-03	1.4E-04	1.6E-02	2.2E-02	-2.1E-02	-97%
Te – Ecot	kg 1,4-DB eq	3.3E-05	7.8E-06	1.1E-05	5.2E-05	2.3E-05	4.0E-06	2.1E-04	2.3E-04	-1.8E-04	-78%
FW - Ecot	kg 1,4-DB eq	8.9E-05	2.1E-05	5.5E-04	6.6E-04	2.9E-03	2.0E-04	9.2E-05	3.2E-03	-2.5E-03	-79%
Me-Dep	kg Fe eq	1.1E-03	2.5E-04	2.4E-03	3.8E-03	1.5E-02	1.2E-03	1.1E-05	1.6E-02	-1.3E-02	-77%
Fo-Dep	kg oil eq	4.0E-03	9.6E-04	2.0E-01	2.1E-01	3.2E-01	6.3E-02	3.9E-03	3.9E-01	-1.8E-01	-46%
Oz-Dep	kg CFC-11eq	1.6E-09	3.8E-10	1.1E-07	1.1E-07	1.7E-07	3.3E-08	1.1E-11	2.0E-07	-9.1E-08	-45%

Table 56. Net Environmental Impacts of Case C3: Bio-Electricity + Bio-Heat + Electric cookst vs Grid Electricity + Heat-Coal (for coffee drying) + CS cookst

Impact Category	Units	Bio-Elect (1 kWh)	Bio-heat (1.56 kWh)	Heat LPG-Cookst (0.97 kWh)	Total impact indicators	Grid-Elect (1 kWh)	Heat-Coal (1.56 kWh)	Heat CS Cookst (0.96 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.2E-02	3.0E-03	5.9E-01	6.1E-01	1.3E-01	1.0E+00	2.3E-01	1.4E+00	-7.6E-01	-56%
Te – Acid	kg SO2 eq	1.3E-04	3.1E-05	1.2E-03	1.3E-03	3.6E-04	5.1E-03	1.5E-03	6.9E-03	-5.6E-03	-81%
FW – EU	kg P eq	8.6E-05	2.1E-05	1.2E-05	1.2E-04	2.0E-05	2.4E-04	5.4E-04	8.0E-04	-6.8E-04	-85%
Hu – Tox	kg 1,4-DB eq	2.5E-02	5.9E-03	1.6E-02	4.6E-02	1.6E-02	2.0E-01	1.4E-01	3.6E-01	-3.1E-01	-87%
POF	kg NMVOC	1.2E-03	2.8E-04	1.7E-03	3.1E-03	2.2E-04	5.2E-03	2.1E-02	2.6E-02	-2.3E-02	-88%
PMF	kg PM10 eq	6.4E-05	1.5E-05	4.8E-04	5.6E-04	1.2E-04	2.2E-03	1.6E-02	1.9E-02	-1.8E-02	-97%
Te – Ecot	kg 1,4-DB eq	3.3E-05	7.8E-06	1.1E-05	5.2E-05	8.6E-05	2.5E-05	2.1E-04	3.2E-04	-2.7E-04	-84%
FW – Ecot	kg 1,4-DB eq	8.9E-05	2.1E-05	5.5E-04	6.6E-04	4.8E-04	3.9E-03	9.2E-05	4.5E-03	-3.8E-03	-85%
Me-Dep	kg Fe eq	1.1E-03	2.5E-04	2.4E-03	3.8E-03	1.8E-03	5.3E-03	1.1E-05	7.1E-03	-3.3E-03	-47%
Fo-Dep	kg oil eq	4.0E-03	9.6E-04	2.0E-01	2.1E-01	2.4E-02	1.5E-01	3.9E-03	1.8E-01	3.2E-02	18%
Oz-Dep	kg CFC-11eq	1.6E-09	3.8E-10	1.1E-07	1.1E-07	1.9E-09	3.1E-08	1.1E-11	3.3E-08	7.9E-08	240%

Table 57. Net Environmental Impacts of Case C4: Bio-Electricity + Bio-Heat + Electric cookst vs Grid Electricity + Diesel- Heat (drying) + Coffee stems cookst

Impact Category	Units	Bio-Elect (1 kWh)	Bio-heat (1.56 kWh)	Heat LPG-Cookst (0.97 kWh)	Total impact indicators	Grid-Elect (1 kWh)	Heat-Diesel (1.56 kWh)	Heat CS Cookst (0.96 kWh)	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.2E-02	3.0E-03	5.9E-01	6.1E-01	1.3E-01	1.8E-01	2.3E-01	5.5E-01	6.3E-02	11%
Te - Acid	kg SO2 eq	1.3E-04	3.1E-05	1.2E-03	1.3E-03	3.6E-04	4.6E-04	1.5E-03	2.3E-03	-9.6E-04	-41%
FW - EU	kg P eq	8.6E-05	2.1E-05	1.2E-05	1.2E-04	2.0E-05	4.3E-06	5.4E-04	5.7E-04	-4.5E-04	-79%
Hu - Tox	kg 1,4-DB eq	2.5E-02	5.9E-03	1.6E-02	4.6E-02	1.6E-02	6.1E-03	1.4E-01	1.6E-01	-1.2E-01	-71%
POF	kg NMVOC	1.2E-03	2.8E-04	1.7E-03	3.1E-03	2.2E-04	4.4E-04	2.1E-02	2.2E-02	-1.9E-02	-86%
PMF	kg PM10 eq	6.4E-05	1.5E-05	4.8E-04	5.6E-04	1.2E-04	1.4E-04	1.6E-02	1.7E-02	-1.6E-02	-97%
Te – Ecot	kg 1,4-DB eq	3.3E-05	7.8E-06	1.1E-05	5.2E-05	8.6E-05	4.0E-06	2.1E-04	3.0E-04	-2.5E-04	-83%
FW - Ecot	kg 1,4-DB eq	8.9E-05	2.1E-05	5.5E-04	6.6E-04	4.8E-04	2.0E-04	9.2E-05	7.8E-04	-1.1E-04	-14%
Me-Dep	kg Fe eq	1.1E-03	2.5E-04	2.4E-03	3.8E-03	1.8E-03	1.2E-03	1.1E-05	3.0E-03	8.0E-04	27%
Fo-Dep	kg oil eq	4.0E-03	9.6E-04	2.0E-01	2.1E-01	2.4E-02	6.3E-02	3.9E-03	9.1E-02	1.2E-01	129%
Oz-Dep	kg CFC-11eq	1.6E-09	3.8E-10	1.1E-07	1.1E-07	1.9E-09	3.3E-08	1.1E-11	3.5E-08	7.6E-08	216%

Table 58. Net Environmental Impacts of Case D1: Bio-Electricity + Bio-heat vs Diesel Electricity + Coffee stems direct-combustion (drying)

Impact Category	Units	Bio-Elect (1 kWh)	Bio-Heat (1.56 kWh)	Total impact indicators	Diesel-Elect (1 kWh)	CS direct-combust	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.2E-02	3.0E-03	1.5E-02	9.4E-01	3.7E-02	9.8E-01	-9.6E-01	-98%
Te - Acid	kg SO2 eq	1.3E-04	3.1E-05	1.6E-04	1.0E-02	6.6E-04	1.1E-02	-1.1E-02	-99%
FW - EU	kg P eq	8.6E-05	2.1E-05	1.1E-04	4.4E-05	4.8E-05	9.2E-05	1.4E-05	16%
Hu - Tox	kg 1,4-DB eq	2.5E-02	5.9E-03	3.0E-02	6.2E-02	2.9E-02	9.1E-02	-6.0E-02	-66%
POF	kg NMVOC	1.2E-03	2.8E-04	1.4E-03	1.6E-02	1.9E-03	1.8E-02	-1.7E-02	-92%
PMF	kg PM10 eq	6.4E-05	1.5E-05	8.0E-05	5.5E-03	6.7E-04	6.2E-03	-6.1E-03	-99%
Te – Ecot	kg 1,4-DB eq	3.3E-05	7.8E-06	4.0E-05	2.3E-05	3.4E-05	5.7E-05	-1.7E-05	-29%
FW - Ecot	kg 1,4-DB eq	8.9E-05	2.1E-05	1.1E-04	2.9E-03	2.2E-04	3.1E-03	-3.0E-03	-96%
Me-Dep	kg Fe eq	1.1E-03	2.5E-04	1.3E-03	1.5E-02	3.4E-03	1.9E-02	-1.7E-02	-93%
Fo-Dep	kg oil eq	4.0E-03	9.6E-04	4.9E-03	3.2E-01	8.1E-03	3.3E-01	-3.2E-01	-98%
Oz-Dep	kg CFC-11eq	1.6E-09	3.8E-10	1.9E-09	1.7E-07	4.0E-09	1.7E-07	-1.7E-07	-99%

Table 59. Net Environmental Impacts of Case D2: Bio-Electricity + Bio-heat vs Grid Electricity + Coffee stems direct-combustion (drying)

Impact Category	Units	Bio-Elect (1 kWh)	Bio-Heat (1.56 kWh)	Total impact indicators	Grid-Elect (1 kWh)	CS direct-combust	Total impact indicators	Net Env-Impact	% change Env-Impact
CC	kg CO2 eq	1.2E-02	3.0E-03	1.5E-02	1.3E-01	3.7E-02	1.7E-01	-1.5E-01	-91%
Te - Acid	kg SO2 eq	1.3E-04	3.1E-05	1.6E-04	3.6E-04	6.6E-04	1.0E-03	-8.6E-04	-84%
FW - EU	kg P eq	8.6E-05	2.1E-05	1.1E-04	2.0E-05	4.8E-05	6.8E-05	3.8E-05	56%
Hu - Tox	kg 1,4-DB eq	2.5E-02	5.9E-03	3.0E-02	1.6E-02	2.9E-02	4.5E-02	-1.4E-02	-32%
POF	kg NMVOC	1.2E-03	2.8E-04	1.4E-03	2.2E-04	1.9E-03	2.1E-03	-6.4E-04	-31%
PMF	kg PM10 eq	6.4E-05	1.5E-05	8.0E-05	1.2E-04	6.7E-04	7.8E-04	-7.0E-04	-90%
Te – Ecot	kg 1,4-DB eq	3.3E-05	7.8E-06	4.0E-05	8.6E-05	3.4E-05	1.2E-04	-8.0E-05	-66%
FW - Ecot	kg 1,4-DB eq	8.9E-05	2.1E-05	1.1E-04	4.8E-04	2.2E-04	7.0E-04	-5.9E-04	-84%
Me-Dep	kg Fe eq	1.1E-03	2.5E-04	1.3E-03	1.8E-03	3.4E-03	5.2E-03	-3.8E-03	-75%
Fo-Dep	kg oil eq	4.0E-03	9.6E-04	4.9E-03	2.4E-02	8.1E-03	3.2E-02	-2.7E-02	-85%
Oz-Dep	kg CFC-11eq	1.6E-09	3.8E-10	1.9E-09	1.9E-09	4.0E-09	6.0E-09	-4.0E-09	-67.4%