IMPACT OF CHANGES IN THE SYNGAS-BIOCHAR MIX AND PLANT SIZE ON THE ECONOMICS AND ENVIRONMENTAL PERFORMANCE OF DISTRIBUTED BIOMASS GASIFICATION SYSTEMS

by

Sofia Ines Camarero Lema

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Assistant Professor of Practice Jose Alfaro
Assistant Professor Parth Vaishnav

Abstract

Agriculture and forestry residues are potential sources of sustainable energy that do not compete with food or demand land use changes. Small-scale biomass gasification could be used to generate decentralized renewable electricity where these biomass stocks are locally available, while co-producing biochar to sequester carbon. This study evaluated how the scale and the syngas-biochar trade-offs impact the economics and decarbonization potential of a gasification system. A small-scale downdraft gasifier fed with logging residues in Michigan was used as case study. A Life Cycle Assessment (LCA) approach was used to formulate Economic Benefit (EB) and Carbon Abatement (CA) objective functions that formed a Multi Criteria Decision Analysis (MCDA) problem. Feasible product mix and scale configurations were mapped, and a pareto frontier was identified. EB is maximized when the electricity generation and the scale are maximized, at expense of emitting 1.683 kg CO_2eq/kWh. Conversely, CA is maximized to 0.348 kg CO_2eq abated per kWh for the highest biochar production and the smallest scale. Results were found to be sensitive to external factors: EB optimum shifted to maximize biochar when the carbon price was increased from 5 \$/ton CO_2eq to match the social cost of carbon (50 \$/ton CO_2eq) and 2030 projections (100 \$/ton CO_2eq), CA increased 112.0% when grid electricity emissions were increased from 0.48 kg CO_2eq/kWh (Michigan's) to 0.87 kg CO_2eq/kWh (West Virignia's), and EB reached 0.147 \$/kWh when a high electricity price of 33 ¢/kWh (Hawaii's) is considered instead of Michigan's 13 ¢/kWh. For different stakeholders and contexts, the maximization of positive impacts can require different technology configurations. The developed LCA-MCDA combined methodology provides an example of a framework that could inform decision-making in the deployment of biomass gasification to reconcile economic and climate change mitigation objectives.

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Abbreviations

BECCS : bioenergy with carbon capture and storage
bm : biomass
bc : biochar
CA : carbon abatement
CGE : cold gas efficiency
EB : economic benefit
ER : equivalence ratio
GHG : greenhouse gases
LCA : life cycle assessment
LCOE : levelized cost of electricity
LHV : low heating value
MCDA : multi criteria decision analysis
sg : syngas
US : United States

1. Introduction

Study objectives

Using a theoretical small-scale gasification system as a case study, the objective of this work is to evaluate the impact of changes in the syngas-biochar product mix on the economics and GHG impact of the system. Because small-scale gasification applications cover a wide range of plant sizes that could have different costs and emissions, apart from product mix, the impact of plant size was also assessed. By elucidating the relationship between these factors and impacts, this study expects to demonstrate how a holistic assessment can inform technology development for effective implementation of small-scale biomass gasifiers.

Background

The energy sector is the largest contributor to global greenhouse gas (GHG) emissions as most of the increasing energy demand of anthropogenic activities is satisfied by fossil fuels (IPCC, 2014). Deployment of renewable and sustainable energy systems is required to decrease dependence on fossil fuels and mitigate climate change while securing energy supply to modern societies. The share of electricity in total final energy use is expected to increase from 20% up to 50% in the next three decades (IRENA, 2020). Projections indicate that electricity generation will have to more than double by 2050 and renewables, mostly wind, solar and hydropower, will have to generate over 85% of that electricity. As the fourth largest renewable power source, the installed capacity of biomass-based electricity will have to increase from 108 GW in 2017 to 685 GW in 2050 (IRENA, 2020).

Even though, when compared to other renewables, bioenergy state-of-the-art technologies have high costs and still struggle to compete with fossil fuel generators (IRENA, 2020), modern bioenergy can play an important role as a flexible resource in renewable power systems. Bioenergy can be produced from small to large scales and, since biomass can be stored, bioenergy can supply electricity at a steadier rate than variable and uncertain renewables that depend on the weather (Arasto et al., 2017). Furthermore, international climate mitigation goals require achieving net negative GHG emissions in the second half of this century (IEA, 2020). While displacing fossil fuels with wind, solar and hydropower can help reach these goals, they do not have the potential of removing carbon dioxide (CO_2) from the atmosphere as bioenergy (Lehmann, 2007). In the 2018 Intergovernmental Panel on Climate Change (IPCC) special report, all the pathways to keep global warming below 1.5 degrees Celsius implied achieving net negative emissions after 2050 through carbon removal approaches (IPCC, 2018). Apart from direct air capture, bioenergy with carbon capture and storage (BECCS), which is electricity generation through biomass combustion and coupled on-site capture and permanent storage of emitted CO_2, is included in the IPCC technology solutions for carbon removal (IEA, 2020). An alternative to BECCS for carbon removal is the thermochemical conversion of biomass to produce biochar, a stabilized carbon-rich residue that can be incorporated to the soil; like BECCS, the approach relies on photosynthesis to fix CO_2, which is then stored in biochar and sequestered in a stable reservoir (Woolf et al., 2016).

A big pitfall of bioenergy can be the conversion of land to generate feedstock, as it can have negative impacts on ecosystem conservation and high GHG emissions (Woolf et al., 2010). Agriculture and forestry residues are potential sources of sustainable energy, with the advantage of being a cost-effective feedstock supply that does not compete with food or demand land use changes. Securing sustainable biomass supply at large scale can be a challenge because biomass is widely spatially distributed, hence, small-scale applications could allow full utilization of biomass in remote areas (Situmorang et al., 2020). Biomass gasification is a technology that could be used to produce renewable energy to fuel heating systems or micro-grids and generate electricity in a decentralized way at places where these biomass stocks are locally available (Klavins, Bisters and Burlakovs, 2018). Capacities below 200kW are considered to be small-scale for gasifiers, and could be suitable to supply energy for small rural communities or even a single family (Situmorang et al., 2020). Compared to other biomass thermochemical conversion processes, such as pyrolysis or combustion, gasification has been demonstrated to be more suitable for small-scale throughputs due to its higher efficiency (Yao et al., 2018). Nevertheless, small-scale gasification has not penetrated energy markets in the United States (US). A 2020 review on gasification technology reported only two out of 188 biomass power plants, that were below 1 MW: City of Covington Waste-To-Energy Gasification Plant in Tennessee, a gasification based power plant with a capacity of 125 kW operated since 2013, and Sullivan County Biomass Project in New Hampshire with a capacity of 40 kW (Situmorang et al., 2020).

Gasification is a thermochemical process that converts biomass to combustible gases (Zainal *et al.*, 2001) at high temperatures (typically 700-1000°C) and reduced oxygen conditions (Reed and Das, 1988). The final gas product, known as syngas or synthesis gas, is mainly the mixture of carbon monoxide (CO), methane (CH_4) and hydrogen (H_2) which, after cleaning, can be used in various applications such as internal combustion engines or electricity generation (Sarker and Nielsen, 2015). Another product of the process is biochar, charcoal or biomass-derived black carbon, which is generated through pyrolysis reactions. Due to its stability, the application of biochar to soil can establish a long-term sink for atmospheric carbon dioxide: the residence time of biochar is estimated to be orders of magnitude above that for crop residues, which is decades (Jeffery et al., 2011). Apart from carbon sequestration, its application to soil can improve soil fertility by retaining nutrients and providing other services such as improving soil physical and biological properties, enhancing plant growth (Lehmann, Gaunt and Rondon, 2006). Studies have shown that on average, the incorporation of biochar to the soil can lead to a statistically significant increase in crop yields, especially for agroecological locations with poor soils (Crane-Droesch et al., 2013). Regarding its decarbonization potential, studies have shown that sustainable biochar production has the technical potential to make a substantial contribution to climate change mitigation (Woolf et al., 2010); the maximum carbon abatement potential of biochar was estimated at 3.3 Gt CO_2eq per year (Amonette et al., 2021).

For the design of syngas-biochar systems, the initial biomass selection is a key step since it can have major implications in the resulting carbon footprint (You and Wang, 2019). A wide range of lignocellulosic biomass feedstocks can be processed through gasification; many of which are inexpensive and available in large volumes. Lignocellulosic biomass is mainly composed of three polymers - cellulose, hemicellulose and lignin - which are presented at a relatively constant atomic ratio for large samples: $CH_{1.4}O_{0.6}$. Gasification can thus be approximated by the reaction equation below, although it is known that additional reactions can occur between products and produce methane (Reed and Das, 1988).

$$CH_{1.4}O_{0.6} + 0.4O_2 \rightarrow 0.7CO_{0.3}CO_2 + 0.6H_2 + 0.1H_2O$$ *Equation 1.*

In biomass gasification, biochar production will depend on the rate of heating and the particle size of the feedstock (Lehmann *et al.*, 2015). During downdraft gasification, it is estimated that between 10% to 20% of the biomass will remain as biochar after pyrolysis is complete, and depending on the conditions, the char will continue to react to form gases (Reed and Das, 1988).

Despite the complexities of the chemistry and thermodynamics of gasification, gasifiers are relatively simple devices that can have inexpensive designs and be easy to operate (Boravelli, 2016). The downdraft gasifier design, originating in the 1920s, has been most widely used for small-scale off-grid power applications (Rollinson, 2016). Fixed-bed downdraft reactors offer the additional advantage of yielding less tar, which is an undesired co-product, and are therefore technically more attractive (Sarker and Nielsen, 2015).

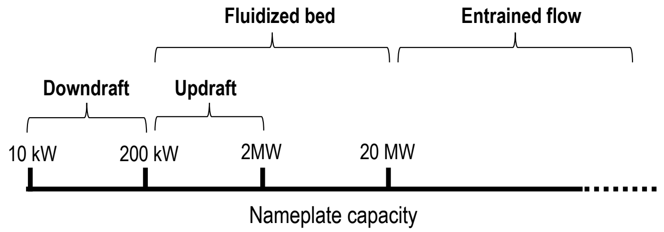

Figure 1. Estimation of the different types of gasification technologies used for different scales. *(Díaz González and Pacheco Sandoval, 2020)*

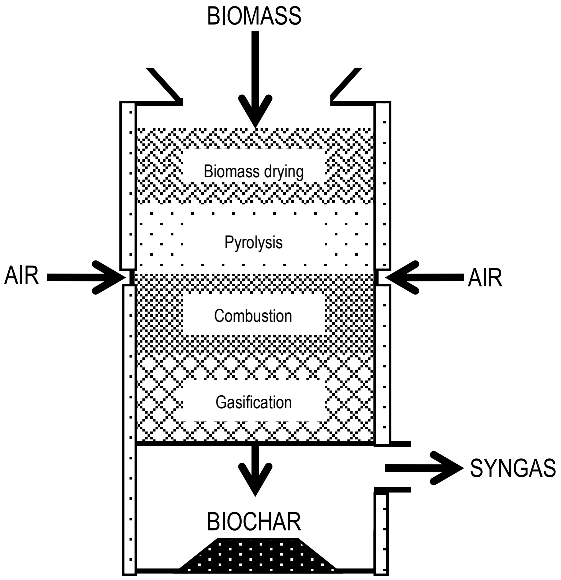

Figure 2. Schematic representation of a downdraft gasifier reactor. Within the reactor, temperature profiles develop, resulting in zones where different physical and chemical processes occur *(Basu, 2018b).*

Air or oxygen flow is a critical operation variable in gasification, since the amount of oxygen available in the system will determine the extension of the reactions taking place and the quality of the products and the temperatures. The ratio between incomplete and complete combustion products (CO/CO_2 or H_2/H_2O) is a measure of the gas quality. Ideally the smallest amount of oxygen possible to carry the solid composition to the composition mixture of CO and H_2 should be supplied, but in practice excess oxygen is required yielding CO2 and H_2O (Reed and Das, 1988). In addition to this, the amount of biochar produced generally decreases with increasing O_2 (Lehmann et al., 2015) (Kirch et al., 2020). Thus, although gasification can provide both biochar and bioenergy, a trade-off exists: for a given amount of biomass, increasing biochar production entails a corresponding reduction in the syngas that can be produced (Woolf et al., 2014).

Different biomass feedstocks, reactor designs and operating conditions affect the process outputs and its capacity to serve electricity and biochar purposes; thus, understanding the impact of these variables on the product mix is required for the effective implementation of the technology. Multiple theoretical and empirical studies have been carried out to construct thermodynamic models of the gasification process for various conditions. However, a gap was identified regarding syngas-biochar systems optimization since most scientific literature focuses on one objective or the other. Because gasification has a high thermal efficiency, of 75−80%, and generally low biochar yields when compared to other thermal processes (Woolf *et al.*, 2014), deployment of clean energy is frequently identified as the ultimate objective of gasification. Nevertheless, a gasifier could also intend to meet carbon sequestration and soil fertility management needs through biochar production at the same time.

Even though evidence on how process parameters can affect gasification product mix was found, the impact of these tradeoffs on the economics and environmental performance of the system has not been fully explored. Some studies analyzing partial aspects of this research question were found in the literature, most of them focusing on a broader range of bioenergy technologies. For example, Woolf et. al (Woolf et al., 2014) developed an empirical model to calculate energy penalties per unit mass of additional biochar produced in several pathways for biochar coproduction with gaseous and liquid biofuels. Another study proposed a life cycle GHG and economic operating cost assessment model to compare the coproduction of biochar and bioenergy from biomass residue feedstocks between slow pyrolysis, fast pyrolysis and gasification systems (Field et al., 2013).

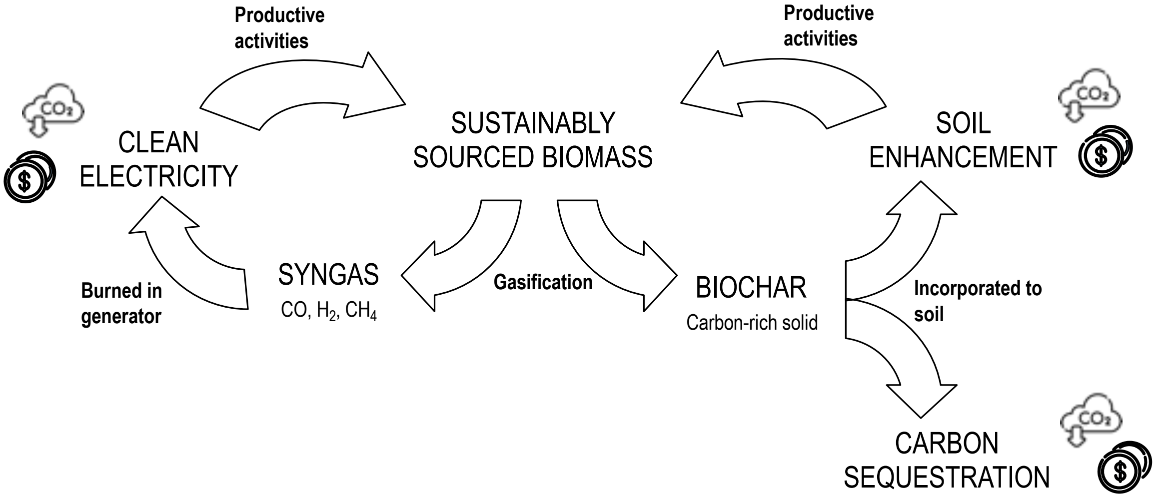

Figure 3. Diagram of a biomass gasification system identifying the carbon abatement and economic benefit points. The main products of biomass gasification are gaseous fuel (syngas) and biochar. Syngas can be used to generate electricity. Apart from carbon sequestration, carbon-rich biochar can be incorporated to the soil for its enhancement, improving the agricultural productivity contributing to the circular economy and overall carbon abatement capacity of the system (Hansen et al., 2015).

2. Methods

To study the trade-offs associated to product mix and scale in distributed biomass gasification, a model gasification system was specified: implementation of small-scale gasification in managed forests in Michigan, United States. The technology chosen for the model was a downdraft gasifier, the most widely used and recommended for small-scale applications (Díaz González and Pacheco Sandoval, 2020). The energy feedstock was assumed to be logging residues, which are the treetops and branches that are commonly left in the forest unused (Swinton et al., 2021). Logging residues are one form of timber residues, the other one is mill residues which have seen more use. The gasification facility is assumed to be located within the forested property and operate using residues generated on-site. All the electricity generated is destined for self-consumption, and all the biochar produced is incorporated to the soil by the landowners, who trades the accounted sequestered carbon for carbon credits. There is an emerging business model where entities removing atmospheric carbon are paid by entities who neutralize their residual emissions with said verified carbon removals (Thengane et al., 2021).

Two impact metrics were selected for the evaluation of the implementation of the proposed gasification system: economic costs and carbon abatement potential. A positive framing was used for both metrics, defining the economic impact as Economic Benefit (EB) for the landowner in US dollars ($), and Carbon Abatement (CA) potential in kg of CO_2eq. To quantify these metrics, a Life Cycle Assessment (LCA) was conducted to track the economic costs/savings and GHG emissions fluxes across the system using 1kWh of electricity generated as the functional unit for the assessment.

All forestry activities that happen before the logging residues are created were left outside of the system's boundaries, as they are independent from the functional unit and are not driven or determined by the waste management strategy. Therefore, the first stage considered is the biomass procurement. Residues are assumed to be collected, chipped in situ and transported to the gasification facility, where they are left to air dry before being fed to the gasifier. From the downstream processes of the gasification stage, only generated electricity and carbon sequestration were included in the analysis. Tar handling and disposal, and the storage, distribution and application of biochar were considered to have negligible contributions to the EB and CA metrics and were left out of scope. The analysis did not account for economic savings/costs or GHG emissions from avoided forestry residues management practices, since it was assumed that the alternative scenario is to leave them in the forest unused. Furthermore, potential Renewable Electricity Certificate economic benefits were not included because the electricity is self-consumed and no interactions with electricity utilities is considered. Potential benefits from biochar application to the soil such as increased crop yields or savings from reduced use of fertilizers were left out of the system boundaries.

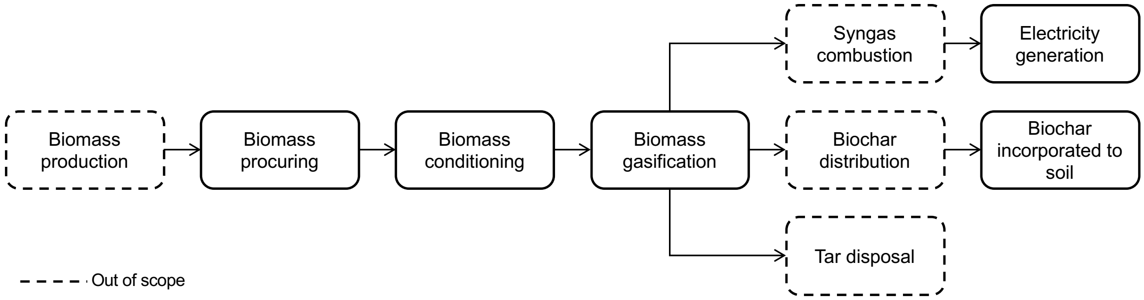

Figure 4. Process flow diagram for biomass gasification.

Optimization problem

With the LCA approach, the equations to calculate the EB and CA per functional unit were constructed as a function of the amounts of syngas and biochar produced, and as a function of the plant size or scale of the gasification system, with scale defined as nameplate capacity in kW. These equations, or objective functions, determine a Multi Criteria Decision Analysis (MCDA) problem: the optimum system configuration could change depending on the objective being pursued. The non-linear system of equations was solved and optimized using the generalized reduced gradient method (Lasdon et al., 1974) with Microsoft® Excel's Solver Add-in.

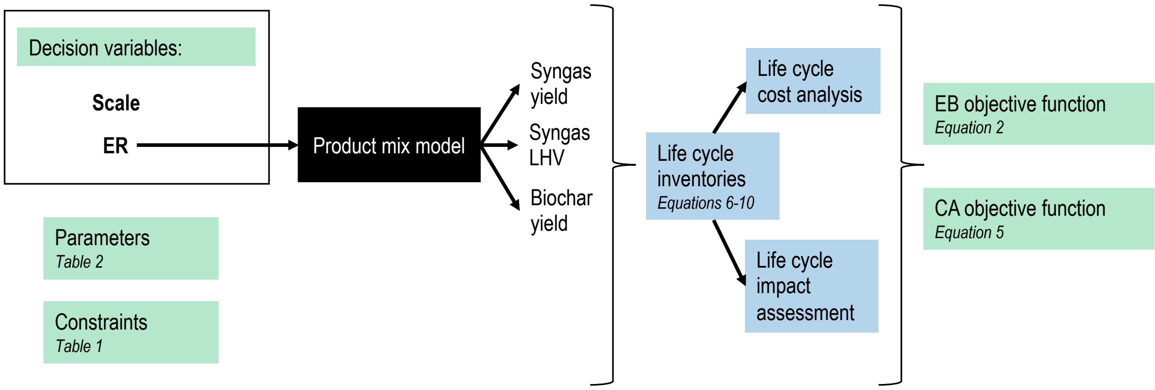

Figure 5. Diagram of the flow of the model constructed to characterize the gasification system and calculate EB and CA.

Economic benefit objective function

The EB objective function has the following terms:

$$EB\left(\frac{\$}{kWh}\right) = -\,Biomass\ procuring\ cost - Levelized\ cost\ of\ electricity + Electricity\ displaced\ cost + \ Carbon\ credits\ revenue$$

Equation 2

For the economic analysis, a levelized cost of electricity (LCOE) (Masters, 2013), excluding the cost of the fuel, was calculated.

$$LCOE\ \left(\frac{\$}{kWh}\right) = \frac{CRF\times Capital\ cost\times Scale+O\&M_{fixed}+O\&M_{variable}\times Scale}{Scale\times Operation\ duty}$$

Equation 3

$$CRF = \frac{i\times(i+i)^{n}}{(i+i)^{n}-1}$$

Equation 4

CRF is the capital recovery factor in 1/year
Capital cost is the upfront investment in \$/kW
$O\&M_{fixed}$ is the fixed operations and maintenance cost in \$/year
$O\&M_{variable}$ is the variable operations and maintenance cost in \$/kW/year
Operation duty is the number of hours the gasifier operates in a year in h/year
i is the discount rate
n is the project timeline in years

Indrawan et al., 2020 reports capital costs of \$112,500 for a 60kW application, \$442,198 for 250kW and \$325,635 for 75kW gasifier. Likewise, Situmorang et al., 2020 reports costs of \$563 per kW, \$1,267 per kW, \$1698.5 per kW for a 100 kW gasifier and \$1,503.745 per kW for a 1,000kW. The capital costs of implementing a downdraft gasifier were assumed to be an average of the \$/kW costs identified in these sources: \$1,860 per kW. Operations and Maintenance (O&M) costs were classified as fixed and variable; the fixed costs were considered to be labor (\$7.25/hour for 50% of the annual operating hours of the gasification system), tools and spare parts, and the variable costs were estimated as cleaning and propane gas to start up (Indrawan et al., 2020).

The economic benefit of applying biochar to the soil was estimated by assuming that carbon credits could be traded at a conservative carbon price of 5 \$/ton CO_2eq.

Carbon abatement objective function

The CA objective function has the following terms:

$$CA\left(\frac{kg\ CO2eq}{kWh}\right) = -\,Biomass\ procuring\ emissions - Gasifier\ emissions + Emissions\ of\ electricity\ displaced + Carbon\ sequestered\ in\ biochar \quad \text{Equation 5}$$

GHG emissions were calculated using a mixed methods approach. In most cases impact factors were retrieved from the literature or Ecoinvent databases from SimaPro®. The impact of biochar application to the soil in the form of carbon sequestration in kg CO_2 eq, was calculated using the methodology developed by Woolf et al., 2021. When assessing effect of biochar on soil priming (changes in mineralization of existing non-pyrogenic soil organic carbon) and methane emissions were not considered.

Emissions from gasifier manufacturing were included and approached using emissions from a power plant that uses a wood chip furnace, amortized in the project's timeline. During the operation of a gasifier combustion of syngas in the generator is the main source of emissions, but because they can be considered to be mostly biogenic carbon emissions, they were left out of the scope of the model used in this study (Pa et al., 2011). Originated from plants, biogenic carbon emissions have no GHG impact as they do not increase carbon content of the atmosphere as opposed to their fossil-origin counterparts. A system expansion methodology was followed to account for the reduction in the emissions due to grid electricity displacement.

Modeling the product mix

The amounts of syngas and biochar produced by the gasifier determine the electricity produced and the carbon sequestered, and their associated economic and GHG impacts. These variables are not independent from each other, they are both related to the extent of the thermochemical conversion of the biomass and are thus controlled by the process operation variables that control the reaction. For this study, it was necessary to identify the feasible product mixes for the gasification of woody biomass in a downdraft gasifier. This was achieved by using a simplified model that has the equivalence ratio (ER) as the single critical process variable that describes the reaction (Reed, 1981). ER is the ratio between the air to fuel ratio supplied to the reactor and the air to fuel ratio required for complete combustion, which is also referred to as stoichiometric condition; gasification occurs in sub-stoichiometric condition (Upadhyay et al., 2019). The model also predicts syngas Low Heating Value (LHV), a measure of the energy per unit volume of gas, as a function of the equivalence ratio. It was assumed that this model is independent of scale. For more details on the model construction see Supplementary Materials.

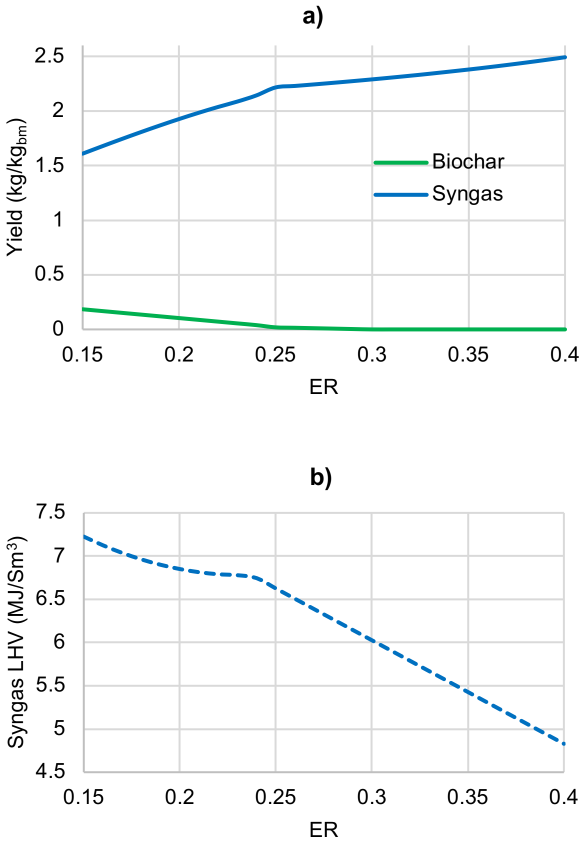

Figure 6. a) Gasification model results for biochar and syngas yields as a function of the equivalence ratio. b) Gasification model results for low heating value of syngas as a function of the equivalence ratio.

This model is based on thermodynamic calculations at equilibrium which are expected to provide a threshold of what can possibly occur, but may not describe the behavior of a real gasifier with great accuracy (Reed, 1981). To validate this assumption and assess its agreement with empirical data, a comparison between model predictions and experimental results from the literature was done for different ER values.

Decision variables and constraints

The decision variables for the model are the ER, which determines the product mix, and the scale of the gasification system. Once the product mix and the syngas LHV were determined for the particular ER, the life cycle inventories were calculated.

$$CGE = \frac{Y_{\frac{sg}{bm}} \times LHV_{sg}}{LHV_{bm}}$$ *Equation 6*

$$W_{bm} = \frac{Scale \times 3.6 \frac{MJ_{electricity}}{h \cdot kW}}{\eta_{gen} \times (1 - \theta/100) \times CGE \times LHV_{bm}}$$ *Equation 7*

$$FU_{bm} = \frac{W_{bm}}{Scale}$$ *Equation 8*

$$FU_{sg} = FU_{bm} \times Y_{\frac{sg}{bm}}$$ Equation 9

$$FU_{bc} = FU_{bm} \times Y_{\frac{bc}{bm}}$$ Equation 10

The subscript "sg" refers to syngas, "bm" refers to biomass, "bc" refers to biochar
$Y_{sg/bm}$ *is the yield of syngas in* kg_{sg}/kg_{bm}
CGE is the cold gas efficiency in MJ_{sg}/MJ_{bm}
LHV_{sg} *is the low heating value of syngas in* MJ_{sg}/kg_{sg}
LHV_{bm} *is the low heating value of biomass in* MJ_{bm}/kg_{bm}
W_{bm} *is biomass flow rate in* kg_{bm}/h
Scale is the plant size in kW
η_{gen} *is the generator efficiency in* $MJ_{electricity}/MJ_{sg}$
θ *is the percentage of the generated electricity consumed by the gasifier during operation*
FU_{bm} *refers to the quantity of dry biomass required per functional unit* (kg_{bm}/kWh)
FU_{sg} *refers to the quantity of syngas required per functional unit* (kg_{sg}/kWh)
FU_{bc} *refers to the quantity of biochar produced per functional unit* (kg_{bc}/kWh)
$Y_{bc/bm}$ *is the yield of biochar in* kg_{bc}/kg_{bm}

Using the dry biomass mass flow rate (15% moisture content) and assuming wet biomass has a moisture content of 52%, the amount of wet biomass required per functional unit was calculated. This allowed the calculation of the yearly wet biomass supply required as a function of the scale, which determines the total land required to procure the biomass. Logging residues in Michigan forests are 31.13 metric tons of wet biomass per km^2 per year (Swinton et al., 2021).

The hauling distance used to calculate the costs and emissions associated to transportation in the biomass procuring stage was assumed to be the radius of the total land area required.

Constraints for the decision variables and for intermediate variables were included in the mathematical model to ensure results with physical sense. The feasible range for ER was determined based on the ER values for gasification found across the literature. The feasible range for the scale was determined based on the definition of small-scale gasification systems. The feasible range for cold gas efficiency (CGE) was determined based on the CGE values for gasification found across the literature. The feasible range for biochar yield was based on thermo gravimetric analysis (TGA) results for wood that show that approximately 30% of biomass weight is char, with the rest being volatiles, moisture, and ash.

Table 1. Constraints.

Variable	Maximum	Minimum	Reference
ER	0.4	0.15	(Basu, 2018b) (Torres et al., 2018)
Scale (kW)	200	10	(Díaz González and Pacheco Sandoval, 2020) (Situmorang et al., 2020)
CGE (MJ_{sg}/MJ_{bm})	0.9	0.5	(Basu, 2018b) (Reed and Das, 1988)
Biochar yield (kg_{bc}/kg_{bm})	0.3	0*	(Reed and Das, 1988)

*A yield of 0 for char would still have some solid remaining in the form of ash, which for the model was assumed to be 1% of biomass feedstock weight.

Table 2. System parameters.

Parameters		Reference
Biomass feedstock		
Biomass LHV (MJ/kg)	16.000	(Telmo and Lousada, 2011)
Biomass moisture content (%)	52	(Kizha et al., 2018)
After drying moisture content (%)	15	(Nurek et al., 2019)
Area for biomass source (ton wet bm/km^2/year)	31.13	(Swinton et al., 2021)
Gasification process		
Syngas density (kg/Sm^3)	1.02	Calculated assuming ideal gas and a composition of: CO 23%, CO_2 10%, H_2 18%, CH_4 2%, N_2 48% (Patuzzi et al., 2021)
Biochar LHV (MJ/kg)	19.76	(Bilbao and Garcia-Bacaicoa, 1993)
Generator efficiency ($MJ_{electricity}/MJ_{sg}$)	0.199	(Patuzzi et al., 2021)
Electricity used during operation (%)	12.7	(Patuzzi et al., 2021)
Operation duty (hours/year)	2,680	-
Economics		
Biomass transportation cost ($/kg/km)	0.000089	(Swinton et al., 2021)
Biomass harvesting cost ($/kg)	0.02	(Swinton et al., 2021)
Biomass conditioning cost ($/kg)	0	-
Capital costs of gasifier ($/kW)	1860	Average (Indrawan et al., 2020) (Situmorang et al., 2020)
Plant lifetime (years)	20	-
Discount rate (%)	7	-
O&M fixed costs ($/year)	12,859	Calculated based on (Indrawan et al., 2020)
O&M variable costs ($/kW/year)	146	Calculated based on (Indrawan et al., 2020)
Sales price of carbon offset ($/kg CO_2 eq)	0.005	("Carbon offset prices set to increase tenfold by 2030 | Greenbiz," n.d.)
Price of grid electricity ($/kWh)	0.1285	("Electric Power Monthly - U.S. Energy Information Administration (EIA)," n.d.)
GHG impact		
Emissions of harvesting (kg CO_2 eq/kg wet bm)	0.043	(Ahmed et al., 2019)
Emissions of transport (kg CO_2 eq/tkm)	0.437	(Ahmed et al., 2019)
Emissions of conditioning	0	-
Gasifier manufacturing emissions (kg CO_2 eq/kWh/kW)	0.00072	SimaPro. Impact method: IPCC GWP 2021 100; Furnace, wood chips, average storage area, 1000kW {GLO}| market for | Cut-off, S
Emissions of grid electricity (kg CO_2 eq/kWh)	0.4765	(CMU Power Sector Carbon Index, 2022)
Biochar application		
Annual fertilizer application (ton N/ha)	0.1681	(Warncke et al., 2009)
Reaction temperature (°C)	>600	(Basu, 2018a)
Fraction of carbon remaining in soil after a specific number of years and annual cropland temperature	0.82	(Woolf et al., 2021)
Fraction of organic carbon in biochar	0.63	(Woolf et al., 2021)

Scenario Analysis

Parameters such as electricity price, emissions of grid electricity and carbon price that depend on where the system is being deployed. Different scenarios for these parameters were selected to understand how these externalities affect the optimum system configuration, and the potential economic benefit and decarbonization potential. This was used as an artificial way of elucidating how context can change the outcomes of the technology, which does not mean that the set of tested parameters could coexist with the defined gasification system. It was also used as a way to factor in not only spatial but also time variations, since in the transition to renewables it is expected that grid emissions per kWh decrease, for example.

Table 3. Price electricity, carbon price, emissions from grid electricity scenarios. References: price of electricity ("Electric Power Monthly - U.S. Energy Information Administration (EIA)," n.d.); emissions of electricity (CMU Power Sector Carbon Index, 2022).

Scenario	Description	Price of grid electricity ($/kWh)	Carbon price ($/kgCO$_2$eq)	Emissions of grid electricity (kgCO$_2$eq/kWh)
0	Base case	0.1285	0.005	0.4765
1	Hawaii: highest electricity price in the U.S. in December 2021	0.3346	0.005	0.6364
2	West Virginia: highest GHG emissions per kWh in the U.S in 2020	0.0879	0.005	0.8668
3	Vermont: grid electricity with lowest GHG impact in the U.S. in 2020	0.1679	0.005	0.0005
4	Social cost of carbon (Backman, 2021)	0.1285	0.050	0.4765
5	Carbon price projection for 2030 ("Carbon offset prices set to increase tenfold by 2030 | Greenbiz," n.d.)	0.1285	0.100	0.4765

Uncertainty Analysis

The biomass LHV, which describes the energy density of the forestry residues, is the property that determines the maximum amount of energy that can be extracted in the gasification process. This property can vary with the type of wood and moisture content. Different LHVs for woody biomass were found in the literature; for example Nurek et al., 2019 report the range 15.78-18.77 MJ/kg, Telmo and Lousada, 2011 report the range 14.41-17.91 MJ/kg, and Reed and Das, 1988 report a value of 20.40 MJ/kg. Another critical parameter in the gasification process is the electrical efficiency of the generator, which determines the amount of electricity that can be produced. Electrical efficiency for internal combustion engine generators using bio-derived syngas is not widely reported. Significant differences were found among capital costs and an average value was used in the model. The response of the model to the uncertainties of these system parameters was tested through Monte Carlo simulations using SimVoi® Monte Carlo Simulation Add-in for Excel with triangular distributions and 10,000 trials.

This analysis was done using fixed values for the decision variables: ER=0.15 and Scale=23.6kW. This system configuration is the economic optimum when carbon neutrality is forced in the solver as a constraint. In other words, the CA objective function is set to zero, and the EB objective function is maximized.

Table 4. Parameters for uncertainty analysis.

Parameter	Distribution	Mode	Minimum	Maximum
Biomass LHV (MJ/kg)	Triangular	16.0 (Telmo and Lousada, 2011)	14.4 (Telmo and Lousada, 2011)	20.8 (Wright et al., 2009)
Generator efficiency ($MJ_{electricity}/MJ_{sg}$)	Triangular	0.199 (Patuzzi et al., 2021)	0.15 (Reed and Das, 1988)	0.32 (Capaldi, 2014)
Capital costs of gasifier ($/kW)	Triangular	1,860 (Average used for base case)	563 (Situmorang et al., 2020)	4,342 (Indrawan et al., 2020)

A preliminary sensitivity analysis was conducted before the uncertainty and scenario analysis were defined. Variations of plus and minus 20% were tested in relevant parameters, and EB and CA results were recalculated. More details can be found in the supplementary materials.

3. Results

The optimum product mix and scale obtained for the model varied depending on which objective was being pursued. EB is maximized when the ER is 0.248, which maximizes the CGE with a syngas yield of 2.207 kg_{sg}/kg_{bm} and a syngas LHV of 6.654 MJ/Sm^3. Conversely, the CA potential of the system is maximized for the lowest ER in the decision space, 0.15, that is the one that maximizes biochar production by yielding 0.184 kg_{bc}/kg_{bm}. Similarly, the scales that maximize EB and CA are on opposite sides of the decision space: the total power output for the economic optimum is the 200 kW, whereas the carbon abatement optimum is 10kW.

At the economic optimum the EB is -0.059 $/kWh, which means that bio-based electricity would be approximately 6 ¢ higher than grid electricity, and the CA potential is -1.683 kg CO_2eq/kWh, which means that the system would have net GHG emissions instead of GHG reductions. At the carbon abatement optimum, the EB is -0.523 $/kWh, which means that bio-based electricity would be approximately 52 ¢ higher than grid electricity, and the CA potential is 0.348 kg CO_2eq/kWh. In both cases the resulting EB is negative, which means that, under the assumptions made, the adoption of the gasification system would represent an economic cost. When carbon abatement is prioritized, the system has the potential to decrease overall GHG emissions. However, when the EB is maximized, the adoption of the proposed gasification system leads to an increase in GHG emissions.

The contribution of the different terms in the objective function was analyzed to identify the most relevant stages of the process for each result. For the EB, it was found that the costs associated to the gasification stage are more significant than the costs of procuring the biomass. Moreover, the benefit of trading biochar carbon credits was found to be negligible compared to the savings that come from grid electricity displacement. When carbon abatement is maximized, the EB becomes suboptimal mainly because of the increased gasification costs caused by the smaller scale and consequent loss of economies of scale savings. For the carbon abatement optimum, both biochar carbon sequestration and grid electricity have significant and comparable contributions to the overall carbon abatement capacity of the system with shares of 57% and 43% in the GHG emissions reduction, respectively. However, biochar carbon sequestration impact becomes less significant at the economic optimum. For the carbon abatement optimum, it was observed that the GHG impact of procuring the biomass is higher than the individual contributions to GHG emissions reductions of biochar application and electricity displaced. The increased scale at the EB optimum leads to a significant increase in biomass procuring emissions due to the increased transportation distances, making biomass procuring the main contributor to the suboptimal carbon abatement result.

Table 5. Model optimization results.

	Maximize EB	**Maximize CA**
ER	0.248	0.15
Scale (kW)	200	10
Syngas yield (kg_{sg}/kg_{bm})	2.207	1.609
Biochar yield (kg_{bc}/kg_{bm})	0.027	0.184
CGE (MJ_{sg}/MJ_{bm})	0.900	0.712
Biomass, wet (kg_{bm}/kWh)	2.284	2.886
Syngas (kg/kWh)	3.177	2.925
Biochar (kg/kWh)	0.039	0.335
EB ($/kWh)	-0.059	-0.523
CA (kg CO_2eq/kWh)	-1.683	0.348

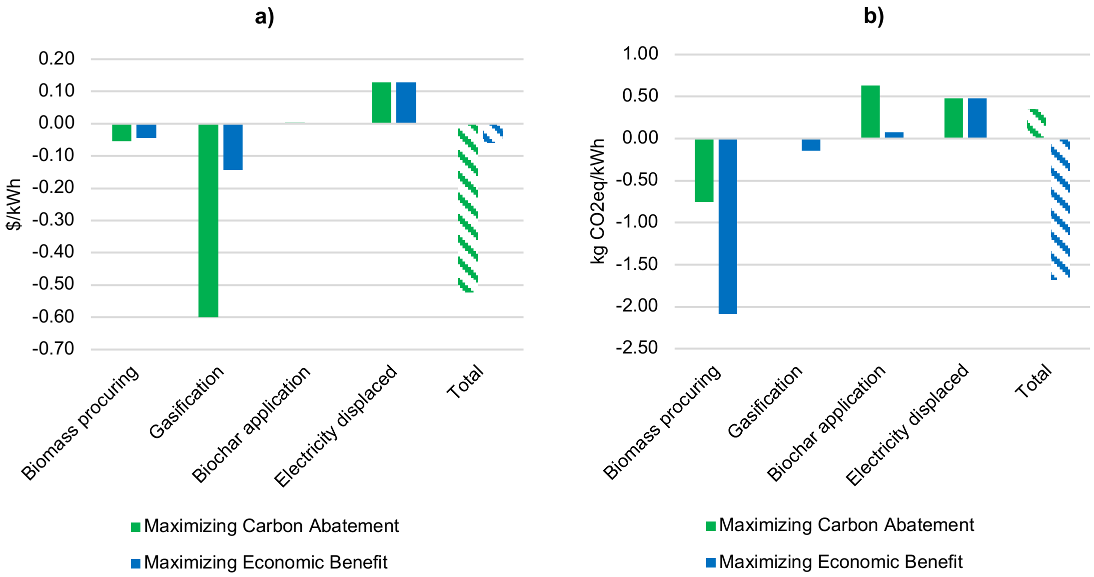

Figure 7. a) Contribution of each term of the economic benefit objective function at the different optima. b) Contribution of each term of the carbon abatement objective function at the different optima.

All the ER and scale feasible configurations were mapped, and the objective functions were calculated. Figure 6 presents a visualization of the decision space and the corresponding combinations of economic benefit and carbon abatement results. There is no single configuration that maximizes both objectives at the same time, demonstrating the existence of trade-offs among the decision variables. The pareto frontier, set of points where the EB cannot be improved without making CA potential worse and vice versa, was identified. The system configurations at the pareto frontier cover the whole range of possible scales, with a product mix of 1.609 kg_{sg}/kg_{bm} and 0.184 kg_{bc}/kg_{bm} for scales below 73 kW, and a product mix of 2.207 kg_{sg}/kg_{bm} and 0.027 kg_{bc}/kg_{bm} for scales above 93 kW.

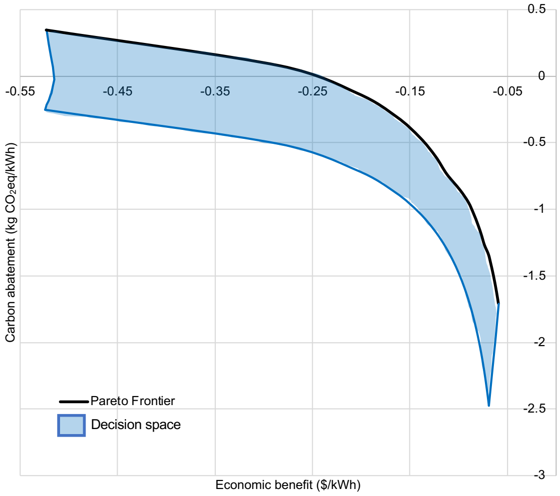

Figure 9. Carbon abatement versus economic benefit for the different system configurations in the decision space.

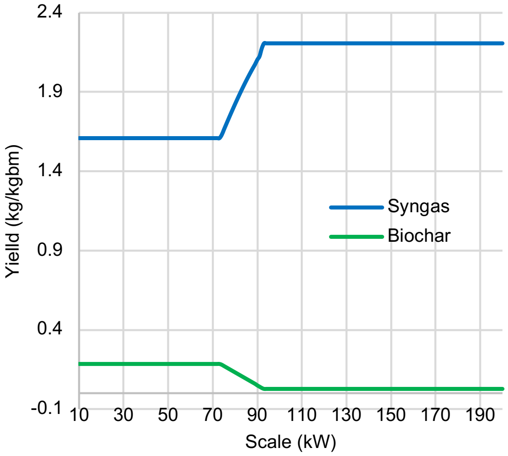

Figure 8 System configurations at the pareto frontier: syngas yield, biochar yields and scale.

Product mix model validation

The gasification model was compared to other experimental results in the literature to validate the approach and learn how it differs from real data. Figure 3 compares the predicted product mix with the empirical data set published by Bilbao and Garcia-Bacaicoa, 1993. The trade-off between syngas and biochar yields can be observed in both cases; there is a general trend for biochar yield to decrease as syngas yield increases. Nevertheless, the empirical data set presents outliers, dispersion, and overall lower biochar yields for the same syngas yields than the model predictions, Even though there is agreement on general trends there is no consensus on how to model the product mix and most work has focused in the modeling of syngas composition, LHV and CGE. Trninić et al., 2020 and. Yao et al., 2018 also developed mathematical models for downdraft gasifiers that predict similar trends to the ones predicted by the model used in this study.

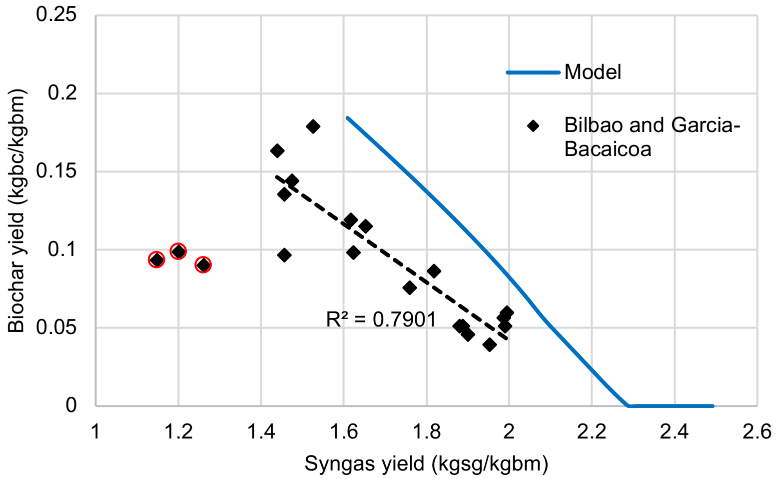

Figure 10. Biochar yield versus syngas yield for the gasification model and the experimental results published by Bilbao and Garcia-Barcaicoa using a 200 kg_{bm}/h gasifier. The highlighted outliers were discarded for the linear regression fit.

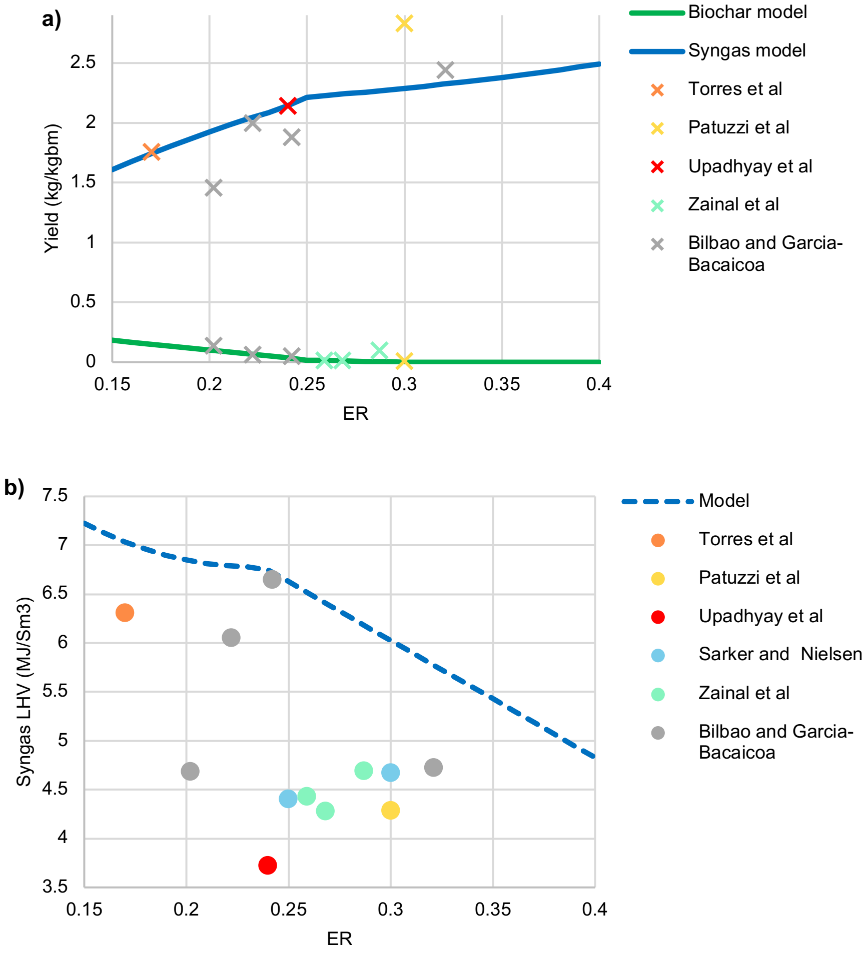

Figure 11. Comparison of the gasification model predictions to empirical data from the literature. All cited experiments used woody biomass as feedstock in small-scale downdraft gasifiers. a) Product yields as a function of ER. b) Syngas LHV as a function of ER.

Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of the model predictions were calculated: MAE is 0.212 kg_{sg}/kg_{bm}, 0.024 kg_{bc}/kg_{bm} and 1.694 MJ/Sm^3 and RMSE is 0.297 kg_{sg}/kg_{bm}, 0.039 kg_{bc}/kg_{bm} and 1.871 MJ/Sm^3, for the syngas yield, biochar yield and syngas LHV, respectively.

Scenario Analysis

Sensitivities to the variation of key contextual parameters (grid electricity prices, grid electricity emissions and carbon price) were assessed by testing the five different scenarios presented in Table 3 in the Methods section. It was found that the optimum system configurations for the objective functions remained mostly unchanged in scenario 0; only scenarios 4 and 5 had the economic optimum moved to match the ER of the carbon abatement optimum but maintaining its economic scale of 200 kW. Except for scenario 2, all scenarios showed a higher EB optimum respect to scenario 0, with scenario 1 achieving a positive EB of 0.147 $/kWh and scenario 5 achieving almost zero EB (-0.007 $/kWh). Regarding carbon abatement potential, scenarios 1 and 2 saw an increase of 45.9% and 112.0% in kg of CO_2eq reduced per kWh, while scenario 3 saw a decrease of 136.6% in the carbon abatement capacity of the system.

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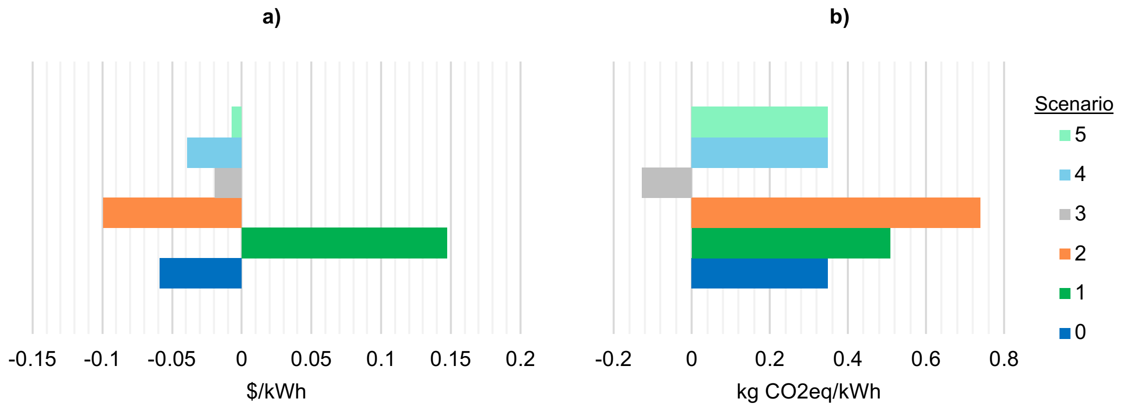

Figure 12. a) EB at economic optimum for each scenario. b) CA at carbon abatement optimum for each scenario.

Uncertainty Analysis

The system configuration of scale 23.6kW and ER 0.15 ER is the economic optimum when carbon neutrality is set as a constraint in the model, resulting in an EB of -0.247 $/kWh. Figure 7 shows how these results are affected when the uncertainty of the assumptions for the parameters biomass LHV, electrical efficiency of the generator, and capital costs of the gasifier is captured using Monte Carlo simulations. With a range that goes from -0.333 $/kWh to -0.202 $/kWh, and a percentage change of up to 35% from the base case value, the EB is considerably more sensitive to capital costs uncertainty than the uncertainties of biomass LHV and generator efficiency. The carbon abatement results shift slightly above 0.000 kg CO_2eq/kWh, as the median for biomass LHV and for generator efficiency results distributions are 0.082 kg CO_2eq/kWh and 0.084 kg CO_2eq/kWh, respectively. In a worst-case scenario, the carbon abatement potential could be reduced to -0.176 kg CO_2eq/kWh if a biomass LHV of 14.412 MJ/kg is used or to -0.341 kg CO_2eq/kWh if an electrical efficiency of 0.15 is considered.

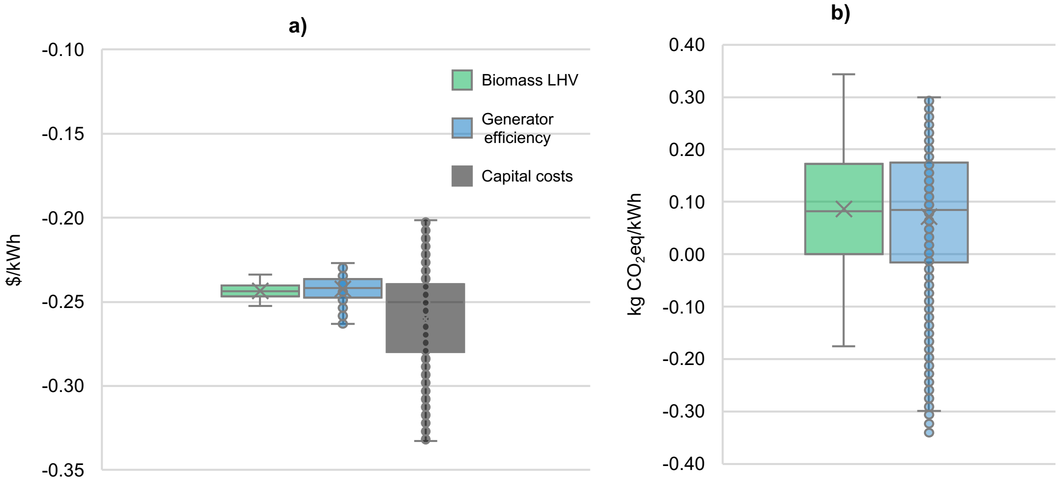

Figure 13. Impact of parameter uncertainty on objective functions, for a system configuration of ER 0.15 and a scale of 23.6kW, which maximizes economic benefit when carbon neutrality is forced in the solver as a constraint. Uncertainty was tested through 1,000 Monte Carlo simulations. a) Economic benefit results. b) Carbon abatement potential results.

4. Discussion

Energy generation is the main goal behind the implementation of biomass gasification, since other processes like slow pyrolysis are more efficient ways of producing biochar (Jeffery et al., 2015). Nevertheless, it was found that even when energy demand is what drives the use of the technology, if non-emitting electricity is what is desired, operating the gasifier to maximize energy production is suboptimal even in scenarios where the grid electricity being displaced comes from fossil fuels. In the CA optimization it was found that maximizing biochar production significantly increases the carbon abatement capacity of the system, which is consistent with other studies where it is stated that pyrolysis systems tend to have higher carbon abatement potential than gasification systems because of the greater contributions from carbon sequestered in biochar (You et al., 2017). Results obtained show that when CA is maximized, an estimated range of 0.2-0.4 kg CO2eq/kg_{bm} can be mitigated through the implementation of the proposed gasification system, which is below the estimates of 0.6-1.4 kg CO2eq/kg_{bm} reported in the literature for slow pyrolysis (Field et al., 2013).

When a year of operation for the 200 kW plant at economic optimum is evaluated, the annual generation of 536 MWh has a net GHG impact of 902 tonCO2eq. Comparing this with a twenty 10kW gasifiers at the carbon abatement optimum, the avoided GHG emissions are 187 tonCO2eq per year. Both systems represent an economic cost, but the implementation of 20 smaller gasifiers is 8.89 times more costly.

It should be noted that because of the specificity of some of the assumptions, such as geographic location and feedstock, results will not necessarily be transferrable to different biomass gasification applications. This model system was mainly scoped based on data availability and simplification reasons, with the objective of providing an example of a decision-making framework and assessment methodology.

Overall, it was found that the environmental performance of the system could be compromised if the economic benefit is prioritized and vice versa. The plant size was shown to have a significant impact on these tradeoffs. The decrease in costs achieved by economies of scale at larger plant sizes is the main contributor to EB, while increased GHG emissions from biomass procuring at larger plant sizes significantly reduced the carbon abatement capacity of the system. This indicates that to take advantage of the reduction in \$/MWh of larger plant sizes, reducing biomass procuring emissions by decarbonizing agriculture operations could be an impactful improvement. Other assessments on the scale of bioenergy operations present biomass procuring as a major economic barrier (Pokharel et al., 2019). Nonetheless, that has not been the case in this study, which could imply that at the defined range of plant sizes for small-scale applications, transportation costs are not critical.

Air to fuel ratio has been identified as one of the critical parameters for process optimization in downdraft gasifiers (Susastriawan et al., 2017); thus, ER was the process variable used in the simplified model created to predict biochar-bioenergy yields. Although general trends agree between the product mix model used and empirical data reported in the literature, MAE and RMSE of the predictive model are high. To make the model more robust and more precise at fitting the experimental data other process variables could be added, but for the purpose of this study the increased complexity was considered to be unnecessary. Besides, other studies present similar economic optimization results with an optimum economic equivalence ratio of 0.25 (Yao et al., 2018).

Despite the fact that the process of gasification has been around for over 180 years and that the technology has been well demonstrated, economic and non-technical barriers have hindered its participation in energy markets (Sansaniwal et al., 2017). Hence, process optimization together with stakeholder engagement are areas for improvement to increase the feasibility of these systems (Situmorang et al., 2020). Moreover, as climate change mitigation becomes a priority, the tradeoffs between economics and decarbonization potential are relevant to inform decisions and fill said gaps in the technology development and deployment. Following the proposed LCA-MCDA framework, a possible way of reconciling both objectives is to turn the CA objective function into a carbon neutrality constraint, and then solve for maximum economic benefit. An ER of 0.15, which results in the highest biochar yield, and a scale of 23.6 kW is the most economical carbon neutral configuration for the studied system with an EB of -0.247 \$/kWh.

Biochar economics

Context has been proved to be an important factor for the outcomes of biomass gasification systems. Integration of distributed electricity has been widely adopted with both fossil fuels, for example internal combustion engine generators powered by diesel, and renewable energy sources such as photovoltaic solar. Conversely, the carbon market for biochar is under development, requiring policy interventions and strategies that enable the establishment of appropriate contracts between biochar generators and carbon credits buyers. Studies have estimated the breakeven price of carbon credits to be in the range of \$70 to \$100 per ton CO2eq. Among the pioneers in this field in the US are Pacific Biochar, which has secured the first carbon credits for biochar in the US, and Puro.Earth, a carbon marketplace that has qualified biochar for carbon credit (Thengane et al., 2021). For the purposes of this study, carbon credits were assumed to be the only economic incentive for biochar production, but it should be noted that there is an established market for biochar as a soil amendment, which was estimated to have a size of $125.3 million in the US in 2020 and is expected to grow at a compound annual growth rate (CAGR) of 16.8% from 2021 to 2028 ("U.S. Biochar Market Size & Share Report, 2021-2028," n.d.). Therefore, even though electricity was identified to be the most profitable product of the process right now, this could change as demand for gasification biochar increases and other applications are explored and considered (You et al., 2017).

Comparing the impact with other residue management

To further understand the carbon abatement capacity of the biomass gasification system, it can be helpful to compare the GHG emissions of biomass gasification to alternative end of life treatments the logging residues could have. To do that, biogenic carbon has to be included in the GHG inventories, which means that the emissions associated to the combustion of syngas in the generator should be estimated. Ahmed et al., 2019 quantified the emissions of an internal combustion engine powered by syngas from woody biomass gasification and compared them to alternative processes. Apart from being a potential feedstock for gasification, logging residues could be burnt on site, left to decompose in the field, or used for other energy applications such as residential stoves or larger scale plants. The study found decomposition to be the largest emitter, with CH_4 accounting for half of its GHG emissions. Large scale energy units such as steam turbines were found to have the similar high combustion efficiencies of gasification, but the latter was found to be the lowest emitter due to the addition of biochar production.

Table 6. GHG emissions of logging residues end of life treatments (Ahmed et al., 2019)

	GHG emissions (kg CO2eq/kg$_{bm}$)
Open burning	1.888
Residential	1.740-2.112
Decomposition	2.584
Steam turbine	1.854
Gasification	1.570-1.966

Feasibility of sustainable biomass procuring and the challenge of integrating biomass gasification to productive activities

As a bioenergy feedstock, forestry residues can be co-managed with conventional timber increasing the economic value of products from managed forests (Titus et al., 2021). Nevertheless, complexities of crop residues removal, logging residues in this case, should be taken into consideration when quantifying biomass availability. Because residue removal can cause disturbances that affect ecosystem services of forestland or affect remaining timber, landowners could be reluctant to use them. When landowner's willingness to remove residues is factored in, northern Michigan and Wisconsin's available forest residues are reduced to 52% (Swinton et al., 2021). Furthermore, Titus et al., 2021 analyzed the existing residue harvest guidelines for sustainable forest biomass procuring and found that almost all of them, with different guidance strength, recommend leaving some standing live or dead trees and downed wood on-site when harvesting biomass, since it can reduce direct harvesting impacts. Different residue retention thresholds are provided, which should be considered at the time of planning the integration of biomass gasification to forestry activities. The same study shows that there is no consensus on the GHG emissions associated with harvest residue removal in the literature; some meta-analyses indicate that harvest residue removal can cause a decrease in soil carbon while other studies show no effect of residue removal.

GHG mitigation benefits of biomass gasification were assessed, but there are other advantages to this technology in face of the climate crisis: resiliency and adaptation. As a distributed energy source, biomass gasification can provide energy independence and security, while creating a circular economy using low value wastes. The consideration of the agronomic benefits of biochar increases the complexity of the analysis since other tradeoffs appear such as the quality of biochar, which determines its agronomic performance, will depend on the gasification process parameters as well. Process conditions that maximize carbon sequestration in biochar are not the same as the conditions that maximize the cationic exchange capacity of biochar, which helps biochar to adsorb cations and reduce nutrient leaching (Jeffery et al., 2015). These are examples of additional factors that should be explored to understand how a biomass gasification system could be fully integrated to productive activities in forestry and agriculture, and to characterize its entailed benefits.

5. Conclusions

Deployment of sustainable energy systems that decouple from fossil fuels, promotion of circular economies and scaling atmospheric carbon dioxide removal, are required to mitigate climate change. Small-scale biomass gasification systems have the potential to contribute to these through the transformation of agriculture wastes to clean electricity and biochar.

The objective of this study was to characterize tradeoffs in the economics and carbon abatement of a small-scale biomass gasification system and to assess the respective optimum configurations of syngas-biochar mix and plant size. For the theoretical case study analyzed, it was found that smaller scales and high biochar yields maximize decarbonization potential of the system. Despite the fact that it was shown that the system could be designed to have net negative GHG emissions, not all configurations achieve that: operating the gasifier to maximize economic benefit and energy production result in net positive GHG emissions even in scenarios where the grid electricity being displaced is highly fossil fuel based. Moreover, for the defined system, no configuration resulted in a profitable system, which is consistent with statements on the literature that mention that economic costs are a current barrier for the technology. At scenarios of extremely high grid electricity prices, biomass gasification could be a cheaper alternative at the expense of compromising environmental performance. These conclusions demonstrate that the impacts of biomass gasification technology development depend on context, hence, a holistic approach towards implementation is required.

This conflict between economic and climate change mitigation objectives could be resolved by the increasing economic value of carbon sequestration which could increase the range of situations in which biochar production would be favorable, technology developments that reduce gasifier related costs, or by the decarbonization of agricultural operations for less emitting biomass procuring. In the meantime, the developed LCA-MCDA framework could be used as an example and applied to other biomass gasification systems to understand how the different stakeholder objectives are being met, identify environmental and economic tension points in the life cycle, and determine how the system and the technology could be modified to address them. Future work should focus on challenging the assumptions made in the model such as the fact that product mix was considered to be independent of scale. The product mix model used could be also improved as it had disagreements with empirical data. However, putting this together with the fact that no consensus for a mathematical model that describes gasification in downdraft gasifiers was found in the literature indicates that, for the moment, specific experimental data of the reactor and feedstock being implemented might be needed for accurate results. More complex LCA-MCDA models could be built upon this work to include other stakeholder objectives and broaden context considerations.

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Appendix

Gasification model construction details

Reed published a model for wood gasification that among other process phenomena predicts how energy is distributed between the gas and char when the reaction approaches equilibrium as a function of the equivalence ratio (Reed, 1981). It also predicts syngas LHV as a function of the equivalence ratio.

The model plots were digitalized and the data was used to calculate CGE (MJ_{sg}/MJ_{bm}) and biochar thermal efficiency (MJ_{bc}/MJ_{bm}) taking the wood LHV as 20.4 MJ/kg (Reed and Das, 1988). Data was fitted with first and second order polynomial equations. The thermal efficiency of each product can then be used to calculate a mass yield using corresponding LHV values. Biochar LHV was assumed to be constant for this purpose.

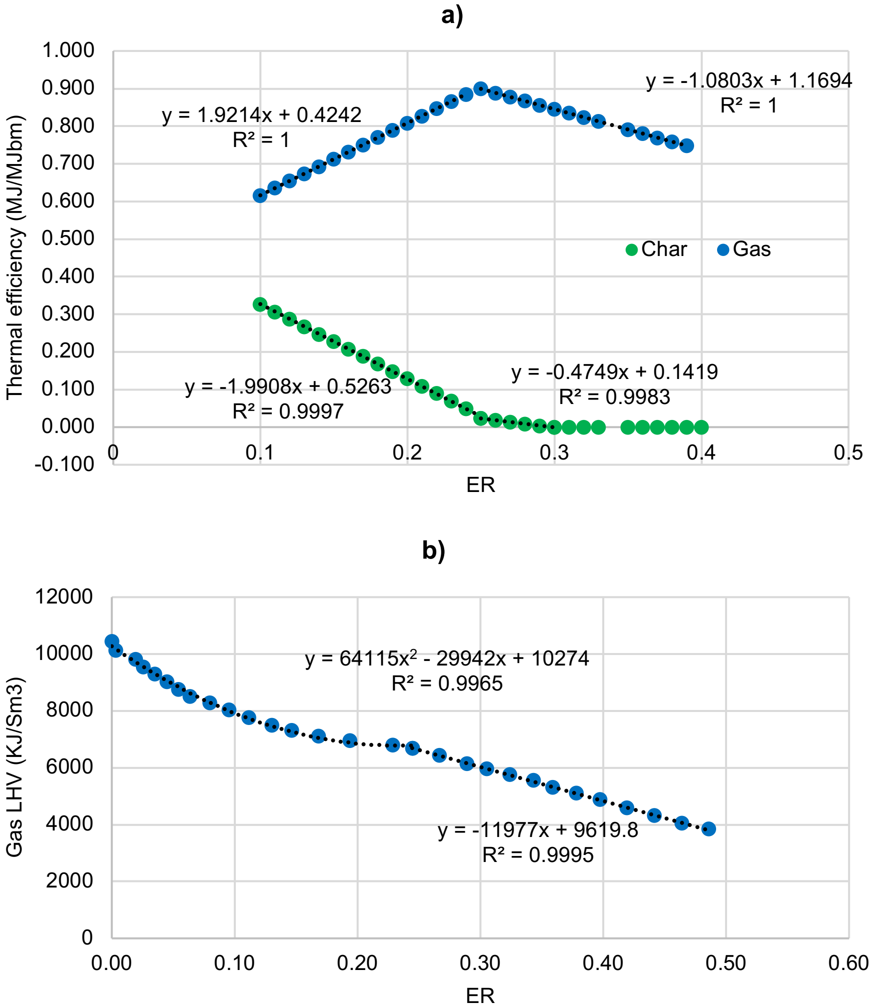

Figure 14. a) Product distribution: fitted equations used to model thermal efficiencies of syngas and biochar, energy in solid and in gas, as a function of ER. b) Fitted equations used to model syngas LHV, energy in gas per unit volume, as a function of ER. (Reed and Das, 1988)

Gasification mass balance

To verify that the inputs and outputs were physical sense, the model included a mass balance although these equations were not embedded in the objective functions. Biomass, syngas and biochar flows were quantified as part of the life cycle inventories for the functional unit. Apart from biochar and syngas, ash and tar are generated during the thermochemical conversion of the biomass. Tar yield was assumed to be constant, and the ash content in the biomass was assumed to be conserved. Air input was calculated from the ER values (Upadhyay et al., 2019).

W refers to mass flow rate in kg/h and $Y_{x/z}$ refers to yield in kg_x/kg_z.

$$ER = \frac{(\frac{W_{air}}{W_{bm}})_{actual}}{(\frac{W_{air}}{W_{bm}})_{stoich}}$$

Equation 11

$$(\frac{W_{air}}{W_{bm}})_{actual} = ER \times (\frac{W_{air}}{W_{bm}})_{stoich}$$

Equation 12

$$\left(\frac{W_{air}}{W_{bm}}\right)_{stoichic} = 0.1153 \times C\% + 0.3434 \times \left(H\% - \frac{O\%}{8}\right) + 0.0434 \times S\%$$

Equation 13

Table 7. Additional system parameters used for mass balance calculations.

Parameters		Reference
Biomass C content, dry basis (% weight)	50.84	(Nurek et al., 2019)
Biomass H content, dry basis (% weight)	5.72	(Nurek et al., 2019)
Biomass O content, dry basis (% weight)	41.46	(Nurek et al., 2019)
Biomass S content, dry basis (% weight)	0.25	(Nurek et al., 2019)
Tar yield (kg_{tar}/kg_{sg})	0.003	(Basu, 2018b)
Biomass ash content, dry basis (% weight)	1	(Nurek et al., 2019)

Mass balance equation:

$$W_{air} + W_{bm} = W_{sg} + W_{bc} + W_{tar} + W_{ash}$$

Equation 14

$$\frac{W_{air}}{W_{bm}} + 1 = Y_{sg/bm} + Y_{bc/bm} + Y_{sg/bm} \times Y_{tar/sg} + W_{bm} \times (Bm\ ash\ content) \times 100$$

Equation 15

Mass balance error equation:

$$Err\ (\%) = \frac{\frac{W_{air}}{W_{bm}} + 1 - [Y_{sg/bm} + Y_{bc/bm} + Y_{sg/bm} \times Y_{tar/sg} + W_{bm} \times (Bm\ ash\ content) \times 100]}{\frac{W_{air}}{W_{bm}} + 1} \times 100$$

Equation 16

In the decision space the mass balance errors ranged from 5.79% to 26.99%. Mass balance error for results reported in the literature were calculated and a similar range was found: 21.1% and 11.0% (Torres et al., 2018), 4.5% (Patuzzi et al., 2021), from 3.7% to 37.7% (Bilbao and Garcia-Bacaicoa, 1993).

Sensitivity analysis

Before selecting which parameters to test under the uncertainty and scenario analysis, a sensitivity analysis was conducted to understand how EB and CA optimums change when parameters vary. Twelve of the twenty-eight parameters were increased and decreased by 20%, one at a time, and the optimization solver was re-run. It was found that optimum configurations did not change; for 20% variations, the ER and scale values that maximize EB and CA remain the same. However, the EB and CA values did change. Figure 15 shows the percentage change of the EB optimum and CA optimum. It can be observed that the economic benefit results change significantly with the price of grid electricity and capital costs (capex). Furthermore, it can be observed that the carbon abatement potential of the system is sensitive to biomass LHV, generator efficiency, emissions of biomass transportation and emissions of the displaced grid electricity.

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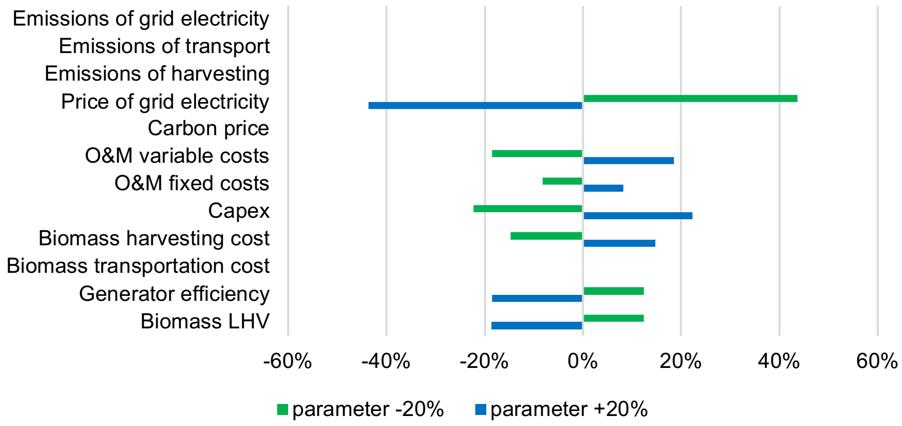
a) Percentage change in Economic Benefit at EB optimum



b) Percentage change in Carbon Abatement at CA optimum

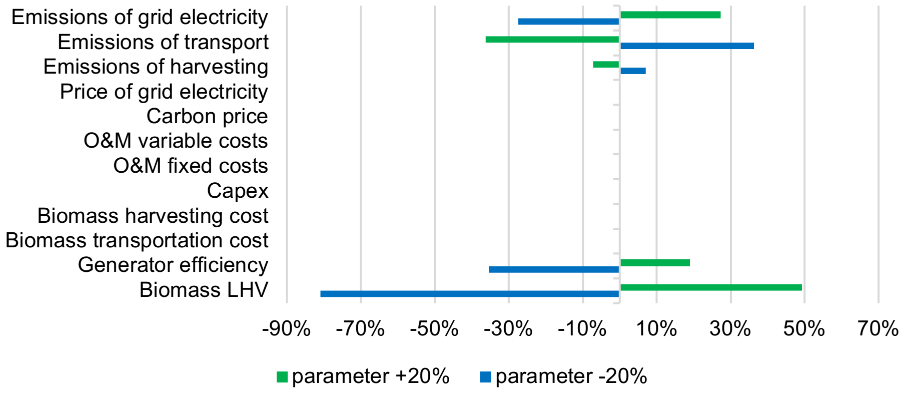


Figure 15. a) Sensitivity analysis results for economic benefit optimization. b) Sensitivity analysis results for carbon abatement optimization.