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MASTER THESIS

GASIFICATION OF SUGARCANE BAGASSE FOR ELECTRICITY GENERATION AND HYDROGEN PRODUCTION IN BURKINA FASO

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ABSTRACT

The thesis focuses on the gasification of sugarcane bagasse in Burkina Faso using the SN-SOSUCO as a case study. The SN SOSUCO specializes in manufacturing light brown and refined sugar and also produces 122,552 tons of sugarcane bagasse per year as agricultural residues. The production of electrical energy for the sugar processing plant through the Rankine Cycle using the bagasse as Fuels releases more greenhouse gases into the atmosphere and also involves airborne ash which is responsible for many health hazards. This thesis analyses the theoretical design of a downdraft gasifier in an air medium, including the evaluation of the electrical and hydrogen potential of the plant through modeling and simulation of the downdraft gasifier coupled with an open cycle gas turbine on Aspen Plus software using a thermodynamic equilibrium model, then followed by the techno-economic analysis of the simulated model and eventually, the life cycle assessment of the entire process on OpenLCA software. The results revealed that the gasification process coupled with a simple cycle gas turbine and membrane is more efficient than the Rankine Cycle in terms of hydrogen production and electricity generation and yet the techno-economic assessment showed that the simulated model was also economically viable with a total Net Present Worth of 3.38 million USD over a lifetime of 20 years. The Life Cycle Impact Assessment has shown that the simulated model has a lower Global Warming potential of 1.86 kg CO_2 eq/MWh, while the sugarcane bagasse cogeneration plant of the SN-SOSUCO has a Global Warming Potential of 2.09 kg CO_2 eq/MWh. However, more study needs to be undertaken for both technologies to reduce their impact on the environment.

Keywords: Gasification, Hydrogen, Electricity, Gas turbine.

RÉSUMÉ

La thèse se concentre sur la gazéification de la bagasse de canne à sucre au Burkina Faso en utilisant la SN-SOSUCO comme étude de cas. La SN SOSUCO est spécialisée dans la fabrication de sucre brun léger et de sucre raffiné et produit également 122 552 tonnes de bagasse de canne à sucre par an en tant que résidus agricoles. La production d'énergie électrique pour l'usine de traitement du sucre par le biais du cycle de Rankine en utilisant la bagasse comme combustible libère davantage de gaz à effet de serre dans l'atmosphère et implique également des cendres en suspension dans l'air qui sont responsables de nombreux risques pour la santé. Cette thèse analyse la conception théorique d'un gazéifieur à courant descendant dans un milieu aérien, y compris l'évaluation du potentiel électrique et d'hydrogène de l'usine par la modélisation et la simulation du gazéifieur à courant descendant couplé à une turbine à gaz à cycle ouvert sur le logiciel Aspen Plus en utilisant un modèle d'équilibre thermodynamique, suivi par l'analyse technico-économique du modèle simulé et enfin, l'évaluation du cycle de vie de l'ensemble du processus sur le logiciel OpenLCA. Les résultats ont révélé que le processus de gazéification associé à une turbine à gaz à cycle simple et à une membrane est plus efficace que le cycle de Rankine en termes de production d'hydrogène et d'électricité. L'évaluation technico-économique a également montré que le modèle simulé était économiquement viable avec une valeur actuelle nette totale de 3,38 millions USD sur une durée de vie de 20 ans. L'évaluation de l'impact du cycle de vie a montré que le modèle simulé a un potentiel de réchauffement global inférieur de 1,86 kg CO2 eq/MWh, tandis que la centrale de cogénération à la bagasse de canne à sucre de la SN-SOSUCO a un potentiel de réchauffement global de 2,09 kg CO2 eq/MWh. Toutefois, les deux technologies doivent faire l'objet d'études plus approfondies afin de réduire leur impact sur l'environnement.

Mots-clés: Gazéification, hydrogène, électricité, turbine à gaz

DECLARATION

I, Wendilia Jean Toussaint hereby that the master thesis has been completely done by me and I have not used any other documents than permitted reference materials. All references used by me have been acknowledged in the Master Thesis and also, I declare that this thesis work has not yet been submitted for any academic examination.

ACRONYMS AND ABBREVIATIONS

A: Area,

C: Carbon,

C_{AD}: Administration Costs,

CAPEX: Capital Expenditures,

CARBON-M: Carbon Monoxide**.**

C_{CC}: Contingency Costs,

CCS: Carbon Capture and, Storage,

C_D: Depreciation Costs,

C_{DS}: Distribution and Selling Costs,

C_{ENG}: Engineering Costs,

CEPCI: Chemical Engineering Plant Cost Index,

CFC-11: Trichlorofluoromethane,

CH_4: Methane,

C_L: Laboratory Costs,

C_{LTI}: Costs of Local Taxes and Insurances,

C_{MR}: Maintenance and Repairs Costs,

CO_2: Carbon Dioxide,

C_{OL}: Operating Labor Costs,

COM-OUT: The compressor outlet,

COP: Conference of the Parties,

C_{OP}: The Overhead Plant Costs,

C_{OS}: Operating Supplies Costs,

C_{PR}: Patents and Royalties Costs,

C_{RD}: Research and Development Costs,

C_{RM}: Raw Material Costs,

CTUe: Comparative Toxic Units (CTUe) for aquatic ecotoxicity,

CTUh: Comparative Toxic Units for humans,

C_{UT}: Utility Costs,

D: Diameter,

DECOMP: Decomposition,

DMC: Direct Manufacturing Costs,

ECOWAS: Economic Community of West African States,

ECREEE: Ecowas Center for Renewable Energy and Energy Efficiency,

ER: Equivalence Ratio,

FCI: Fixed Capital Investment,

FMC: Fixed Manufacturing Cost,

GE: General Expenses,

h_1: Enthalpy of the system at the inlet of the compressor,

h_2: Enthalpy of the system at the outlet of the compressor,

H_2O: Water,

h_3: Enthalpy of the system at the inlet of the turbine,

h_4: Enthalpy of the system at the outlet of the turbine,

HHV: Higher Heating Value,

IC: Internal Combustion

ISBL: Inside Battery Limits,

ISO: International Organization for Standardization,

J: Joule,

K: Kelvin,

k: Specific heat ratio of air,

Kg: Kilogram,

kW: Kilowatts,

kWh: Kilowatt-hour,

LCA: Life Cycle Assessment,

LCIA: Life Cycle Impact Assessment,

LHV_{bio}: Lower Heating Value of the Biomass,

LHV_g: Lower Heating Value of the product gas,

m: Meter,

m^3: Cubic Meter,

M_a: The amount of air required in the gasifier,

M_f: The sugarcane bagasse feed rate,

Mf_a: Total amount of air required in the gasifier per hour,

MJ: Megajoule,

M_{th}: The theoretical air required for the complete combustion of the SCB,

MW: Megawatt,

MWh: Megawatt-hour,

N_2: Nitrogen,

η_g: The efficiency of the gasification process,

NPW: Net Present Worth,

ηth: The thermal efficiency of the gas turbine,

O_2: Oxygen,

O_3: Ozone,

OPEX: Operational Expenditure,

OSBL: Outside Battery Limits,

OXI: Oxidation,

P: Pressure

P_1: Pressure at the inlet of the compressor,

P_2: Pressure at the outlet of the compressor,

P_3: Pressure at the inlet of the turbine,

P_4: Pressure at the outlet of the turbine,

PD-GAS: product gas,

PM: Particulate Matter,

Q: The gasifier output power,

R_{bw}: The work Back Ratio of the gas turbine,

RED: Reduction,

r_P: Pressure Ratio,

S: Sulfur,

SCB: Sugarcane Bagasse,

SERI: Solar Energy Research Institute,

SGR: Specific Gasification Rate,

SN-SOSUCO: Nouvelle Societe Sucriere de la Comoe,

SO_2: Sulfur Dioxide,

T: Temperature,

T_1: Temperature at the inlet of the compressor,

T_2: Temperature at the outlet of the compressor,

T_3: Temperature at the inlet of the turbine,

T_4: Temperature at the outlet of the turbine,

TFCI: Total Fixed Capital Investment,

TRACI: Tool for the Reduction and Assessment of Chemical and other Environmental Impacts.

UNFCCC: The United Nations Framework Convention on Climate Change,

USAID: United States Agency for International Development.

USD: United States Dollars,

V_g: Product gas flow rate,

VM: Volatile Matter,

V_r: Volume of the reactor,

WASCAL: West African Science Service Center on Climate Change and Adapted Land Use.

W_c: The isentropic work of the compressor,

WCI: Working Capital Investment,

Wt%: Mass Fraction,

W_t: The isentropic work of the turbine,

φ_{AIR}: The air density,

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INTRODUCTION

Background

Gasification is a thermochemical conversion process of carbon-based materials such as biomass and coal into synthesis gas. The synthetic gas known as syngas is a mixture of H_2, CO_2, CO, and CH_4 as fuel gas (Makwana et al., 2019). The syngas are generally used for electricity and heat generation and also for chemical (hydrogen and methanol) production (Giuliano et al., 2020). In late 1812, the synthetic gas from gasification was used for town lighting and domestic heating. Later on, the use of syngas for fuel generation increased due to the diminishment of the natural gas supply during the Second War. Moreover, in 1973, the oil embargo extended the use of gasifiers as a result of oil price inflations. However, the use of oils for energy generation is not without drawbacks namely the greenhouse gas emissions into the atmosphere. In 2000, the threat of climate change due to greenhouse gas emissions gave fresh momentum to gasification as a natural choice for the renewable conversion of carbon-neutral fuel such as biomass into syngas. In the conquest of carbon-neutral fuel and decarbonization, the world through the Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris agreed to take action to decrease global greenhouse gas emissions by limiting the global average temperature increase at 1.5° Celsius, on the 12 December 2015. Therefore in 2019, several countries such as France, China, Japan, Germany, and South Korea as a recommendation of UNFCCC in Paris (COP21) set investment goals to spread out hydrogen energy technologies around the world for the transition to green energy using renewable energy (Ballo et al., 2022). Further, to contribute to sustainable economic, environmental, and social growth, ECREEE and WASCAL are working closely in West Africa in the sustainable energy field and facilitating green hydrogen research and promotion in the ECOWAS regions (www.ecreee.org, last accessed on 23/02/2023).

In Burkina Faso, the average electrical energy consumption is estimated at 1.5 billion kWh per year with 990 million kWh and 630 million kWh of electricity generation and importation, respectively (www.worlddata.info, Last accessed on 23/03/2023). According to the United States Agency for International Development (USAID), the total installed capacity for power generation was solar (37 MW), hydro (51 MW), thermal (72 MW), and diesel (259 MW) (www.usaid.gov, Last accessed on 23/03/2023). In addition, 64 % of the urban population has access to electricity and less than 5 % of the people living in rural areas have access to electrical energy. However, among the renewable energy resources; solar and hydropower are the most used for electricity generation compared to biomass, although 80 % of the working population relies on agriculture. The country is endowed with enormous biomass potential from different resources such as agricultural residues estimated at 8 million tons which are not potentially valorized (Barry et al., 2022). Most of the gasification plants in Burkina Faso utilize stalks of millet, sorghum, maize, cotton, rice husks, and groundnut shells as biomass resources to generate thermal and electrical energy (Barry et al., 2021). In light of the above-mentioned information, comes the need to fill the gap with the gasification of sugarcane bagasse for electricity generation and H_2 production in Burkina Faso using the SN-SOSUCO as a case study.

The SN-SOSUCO is a bilateral partnership between public and private sectors in the South-Western part of Burkina Faso. The company focuses on sugarcane cultivation and manufactures light brown and refined sugar (www. sn sosuco.com, last accessed on 17/01/2023). Situated on a concession of ten thousand hectares, the SN-SOSUCO farm is estimated at four thousand hectares and employs more than three thousand people. The sugarcane CO997 and R570 varieties from India and Réunion, respectively, are the most used as a result of their agricultural yield and ability to withstand climate change (Daryle, 2017). Ouedraogo et al., (2022) said that the society produces annually 490 208 tons of sugarcane whereby the sugarcane bagasse represents 25% of the total mass harvested which is around 122 552 tons. The bagasse is used as fertilizers for sugarcane growing and feedstock for electricity generation. The electricity is generated through the direct combustion of sugarcane bagasse to produce heat. Then, the heat is used to warm up a water tube boiler followed by the recovery of the steam from the boiler to drive steam turbines related to an alternator (turbo generator). The company owns three turbo generators and two of them are operational with an average daily energy production of 42063.5 kWh. The direct combustion of sugarcane bagasse for electricity production of the SN-SOSUCO releases CO_2, O_2, H_2O, and N_2 into the atmosphere (Moussa, 2012).

Figure 1: Location of the SN SOSUCO

Problem statement

The direct combustion of sugarcane bagasse releases greenhouse gases into the atmosphere and also entails airborne ash which is in charge of many health hazards. Le Blond et al., (2017) showed that the particulate matter exposure due to the pre-harvest agricultural burning of sugarcane and the sugar processing in the factory leads to a potential danger to human health, especially chronic exposures in occupational scenarios. The major problem is the effects of greenhouse gas emissions. Greenhouse gases have prominent effects on health and the environment. They trap the heat from the sun by causing climate change and also contribute to lung disorder and pulmonary disease from smoke and air pollution (www.nationalgeographic.com, last accessed on 26/03/2023).

Objectives

The main objective of this thesis is to achieve lower CO_2 emissions from the atmosphere in the sugar processing plant. Particularly, the study emphasizes the following: (a) perform a theoretical design of a downdraft gasifier in an air medium, (b) Evaluate the hydrogen and the electrical potential of the plant through modeling and simulation of a downdraft gasifier in an air medium coupled with a gas turbine on Aspen Plus Software, (c) analyze the economic performance of the simulated model through OPEX and CAPEX, (d) estimate the impact of the simulated model on global CO_2 emissions compared to the current installed capacity of the SN-SOSUCO. To reach these objectives fourth research questions have been addressed: (i) What are the different operating parameters involved in designing a gasifier reactor?, (ii) what are the drivers required to perform a simulation model?, (iii) what are the components involved in the techno-economic assessment of the simulated model?, and (vi) what is the contribution of the simulated model to the greenhouse gas abatement compare to the current power plant of the SN SOSUCO?.

Structure of the thesis

The structure of the thesis is organized as follows:

The first part carries out the theoretical design of a downdraft gasifier by calculating the gas production rate, feedstock consumption, and geometric parameters of the gasifier.

The second part focuses on the modeling and simulation of a downdraft gasifier in an air medium on aspen plus software using a thermodynamic equilibrium model to foresee the utmost achievable yield of the product gas. Then hydrogen is separated from the product gas through a membrane and the remaining gases are used to power an open-cycle gas turbine to estimate the amount of electricity that could be generated on Aspen Plus.

The third part performs the techno-economic analysis of the simulated model to see the economic viability of the plant.

The fourth part does the Life Cycle Assessment (LCA) of the simulated model and the current power plant of the company using openLCA software

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I. STATE OF KNOWLEDGE

I.1. Biomass

Biomass is a renewable energy that comes from plants and animals and its exploitation further increases due to global warming and climate change concerns. The energy within the biomass originates from the sun through photosynthesis processes. Biomass as a source of renewable energy could play an important part in the production of biofuel for transportation, heat, and electricity (Lauri et al., 2014). Biomass naturally derives from plants, crops, trees, shrubs, and algae as well as organic materials excluding plastic materials from fossil fuels. Agricultural residues such as sugarcane bagasse, Municipal solid waste, forestry residues (Waste from wood), sewage, animal residues, and industrial residues are sources of biomass (Tursi, 2019).

I.1.1. Biomass classification

Biomass is classified based on its origin, roles, and products (Bogotá-Gregory et al., 2020; Mitros et al., 2020). It can be represented as follows:

- Woody biomass from higher plants,
- Herbaceous (agricultural waste and energy crops),
- Animal residues and human waste (Food waste…),
- Aquatic weeds and animals (algae),
- Mixed biomass (Municipal Solid Waste).

I.1.2. Chemical characterization of biomass

The residues of plants (lignocellulosic biomass) mainly consist of cellulose, hemicellulose, and lignin with different percentages, whereas the animal residues are made of protein and cereals consist of starch.

Cellulose is a linear polymer and complex polysaccharide with high molecular weight. As environmental remediation agents, cellulose derivatives have huge potential in industry and household chemical wastewater pretreatment (Sjahro et al., 2021).

Hemicellulose consists of heterogeneous polysaccharides. Its content and structure vary depending on the type of plant (Bala et al., 2016). Hemicellulose comprises sugars with five carbon atoms (xylose and arabinose) and six carbon atoms (glucose, galactose, mannose, and rhamnose) while cellulose is composed of glucose units. Xylans, mannans, galactans, and arabinogalactans are the different groups of molecules representing hemicellulose.

Lignin is also present in the plant cell wall and plays the role of mechanical support to the plant by binding, cementing, and putting the cellulose and hemicellulose together. Lignin has an important calorific value than cellulose and hemicellulose (Xie et al., 2016).

Starch: In vegetable tubers and seeds, starch represents the main reserve of carbohydrates. However, the starch can be found in two ways: 25-27 % as amylose (corn starch and rice starch) and 73-75% as amylopectin which are soluble in hot water and not soluble in water, respectively.

I.1.3. Biomass Physical Properties

The physical properties of the biomass are as follows:

- The particle size,
- The density,
- The thermal conductivity **($W \cdot m^{-1} . K^{-1}$)**,
- The specific heat (**J/kg.°C**).

I.1.4. Biomass Chemical Properties

I.1.4.1. Proximate analysis

The proximate analysis is performed by making use of an oven, laboratory furnace, and balance. It figures out the amount of Moisture (M), Ash (A), Volatile Matter (VM), and Fixed Carbon (FC) in a biomass sample.

I.1.4.2. Ultimate analysis

The ultimate analysis is used to determine the contents of Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), and Oxygen (O) in the biomass.

The heating value is also a property used to calculate the energy balance and the flame temperature concerning thermochemical conversions such as combustion (de Jong, 2014).

I.1.5. Biomass conversion technologies for bioenergy generation

Biomass can be converted into heat, electricity, or chemicals through several methods of conversion. The choice of the conversion technologies is impacted by several features such as the quality, quantity, and availability of biomass feedstock, the choice of end-products (biogas, methane, H_2, bio-ethanol, bio-diesel, and syngas), the economic viability of the process and environmental issues (Matsumura, 2015). Thermochemical and biochemical methods are the technologies used in the conversion of biomass (figure 2).

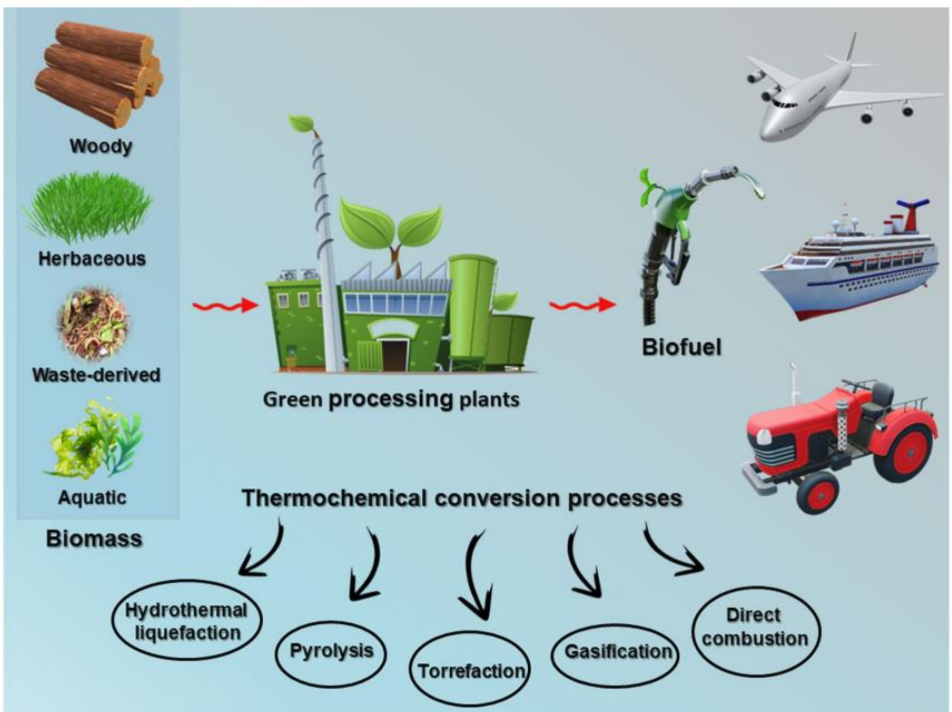

Figure I.2: Thermochemical route of biomass conversion ((Osman et al., 2021)**)**

I.2. Hydrogen

Hydrogen is an energy carrier, meaning that it does not exist freely in the atmosphere. It needs to be generated from primary energy sources such as coal, natural gas, oil, solar, wind, geothermal, and hydropower. Hydrogen could be clustered mainly into three groups (green, blue, and grey) depending on the method of production. Green hydrogen is produced by renewable energy, blue hydrogen is produced by making use of natural gas or methane with carbon capture, and grey hydrogen is produced by using natural gas or methane without carbon capture. Global hydrogen production was estimated at 90 million tons using both renewable and non-renewable resources (*Global Hydrogen Review*, 2022). Hydrogen is used in steel production, transportation (Fuel Cell Vehicles), power generation, hydrocarbon, and ammonia Production.

I.3. Gasification

Gasification is a thermochemical conversion of carbon-based material into syngas. Gasification has a great efficiency for electricity generation compared to a conventional alternative such as incineration or combustion (to generate steam for a turbine) (Safarian et al., 2019). Electricity could be generated from syngas using engines, gas turbines, and fuel cells (Patra & Sheth, 2015). Drying, pyrolysis (thermal decomposition of biomass), oxidation (combustion), and reduction (gasification) are the fourth stages of the gasification process (Basu, 2010).

Table I.1: Main reactions of a gasification process (Molino et al., 2018)

Gasification Step	Reaction
Pyrolysis	• Biomass → $CO + H_2 + CO_2 + CH_4 + H_2O$ + Tar + Char
Oxidation	• Char + $O_2 \rightarrow CO_2$ (Char Oxidation) • $C + 1/2\ O_2 \rightarrow CO$ (Partial Oxidation) • $H_2 + 1/2\ O_2 \rightarrow H_2O$ (Hydrogen Oxidation)
Reduction	• $C + CO_2 \leftrightarrow 2CO$ (Boudouard Reaction) • $C + H_2O \leftrightarrow CO + H_2$ (Reforming of Char) • $CO + H_2O \leftrightarrow CO_2 + H_2$ (Water Gas Shift (WGS) Reaction)

	• $C + 2H_2 \leftrightarrow CH_4$ (Methanation Reaction) • $CH_4 + H_2O \leftrightarrow CO + 3H_2$ (Steam Reforming of Methane) • $CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ (Dry Reforming of Methane)
Tar reforming	• $Tar + H_2O \rightarrow H_2 + CO_2 + CO + CxHy$ (Steam Reforming of Tar)

Drying: During the drying process, the biomass is heated from 100°C to 150°C to remove the moisture content**.** Biomass with moisture content ranging from 10% to 20% is suitable for syngas production with higher heating values (Molino et al., 2018). However, high moisture content in biomass can lead to energy losses and syngas degradation (A. Kumar, Eskridge, et al., 2009; Shayan et al., 2018).

Pyrolysis: After drying the biomass, it starts to be decomposed into hydrocarbons to produce biochar, liquid products such as bio-oil, and gaseous compounds (GHALY, 1991). The hemicellulose starts decomposing within a temperature range of 150°C to 350°C to form vapors, char, and tar while the cellulose in the biomass begins to decompose at 275°C to 350°C forming tar, char, and gaseous compound (Mishra & Upadhyay, 2021). Moreover, the lignin decomposition begins at 250°C to 500°C to produce more char than the cellulosic materials (Basu, 2013).

Combustion: The char from the pyrolysis zone is partially combusted into gaseous products such as CO, CO_2, H_2, and H_2O, and then an exothermic reaction occurs and increases the temperature of the gasifier (A. Kumar, Jones, et al., 2009; Sansaniwal et al., 2017). The heat liberated by the gasifier is partially used for biomass drying and pyrolysis.

Reduction: In the reduction zone, the tar particle in the produced gas is reduced to a high temperature at 1000°C (Dassey et al., 2013). However, the tar should be removed because the overall efficiency of biomass conversion may drop due to the excessive tar content in the fuel gas. **Table 2** shows the tar content limit in fuel gas for various end uses of biomass gasification.

Table I.2: Maximum tar limits in the different applications (Basu, 2010)

Application	Tar (g/N.m^3)
Syngas Production	0.1
Gas Turbine	0.05-5
Internal Combustion Engine	50-100
Fuel Cells	<1.0

I.3.1. Operating parameters of a Gasifier

The residence time, gasification medium, equivalence ratio, reactor pressure, and temperature are the operating parameters influencing the conversion of biomass and tar formation (Gallucci et al., 2020; S et al., 2022).

Gasifier medium: biomass requires a gasifying medium such as air, oxygen, steam, or supercritical water to produce syngas. Fuel gas (syngas) from air medium gasifiers has a calorific value of 5MJ/m^3 compared to fuel gas from oxygen-fed gasifiers (10 to 20 MJ/m^3) (Ingle & Lakade, 2016). Among the gasifying medium, air is the most commonly used due to its availability and low cost (Meng et al., 2011).

Gasification temperature: The tar formation, the product gas quality, the reactor requirement, and the capital cost are figured out by the gasification temperature ((Guo et al., 2010; Matsumura et al., 2005)).

Gasification pressure: the partial pressure of the gasifying medium and the gasification pressure have an impact on the product gas quality and the gasification performance(Guo et al., 2010).

Equivalence ratio: the equivalence ratio is the actual air-to-fuel ratio in the gasifier divided by the theoretical air required for complete combustion (stoichiometric Air-fuel ratio). Jangsawang et al., (2015); Kirsanovs et al., (2017) concluded that by performing gasification using Birchwood and cellulose as feedstocks, respectively, the ER has an effluence on the syngas yield.

Residence time is the time spent by the biomass or molecules in the reactor. Hernández et al., (2010) carried out experiments on three biomass fuels and found that the syngas yield increases with longer residence time but remains constant at 1050 °C. The residence time increases the hydrogen production yield and the efficiency of the process (Ling et al., 2016).

I.3.2. Gasifier types

Fixed bed, fluidized bed, and entrained flow gasifier are the three main types of gasifiers. They can also be classified based on their temperatures such as low-temperature gasifiers and high-temperature gasifiers. The fluidized and fixed bed are both considered as low-temperature gasifiers (800-950°C) while the entrained flow is seen as a high-temperature gasifier (higher than 1300°C) (Nanou, 2013). Table 3 shows the differences between the fixed bed gasifiers.

Table I.3: The different types of fixed bed gasifiers, adapted from (Basu, 2013; Chhiti & Kemiha, n.d.; Molino et al., 2018; Pang, 2016; Ren et al., 2019; Sharma & Kaushal, 2020)

Type of gasifier	Advantages	Disadvantages
Updraft gasifier	• Can handle biomass with high moisture (<60%) and ash content (<25%) • Overall good thermal efficiency • Utilizes heat of combustion effectively because of counter-current operation • Fewer pressure drops • Slight tendency to form slag	• Ideal only for small-scale uses • Highest tar yield (30-150 g/N.m^3) • Not suitable for high-volatility fuels • Takes a long time to start the engine • Low production of syngas • Low reaction capability
Downdraft gasifier	• Low tar production rate than updraft gasifiers (0.015–3 g/N.m^3) • Takes less time to ignite	• Induces low thermal efficiency because of the high outlet temperature of a gas • Particulate content is high

Cross-draft gasifier	• Lowest tar production (0.01–0.1 g/N.m^3) • The good permeability of the bed offered • Offer faster response time • The start-up time for an engine is relatively low • Can handle high-moisture biomass only if the top part of the gasifier remains open for escape	• Suitable for small-scale units • Not suitable for a high ash and tar content

I.3.3. The design process of a gasifier

A biomass gasification plant design includes the biomass handling system, the biomass feeding system, the gas clean-up system, the ash removal system, and the gasifier reactor. The design specification of the gasification plant such as the ultimate and the proximate analysis, operating temperature, gasifying medium, heating values of the product gas, the ash properties, the ER, the CAPEX, and thermal capacity of the plant are the most important parameters to be considered before any design process (Basu, 2010). The design process of a gasifier consists of calculating the product gas flow rate, fuel feed rate, flow rate of the gasifying medium, the heat of the reaction, the gasification temperature, and the geometric parameters of the gasifier (the height of the reactor, cross-sectional area of the reactor and the diameter of the reactor). Most of the manufactured gasifiers reported in the literature reviews follow the design methodology explained in the Solar Energy Research Institute (SERI) report (*Generator Gas*, 1998).

Table I.4: Thermal capacity of different gasifier designs (Bukar et al., 2019)

Design type	Capacity
Downdraft gasifier	1 kW -1 MW
Updraft gasifier	1.1 MW -12 MW

Fluidized-bed gasifier	1 MW -50 MW
Cross draft gasifiers	10 MW -200 MW

I.3.4. Gasifier models

The gasification models can be classified into fourth groups namely the thermodynamic equilibrium model, the kinetic model, Artificial Neural Networks, and the Computational Fluid Dynamic (Boumeddane, 2009). Modeling plays a crucial role in applying for gasification R&D works or in fundamental research studies and is good at optimizing and exploring the operation of an existing gasifier as well as gaining an overview between the operating parameters and the trend of the data (Basu, 2006).

Kumar, (2018) made a comparative study on sugarcane bagasse gasification and its direct combustion process in a boiler in a sugar plant through modeling and simulation on Aspen Plus software and the results showed that both processes could generate the same amount of energy, but due to the environmental issues, the plant has to adopt the gasification technology.

Mavukwana et al., (2013) modeled a gasification process on Aspen plus by the decomposition of dried sugarcane bagasse into volatile components and ash followed by partial combustion and gasification reaction where the total Gibbs energy of the system has its minimum value. The modeled data of the bagasse were compared with other biomass results published in literature with comparable ultimate analysis. The simulation data over-predicted Hydrogen formation and under-predicted methane formation.

(Kombe et al., 2022) carried out a thermodynamic equilibrium model of sugarcane bagasse gasification in an air medium on Aspen Plus to predict the syngas composition of a downdraft gasifier at various operating conditions, and the results of the model were validated with previous experimental studies.

Artificial Neural Networks are inspired by human brain architecture and use a mathematical series of equations to simulate biological processes such as learning and memory (Puig-Arnavat & Bruno, 2015). Though Artificial Neural Networks can predict the composition of the product gas of biomass gasification, they are barely used (Zoungrana et al., 2019).

The thermodynamic equilibrium model is used to determine the theoretical performance of a desired product gas in a reagent system. The thermodynamic equilibrium model calculation is independent of the design process of a gasifier and it only studies the influence of fuels and the parameters of the process (Patra & Sheth, 2015). Stoichiometric and non-stoichiometric approaches are the methods of calculation of equilibrium models. The stoichiometric approach requires all the chemical reaction and the species involved in the gasification process while the non-stoichiometric approach is based on the Gibbs free energy minimization methods and do not require any knowledge of chemical reaction mechanisms to determine equilibrium syngas composition (Zoungrana et al., 2019).

The kinetic model uses physical parameters of the reactor such as the reaction rate, residence time, internal hydrodynamics, and reactor size to evaluate, mimic, and predict both behaviors and chemical composition of species present within the reactor in each reaction zone (Baruah & Baruah, 2014).

Computational Fluid dynamics is used to calculate the differential equations that govern a fluid motion such as the momentum conservation species dynamics, mass conservation, the energy flow over a defined region, the drag force, the biomass porosity, and the turbulence flow.

I.4. Techno-economic analysis

The techno-economic analysis is a salient tool used to assess the technical performance and economic feasibility of industrial processes as a result of the increasing competition among businesses across various industries. It is well known to be conducted via modeling software (i.e., Python, MATLAB, Aspen plus, Homer pro, AMIS, Aspen HYSYS, FORTRAN, R-Studio, SysML, and Microsoft Excel) and consists of holistic analysis series that must be executed consecutively such as process design, process modeling, equipment sizing, capital cost estimation, operating cost estimation, and cash flow analysis (Chai et al., 2022).

I.5. Life Cycle Analysis

LCA evaluates the environmental impact of a product system from raw material extraction to elimination throughout its life cycle (Mahmud et al., 2021). Carvalho et al., (2019) show that the production of electricity from sugarcane bagasse has a lower carbon footprint than diesel engines, and can potentially help to mitigate climate change based on the life cycle analysis.

II. MATERIALS AND METHODS

Several materials have been used to shape this study such as literature reviews, articles, journals, Geographic Information System (GIS) Software, Aspen Plus software, Microsoft Office 2021, EdrawMax software, and OpenLCA software.

II.2.1. Approaches for theoretical designing of the downdraft gasifier in an air medium

The theoretical design process of the gasification plant focuses on the gasifier (reactor) following those methodologies (Basu, 2010; Bukar et al., 2019). The procedure of the theoretical design consists of calculating the mass balance, the energy balance, and the geometric parameters of the gasifier based on assumptions:

- The energy balance of the plant is estimated at **42043.3 kWh/day** with a rated power of **1751 kW** (Moussa, 2012),
- The time required to consume the biomass is assumed to be **1 hour**,
- The amount of SCB used per unit time, per unit area, (The specific Gasification Rate of SCB is about **210 kg/h/m^2)** (Lanh et al., 2018)**,**
- The annual quantity of sugarcane bagasse produced by the SN SOSUCO is estimated at **122552 Tons** per year (Ouedraogo et al., 2022).
- Gasification efficiency is assumed to be **60%**.
- The optimum Equivalence Ratio for the reactor design is estimated at **0.25** (Reed & Das, 1988)**.**
- The bulk density of the sugarcane bagasse with 7 % moisture content is estimated at **550 kg/m^3** (Phyllis2, 2023).
- The Gasifier type (throatless or stratified auto-thermal gasifier).
- The lower heating value of the product gas is estimated at **5 MJ/N.m^3** (Basu, 2010).
- The proximate and ultimate analysis of the sugarcane bagasse is represented below (Phyllis2, 2023):

Table II.5: Proximate analysis on a wet basis

Moisture content	**wt (%)**	**7.00**
Ash content	wt (%)	1.49
Volatile matter	wt (%)	76.35

Fixed carbon	wt (%)	15,16

Table II.6: Proximate analysis on a dry basis

Moisture content	**wt (%)**	0.0
Ash content	wt (%)	1.60
Volatile matter	wt (%)	82.10
Fixed carbon	wt (%)	16.30

Table II.7: Ultimate analysis on a wet basis

Carbon	**wt (%)**	**45.39**
Hydrogen	wt (%)	5.49
Oxygen	wt (%)	40.08
Nitrogen	wt (%)	0.46
Sulfur	wt (%)	……

Table II.8: Ultimate analysis on a dry basis

Carbon	**wt (%)**	**48.81**
Hydrogen	wt (%)	5.9
Oxygen	wt (%)	43.10
Nitrogen	wt (%)	0.49
Sulfur	wt (%)	0.10

II.2.1.1. Mass and Energy Balance of the Gasifier

The Energy and Mass balance is similar for all types of gasifiers (fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier). It entails calculations for the SCB feed rate and product gas flow rate.

- **Product gas flow rate**

$$Vg = \frac{Q}{LHVg} N.m^3/s$$

Eq 1

Where:

Vg, Product gas flow rate, N.m^3/s;

Q, Gasifier's required output power, MWth;

LHV$_g$, Lower Heating Value of the Product gas, MJ/Nm^3.

- **Fuel feed rate in the gasifier**

$$Mf = \frac{Q}{LHV_{bio} \times \eta g}$$

Eq 2

Where:

Mf: the sugarcane bagasse feed rate, kg/h;

LHV$_{bio}$: Biomass Lower Heating Value, MJ/kg;

Q: Gasifier output power, MWth;

Ƞg: the efficiency of the gasification Process,

To find the Lower heating value of the biomass (**LHV$_{bio}$**), the Higher Heating Value of the biomass was first calculated using empirical equation **(3)** of (Channiwala & Parikh, 2002) with an average error of 1,45% as experimental data.

$$\mathbf{HHV = 0{,}3491 \cdot P_C + 1{,}1783 \cdot P_H + 0{,}1005 \cdot P_S - 0{,}0151 \cdot P_N - 0{,}1034 \cdot P_O - 0{,}0211 \cdot P_{ASH}}$$

Eq 3

Where:

P_i: The dry mass fraction of Carbon (**C**), Hydrogen (**H**), Sulfur (**S**), Nitrogen (**N**), Oxygen (**O**), and **ASH** obtained from the proximate and ultimate analysis on a dry basis (Phyllis2, 2023);

HHV: Higher Heating Value on a dry basis (in kJ/g).

Then, from the High Heating Value on a dry basis, the Lower Heating Value on a wet basis is predicted using equation **(4)** in the study (van Loo & Koppejan, 2008).

$$\boldsymbol{LHV = HHV \times \left(1 - \frac{H_2O}{100}\right) - 2.444 \times \left(\frac{H_2O}{100}\right) - 2.444 \times \left(\frac{H}{100}\right) \times 8.936 \times \left(1 - \frac{H_2O}{100}\right)}$$

Eq 4

Where:

LHV: Lower Heating Value on a wet basis (**$MJ.\ kg^{-1}$**);

HHV: Higher Heating Value on a dry basis (**$MJ.\ kg^{-1}$**);

H_2O: Sugarcane bagasse moisture content on a wet basis (wt (%));

H_2: Dry mass fraction of Hydrogen in the SCB.

- **The stoichiometric amount of air or theoretical air required for the complete combustion of 1kg sugarcane bagasse.**

$$\mathbf{Ma = ER*M_{th}}$$

Eq 5

Where:

Ma: The amount of air required in the gasifier,

ER: Equivalence Ratio,

M_{th}: The theoretical amount of air required for complete combustion of SCB, (kg of air/kg of sugarcane bagasse).

Beforehand, to figure out the amount of air in the gasifier, the stoichiometric air-to-sugarcane bagasse ratio for complete combustion is calculated based on the ultimate analysis of the SCB on a dry basis. For a complete combustion of sugarcane bagasse, the carbon in the bagasse is converted into CO_2, Hydrogen into water, and sulfur into sulfur dioxide (Abdalla et al., 2018). Therefore, for optimal combustion to occur oxygen, good turbulence, and sufficient time are required. Oxygen represents 20.95% of air, and it is the second most prevalent gas in the atmosphere. In a complete combustion reaction, according to the mass conservation law, the total mass of reactants is equal to the total mass of the products (Paraschiv et al., 2020). Therefore, the elements Carbon, H_2, and Sulfur in the sugarcane bagasse during complete combustion are represented below, except for ash and nitrogen which are assumed to not undergo any chemical reaction:

- 12 kg of Carbon (**1 kmol**) will react with 32 kg of Oxygen (**1 kmol**) to produce 44kg of CO_2 (**1 kmol**).
- 2 kg of Hydrogen (**1 kmol**) will react with 16 kg of Oxygen (**1 kmol**) to produce 18 kg of H_2O (**1 kmol**).
- 32 kg of Sulfur (**1 kmol**) will react with 32 kg of Oxygen (**1 kmol**) to generate 64 kg of SO_2 (**1 kmol**).

However, 1 kg of carbon requires 2.66 kg of oxygen, 1 kg of Hydrogen requires 8 kg of oxygen and 1 kg of sulfur requires 1 kg of oxygen.

Table II.9: The oxygen required for the complete combustion of SCB

Ultimate analysis of SCB on a dry basis	Wt(%) (1 kg of SCB)	Oxygen required for 1kg of C, H, and S	The theoretical amount of oxygen required (kg of oxygen /kg of sugarcane bagasse)
Carbon (C)	48.81%	2.66	1.298
Hydrogen (H)	5.9 %	8	0.472
Sulfur (S)	0.10%	1	0.001
Oxygen	43.10%	-1	-0.431

Total	**1.34 kg of oxygen/ kg of sugarcane bagasse**

As air represents 20.95% oxygen, using the rule of thumb, the stoichiometric air-to-sugarcane bagasse ratio for complete combustion will be 6.39 kg of air kg^- of sugarcane bagasse.

- **The total amount of air required in the gasifier**

$$M_{fa} = \frac{(Mth \times ER \times Mf)}{\varphi_{Air}}$$

Eq 6

Where:

M_{fa}: Total amount of air required in the gasifier per hour,

φ_{Air} density, **1.25 kg/m³.**

II.2.1.2. Gasifier sizing

The geometric design or configuration of the reactor relies mainly on the type of gasifier that has been chosen (fixed bed or moving bed gasifier, fluidized bed gasifier, and entrained flow gasifier). For the theoretical design, the gasifier (reactor) is assumed to be a fixed-bed gasifier. The Gasifier sizing consists of calculating the geometric parameters of the gasifier such as the grate area, the height, the diameter, and the volume of the reactor.

- **The grate area of the reactor**

The grate area is the cross-sectional area of the gasifier.

$$A = \frac{Mf}{SGR}$$

Eq 7

Where:

A: Area of the Gasifier,

SGR: The Specific Gasification Rate, **210 kg/h/m^2.**

- **The diameter of the reactor**

$$D = \left[\frac{1.27 \times Mf}{SGR}\right]^{1/2}$$

Eq 8

Where:

D: the diameter of the reactor,

- **The height of the reactor**

$$H = \left(\frac{SGR \times T}{\varphi_{bio}}\right)$$

Eq 9

Where:

H: The height of the reactor,

T: The residence time of the biomass in the reactor,

$\boldsymbol{\varphi}_{\mathbf{bio}}$**:** The density of the biomass, **kg/m^3.**

- **The volume of the reactor**

$$Vr = \pi R^2 \times H$$

Eq 10

Where:

V$_r$: Volume of the reactor,

II.2.2. Modelling and simulation of a downdraft gasifier in an air medium for hydrogen production and electricity generation using Aspen Plus software.

The Present work aimed at estimating the hydrogen and electrical potential of the SN-SOSUCO plant on aspen plus software using a thermodynamic equilibrium model. The energy and mass balance from Chapter 2 was used to perform the simulation on aspen plus.

A co-current gasifier model using air as a gasifying medium has been developed in Aspen Plus due to the absence of a specific block to represent the gasification reactor. Hence, according to a literature study by Atnaw et al., (2010), the combination of two or more blocks such as R-yield and R-Gibbs reactors is necessary for a downdraft gasifier modeling in Aspen Plus.

The gasifier model developed is coupled to an Open Brayton Cycle (open cycle gas turbine) which has been modeled and simulated in three phases on Aspen plus using an R-Stoic reactor for the combustion zone, isentropic compressor block for the air and fuel compression and, isentropic turbine block for Expansion (electricity generation).

In Aspen Plus software, the biomass in the gasifier is characterized by its ultimate and proximate analyses and is not represented by its chemical formulas (Adeyemi & Janajreh, 2015). Aspen Plus is widely used for biomass gasification simulation by many researchers (Gagliano et al., 2017).

II.2.2.1. Modelling and simulation approaches of the downdraft gasifier for hydrogen production.

The downdraft gasifier model in an air medium has been developed based on assumptions:

- The temperature within the reactor varies between **800**°C **- 1000** °C (Omar et al., 2018);
- The pressure within the gasifier is estimated at **1 atm,**
- Long residence time is assumed to reach the thermodynamic equilibrium in the **R-Gibbs block;**
- The gas is assumed to be an **ideal gas** due to its high temperature and lower pressure;
- The gasifier is assumed to be a continuous feeding process,
- The process is a steady-state process (Properties such as the pressure and density remain unchanging over time),
- The gasifier is assumed to be adiabatic and isothermal,

- The product gas is assumed to be Tars free,
- Ash, sulfur, and nitrogen are inert and do not participate in the reactions,
- The reaction reaches a chemical equilibrium (the concentration of the products and reactants are constant and, remain unchanged over time, meaning that there is no flow of energy or matter within the gasifier or at its boundary with the surrounding.).
- The biomass is assumed to be dried,

In the present study, a downdraft gasifier has been modeled in three phases as follows: 1) the conversion of non-conventional components (SCB) into conventional components (SCB) in Aspen plus using the SCB proximate and ultimate analysis. 2) The thermochemical decomposition of biomass into volatile components, namely Ash, CH_4, CO, CO_2, and H_2 in an inert atmosphere. 3) The partial oxidation and the reduction of the components from the pyrolysis zone into syngas using a non-stoichiometric approach by considering all the components as reactants in the reactor.

Model Process Description: Aspen Plus V14 software has been used for gasifier modeling and simulation. Beforehand, the components and methods used for the simulation process have been defined in the toolbars Properties of the software.

Table II.10: Component specifications

Component ID	Type	Component name
Biomass	Nonconventional	
C	Solid	CARBON-GRAPHITE
ASH	Nonconventional	
H_2	Conventional	HYDROGEN
N_2	Conventional	NITROGEN
S	Conventional	SULFUR
CO	Conventional	CARBON-MONOXIDE
CO_2	Conventional	CARBON-DIOXIDE
O_2	Conventional	OXYGEN
H_2O	Conventional	WATER

The tools HCOALGEN (Enthalpy) and DCOALIG (Density) were used to calculate the physical properties of the non-conventional components in Aspen Plus such as biomass and Ash using their proximate and ultimate analysis (*Aspen Physical Property Methods*, n.d.). Then, the physical properties of the conventional components produced by the gasification process (H_2, CO, CO_2, CH_4, H_2O) were figured out using the Peng-Robinson equation State method in Aspen plus (Peng & Robinson, 1976). After defining all the physical properties of conventional and non-conventional Components in the toolbar's properties, the model has been developed through a model palette in the toolbar's simulation. The model palette is made of material streams and many blocks such as Mixers, splitters, separators, Exchangers, Solid separators and reactors.

- **Materials streams** have been used to link each block through an inlet (Biomass) and outlet (syngas).
- **Mixer blocks** ensure the mixing of different streams (inlet or outlet) into a given block.
- **Reactor blocks** namely the **R-Yield reactor** convert the non-conventional components (Biomass and ash) into conventional components and also specify the yield distribution of the components in the reactor. In a nutshell, it decomposes the biomass into individual components before feeding them into the gasifier (R-Gibbs's reactor) for further reaction to take place.

Table II.11: Components Yield distribution

Components	Basis mass wt (%)	Basis Yield
ASH	16	0.016
C (MIXED)	48.81	0.4881
H_2	5.9	0.059
N_2	0.49	0.0049
S	0.1	0.001
O_2	43.1	0.431
WATER	0.0	0

- **R-Gibb's reactor** has been used to represent the pyrolysis, oxidation, and reduction zone in the gasifier process where pressure and temperature are known and the reaction Stoichiometry is unknown.

- **Solid separator blocks** such as Cyclone have been used to separate the ash (solid) from the product gas.
- **Heat exchanger blocks** have been used to cool the produced syngas**.**
- **Separator blocks** have been used as a membrane for hydrogen production from the syngas.

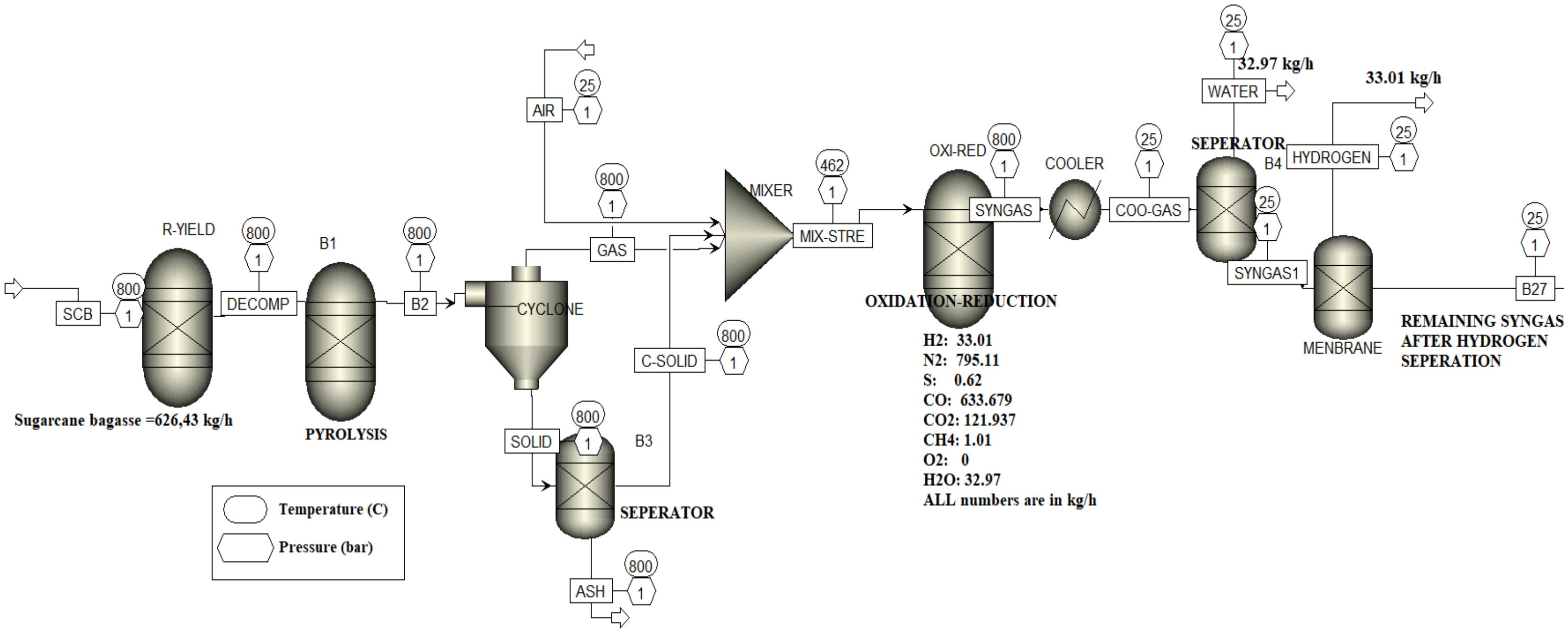

Figure II.3: Flow sheet process of the gasifier model developed for hydrogen production

II.2.2.2. Modeling and simulation of an Open Cycle Gas Turbine for electricity generation

The remaining products from the syngas after hydrogen production have been used for electricity generation through an open-cycle gas turbine. The gas turbine has been modeled on Aspen Plus based on assumptions:

- The system is a Steady-state process,
- A continuous feeding system is assumed,
- The standard air assumption is used for the modeling process. This means that the working fluid is considered to be air and also an ideal gas for the calculation of operating parameters such as the discharge temperature and pressure.
- The specific heat varies with the temperature,
- The specific heat ratio of air is 1.4,
- The inlet temperature of the compressor is assumed to be **298 K**,
- The discharge temperature at the combustion zone is **1573K**,
- The inlet pressure of the compressor is **1.38 bar**,
- The pressure ratio (r_P) is assumed to be 11,
- The gas turbine operates on a simple Brayton Cycle,
- Isentropic compression (compressor) is assumed,
- Isentropic expansion (Turbine) is assumed,
- Constant pressure heat addition in the combustion zone is assumed,
- Constant pressure heat rejection in the turbine exhaust is assumed,

Model process description: First of all, before modeling the gas turbine for power generation, the operating parameters such as temperature and pressure at each phase (compression, combustion, and expansion), as well as the thermal efficiency and the workback ratio, have been calculated using air as a working fluid to predict the behavior of the fuel gas once in the gas turbine. The gas turbine has been modeled in three phases:

1) The air is compressed using an isentropic compressor.

2) The compressed air and fuel (CO, CH4) are combusted using a combustor with constant pressure heat addition.

3) The electricity is generated through a turbine (isentropic expansion)

Moreover, Pressure changes (compressor and turbine) blocks and reactor blocks from the model palette in Aspen Plus have been used for the gas turbine modeling. The operating parameters of the different phases (Compression, combustion, and expansion) have been estimated on a standard air assumption basis.

- **The compressor**

The pressure, temperature, and work of the compressor have been calculated using air as a working fluid.

$$\mathbf{rp} = {}^{\boldsymbol{P_2}}\!/_{\boldsymbol{P_1}}$$

Eq 11

Where:

$\mathbf{r_p}$, the pressure ratio;

$\mathbf{P_1}$, the inlet pressure of the compressor;

$\mathbf{P_2}$, the outlet pressure of the compressor;

$$\frac{\boldsymbol{T_2}}{\boldsymbol{T_1}} = \left(\frac{\boldsymbol{P_2}}{\boldsymbol{P_1}}\right)^{(\boldsymbol{k}-\mathbf{1})/\boldsymbol{k}}$$

Eq 12

Where:

$\mathbf{T_2}$, the outlet temperature of the compressor,

k, Specific heat ratio of air, **1.4.**

$\mathbf{T_1}$, The inlet temperature of the compressor;

$$W_c = h_2 - h_1$$

Eq 13

Where:

Wc: The compressor isentropic work,

h_2: the enthalpy of the system at the outlet of the compressor**.**

h_1: the enthalpy of the system at the inlet of the compressor

- **The combustor**

In the combustion chamber, the temperature was estimated at **1573 K** with a constant pressure heat addition where **P_3** (outlet pressure of combustor) egal at **746,67 bar**. Then, the stoichiometry of air to fuel (CO and CH_4) ratio was figured out using their complete combustion stoichiometry. Stoichiometric or theoretical combustion is a burning process where carbon (C) is converted into carbon dioxide (CO_2), Hydrogen (H_2) to Water (H_2O), and Sulphur (S) to Sulphur dioxide (SO_2).

The remaining products from the syngas after hydrogen production have been compressed and fed into the combustion zone. The remaining gas products were assumed to be made of methane and carbon monoxide as ash, nitrogen, and Sulphur are inert and do not participate in the reaction. Therefore, for further complete combustion to occur, based on the mass conservation principle:

- 16 (g) **CH_4** (**1 mol**) will react with 64 (g) **O_2** (**2 mol**) to produce 44 (g) **CO_2** (**1 mol**) and 36 (g) **H_2O** (**2 mol**).
- 56 (g) **CO** (**2 mol**) will react with 32 (g) **O_2** (**1 mol**) to produce 88 (g) **CO_2** (**2 mol**).

After modeling and simulation of the downdraft gasifier and hydrogen separation from the syngas in Aspen Plus software, the remaining gas products were composed of methane (**1011.54 g/h**) and carbon monoxide (**633679 g/h**).

- The reaction of methane with O_2:

The chemical equation was balanced based on the mass conservation principle.

CH_4	+	**$2O_2$**	→	**CO_2**	+	**$2H_2O$**
16 (g) CH_4	+	**64 (g) O_2**	→	**44 (g) CO_2**	+	**36 (g) H_2O**
1 mol	+	**2 mol**	→	**1 mol**	+	**2 mol**

Eq 14

Based on equation (14), one gram of methane will react with four grams of Oxygen for the combustion to be completed. Therefore, using the mass flow rate of methane (1011.54 g/h) obtained from the gasification process of the simulated model on Aspen Plus, the overall amount of oxygen required for complete combustion will be 4040 grams of oxygen per hour.

- The reaction of carbon monoxide with O_2:

The chemical equation was balanced based on the mass conservation principle:

2CO	+	**O_2**	→	**$2CO_2$**
56 (g) CO	+	**32 (g) O_2**	→	**88 (g) CO_2**
2 mol	+	**1 mol**	→	**2 mol**

Eq 15

Based on equation (15), for the combustion to be completed, one gram of CO will react with 0.571429 grams of O_2. Therefore, using the mass flow rate of CO (633679 g/h) from the gasification process of the simulated model, the amount of oxygen required for the process will be 362102.6 g of oxygen per hour.

The turbine

The temperature, the pressure, the work of the turbine, and the back-work ratio have been calculated using air as the working fluids.

$$\frac{T_3}{T_4} = \left(P_3/p_4\right)^{(k-1)/k}$$

Eq 16

Where:

T_3, The inlet temperature of the turbine,

T_4, the outlet temperature of the turbine or exit temperature of the gas turbine,

P_4, the outlet pressure of the turbine,

P_3, the inlet pressure of the turbine.

$$\boldsymbol{W_t = h_3 - h_4}$$

Eq 17

Where:

W_t, the isentropic work of the turbine,

h_3, the enthalpy of the system at the inlet of the turbine**,**

h_4, the enthalpy of the system at the outlet of the turbine**.**

$$\boldsymbol{rbw = \frac{W_{c,in}}{W_{t,out}}}$$

Eq 18

Where:

$W_{c, in}$, the work required by the compressor,

$W_{t, out}$, the work delivered by the turbine,

R_{bw}, the work-back ratio,

- The thermal efficiency of the gas turbine

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{(W_t - W_c)}{(h_3 - h_2)}$$

Eq 19

Where:

η_{th}: the thermal efficiency of the gas turbine,

The operating parameters mentioned above such as the discharge pressure and temperature for both compressor and turbine calculated based on the air standard assumption have been used for the gas turbine simulation on Aspen Plus Software to estimate the amount of electricity that could be generated from the remaining syngas.

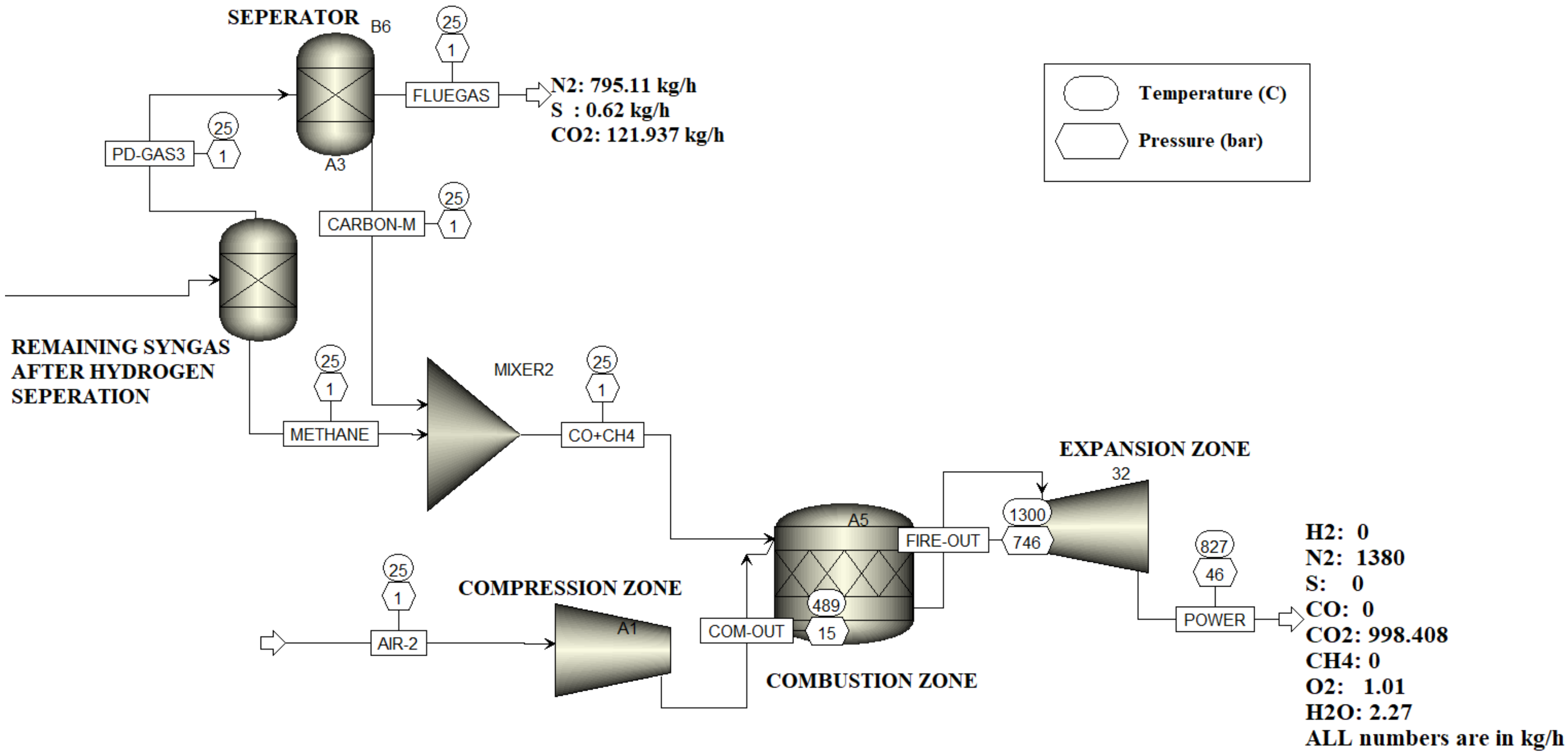

Figure II.4: Process flow sheet of the Open Cycle gas turbine model developed for electricity generation

II.2.3. The techno-economic evaluation of the simulated model

The techno-economic assessment entails the calculation of the CAPEX, OPEX, revenues, and profits for an industrial process. The simulated model on Aspen Plus has been used for the techno-economic analysis. The gasifier was assumed to have an efficiency of 60% at T=800 °C and P=1 bar with SCB input of 19887.31 kWh (4269.191 kg/h) and syngas output of 11932.39 kWh, the membrane was assumed to have an efficiency of 100% with a hydrogen output of 4536.82 kWh (136.11 kg/h) and the gas turbine was assumed to have an efficiency of 23.9 % with output energy of 1750 kWh as that of the studies of Moussa, (2012) at the SN-SOSUCO. Moreover, the simulated model was assumed to be a continuous feeding system for economic performance evaluation. However, Turton, (2012) studies were used for the cost structure design below.

Table II.12: Cost structure

	CAPITAL EXPENDITURES (CAPEX)	**OPERATIONAL EXPENDITURES (OPEX)**
Non-variable costs	**Fixed Capital Investment (FCI) associated with the ISBL**	**Fixed Manufacturing costs (FMC)**
	✓ Engineering costs: C_{ENG} ✓ Contingency costs: C_{CC} ✓ Utilities cost: C_{UT}	✓ Depreciation cost: C_D ✓ Local taxes and Insurance cost: C_{LTI} ✓ Overhead plant cost: C_{OP}
	Total Fixed Capital Investment (TFCI)	**General Expenses (GE)**
	✓ OSBL + ISBL	✓ Administration costs: C_{AD} ✓ Distribution and selling costs: C_{DS} ✓ Research and development costs: C_{RD}
	Working Capital Investment (WCI =10% of FCI)	
	Capital Expenditures (CAPEX) = TFCI +WCI	
		Direct Manufacturing Costs (DMC)
		✓ SCB costs as feedstock: C_{SCB}

Variable costs		✓ Other raw materials cost: C_{RM} ✓ Utilities cost: C_{UL} ✓ Operating labor cost: C_{OL} ✓ Direct supervision and clerical labor cost: C_{DS} ✓ Maintenance and repairs cost: C_{MR} ✓ Operating supplies cost: C_{OS} ✓ Laboratory cost: C_L ✓ Patents and royalties cost: C_{PR}
		Operating Expenditures (OPEX) = FMC + DMC + GE

II.2.3.1. Capital Expenditures (CAPEX)

The total investment needed for a project also known as the CAPEX, is a one-time investment used by a company to purchase, maintain, or expand fixed assets. The CAPEX is the sum of the Total Fixed Capital Investment (TFCI) and Working Capital Investment (WCI).

According to Coulson et al., (2005); the FCI includes the cost of:

- ✓ Construction supervision, engineering, and design;
- ✓ Equipment and their Installation,
- ✓ Instrumentation, Pipping, and control systems,
- ✓ Structures and construction,
- ✓ Land and civil engineering work.

The WCI is an additional investment to the FCI required for the start-up and operation of the plant before any profit. To Coulson et al., (2005), it entails initial costs such as feedstock and catalyst costs, as well as fees needed for labor and services required to commence the plant operation. However, there are several methods for estimating the capital cost in an industrial process (Turton, 2009):

- ✓ Order-of-magnitude (ratio Estimate) using rule-of-thumb methods,
- ✓ Study estimate,

- ✓ Preliminary Design Estimate,
- ✓ Definitive estimate, known as Project control,
- ✓ Detailed estimate, known as Firm or contractor's

In addition to those methods, (Lange, 2001) showed that the power losses of a process, namely the difference between the Lower Heating Values of the plant input (feed and fuel streams) and that of the product stream leaving the plant could be used as a first approximation of investment costs using this equation:

$$\boldsymbol{OSBL + ISBL = TFCI = 3 \times Power\ losses[MW]^{0.84}}$$

Eq 20

Where:

TFCI: Total Fixed Capital Investment in Million USD 1993;

Therefore, as the simulated model was assumed to be a continuous feeding system, this method has been used for the TFCI of the study by assuming that the plant intake was 19887.31 kW as rated power input and both hydrogen and electricity production represented the rated output power (6286.82 kW) of the product stream leaving the plant. Then, the Chemical Engineering Plant Cost Index (CEPCI) has been used to account the inflation through this equation:

$$\boldsymbol{C2 = C1 \times (I2/I1)}$$

Eq 21

Where:

C_2: The TFCI in 2023,

C_1: The TFCI in 1993,

I_2: The CEPCI 2023,

I_1: The CEPCI 1993,

II.2.3.2. The annual operating expenses (OPEX)

The OPEX is the sum of Direct Manufacturing Costs (DMC), Fixed Manufacturing Costs (FMC), and General Expenses (GE) (Turton, 2012). Among them, the Fixed Manufacturing Costs and the

General Expenses can be classified as fixed costs because the plant or the organization does not have any control over the different costs while the Direct Manufacturing Costs can be held accountable by the plant (Coulson et al., 2005).

II.2.3.2.1. Fixed Manufacturing Costs (FMC)

FMC does not depend on the production rate of the organization. It is a bunch of depreciation costs, local taxes and insurance costs, and plant overhead costs. The FMC was figured out using the cost structure design of Turton.

- Depreciation costs (Fund for future investment): **0.067*FCI**; (Turton, 2012).
- Insurance and Local tax costs: **0.02*FCI**; (Turton, 2012).
- Plant overhead costs (plant and personnel safety): **0.708*C_{OL} + 0.036*FCI**; (Turton, 2012).

II.2.3.2.2. Direct Manufacturing Costs (DMC)

DMC varies with the production rate of the company and does represent the operating expenses. They include sugarcane bagasse as feedstock, other raw materials, utilities (water, electricity…), labor, direct supervisory, operating supplies, Laboratory charges, and, patents and royalties’ costs.

- Sugarcane bagasse as feedstock costs,
- Raw materials costs,
- Utilities cost,
- Labor costs,
- Direct supervision and clerical labor costs: **0.18*C_{OL},** (Turton, 2012)
- Maintenance and repair costs: **0.02*FCI,** (Turton, 2012)
- Operating supplies costs: **0.003*FCI,** (Turton, 2012)
- Laboratory charges costs: **0.15*C_{OL},** (Turton, 2012)
- Patents and royalty costs: **0.03*OPEX,** (Turton, 2012)

II.2.3.2.3. General Expenditures (GE)

The General Expenses are an overhead burden required to carry out business. It entails administration costs, distribution and selling costs, research, and development costs.

- Selling and distribution costs: **0.11* OPEX,** (Turton, 2012)
- Research and development costs: **0.05*OPEX,** (Turton, 2012)
- Administration costs: **0.177*C_{OL} + 0.003 FCI,** (Turton, 2012)

Therefore, summing up the different elements of the OPEX (DMC, FMC, and GE) mentioned above leads to the following equation:

$$\mathbf{OPEX = 1.25 * (C_{UT} + C_{SCB} + C_{RM}) + 2.734 * C_{OL} + 0.184 * FCI}$$

Eq 22

The annual operating cost of the simulated model has been estimated using the equation (22). As the company does not purchase any feedstock for the combustion process, the sugarcane bagasse cost was assumed to be zero.

Several assumptions have been made to calculate the different parameters of the OPEX such as the FCI, operating labor cost (C_{OL}), sugarcane bagasse cost (C_{SCB}), and the cost of utilities (C_{UT}).

- The Fixed Capital Investment has been calculated from TFCI ((ISBL or FCI) + (OSBL)) mentioned above in the study of Lange (2001). According to **(Chauvel, 2003)**, the OSBL can be estimated as a percentage of the ISBL costs (FCI) using a rule of thumb (OSBL = 40% ISBL).
- The annual sugarcane bagasse is assumed to be zero USD as far as it is a waste produced by the SN. SOSUCO.
- The cost of the utilities (C_{UT}) includes the electricity that has been consumed by the gasifier and syngas cooling process. According to **(Olivier, 2017)**, for gasifiers ranging in power from 20 to 60 kW, the fan consumes up to 7.2 Watts. Therefore, the input power of the fan (air required for the gasification process) has been estimated based on the simulated model on Aspen Plus with an output power of 11.9 MW using the Rule of thumb. Moreover, air has been

used for the syngas cooling process by assuming that the power of the fan for the cooling process is two times the gasifier fan power.

- Labor Cost (C_{OL}): 9 persons are assumed to work in the plant. They have been divided into 3 groups A, B, and C. It was assumed that each person would receive the same wages about 1 USD/h and the plant operates 8500 h/year with a lifetime of 20 years.

II.2.3.3. Revenues or earnings

The revenues were obtained by multiplying the price of the good (Electricity and Hydrogen) by the quantity manufactured. The price of kWh is estimated at 0.22 USD/kWh in Burkina Faso (Mogmenga et al., 2019) while the hydrogen price was assumed to be 4 USD/kg.

II.2.3.4. Net Present Worth (Net Present Value) of the Project

The NPW is the difference between the discounted gross revenue and expenses (OPEX + CAPEX) involved in an investment. A positive NPW means that the project is economically viable while a negative NPW indicates a financial loss.

$$Net\ Present\ Worth\ (NPW) = \frac{Estimated\ net\ cash\ flow\ in\ year\ n\ (NFW)}{(1+r)^n}$$

Eq 23

$$TOTAL\ NET\ PRESENT\ WORTH = \sum_{n=1}^{n=t} \frac{NFW}{(1+r)^n}$$

Eq 24

Where:

t; the lifetime (20 years) of the project,

r, the discount rate (interest rate); the lending interest rate was assumed to be 6.25%.

II.2.4. Life cycle assessment (LCA) of the power generation

According to (ISO 14040, 2006), LCA is a method used to address the environmental aspects and potential environmental impacts throughout a product's life cycle. The Life Cycle Assessment is developed in four phases (ISO 14040, 2006):

- The goal and scope definition aspect,
- The inventory analysis aspect,
- The impact assessment aspect, and
- The interpretation aspect.

The four aspects are explained below regarding the topic to be undertaken in the study.

II.2.4.1. Goal and scope definition

This chapter aims to evaluate the emission indicators of two systems mentioned previously namely the simulated model (gasifier coupled with an open cycle gas turbine) on Aspen Plus and SN-SOSUCO sugarcane bagasse cogeneration (heat and power generation) in the study of (Moussa, 2012). However, a comparative study has been made for both systems. Both systems were assumed to be equipped without any Carbon Capture and Storage (CCS) technologies. A gate-to-gate life cycle assessment was performed for both systems on OpenLCA software using the TRACI 2.1 tool (methods) for the environmental impact assessment (Bare, 2012). This method provides a characterization factor for the life cycle assessment which quantifies the input and output potential impact of a system on a specific impact category. The impact categories entail Ozone depletion, Climate change, acidification, eutrophication, smog formation, human health impacts, and ecotoxicity.

The scope of this study includes the product system, the functional unit, the system boundaries, and inventory analyses or impact assessments to be followed in the study (ISO 14040, 2006). However, two product systems (simulated model on Aspen Plus and Sugarcane bagasse cogeneration) have been considered in the study with the function of generating electricity (MWh). The functional unit for both systems is assumed to be one Megawatt hour (MWh) of electricity produced and the system boundaries that define the unit processes of both systems are represented below:

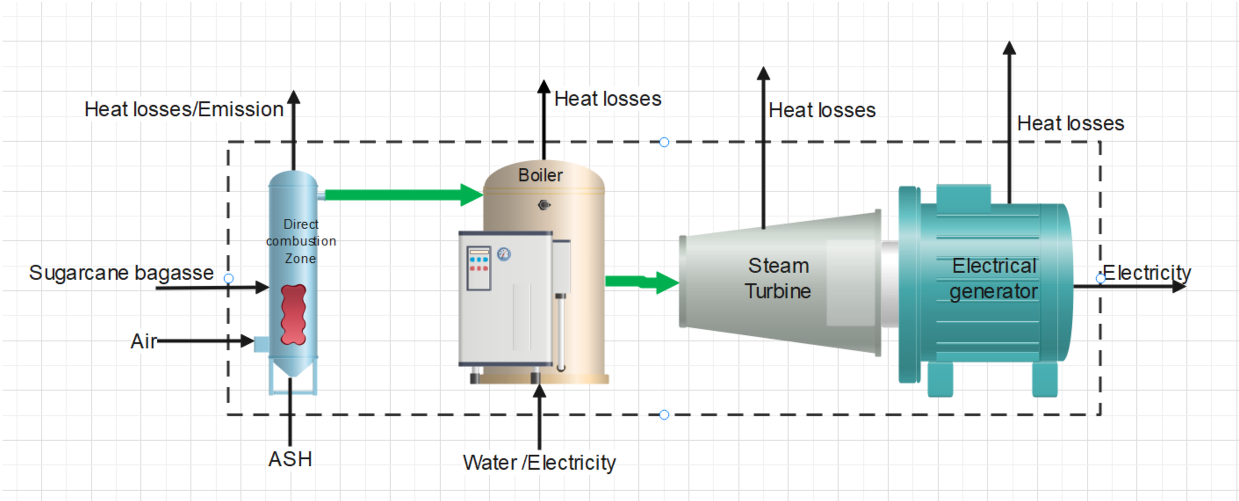

Figure II.5: System boundary and processes of Sugarcane bagasse cogeneration for both electricity and heat production

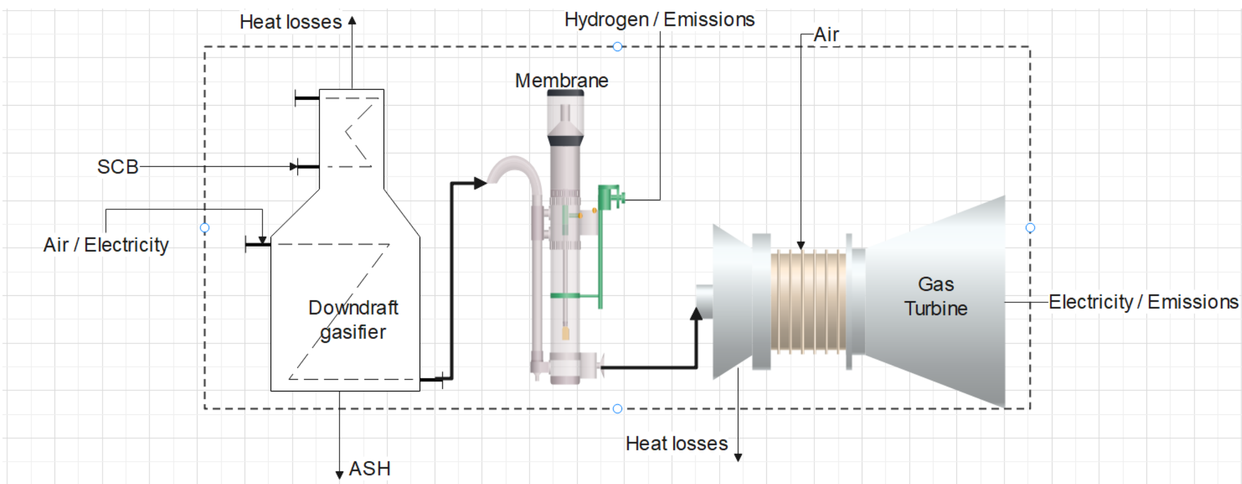

Figure II.6: System boundary and processes of the simulated model on Aspen Plus

II.2.4.2. The inventory analysis

The inventory analysis is the second phase of the Life Cycle Assessment. The inventory analysis involves the data collection (input and output flows) of the two systems to meet the pre-defined goals. In this chapter, information was collected from the literature (Moussa, 2012), assumptions, and Aspen simulation results for both downdraft gasifier and gas turbine with an efficiency of 60% and 23.9%, respectively. Both systems were assumed to be a continuous feeding system for inventory data collection with an average output energy of 1 MWh (electricity). Most of the data collected represent approximately the current condition of the SN-SOSUCO.

Table II.13: Inventory data of heat and power generation from sugarcane bagasse combustion per MWh of electricity produced.

FLOW	TYPE	AMOUNT	UNIT	REFERENCES
		INPUT FLOWS		
Sugarcane bagasse required for the combustion process	Product	75724.4765	MJ/MWh	
The air required in the combustor	Elementary flow (nature)	63310.3951	Kg/MWh	(Moussa, 2012)
Water required in the boiler	Elementary flow (nature)	5272.70475	Kg/MWh	
The electricity required for the system operation	Product	50	KWh/MWh	Assumptions
		OUTPUT FLOWS		
Electricity produced by the steam turbine	Product	1	MWh	
The heat lost by the system during the process.	Elementary flow (nature)	72124.4765	MJ/MWh	
The quantity of water vapor in the smock after the combustion process	Elementary flow (nature)	12620746.1	Kg/MWh	(Moussa, 2012)

The quantity of oxygen in the smock after the combustion process	Elementary Flow (nature)	7178.04933	Kg/MWh
The quantity of CO_2 in the smock after the combustion process	Elementary Flow (nature)	18839.4215	Kg/MWh
The quantity of nitrogen in the smock after the combustion process	Elementary Flow (nature)	72523.9342	Kg/MWh
The quantity of ash obtained after the combustion process.	Waste	916.976083	Kg/ MWh

Table II.14: Inventory data for hydrogen production and electricity generation on Aspen Plus Software

FLOW	TYPE	AMOUNT	UNIT	REFERENCES
INPUT FLOWS				
Sugarcane bagasse required for the gasification process (Efficiency = 60%)	Product	40863.29998	MJ/MWh	Aspen simulation results
The air required for both gasifier and gas turbine operation	Elementary flow (nature)	7981.146542	kg/MWh	
The electricity required for the system operation	Product	50	kWh/MWh	Assumptions
OUTPUT FLOW				

Electricity produced by the gas turbine (Efficiency = 23%)	Product	1	MWh	
The heat lost by the system during the process	Elementary Flow (Nature)	27931.84998	MJ/MWh	Aspen simulation results
The quantity of hydrogen produced by the membrane (Efficiency = 100%)	Elementary Flow (Nature)	77.8425168	kg/MWh	
The quantity of water vapor out of the system	Elementary Flow (Nature)	82.31804117	kg/MWh	
Quantity of nitrogen out of the system	Elementary Flow (Nature)	5329.1781	kg/MWh	
Quantity of CO_2 out of the system	Elementary Flow (Nature)	2681.489439	kg/MWh	
Quantity of O_2 out of the system	Elementary Flow (Nature)	2.41271324	kg/MWh	
Ash obtained after the gasification process	Waste	23.39946055	kg/MWh	

II.2.4.3. The impact assessment

TRACI 2.1 methods have been used for the impact assessment of both systems on OpenLCA software. After compiling the input and output data of the two product systems on OpenLCA using the TRACI 2.1 tool, the impact categories have been identified. Impact categories are represented as follows:

- **Acidification:** it is the accumulation of hydrogen ions (H^+) within a local environment (Bare, 2012).
- **Eutrophication:** It is the enhancement or enrichment of the aquatic ecosystem with nutrients such as phosphates and nitrates that increase the growth of undesirable algal biomass and weeds (Bare, 2012).
- **Climate Change:** It is one of the consequences of global warming. Global warming is the result of an increase in the magnitude of the greenhouse effect due to anthropogenic greenhouse gas emissions into the atmosphere.
- **Ozone depletion:** Ozone located at the stratosphere level ensures the protection of living beings (Humans, animals, and plants) against the sun's radiation. Ozone depletion can lead to skin cancer and cataracts in the human population.
- **Human health particulate:** Particulate matter (dust and smoke) is a set of small particles in the atmosphere at the troposphere level that may cause negative human health effects such as illness and death.
- **Human health cancer, noncancer, and Ecotoxicity**
- **Photochemical Smog Formation:** Also known as the summer smog or ground-level ozone, Photochemical Smog is the combination of Nitrogen Oxide and Volatile Organic Compounds in the presence of sunlight. This summer smog formation is not without any consequences, it leads to health hazards such as respiratory issues in human beings and also ecological impacts (crop damage) (Bare, 2012).
- **Resource Depletion (fossil fuel use, water use, and land use).**

III. RESULTS AND DISCUSSION

The validation of the gasifier model has been done in two parts using the energy conservation at the inlet and outlet of the simulated gasifier, and also literature reviews.

- The results of the thermodynamic equilibrium model of the downdraft gasifier using a non-stoichiometric approach based on Gibbs free energy minimization have been validated with energy conservation within the system (Gasifier). The results of the simulated downdraft gasifier showed that the input energy (SCB) is equal to the output energy (syngas) at T=800°C and P=1 atm. As the gasifier reaches its thermodynamic equilibrium based on the result of the simulated model on Aspen Plus, the state of the system (gasifier) does not change over time (no losses were assumed). The gasifier has been simulated with an efficiency of one hundred percent.

Table III.15: gasifier model validation using the energy balance

INLET OF THE GASIFIER (SCB).	**DOWNDRAFT GASIFIER (Efficiency =100%, T= 800°C and P=1 atm).**	**OUTLET OF THE GASIFIER (SYNGAS).**
(626.4 Kg *16.77 MJ/Kg =2918.11 KWh) ⇨	⇨	(CO + CH4 + H2 + CO_2) = 2918.11 KWh) ⇨

- The result of the simulated model showed an over-prediction of hydrogen and an under-prediction of methane production as mentioned in the study of (Mavukwana et al., 2013).

At constant pressure and temperature ranging from 800°C to 1000°C, the behavior of the syngas from the simulated gasifier (efficiency =100%) is given in Figure 7.

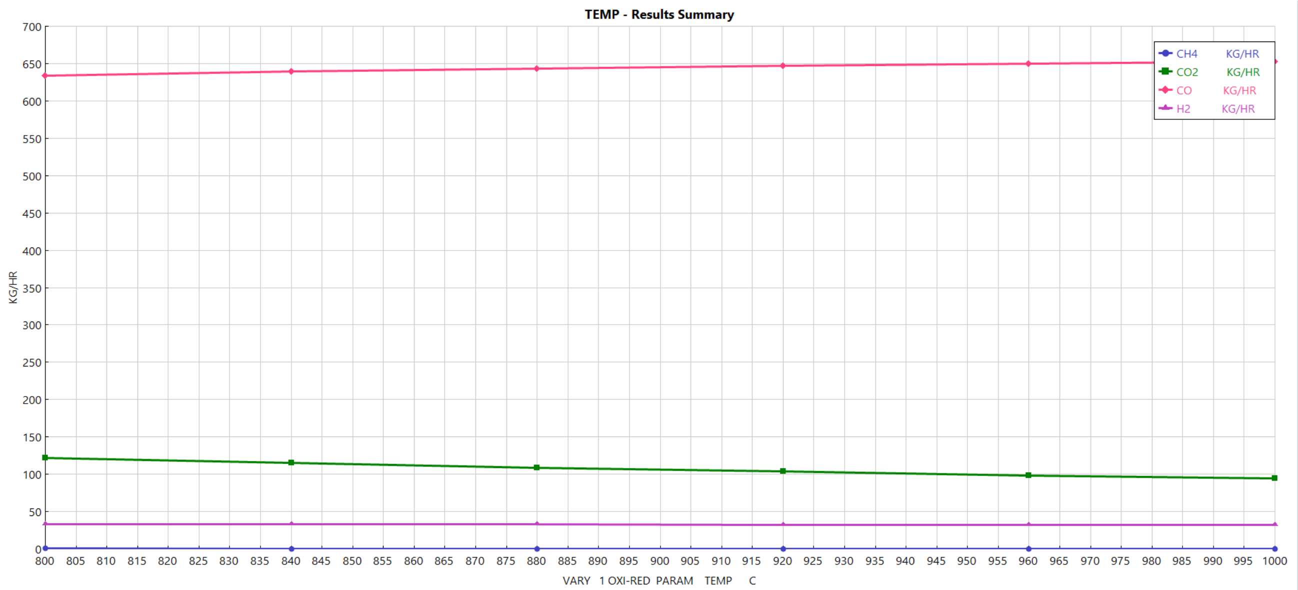

Figure III.7: Sensitivity analysis of the gasifier output at constant pressure (1 bar)

At constant temperature with varying pressure moving from 1 atm to 20 atm, the behavior of the syngas is shown in Figure 8.

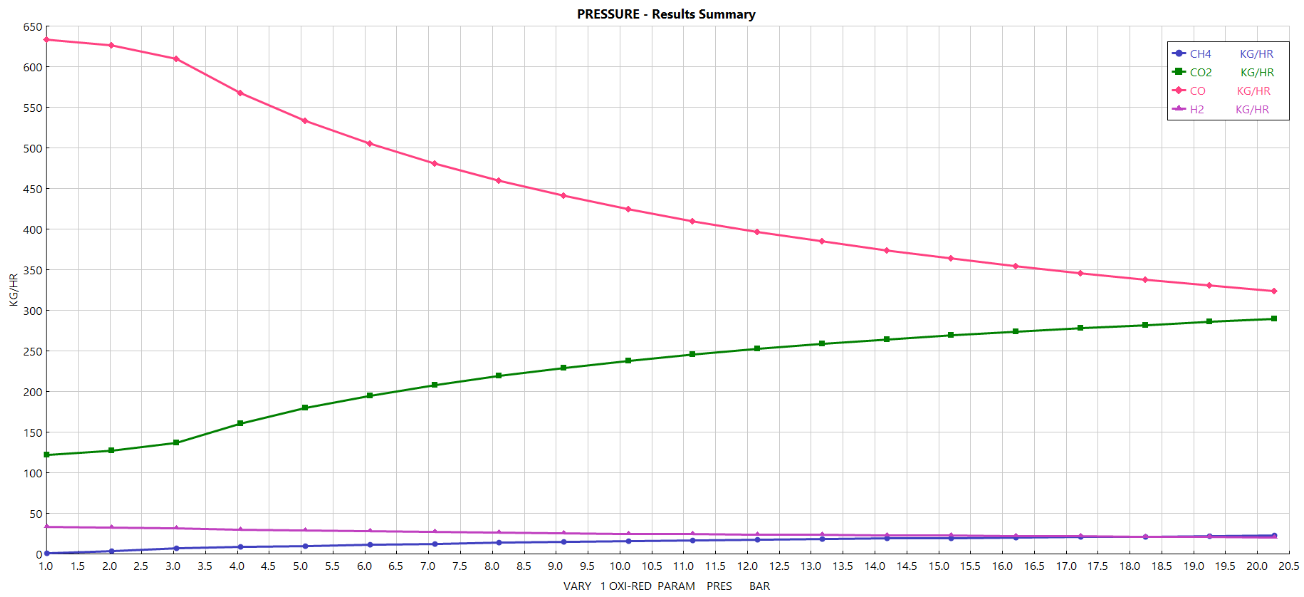

Figure III.8: Sensitivity analysis of the gasifier output at constant Temperature (800°C)

At T= 800°C and 1 atm with a gasifier efficiency of 60% and continuous feeding system of SCB in the gasifier (626,43 kg/h), the result of the simulated model showed an overall production of 20 kg of hydrogen (666 kWh) with a membrane efficiency of 100% and an electricity generation of 256.929 kWh with a gas turbine efficiency of 23,9 %.

The results of the modeling and simulation of the downdraft gasifier in Aspen Plus for hydrogen production and electricity generation showed that the simulated model was economically viable and environmentally friendly in terms of greenhouse gas abatement compared to the sugarcane bagasse cogeneration of the SN-SOSUCO.

However, the LCIA results of the simulated model confirmed the study of (Le Blond et al., 2017) and (Kumar, 2018) about the gasification and combustion process. The simulated model on Aspen Plus contributes less to global warming and smog formation which are responsible for climate change and many health hazards compared to the sugarcane cogeneration plants. In a nutshell, those results met the expectations of the thesis.

In terms of Ecotoxicity and fossil fuel depletion, the simulated model has more impact than the sugarcane cogeneration plant. This phenomenon of ecotoxicity may be explained as a result of the non-complete combustion of syngas in the gas turbine or chemicals used or produced during the process such as hydrogen and Hydrogen Sulfide.

Furthermore, the techno-economic analysis of the simulated model showed a positive net present value of 3.38 million USD over a lifetime of 20 years with both hydrogen and energy selling costs of 4 USD/kg and 0.22 USD/kWh, respectively. The simulated model on Aspen Plus software is only economically viable when the price of Hydrogen is equal to 3.5 USD or greater.

Moreover, it has been found that with a gasifier efficiency of 60 %, only 102.1 Tons/day of SCB is required for the simulated model to produce 3.2 tons of Hydrogen and 42043 MWh of electricity while the sugarcane bagasse cogeneration of the SN-SOSUCO required 409 Tons/day of SCB to produce 42043 MWh of electricity (Moussa, 2012). This low efficiency of the sugarcane bagasse cogeneration may be due to the higher moisture of SCB (50%) during the combustion process. Those results will benefit the company in terms of energy efficiency and also lessen its carbon footprint. Due to the lack of data obtained from the SN SOSUCO company on the sugarcane bagasse cogeneration process, the results cannot be confirmed at one hundred percent

CONCLUSION

The direct combustion of the Sugarcane bagasse by the SN-SOSUCO for both heat and electricity generation releases more greenhouse gases into the atmosphere and also entails airborne ash which is responsible for many health hazards. The objective of this study is to achieve lower CO_2 emissions from the atmosphere in the sugar processing plant. This study emphasizes the theoretical design of a downdraft gasifier, then the modeling and simulation of a downdraft gasifier coupled with an open cycle gas turbine on Aspen Plus software, and also the techno-economic analysis of the simulated model, and, finally a gate-to-gate Life Cycle Assessment of the simulated model and sugarcane bagasse cogeneration of the SN-SOSUCO on OpenLCA using secondary data from the study of (Moussa, 2012). The results have shown that the simulated model was economically viable with a net present value of 3.38 million USD and environmentally friendly. The Life Cycle Impact Assessment has revealed that the simulated model has a Global Warming potential of 1.86 kg CO_2 eq/MWh, while the sugarcane bagasse cogeneration plant of the SN-SOSUCO has a GWP of 2.09 kg CO_2 eq/MWh. However, more studies need to be undertaken for both gasification and combustion processes for further improvement to reduce their environmental impact. What will be the use of hydrogen for ammonia production at SN-SOSUCO? What will be the efficiency of the simulated model on Aspen Plus with heat recovery?

REFERENCES

1. Abdalla, A., Hassan, T., & Mansour, M. (2018). Performance of Wet and Dry Bagasse Combustion in Assalaya Sugar Factory—Sudan. *Innovative Energy & Research*, *07*. https://doi.org/10.4172/2576-1463.1000179
2. Adeyemi, I., & Janajreh, I. (2015). Modeling of the entrained flow gasification: Kinetics-based ASPEN Plus model. *Renewable Energy*, *82*, 77–84. https://doi.org/10.1016/j.renene.2014.10.073
3. *Aspen Physical Property Methods*. (n.d.).
4. Atnaw, S. M., Sulaiman, S. A., & Yusup, S. (2010, June). *A Simulation Study of Downdraft Gasification of Oil-Palm Fronds Using ASPEN PLUS*. International Conference on Plant Equipment and Reliability (ICPER), Kuala Lumpur. http://eprints.utp.edu.my/id/eprint/2615/
5. Bala, J. D., Lalung, J., Al-Gheethi, A. A. S., & Norli, I. (2016). A Review on Biofuel and Bioresources for Environmental Applications. In M. I. Ahmad, M. Ismail, & S. Riffat (Eds.), *Renewable Energy and Sustainable Technologies for Building and Environmental Applications* (pp. 205–225). Springer International Publishing. https://doi.org/10.1007/978-3-319-31840-0_13
6. Ballo, A., Valentin, K. K., Korgo, B., Ogunjobi, K. O., Agbo, S. N., Kone, D., & Savadogo, M. (2022). Law and Policy Review on Green Hydrogen Potential in ECOWAS Countries. *Energies*, *15*(7), Article 7. https://doi.org/10.3390/en15072304
7. Bare, J. (2012). The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.1). *Industrial Ecology*.

8. Barry, F., Sawadogo, M., Ouédraogo, I. W. K., Bologo/Traoré, M., & Dogot, T. (2022). Geographical and economic assessment of feedstock availability for biomass gasification in Burkina Faso. *Energy Conversion and Management: X*, *13*, 100163. https://doi.org/10.1016/j.ecmx.2021.100163
9. Baruah, D., & Baruah, D. C. (2014). Modeling of biomass gasification: A review. *Renewable and Sustainable Energy Reviews*, *39*(C), 806–815.
10. Basu, P. (2006). *Combustion and Gasification in Fluidized Beds*. CRC Press.
11. Basu, P. (2010). *Biomass gasification and pyrolysis: Practical design and theory*. Academic Press.
12. Basu, P. (2013). *Biomass Gasification, Pyrolysis and Torrefaction—2nd Edition*. https://www.elsevier.com/books/biomass-gasification-pyrolysis-and-torrefaction/basu/978-0-12-396488-5
13. Bogotá-Gregory, J. D., Lima, F. C. T., Correa, S. B., Silva-Oliveira, C., Jenkins, D. G., Ribeiro, F. R., Lovejoy, N. R., Reis, R. E., & Crampton, W. G. R. (2020). Biogeochemical water type influences community composition, species richness, and biomass in megadiverse Amazonian fish assemblages. *Scientific Reports*, *10*(1), 15349. https://doi.org/10.1038/s41598-020-72349-0
14. Boumeddane, B. (2009). *Investigations numériques de l'auto inflammation des mélanges méthane/air en mode HCCI*.
15. Bukar, A. A., Oumarou, M. B., Tela, B. M., & Eljummah, A. M. (2019). Assessment of Biomass Gasification: A Review of Basic Design Considerations. *American Journal of Energy Research*, *7*(1), Article 1. https://doi.org/10.12691/ajer-7-1-1

16. Carvalho, M., Segundo, V. B. D. S., Medeiros, M. G. D., Santos, N. A. D., & Junior, L. M. C. (2019). The carbon footprint of the generation of bioelectricity from sugarcane bagasse in a sugar and ethanol industry. *International Journal of Global Warming*, *17*(3), 235. https://doi.org/10.1504/IJGW.2019.098495

17. Chai, S. Y. W., Phang, F. J. F., Yeo, L. S., Ngu, L. H., & How, B. S. (2022). Future era of techno-economic analysis: Insights from review. *Frontiers in Sustainability*, *3*. https://www.frontiersin.org/articles/10.3389/frsus.2022.924047

18. Channiwala, S. A., & Parikh, P. P. (2002). A unified correlation for estimating HHV of solid, liquid, and gaseous fuels. *Fuel*, *81*(8), 1051–1063. https://doi.org/10.1016/S0016-2361(01)00131-4

19. Chauvel, A. (2003). *Manual of process economic evaluation* (New, rev. expanded ed.). Editions Technip.

20. Chhiti, Y., & Kemiha, M. (n.d.). *Thermal Conversion of Biomass, Pyrolysis, and Gasification: A Review*.

21. Coulson, J. M., Richardson, J. F., & Sinnott, R. K. (2005). *Chemical engineering. 6: Chemical engineering design* (4. ed). Elsevier.

22. Daryle, B. O. (2017). *Présenté et soutenu publiquement le 7 Novembre 2017 par*.

23. Dassey, A., Mukherjee, B., Sheffield, R., & Theegala, C. (2013). Catalytic cracking of tars from biomass gasification. *Biomass Conversion and Biorefinery*, *3*(2), 69–77. https://doi.org/10.1007/s13399-012-0063-1

24. de Jong, W. (2014). Biomass Composition, Properties, and Characterization. In *Biomass as a Sustainable Energy Source for the Future* (pp. 36–68). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118916643.ch2

25. Gagliano, A., Nocera, F., Bruno, M., & Cardillo, G. (2017). Development of an Equilibrium-based Model of Gasification of Biomass by Aspen Plus. *Energy Procedia*, *111*, 1010–1019. https://doi.org/10.1016/j.egypro.2017.03.264

26. Gallucci, F., Liberatore, R., Sapegno, L., Volponi, E., Venturini, P., Rispoli, F., Paris, E., Carnevale, M., & Colantoni, A. (2020). Influence of Oxidant Agent on Syngas Composition: Gasification of Hazelnut Shells through an Updraft Reactor. *Energies*, *13*(1), Article 1. https://doi.org/10.3390/en13010102

27. *Generator gas: The Swedish experience-gas 1939-1945* (3rd ed). (1998). Biomass Energy Foundation.

28. GHALY, A. E. (1991). A review of Osamu Kitani and Carl W. Hall (Editors), “Biomass Handbook” (Gordon and Breach Science Publishers, New York, 1989), 963 pp., $349.00. *Energy Sources*, *13*(3), 409–410. https://doi.org/10.1080/00908319108956421

29. Giuliano, A., Freda, C., & Catizzone, E. (2020). Techno-Economic Assessment of Bio-Syngas Production for Methanol Synthesis: A Focus on the Water–Gas Shift and Carbon Capture Sections. *Bioengineering*, *7*(3), Article 3. https://doi.org/10.3390/bioengineering7030070

30. *Global Hydrogen Review 2022*. (2022).

31. Guo, L., Cao, C., Lu, Y., Guo, L., Cao, C., & Lu, Y. (2010). Supercritical Water Gasification of Biomass and Organic Wastes. In *Biomass*. IntechOpen. https://doi.org/10.5772/9774

32. Hernández, J. J., Aranda-Almansa, G., & Bula, A. (2010). Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time. *Fuel Processing Technology*, *91*(6), 681–692. https://doi.org/10.1016/j.fuproc.2010.01.018

33. Ingle, N. A., & Lakade, S. S. (2016). Design and Development of Downdraft Gasifier to Generate Producer Gas. *Energy Procedia*, *90*, 423–431. https://doi.org/10.1016/j.egypro.2016.11.209

34. ISO 14040. (2006, August 31). *Environmental management—Life cycle assessment—Principles and framework*. ISO. https://www.iso.org/standard/37456.html

35. Jangsawang, W., Laohalidanond, K., & Kerdsuwan, S. (2015). Optimum Equivalence Ratio of Biomass Gasification Process Based on Thermodynamic Equilibrium Model. *Energy Procedia*, *79*, 520–527. https://doi.org/10.1016/j.egypro.2015.11.528

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

37. Kombe, E. Y., Lang'at, N., Njogu, P., Malessa, R., Weber, C.-T., Njoka, F., & Krause, U. (2022). Numerical investigation of sugarcane bagasse gasification using Aspen Plus and response surface methodology. *Energy Conversion and Management*, *254*, 115198. https://doi.org/10.1016/j.enconman.2021.115198

38. Kumar, A., Eskridge, K., Jones, D. D., & Hanna, M. A. (2009). Steam–air fluidized bed gasification of distillers grains: Effects of steam to biomass ratio, equivalence ratio, and gasification temperature. *Bioresource Technology*, *100*(6), 2062–2068. https://doi.org/10.1016/j.biortech.2008.10.011

39. Kumar, A., Jones, D. D., & Hanna, M. A. (2009). Thermochemical Biomass Gasification: A Review of the Current Status of the Technology. *Energies*, *2*(3), Article 3. https://doi.org/10.3390/en20300556

40. Kumar, A. S. and S. Y. (2018). A COMPARATIVE STUDY OF SUGARCANE BAGASSE GASIFICATION AND DIRECT COMBUSTION. *Journal of Industrial Pollution Control*, *34*(2), 2063–2074.
41. Lange, J.-P. (2001). *Fuels and Chemicals Manufacturing; Guidelines for Understanding and Minimizing the Production Costs*.
42. Lanh, N., Nguyen, B., Quyen, N. N., Hung, B. N., & Preston, T. (2018). A study on designing, manufacturing, and testing a household rice husk gasifier. *Livestock Research for Rural Development*, *30*.
43. Lauri, P., Havlík, P., Kindermann, G., Forsell, N., Böttcher, H., & Obersteiner, M. (2014). Woody biomass energy potential in 2050. *Energy Policy*, *66*, 19–31. https://doi.org/10.1016/j.enpol.2013.11.033
44. Le Blond, J. S., Woskie, S., Horwell, C. J., & Williamson, B. J. (2017). Particulate matter produced during commercial sugarcane harvesting and processing: A respiratory health hazard? *Atmospheric Environment*, *149*, 34–46. https://doi.org/10.1016/j.atmosenv.2016.11.012
45. Ling, M., Esfahani, M. J., Akbari, H., & Foroughi, A. (2016). Effects of residence time and heating rate on gasification of petroleum residue. *Petroleum Science and Technology*, *34*(22), 1837–1840. https://doi.org/10.1080/10916466.2016.1230752
46. Mahmud, R., Moni, S. M., High, K., & Carbajales-Dale, M. (2021). Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review. *Journal of Cleaner Production*, *317*, 128247. https://doi.org/10.1016/j.jclepro.2021.128247

47. Makwana, J. P., Pandey, J., & Mishra, G. (2019). Improving the properties of producer gas using high-temperature gasification of rice husk in a pilot scale fluidized bed gasifier (FBG). *Renewable Energy*, *130*, 943–951. https://doi.org/10.1016/j.renene.2018.07.011
48. Matsumura, Y. (2015). Chapter 9—Hydrothermal Gasification of Biomass. In A. Pandey, T. Bhaskar, M. Stöcker, & R. K. Sukumaran (Eds.), *Recent Advances in Thermo-Chemical Conversion of Biomass* (pp. 251–267). Elsevier. https://doi.org/10.1016/B978-0-444-63289-0.00009-0
49. Matsumura, Y., Minowa, T., Potic, B., Kersten, S. R. A., Prins, W., van Swaaij, W. P. M., van de Beld, B., Elliott, D. C., Neuenschwander, G. G., Kruse, A., & Jerry Antal Jr., M. (2005). Biomass gasification in near- and super-critical water: Status and prospects. *Biomass and Bioenergy*, *29*(4), 269–292. https://doi.org/10.1016/j.biombioe.2005.04.006
50. Mavukwana, A., Jalama, K., Ntuli, F., & Harding, K. (2013). Simulation of Sugarcane Bagasse Gasification using Aspen Plus. *South Africa*.
51. Meng, X., de Jong, W., Fu, N., & Verkooijen, A. H. M. (2011). Biomass gasification in a 100 kWth steam-oxygen blown circulating fluidized bed gasifier: Effects of operational conditions on product gas distribution and tar formation. *Biomass and Bioenergy*, *35*(7), 2910–2924. https://doi.org/10.1016/j.biombioe.2011.03.028
52. Mishra, S., & Upadhyay, R. K. (2021). Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters. *Materials Science for Energy Technologies*, *4*, 329–340. https://doi.org/10.1016/j.mset.2021.08.009
53. Mitros, T., Session, A. M., James, B. T., Wu, G. A., Belaffif, M. B., Clark, L. V., Shu, S., Dong, H., Barling, A., Holmes, J. R., Mattick, J. E., Bredeson, J. V., Liu, S., Farrar, K., Głowacka, K., Jeżowski, S., Barry, K., Chae, W. B., Juvik, J. A., … Rokhsar, D. S. (2020).

Genome biology of the paleotetraploid perennial biomass crop Miscanthus. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-18923-6

54. Mogmenga, L., Hartiti, B., Diallo, A., Ouedraogo, A., Bado, N., Fadili, S., Thevenin, P., & Bathiebo, J. (2019). Financial Analysis of Photovoltaic Installations in Burkina Faso. *Physical Science International Journal*, 1–13. https://doi.org/10.9734/psij/2019/v22i230125
55. Molino, A., Larocca, V., Chianese, S., & Musmarra, D. (2018). Biofuels Production by Biomass Gasification: A Review. *Energies*, *11*(4), Article 4. https://doi.org/10.3390/en11040811
56. Moussa, R. (2012). *OPTION: ENERGIE ET GENIE DES PROCEDES INDUSTRIELS*; Amélioration du fonctionnement par une revue de l'exploitation des chaudières de la SN-SOSUCO.
57. Nanou, P. (2013). *Biomass gasification for the production of methane* [PhD, University of Twente]. https://doi.org/10.3990/1.9789036535434
58. Olivier, P. (2017). *THE POWER OF SMALL-SCALE GASIFICATION*.
59. Omar, M. M., Munir, A., Ahmad, M., & Tanveer, A. (2018). Downdraft gasifier structure and process improvement for high quality and quantity producer gas production. *Journal of the Energy Institute*, *91*(6), 1034–1044. https://doi.org/10.1016/j.joei.2017.07.005
60. Osman, A. I., Mehta, N., Elgarahy, A. M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2021). Conversion of biomass to biofuels and life cycle assessment: A review. *Environmental Chemistry Letters*, *19*(6), 4075–4118. https://doi.org/10.1007/s10311-021-01273-0

61. Ouedraogo, M., Sawadogo, M., Sanou, I., Barro, M., Nassio, S., Seynou, M., & Zerbo, L. (2022). Characterization of sugar cane bagasse ash from Burkina Faso for cleaner cement production: Influence of calcination temperature and duration. *Results in Materials*, *14*, 100275. https://doi.org/10.1016/j.rinma.2022.100275
62. Pang, S. (2016). 9 - Fuel flexible gas production: Biomass, coal and bio-solid wastes. In J. Oakey (Ed.), *Fuel Flexible Energy Generation* (pp. 241–269). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-378-2.00009-2
63. Paraschiv, L. S., Serban, A., & Paraschiv, S. (2020). Calculation of combustion air required for burning solid fuels (coal/biomass / solid waste) and analysis of flue gas composition. *Energy Reports*, *6*, 36–45. https://doi.org/10.1016/j.egyr.2019.10.016
64. Patra, T., & Sheth, P. (2015). Biomass gasification models for downdraft gasifier: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, *50*, 583. https://doi.org/10.1016/j.rser.2015.05.012
65. Peng, D.-Y., & Robinson, D. B. (1976). A New Two-Constant Equation of State. *Industrial & Engineering Chemistry Fundamentals*, *15*(1), 59–64. https://doi.org/10.1021/i160057a011
66. Phyllis2. (2023). *Database for treated biomass, algae, and feedstocks for biogas production and biochar*. https://Phyllis.nl//
67. Puig-Arnavat, M., & Bruno, J. C. (2015). Chapter 5—Artificial Neural Networks for Thermochemical Conversion of Biomass. In A. Pandey, T. Bhaskar, M. Stöcker, & R. K. Sukumaran (Eds.), *Recent Advances in Thermo-Chemical Conversion of Biomass* (pp. 133–156). Elsevier. https://doi.org/10.1016/B978-0-444-63289-0.00005-3

68. Reed, T. B., & Das, A. (1988). *Handbook of biomass downdraft gasifier engine systems* (SERI/SP-271-3022, 5206099; p. SERI/SP-271-3022, 5206099). https://doi.org/10.2172/5206099
69. Ren, J., Cao, J.-P., Zhao, X.-Y., Yang, F.-L., & Wei, X.-Y. (2019). Recent advances in syngas production from biomass catalytic gasification: A critical review on reactors, catalysts, catalytic mechanisms, and mathematical models. *Renewable and Sustainable Energy Reviews*, *116*, 109426. https://doi.org/10.1016/j.rser.2019.109426
70. S, R., C, M., & P, A. (2022). Influence of Residence Time on Syngas Composition in CaO Enhanced Air–Steam Gasification of Biomass. *Environment, Development and Sustainability*, *24*(6), 8363–8377. https://doi.org/10.1007/s10668-021-01787-1
71. Safarian, S., Unnþórsson, R., & Richter, C. (2019). A review of biomass gasification modeling. *Renewable and Sustainable Energy Reviews*, *110*, 378–391. https://doi.org/10.1016/j.rser.2019.05.003
72. Sansaniwal, S. K., Pal, K., Rosen, M. A., & Tyagi, S. K. (2017). Recent advances in the development of biomass gasification technology: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *72*, 363–384. https://doi.org/10.1016/j.rser.2017.01.038
73. Sharma, M., & Kaushal, R. (2020). Advances and challenges in the generation of bio-based fuels using gasifiers: A comprehensive review. *International Journal of Ambient Energy*, *41*(14), 1645–1663. https://doi.org/10.1080/01430750.2018.1517687
74. Shayan, E., Zare, V., & Mirzaee, I. (2018). Hydrogen production from biomass gasification; a theoretical comparison of using different gasification agents. *Energy Conversion and Management*, *159*, 30–41. https://doi.org/10.1016/j.enconman.2017.12.096

75. Sjahro, N., Yunus, R., Abdullah, L. C., Rashid, S. A., Asis, A. J., & Akhlisah, Z. N. (2021). Recent advances in the application of cellulose derivatives for the removal of contaminants from aquatic environments. *Cellulose*, *28*(12), 7521–7557. https://doi.org/10.1007/s10570-021-03985-6
76. Tursi, A. (2019). A review on biomass: Importance, chemistry, classification, and conversion. *Biofuel Research Journal*, *6*(2), 962–979. https://doi.org/10.18331/BRJ2019.6.2.3
77. Turton, R. (Ed.). (2009). *Analysis, synthesis, and design of chemical processes* (3rd ed). Prentice Hall.
78. Turton, R. (Ed.). (2012). *Analysis, synthesis, and design of chemical processes* (4th ed). Prentice Hall.
79. van loo, S., & Koppejan, J. (2008). *The Handbook of Biomass Combustion and Cofiring*.
80. Xie, S., Ragauskas, A. J., & Yuan, J. S. (2016). Lignin Conversion: Opportunities and Challenges for the Integrated Biorefinery. *Industrial Biotechnology*, *12*(3), 161–167. https://doi.org/10.1089/ind.2016.0007
81. Zoungrana, L., Sidibe, S. D. S., & Richardson, Y. (2019). *Review of gasification modeling and equilibrium model implementation to predict rice husk syngas composition*.
82. ECREEE, ECREEE, and WASCAL Hold Technical Meetings to Advance Green Hydrogen Development in the Ecowas Region. ECREEE and WASCAL Hold Technical Meetings to Advance Green Hydrogen Development in the ECOWAS Region | ECREEE. (Accessed on 23/03/2023).

83. Barry, F.; Sawadogo, M.; Bologo (Traoré), M.; Ouédraogo, I.W.K.; Dogot, T. Key Barriers to the Adoption of Biomass Gasification in Burkina Faso. Sustainability 2021, 13, 7324. https://doi.org/10.3390/ su13137324.

84. www. sn sosuco.com, last accessed on 17/01/2023.

85. Energy Consumption in Burkina Faso. www.worlddata.info, Last accessed on 23/03/2023.

86. Power Africa in Burkina Faso. www.usaid.gov, Last accessed on 23/03/2023.

87. Effects of greenhouse gases. www.nationalgeographic.com, Last accessed on 26/03/2023.

APPENDIX 1

Table 16: The result of the theoretical design of the downdraft gasifier

PARAMETERS	VALUES	UNITS
Product gas flow rate Nm^3/s	0.35	Nm^3/s
The higher heating value of the sugarcane bagasse	19.50	MJ/kg
The lower heating value of the sugarcane bagasse	16.77	MJ/kg
The sugarcane bagasse feeding rate in the gasifier	626.43	kg/h
The theoretical amount of oxygen required for 1 kg of SCB	1.340	kg
The theoretical amount of air required for 1kg of SCB	6.39	kg
The total theoretical amount of air required for the complete combustion of sugarcane bagasse (626.43 kg/h)	4007.80	kg/h
The total amount of air required in the gasifier	1001.95	kg/h
Grate area of the reactor	2.98	m^2
The diameter of the gasifier	1.94	m
The height of the reactor (residence time of the biomass in the reactor =1 hour in the gasifier)	0.38	m
The volume of the reactor (residence time of the biomass in the reactor =1 hour)	1.135	m^3

APPENDIX 2

Table 17: Capital Expenditures (CAPEX)

PARAMETERS	VALUES	PRICES/QUANTITIES
Sugarcane bagasse input power in the gasifier	19887.31	kW
The open-cycle gas turbine output power (Electricity)	1750	kW
The quantity of hydrogen produced by the membrane	136.240	kg
The power losses in the process (Simulated model)	13.60	MW
Total Fixed Capital Investment (ISBL + OSBL) in 1993	26.872	Million USD
CEPCI 1993	359	….
CEPCI 2023	798	….
TFCI (ISBL + OSBL) in 2023	59.73	Million USD
ISBL (FCI) in 2023	42.66	Million USD
WCI	4.2666	Million USD
CAPEX (TFCI + WCI)	**63.99**	**Million USD**

APPENDIX 3

Table 18: Annual Operating Expenditures (OPEX)

PARAMETERS	VALUES	PRICES/QUANTITIES
The annual cost of the sugarcane bagasse	0	USD
The quantity of energy consumed by the fan per hour	1.4	kWh
The annual cost of energy for the gasification air supply	2618	USD
The annual cost of energy for the syngas cooling process	5236	USD
The annual operating labor cost	76500	USD
OPEX	**8.069613**	**Million USD**

APPENDIX 4

Table 19: Annual Gross Revenues

PARAMETERS	VALUES	PRICES
Annual Price of electricity to be sold	3.272	Million USD
The average annual price of hydrogen to be sold	4.632	Million USD
TOTAL ANNUAL GROSS REVENUES	**7.90**	**Million USD**

APPENDIX 5

Table 20: The net present worth of the simulated model over a lifetime of 20 years

YEARS	CAPEX (Million USD)	OPEX (Million USD)	REVENUES (Mill USD)	NPW Million USD
YEAR 0	63.99	0	0	**-63.99**
YEAR 1	0	8.069	7.904	**0.309647059**
YEAR 2	0	8.069	7.904	**0.756373702**
YEAR 3	0	8.069	7.904	**1.176822308**
YEAR 4	0	8.069	7.904	**1.572538643**
YEAR 5	0	8.069	7.904	**1.944977546**
YEAR 6	0	8.069	7.904	**2.295508279**
YEAR 7	0	8.069	7.904	**2.625419557**
YEAR 8	0	8.069	7.904	**2.935924289**
YEAR 9	0	8.069	7.904	**3.228164036**
YEAR 10	0	8.069	7.904	**3.503213211**
YEAR 11	0	8.069	7.904	**3.762083022**
YEAR 12	0	8.069	7.904	**4.005725197**
YEAR 13	0	8.069	7.904	**4.23503548**
YEAR 14	0	8.069	7.904	**4.450856922**
YEAR 15	0	8.069	7.904	**4.653982985**
YEAR 16	0	8.069	7.904	**4.845160457**
YEAR 17	0	8.069	7.904	**5.025092195**
YEAR 18	0	8.069	7.904	**5.194439713**
YEAR 19	0	8.069	7.904	**5.353825612**
YEAR 20	0	8.069	7.904	**5.50383587**
		TOTAL NPW		**3.388626081**

APPENDIX 6

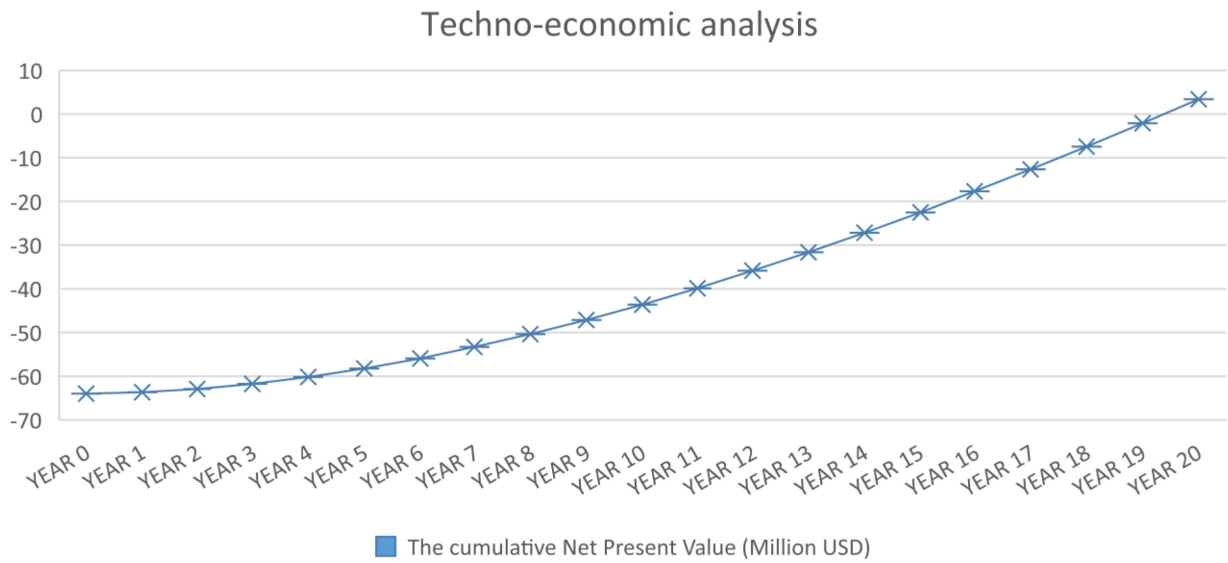

Figure 9: Cumulative Net Present Worth of the simulated model

APPENDIX 7

Table 21: Result of Life Cycle Impact Assessment on OpenLCA Software

Indicators	SCB Cogeneration (Moussa, 2012)	Modeling and simulation of the downdraft gasifier for both hydrogen and electricity generation	Unit (Characterization factor/MWh)
Acidification	1.18E-01	4.23E-02	kg SO_2 eq/MWh
Carcinogenic	1.18E-07	2.82E-07	CTUh/MWh
Ecotoxicity	2.88E+00	7.05E+00	CTUe/MWh
Eutrophication	4.60E-03	3.26E-03	kg N eq/MWh
Fossil fuel depletion	9.04E-01	1.50E+00	MJ surplus/MWh
Global warming	2.09E+00	1.86E+00	kg CO_2 eq/MWh
Non-carcinogenic	1.41E-07	3.30E-07	CTUh/MWh
Ozone depletion	8.67E-08	1.40E-07	kg CFC-11 eq/MWh
Respiratory effects	4.83E-03	2.78E-03	kg PM2.5 eq/MWh
Smog	2.29E+00	1.19E+00	kg O_3 eq/MWh

APPENDIX 8

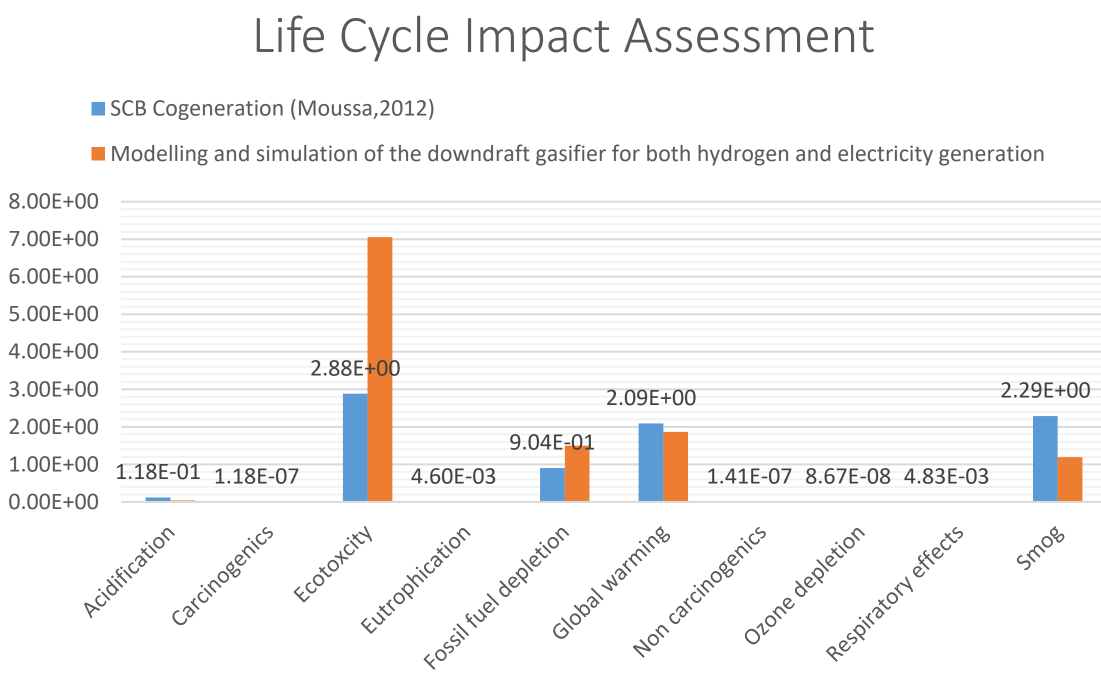

Figure 10: Flow chart of the different impact categories for both product systems