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Sustainability analysis of carbon dioxide emissions on combustion of biomass for electricity

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Sustainability Analysis of Carbon Dioxide Emissions on Combustion of Biomass for Electricity

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Abstract

The transition towards renewable, low-carbon energy is a fundamental element of climate change mitigation. Many countries around the world have set their decarbonization strategies to reduce emissions. The European Union has already declared bioenergy to be carbon-neutral, which has prompted other countries to expand their production. Bioenergy can only reduce atmospheric CO_2 over time through post-harvest increases in net primary production (NPP), defined as the rate at which all the autotrophs in an ecosystem produce net useful chemical energy using inorganic substances, such as CO_2. Therefore, the climate impact of bioenergy depends on CO_2 emissions from the combustion of biomass, the fate of the harvested land, and the dynamics of NPP. This study uses the dynamic bioenergy lifecycle analysis model, which tracks the carbon stocks and fluxes in the atmosphere, biomass, soils, and oceans. The model is used to simulate the substitution of coal for wood in electric power generation, estimating the parameters governing NPP and other fluxes using data for the Canadian boreal forest. Our dynamic analysis revealed that the first impact of displacing coal with wood is an immediate increase in the CO_2 concentration in the atmosphere. The simulation results show that using softwood pellets for electricity results in a 4.8 ppm increase in the atmospheric carbon concentration and 26.6 ppm for the hardwood counterpart. However, these emissions are offset after a breakeven period of about 11 years and 53 years for softwood and hardwood plantations, respectively. In contrast, the CO_2 emissions from coal increase even after a century and can never be repaid. The resulting uncertainty in payback periods could be reduced by either replanting the forest with fast-growing jack pine forests (softwood plantation) or by modification of the forest growth function. Although the carbon debt is repaid, there is still a potential of experiencing climate change because of the CO_2 accumulated before it is sequestered. This is evident as the average temperature increase associated with the use of softwood was determined to be 1.2°C and 1.4°C for the hardwood species. Though the resultant average temperature rise is below Glasgow's average global warming target (1.5°C), there could still be a chance of registering high temperatures if forest regeneration and harvest are not done sustainably. The LCA results also confirmed that the bioelectricity process is a net emitter of CO_2, and hence caution should be exercised when employing biomass for electricity generation. In order to limit emissions, bioelectricity should be sourced from softwood plantations since they grow faster, and the rate of carbon sequestration is very high at the early stages of growth. Additionally, sustainable forestry entails that biomass should be selected based on the forest type, age, and structure of the forest. Selective harvesting is the most preferred method of harvesting biomass since it takes into account all the factors outlined in sustainable forestry. In addition, plant managers should prioritize localized biomass sources when planning biomass procurement strategies to avoid the risks of long-distance biomass distribution. The LCA analysis also proved that renewable energy sources would be the most efficient for electricity generation as they emit significantly less CO_2 than fossil fuels.

Keywords: Renewable energy, bioenergy, decarbonization, carbon-neutral, net primary production (NPP), CO_2 emissions, life cycle analysis, global warming, climate change.

Lay Summary

Global warming caused by the excessive use of fossil fuels has compelled researchers to search for alternative sustainable energy sources. Biomass has emerged as a promising renewable energy source that could facilitate the transition to green energy. A surge in wood biomass energy has grown since plants absorb CO_2 from the atmosphere, thus potentially reducing the risks of climate change. The overall aim of this study is to investigate the feasibility of replacing coal with biomass to produce end-use electricity in Canada. One of the novelties of this work was the simulation of the conventional fossil route and comparing it with biomass and other renewable sources. Global warming is examined based on the climate variables such as an increase in the average temperature. Dynamic bioenergy lifecycle analysis found that the bioelectricity process increases the average temperature but is significantly below the average global warming target (COP26 Glasgow's target). However, the increase associated with the use of coal was found to be substantially greater. In addition, life cycle assessment (LCA) confirmed that the bioelectricity process is a net CO_2 emitter. These emissions are offset after a breakeven period of about 11 years and 53 years for softwood and hardwood plantations, respectively, even if forests are harvested in a sustainable manner. Therefore, prudence needs to be exercised on the choice and amounts of biomass used to generate electricity. Sustainable forest management needs to be enforced to ensure that forest is harvested and regenerated in a carbon neutral manner. This will prevent the accumulation of CO_2 in the atmosphere, thus limiting climate change.

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List of Abbreviations

Acronym	**Abbreviated name**
GHG	Greenhouse gases
NREL	National Renewable Energy Laboratory
CO_2	Carbon dioxide
IPCC	Intergovernmental Panel on Climate Change
ECCC	Environment and Climate Change Canada
NPP	Net Primary Production
LCA	Life Cycle Assessment
CHP	Combined Heat and Power
CER	Canada Energy Regulator
EJ	Exajoules
NASA	National Aeronautics and Space Administration
TW	Terawatt
PPM	Parts Per Million
GtC	Giga tons of carbon
MtC	Million metric tons of carbon
UNCED	United Nations Conference on Environment and Development
WBCSD	World Business Council for Sustainable Development
GDP	Gross Domestic Product
EIA	Energy Information Administration
BECCS	Bioenergy Carbon Capture and Storage
CSP	Concentrated Solar Power

ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
CML	Center of Environmental Science of Leiden University
TRACI	Tool for Reduction and Assessment of Chemicals and other environmental Impacts
GWP	Global Warming Potential
VDI	Verein Deutscher Ingenieure
ILCD	International Reference Life Cycle Data System
MC	Moisture Content
LHV	Lower Heating Value
HHV	Higher Heating Value
IEA	International Energy Agency
kWh	Kilowatt-hour
BIGCC	Biomass Integrated Gasification Combined Cycle
NRC	Natural Resource Canada
LCIA	Life Cycle Impact Assessment
CCS	Carbon Capture and Storage
PV	Photovoltaic
WNA	World Nuclear Association
CER	Canada Energy Regulator
NRC	Natural Resource Canada
Mmt	Million metric tons

Chapter 1: Introduction

The expansion of bioenergy production has gained considerable momentum worldwide because of the desire to limit climate change. The term bioenergy defines any energy from biomass through a chemical reaction. Kazuhiko et al. (2018) states that “biomass” does not only mean biotic mass or biotic standing stock in ecological science but also means biotic mass as an energy source mainly because it has been considered as an alternative energy for fossil fuel since the “oil shock” in the early 1970s. The term biomass covers an accumulation of plant and animal resources, as well as their waste materials (Kassouri, Bilgili, & Kuşkaya, 2022; Srivastava et al., 2021).

There are some substantial traits that make bioenergy unique. One of the key features is its carbon neutrality nature. The carbon neutrality entails that CO_2 emissions for biomass combustion is balanced out by absorbed CO_2 during growth of the plants if forests are harvested sustainably. The Kyoto protocol claims that there is net emission of CO_2, one of the global greenhouse gasses (GHG), from fossil fuel burning, whereas no net emission when biomass is burned (Kim, Tanaka, & Matsuoka, 2020; Maamoun, 2019; Miyamoto & Takeuchi, 2019). Furthermore, the European Union declared bioenergy to be carbon-neutral to help meet its goal of 20% renewable energy (Sikkema et al., 2020). The carbon-neutrality of bioenergy makes it popular, and this is the reason why many governments around the world promote its use (Sterman, Siegel, & Rooney-Varga, 2018).

The renewable nature of bioenergy is another reason for the increasing exploitation of bioenergy. According to the National Renewable Energy Laboratory (NREL), renewable energy is a non-exhaustible resource similar to wind and solar power (Alizadeh, Lund, & Soltanisehat, 2020; Ranta, Laihanen, & Karhunen, 2020). Since bioenergy is generated from plants, it is considered to be renewable energy unless the growth of the plants is stalled (Afolalu et al., 2021; Sameeroddin, Deshmukh, Viswa, & Sattar, 2021; Takeuchi, Shiroyama, Saito, & Matsuura, 2018).

Though bioenergy seems promising, the feasibility of forest bioenergy to potentially mitigate global warming has been increasingly questioned due to the overlap between the CO_2 emissions when forest biomass is used for energy and subsequent sequestration of carbon in a new biomass. This temporal displacement may lead to net emission, which posts a threat to the climate (Favero, Daigneault, & Sohngen, 2020; Yan, 2018). Additionally, there is also a disturbance of both natural decay of dead biomass and growth of living biomass when used for energy, which affect the carbon dynamics of forest ecosystems. The analyses of carbon flux, carbon debt, and its payback time accounts for the perturbation of forest ecosystems (Takeuchi et al., 2018). This study and a number of recent reviews examined the implications of carbon dynamic and carbon debt of forest bioenergy with reference to climate impact (Bentsen, 2017; Lamers & Junginger, 2013; Nabuurs, Arets, & Schelhaas, 2017). A study carried out by Sterman et al. (2018) suggested that the carbon payback time of comparable forest bioenergy scenarios ranges from 44–104 years after clearcut, depending on forest type assuming the land remains forest. This period is quite long thus leading to an emergence of debate and dispute about the potential climate benefit of forest bioenergy (Bentsen, 2017).

Climate researchers acknowledge the significance of considering the full carbon cycle to shun enormous increases of atmospheric carbon dioxide that would lead to radioactive forcing and warming thus causing climate change (Moomaw, Law, & Goetz, 2020). Radioactive forcing is caused by imbalances in the energy flux, which results in overheating of the Earth surface (Bellouin et al., 2019). Climate change has attracted attention of many governments around the world leading to the Glasgow agreement, which set a strict temperature limit that the IPCC suggests in its 1.5°C Degree Report will require reducing net emissions by 45% by 2030 and reaching net zero by 2050 (Hermansen, Lahn, Sundqvist, & Øye, 2021; Hunter, Salzman, & Zaelke, 2021; IPCC, 2018). For this to happen, a contemporaneous reduction in carbon emissions and increasing sequestration is required. Apparently, neither of these efforts have been successful yet. These goals can be achieved by accounting for all the carbon fluxes that involve carbon storage in plant biomass, soils, and in the atmosphere (Takeuchi et al., 2018). Figures 1.1 and 1.2 show world biomass electricity production in 2019 and electricity generation in Canada by fuel type in 2019.

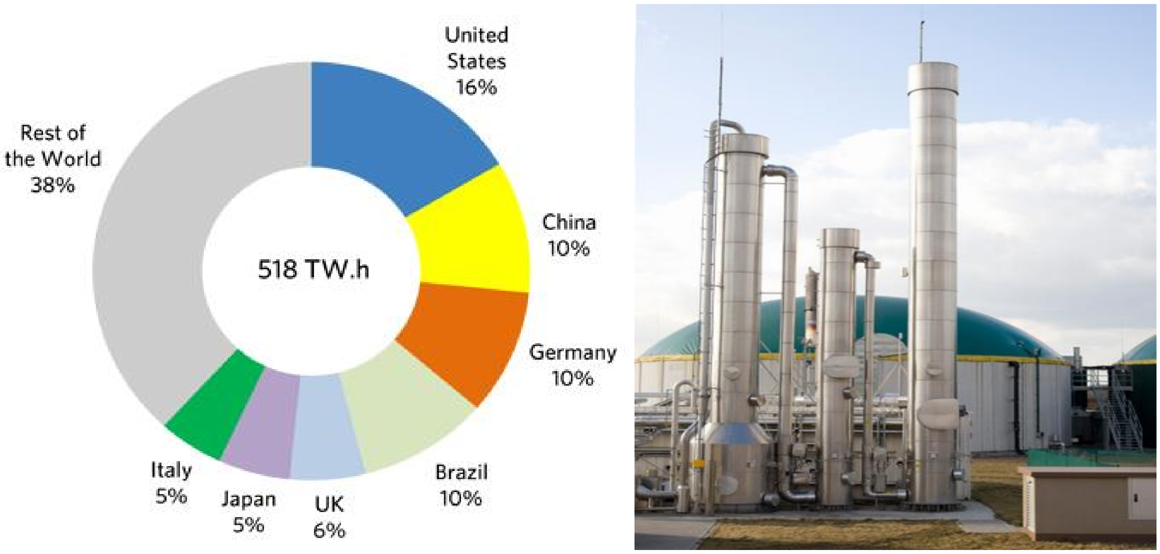

Figure 1.1: World Biomass Electricity Production in 2019 (Source: CER, 2020).

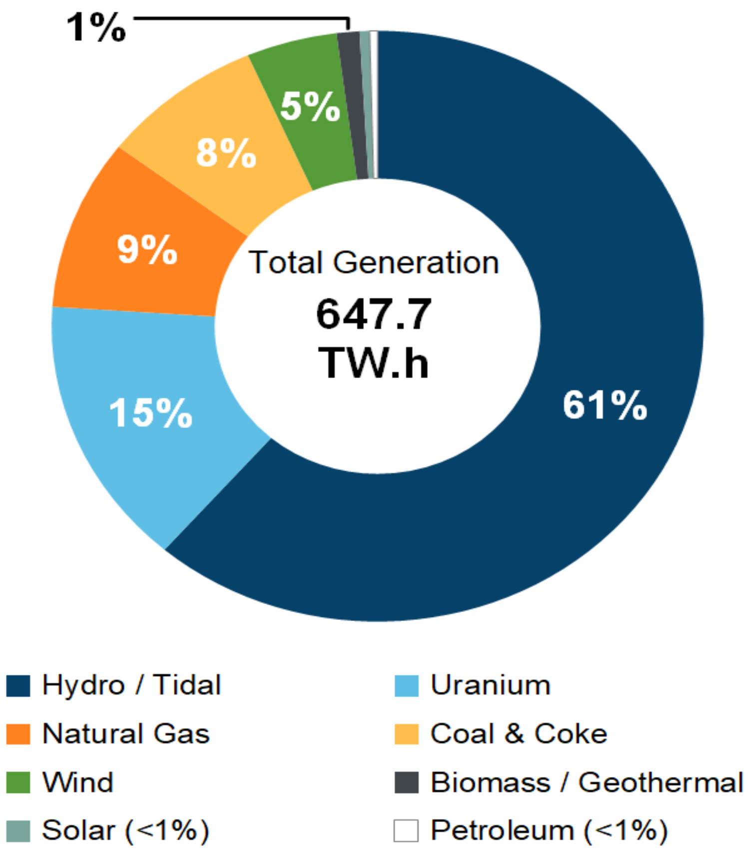

Figure 1.2: Electricity generation in Canada by fuel type in 2019. (**Source:** CER, 2019).

The Environment and Climate Change Canada (ECCC) developed a new regulation under the Canadian Environmental Protection Act of 1999 to reduce Canada's GHG emissions by 30 mega tons annually by 2030 through increased use of low carbon fuels and alternative technologies (Cauchi, 2017; Mike Barrett, 2017). This new regulation would be applicable for not only power generation for electricity, but also for transportation fuels, gas, liquid, and solid fuels for both motive and stationary applications. Littlejohns et al. (2018) projects that the new regulation will be a key driver that shapes the Canadian bioenergy industry in the future**.**

Carbon flux, carbon debt, and payback time studies intend to educate scientists, forest managers, policy makers, and other stakeholders on the climate consequences of harvesting more biomass from forests to meet an increased demand for bioenergy. There are quite a lot of different views on the climate impact of forest bioenergy from the literature, from being a threat to the environment to instantly being beneficial.

The overall objective of this study is to evaluate the viability of harvesting biomass to generate power for electricity. The research examined the feasibility of replacing coal with wood to produce fuels. The specific objectives are to:

i. Determine if biofuels generate more or less CO_2 per unit of end-use energy than fossil fuels
ii. Investigate the dynamics of biomass (re)growth, the Net Primary Production (NPP), and carbon fluxes from biomass and soils
iii. Perform Life Cycle Analysis (LCA) to evaluate the environmental impacts of bioelectricity systems, including the emissions incurred during transportation

Chapter 2: Literature Review

2.1 Detection and Attribution of Climate Change

Human activities have produced substantial volumes of carbon dioxide and other greenhouse gases (GHG) since the industrial revolution, altering the earth's climate. Natural activities such as solar energy fluctuations and volcanic eruptions also affects the earth's temperature. However, the latter does not explain the warming that has occurred over the last century (Abdollahbeigi, 2020; Hagen & Azevedo, 2022).

By evaluating a variety of indirect climate measurements, such as ice cores, tree rings, glacier lengths, pollen remnants, ocean sediments, and tracking variations in the earth's orbit around the sun, scientists have cobbled together a record of the earth's temperature. This data shows that the climate fluctuates naturally across wide time intervals. Still, this variability does not account for the observed warming since the 1950s (see Figure 2.1) with the advent of the industrial revolution and the exponential increase in the use of fossil resources. Human activities are quite likely (> 95%) the primary source of the warming. These activities have contributed to climate change mainly through greenhouse gas emissions (GHG) (Shindell & Smith, 2019).

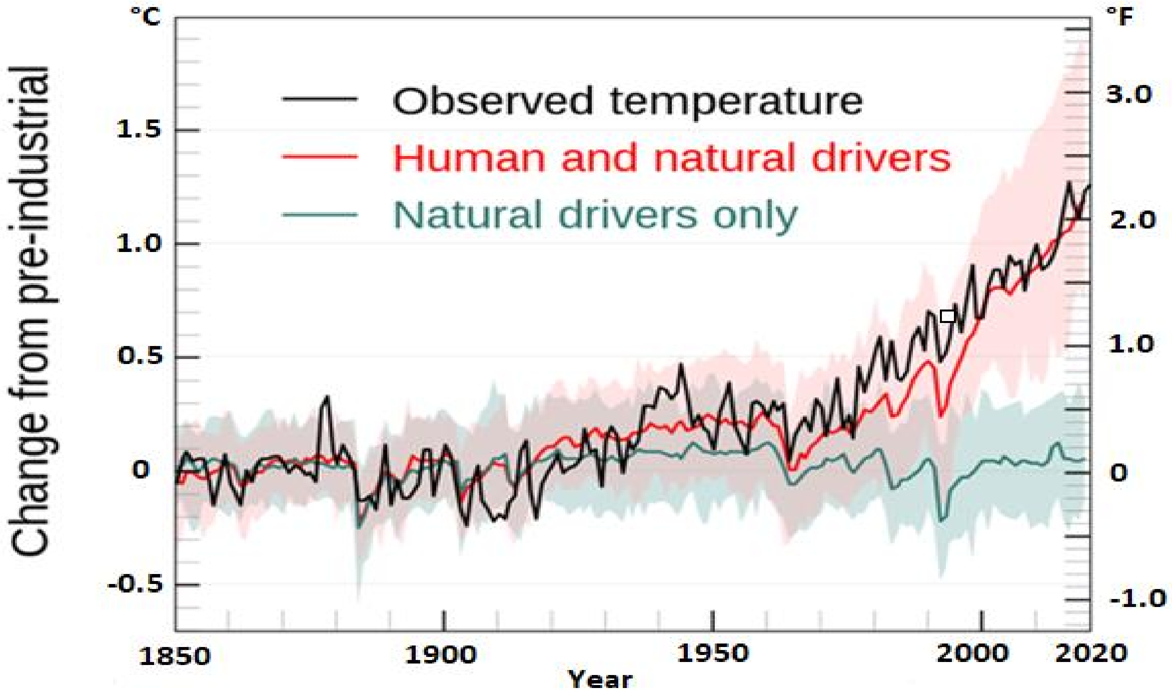

Figure 2.1: Human and natural influences on global temperature (adapted from NASA, 2020).

Human activities have caused concentrations of the primary GHG to rise since the industrial revolution. Carbon dioxide, methane, and nitrous oxide concentrations in the atmosphere are now higher than in the last 800,000 years (Beyi, 2019; Zheng, 2018). The greenhouse effect has been aggravated by these GHG emissions, causing the earth's surface temperature to rise. Burning fossil fuels has the greatest impact on the climate compared to other human activity. Since fossil fuels have adverse effects on the environment, biomass-based energy has been identified as alternative energy as it is expected to have less impact on the environment. If forests are harvested sustainably for energy production, they are expected to sequestrate the emissions that are produced after their end-use. The main aim of our study is to determine the feasibility of substituting wood for coal in power generation.

2.2 Roles of Bioenergy

There is an increasing need for renewable energy resources to facilitate green energy transition and mitigate climate change. Bioenergy has been prioritized as promising end-use energy, and a lot of research is ongoing. Table 2.1 presents some bioenergy products' sources, processes, and uses.

Table 2.1: Bioenergy products' sources, processes and uses.

Fuel Product	**Process**	**Feedstock**	**Use**
Renewable oil	Thermochemical	Wood residues	• Fuel • Platform chemical etc.
Bioethanol	Thermochemical, Fermentation, sugar/starch platform	Corn, grain, wood residues	• Motor fuel • Additive in gasoline etc.
Methanol	Thermochemical	Wood residues	• Fuel • Solvent • Pesticide etc.
Biodiesel	Chemical	Canola, soy, beef tallow, recycled vegetable, yellow, animal fats, recycled cooking oil	• Diesel engines • Heating oils • Fuel filters • Biodiesel electricity generators etc.
Biogas	Anaerobic digestion	Wood residues, municipal wastewater, manure, energy crops	• Cooking gas • Electricity production • Combined heat and power (CHP) operations etc.
Hydrogen	Thermochemical	Wood residues	• Fuel • Platform chemical etc.
Bioelectricity	Combustion/gasification	Wood residues	• Lighting and appliances • Energy for electric vehicles etc.

2.2.1 Why Bioelectricity?

Biomass can serve as a resource for various bioenergy and chemical products. Our study focuses on bioelectricity production because of the need to reduce CO_2 emissions. Canada's Energy Regulator (CER) reports that 8% of the end-use electricity consumed in Canada comes from coal which is the most carbon-intensive fossil resource (CER, 2022). Many government institutions and climate change organizations are working together to find solutions to managing carbon pollution. As part of the effort to find a solution, our research investigates the feasibility of using biomass to produce 0.2 EJ of end-use electricity. This is judged based on the CO_2 emissions, the resultant increase in the average temperatures, and the related environmental impacts.

2.3 Grand Challenges in Bioenergy Production

There are numerous bottlenecks in employing bioenergy to meet our daily energy needs. The environmental concerns remain the priority in adopting a fuel resource, and this is the focal point of the ongoing scientific consensus about the environmental damage caused by emissions of CO_2 and other GHG emissions. The risks of emissions have compelled scientists to search for ways to limit and cut down on the use of fossil fuels. Fossil fuels do represent not only our main source of energy but also are the most carbon-intensive resources, which contribute to a lot of CO_2 emissions (Gabrielli, Gazzani, & Mazzotti, 2020; Jewell et al., 2018). Therefore, it is reasonable to enact methods of reducing their use or even retire them.

Despite the recent advances in technologies for more efficient energy production and usage, the emissions are projected to increase due to population growth and average income. The energy demand is estimated to be at least 27 TW by 2050 compared to 16 TW, the current annual energy demand. Currently, the atmospheric CO_2 concentration is 420.1 parts per million (ppm), and the net accumulation has been continuously increased at a yearly rate of 1.03-2.13 ppm in the last four decades (WBA, 2020). As a result, the global carbon concentration level is expected to reach 500 ppm in 2050 if there are no reductions in emissions (X. Ge & Ma, 2020; Lowe & Drummond, 2022). The danger of the progressive increase in the carbon concentration in the atmosphere is the risk of experiencing global warming, which could eventually lead to climate change with catastrophic results to the environment. Consequently, this will result in the melting of ice sheets in the West Antarctic and Greenland, eventually resulting in a drastic rise in the sea level (Levine & Steele, 2021; C. Zhang et al., 2021). The number of weather events like heavy rainfall and floods occurring on our planet at regular intervals is another major sign of the rapidly changing climate (Hansen, Sato, & Ruedy, 2012).

Much focus has been directed to stabilizing the atmospheric CO_2 concentrations at 450-650 ppm over the next hundred years. In order to stabilize the atmospheric CO_2 concentration at 450 ppm by 2100, analysis show that total annual CO_2 emissions from 2050 and after that should not exceed 6.0 GtC (Gullino, Tabone, Gilardi, & Garibaldi, 2020; A. Zhang et al., 2021). The precise annual emission reductions rate should be at least 44.2 million metric tons of carbon (MtC) per year. Hence, there is a need to produce carbon emission-free energy to meet the reductions targets (Caspeta, Buijs, & Nielsen, 2013).

The growth in technology can achieve the success of a biobased economy, and technological advancement will undoubtedly help overcome the grand challenges of bioenergy production. Some environmental organizations, such as the IPCC Working Group III, recommend the adoption of the new technologies to better reach environmental goals at lower economic costs (Dale, Kline, Parish, & Eichler, 2019; Rodionova et al., 2017). There is a need for technological growth in all aspects of life that require energy. However, the primary focus is on the transportation sector, where there is a target to replace petrol and diesel-based cars with electric cars. The use of electric cars is projected to be environmentally friendly mainly because of their high thermal efficiency, which is approximately 80% as compared to 20% for cars with internal combustion engines (Akal, Öztuna, & Büyükakın, 2020).

Accelerating the green energy transition will ensure that renewable energy is used to charge electric vehicles. For instance, the European Green Deal requires member states to expand their renewable energy production and requires all new cars registered by 2035 to be zero-emission. Furthermore, all member states are required to increase charging capacity in line with zero-emission vehicle sales and establish charging and fueling stations at regular intervals on major highways: every 60 kilometers for electric charging and every 150 kilometers for hydrogen refueling (European_Commission, 2021). Improvements in energy density and reduction in cost are mandatory requirements for electric cars to become a major substitute for cars with internal combustion engines. However, a mismatch with the current infrastructure and an inadequate supply of rare elements used in the engines limit the implementation of electric cars (Mo et al., 2022).

Furthermore, there are issues raised related to costs and the use of agricultural land to produce fuels rather than food (food versus fuel issue). Although biofuels are cheaper than fossil fuels their prices are still costly and thus resulting in calls for the government to chip in by providing subsidies for ensuring the cost-competitive production of biofuels (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018; R. Singh & Sehrawat, 2019). Nevertheless, biofuels produced from biomass waste, and other solid residues from the agro-industry, do not have a land-use issue. This is because these materials are acquired during the processing of crops, and this could also be a solution to the disposal problems (Tonini, Hamelin, Alvarado-Morales, & Astrup, 2016). Even though the process is beneficial, biofuels generated through this process might not be enough to meet the energy needs. Therefore, there is a need for a serious surge in the large-scale production of these fuels or an energy mix that employs renewable energy to supply the energy requirements.

2.4 Bioenergy and Sustainability Science

The bioenergy industry is a very competitive field that has a broad impact on many areas and sectors, such as the environment, economics, and society. Therefore, enacting a sustainable bioenergy development strategy may eventually contribute to a sustainable society. This is possible if the methods are well established by thoroughly analyzing bioenergy's complex features.

Sustainability science sets out to solve global agendas of human subsistence, such as global warming. Many governments and the international arena, such as the United Nations Conference on Environment and Development (UNCED) and the World Business Council for Sustainable Development (WBCSD), are working together to ensure the implementation of sustainable science in controlling strategies of producing the end-use energy. The building of sustainability science entails maintaining fundamental links between science and technology without policy bias (Menton et al., 2020; Takeuchi et al., 2018).

Sustainability science is a solution-oriented science that tries to maintain a balance between the net primary production (NPP) and emissions to avoid overlap that may cause global warming and, ultimately, climate change (Zeigermann, 2021). Figure 2.2 demonstrates the carbon cycle in the atmosphere in a sustainable manner.

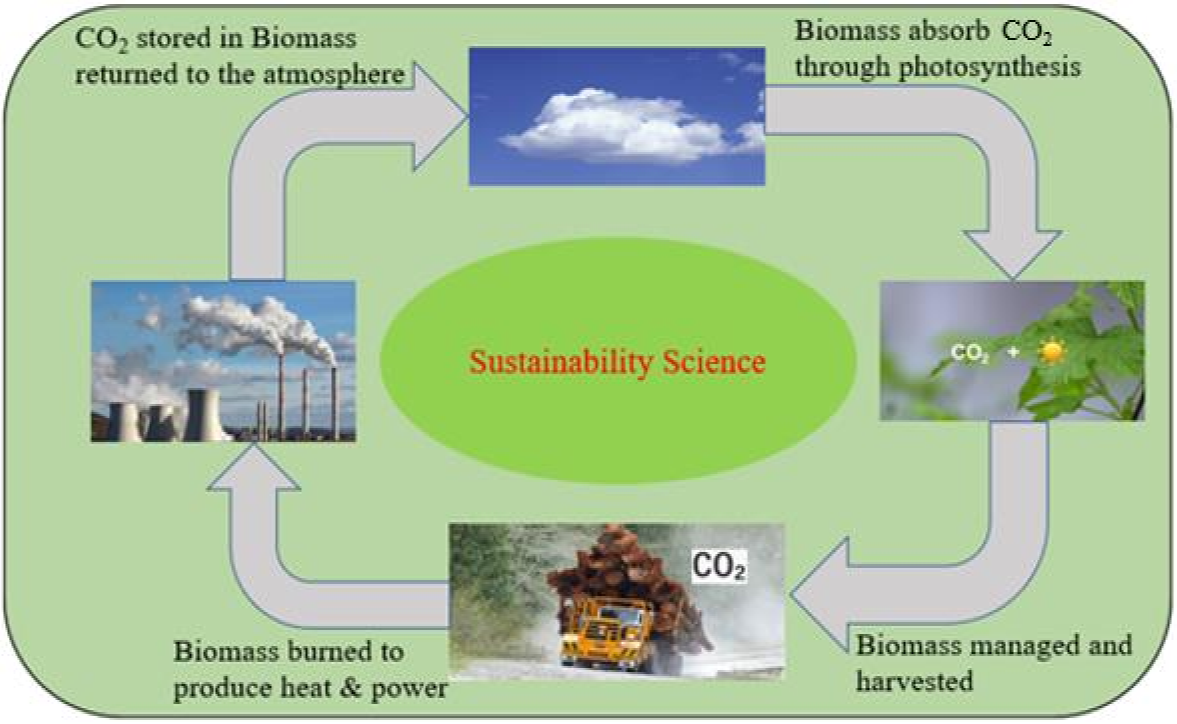

Figure 2.2: CO_2 recycling in the atmosphere in a sustainable manner.

The sustainable science will ensure appropriate policies are applied to secure long-term production of biomass and ensure environmental as well as economic and social benefits of bioenergy cropping systems (Chiaramonti & Maniatis, 2020; Tanneberger et al., 2021). The efforts will eventually ensure there is continuous support for cropping, infrastructure, agricultural management, which all facilitate positive synergies between food crops and bioenergy production (Leibensperger, Yang, Zhao, Wei, & Cai, 2021).

2.5 Current and Future Prospect of Bioenergy Production in the World

As the world enters the third year of the Covid-19 pandemic, the restrictions on movement continue to suppress global energy demand. However, an increase in vaccination provides hope of reviving the economy. Global economic output is expected to rebound by 4.4% in 2022, thus pushing the global GDP to more than 9.4% higher than 2020 levels (Jackson, 2021). There are concerns about whether the rebound will cause CO_2 emissions to reach a new high or whether the new policies targeting a sustainable recovery are going to ensure there is no rebound in emissions.

Though Covid-19 paralyzed global economies, renewables stand out to be the success of this era. This is because the demand for renewables increased by 3% in 2020, and it is projected to increase across all key sectors (power, heating, industry, and transport) in 2022. The power sector has the highest demand for renewables, and the demand is expected to expand by more than 8%, to reach 8,300 TWh (Elshurafa, Al-Atawi, Soummane, & Felder, 2021).

2.5.1 CO_2 emissions

Reduction in global CO_2 emissions is one of the benefits of the pandemic. In 2020, the global CO_2 emissions dropped by 5.8%, almost 2 Gt CO_2. This is the largest fall and almost five times greater than the one recorded in 2009 after the global financial crisis. However, the global energy-related emissions remained at 31.5 Gt in 2020, which caused CO_2 to reach its highest-ever average annual concentration in the atmosphere of 412.5 ppm. This accounts for more than a 50% increase since the beginning of the industrial revolution. Since the demand for coal, oil, and gas is projected to increase in 2022, global energy-related CO_2 emissions are expected to pick up and increase by 4.8% (Skea, van Diemen, Portugal-Pereira, & Khourdajie, 2021). This is equivalent to an increase of 1,500 Mt CO_2, which will be the largest single since the one experienced more than a decade ago after the global financial crisis. As a result, the global emissions in 2022 are around 420.1 ppm, which is quite high compared to 2020 (Xin et al., 2021). Figure 2.3 show the global energy-related CO_2 emissions and recent studies on bioelectricity, respectively.

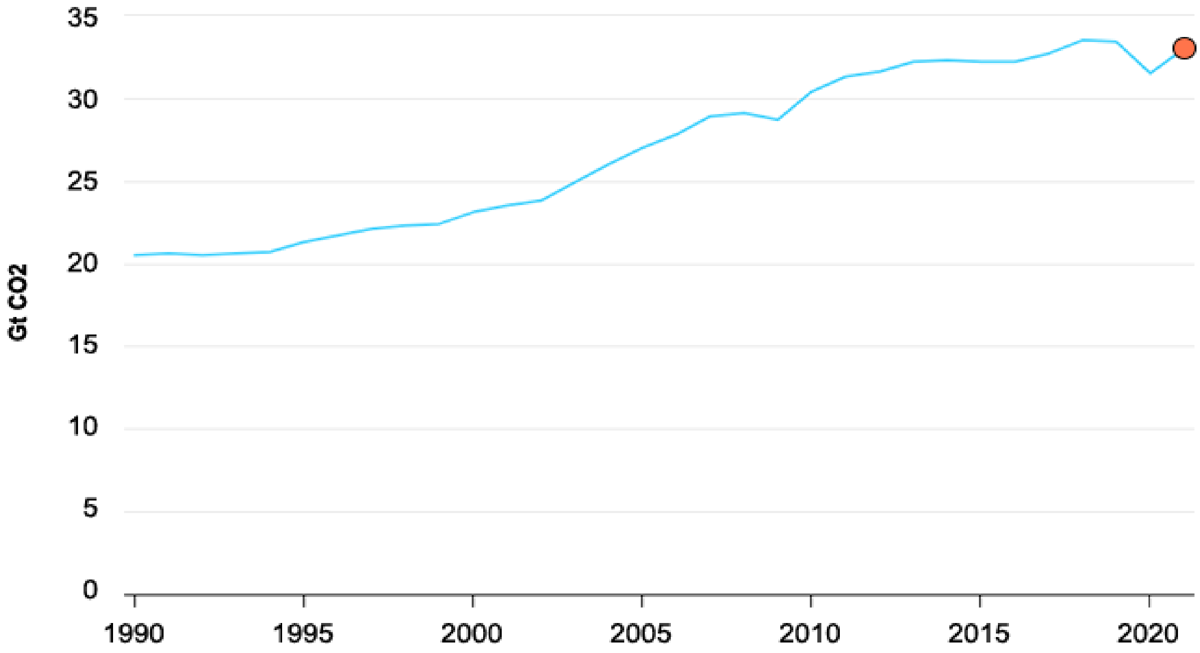

Figure 2.3: Global energy-related CO_2 emissions (Adapted from EIA, 2021).

2.5.2 Carbon Sequestration

Our study uses biomass, which has been identified as an alternative energy source that has the potential to reduce CO_2 emissions when used to produce electricity. Two main wood plantations could be employed to produce bioelectricity, including hardwood and softwood plantations. The hardwood plantation usually grows leaves; however, it goes through a period of dormancy in winter. Most hardwood species take a long time to mature, and they usually lose their leaves in winter and regrow them in spring. Softwood plantations are evergreen plantations that do not shed their needles in the fall and go through a period of dormancy. The softwood plantation matures faster (30 years), and its carbon sequestration rate is high in the initial stages. In contrast, hardwood species grow slowly, and their carbon sequestration rate is quite low even after 50 years, as demonstrated in Figure 2.4.

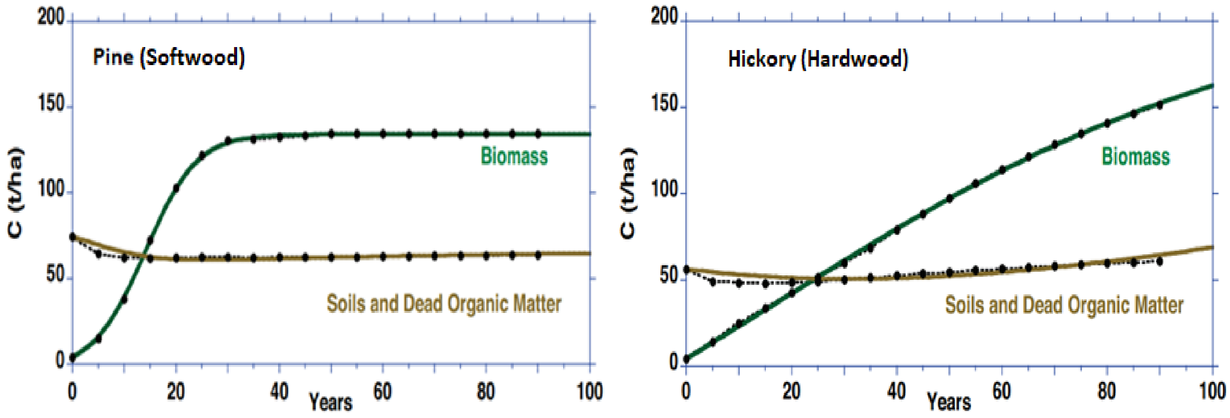

Figure 2.4: Carbon sequestration curves for hardwood and softwood plantations, soils, and dead organic matter with age of the forest biomass (Adapted from Sterman et al., 2018).

As noticed in Figure 2.4, softwood plantation sequesters 130 tC/ha within 30 years. However, it takes hardwood species nearly 70 years to sequester the same amount of carbon from the atmosphere (Sterman et al., 2018). Therefore, they are preferable species from which lignocellulosic biomass can be sourced, especially jack pine species, since it gives substantial biomass that could provide a feedstock for bioelectricity production.

2.5.3 Recent research on Bioelectricity

Table 2.2 shows a list of recent research on bioelectricity and the results. In the following sections, these studies are discussed in detail.

Table 2.2: Recent studies on biomass-based electricity.

Feedstock	**Case study**	**Analysis Method**	**Result**	**Country**	**Reference**
Woody biomass	Does biomass combustion lead to more emissions of CO_2 than coal?	Dynamic analysis	Biomass combustion worsens climate change before benefits accrue.	US	(Sterman et al., 2018)
Energy crop	The implications for energy crops under China's climate change challenges	GCAM-integrated assessment model	Net cumulative emissions of land-use changes will be neutral by 2050. Also, the energy crops and BECCS are relatively low-cost to reduce carbon emissions.	China	(A. Zhang et al., 2021)
Woody biomass	Biomass conversion into electricity and other fuels	Network-based mathematical model for Life cycle optimization	The annual savings of as much as 1.81 Gt CO_{2eq} could be attained by exploiting biomass resources, although biomass cannot fully cover the total EU demand for electricity and biofuels.	UK	(Calvo-Serrano, Guo, Pozo, Galan-Martin, & Guillén-Gosálbez, 2019)
Woody biomass	Modelling of biomass usage in the electricity grid	CleanGrid model improved with biomass electricity dispatch model	As carbon prices increase, bioelectricity will be a cost-effective, flexible option compared to other low-carbon (such as CSP) and fossil-based flexible options (e.g., coal and gas) at higher carbon price scenarios.	Australia	(M. Li et al., 2022)
Woody biomass	Role of woody biomass for reduction of fossil GHG emissions	Partial equilibrium energy system model	The use of woody biomass can reduce the direct emissions from the Northern European power and heat sector by 4–27% for carbon prices in the range of 5–103 €/ton CO_{2eq} in 2030 compared to a scenario where woody biomass is not available for power and heat generation.	Norway	(Jåstad, Bolkesjø, Trømborg, & Rørstad, 2020)
Sugarcane straw	Electricity Production from Sugarcane Straw Recovered Through Bale System	Commercial process simulator (AspenPlus)	Bioelectricity presented a great potential to mitigate greenhouse gas emissions compared with natural gas-based electricity.	Brazil	(Sampaio et al., 2019)

2.5.3.1 CO_2 emissions from Bioelectricity Process

Sterman et al. (2018) made a critical analysis of carbon dioxide emissions caused by the combustion of biomass to produce electricity. Figure 2.5 displays a set of scenarios based on parameters estimated for an oak-hickory forest in the south-central United States. All scenarios look at a 1 EJ of end-use electric energy produced from wood pellets, countering 1 EJ of end-use electric energy generated from coal.

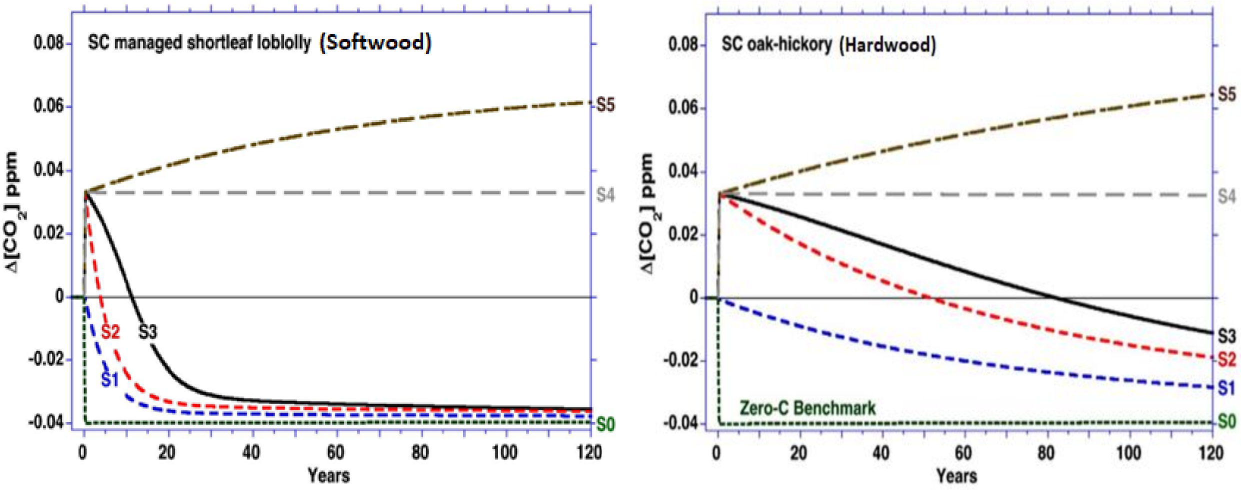

Figure 2.5: Change in atmospheric CO_2 concentration resulting from replacing coal with biomass to produce electricity. All the scenarios show the change in atmospheric $\Delta[CO_2]$. S0: Benchmark showing impact of 1 EJ of renewable energy S1: Bioenergy assumed to have the same combustion and processing efficiency as coal, and the same supply chain emissions; with 25% of biomass removed from the land harvested through thinning. S2: Actual efficiencies and supply chain emissions for wood pellets; 25% of biomass harvested through thinning. S3: S2 with 95% of biomass harvested (clear cut). S4: S3 with clear cut and no regrowth of harvested land and no C released from soil stocks. S5: S4 with C released from soil stocks at the estimated fractional rate (Adapted from Sterman et al., 2018).

Scenario 0 is a baseline that shows how atmospheric CO_2 levels would change if 1 EJ of end-use energy from coal was offset by a zero-carbon energy source like solar or wind. Displacement of 1 EJ of end-use energy from coal with a zero-carbon alternative retains 0.07 GtC of fossil carbon in the ground, lowering atmospheric CO_2 by about 0.04 ppm instantly and permanently compared to continued coal use.

Scenario 1 models a hypothetical scenario where bioenergy emits the same amount of carbon per EJ of end-use energy as coal, with the same combustion and processing efficiency and supply chain emissions. It is assumed that 25% of the biomass is removed from each hectare of the harvested forest by thinning, not clear-cutting. The forest is allowed to regrow with no subsequent harvest, fire, disease, or other disturbances. Because emissions are counterfactually assumed to be the same as coal, there is no immediate change in atmospheric CO_2. However, carbon is gradually removed from the atmosphere to biomass and soils as the forest grows back. After 100 years, the forest has regenerated sufficiently to reduce atmospheric CO_2 by 0.026 ppm, which is still 34% more than the zero-degree case.

Scenario 2 shows the realistic condition, with projected combustion efficiency and supply chain emissions for wood pellets, assuming thinning harvests 25% of the biomass. The initial impact of bioenergy use is increased atmospheric CO_2 because the production and combustion of wood produce more CO_2. Regrowth gradually transfers carbon from the atmosphere to biomass and soil C stocks, resulting in a 52-year carbon debt payback time; after 100 years, CO_2 levels are still 62% higher than in the zero-carbon case.

Scenario 3 is the same as Scenario 2, only that the land is cleared rather than thinned, and 95% of the biomass is harvested. The expanding practice of collecting enitre trees and residues results in near-complete biomass removal (branches, litter etc.). A 95% clear cut takes up 26% less land than S2, but the carbon debt payback time increases to 82 years; after 100 years, CO_2 remains 86% above the zero C case.

Scenario 4 shows the effects of assuming that the harvested area is clear cut as in S3 but never allowed to recover. The carbon flux from soils and dead organic matter to the atmosphere is set to zero. Without regrowth, the carbon debt will never be paid off, and CO_2 levels in the atmosphere will continue to rise indefinitely.

Scenario 5 is the same as Scenario 4, except that the flux of C to the atmosphere from soils and dead organic matter is included at the original fractional rate. There will be no CO_2 flux from the atmosphere to terrestrial biomass or soils if regrowth does not occur, but there will be continuing C flux from soils to the atmosphere, causing CO_2 concentrations to rise beyond the initial impact of bioenergy.

Biomass used to replace fossil fuels emits CO_2 into the atmosphere at the time of combustion and during harvest, processing, and transportation (Akhtari, Sowlati, Siller-Benitez, & Roeser, 2019; Jones & Albanito, 2020; Mohamed et al., 2021). The CO_2 emissions could get worse if biomass is randomly removed from a forest cover and converted the previously forested land to other uses instead of regenerating the forest (Baker et al., 2020).

In order to reduce emissions, sustainable forest management should be enforced to facilitate the existence of a healthy forest cover. Each region should have forest management plans that describe planned forest activities for specific periods and areas. The forest management practice should involve conducting resource inventories. The data produced should provide information about the composition of tree species in the forest, their age, and their structure (NRC, 2020). This information will allow planners to calculate the volume of wood that can be harvested sustainably. Also, the harvested land should be regenerated to ensure that carbon emitted during harvest, processing, and transportation is absorbed by plants. This practice should be stepped up to balance the emissions with the NPP levels, or even better, if the NPP levels exceed the emissions (Gyamfi, Ozturk, Bein, & Bekun, 2021; Y. Li et al., 2018; Sikkema, Proskurina, Banja, & Vakkilainen, 2021). Therefore, the successful implementation of sustainable forest management can potentially reduce CO_2 emissions that result from the bioelectricity process.

2.5.3.2 Limitations of Bioelectricity Studies

The research study carried out by Sterman et al. (2018) presented some phenomenal facts surrounding the employment of lignocellulosic biomass for electricity production. This study lays a foundation for research that is worth critical analysis (Sterman et al., 2018). Though most of the facts aired are relatable, some of the scenarios are unrealistic, making them less useful than those that reflect common practices. Table 2.3 highlights the limitations of some bioelectricity literature studies and comments.

Table 2.3: Comment on the limitations of bioelectricity studies by Stephen et al. (2018).

Limitation	**Comment**
Unclear forest type, age, and structure of the biomass	The forest management process should involve conducting forest inventories, and the data collected provide information about the forest type, age, and structure. This information will allow the planners to calculate the volume of wood to be harvested sustainably (Canada's Forest Annual Report, 2020) **(Objective 1)**.
Unrealistic harvesting time and deforestation	Softwood and hardwood plantations mature after 30 and 50 yrs., respectively. Therefore, it is reasonable to consider harvesting mature biomass to provide enough feedstock for the bioelectricity process. The study carried out by Sterman et al. (2018) hypothetically assumes sustainable deforestation of 25% and 95%, which are unrealistically high. Instead, the rate of deforestation should be calculated based on the amount of energy that can sustainably be sourced from biomass **(Objective 1)**.
Exclusive forest landscape	The whole forest landscape should be considered when analyzing the dynamics of the carbon flux. This will ensure that the carbon density and sequestration of the afforested land are taken into account **(Objective 2)**.
First impact of using biomass is a consequential increase in CO_2 emission	Although this is true, all the bioenergy scenarios display an immediate decrease in CO_2 concentration in the atmosphere. This is unrealistic, and one of the objectives of our study is to determine whether the initial increase is followed by a reduction in CO_2 concentration in the atmosphere, as claimed by many studies (Funk, Forsell, Gunn, & Burns, 2022) **(Objective 2)**.
Results not presented in climate variable such as temperature	Many studies, including Sterman et al. (2018), judge climate change based on the CO_2 concentration in the atmosphere. However, a more accurate way would be to present results in climate-specific variables, such as temperature **(Objective 2)**.

Lack of extensive study on the environmental impacts of bioelectricity process	The feasibility of the bioelectricity process should not only focus on the global warming potential but also the other environmental impacts, such as human respiratory effect, ecotoxicity, acidification etc. Therefore, there is a need for an extensive study on the environmental impacts of the bioelectricity process **(Objective 3)**.

In order to generate some factual results, realistic scenarios need to be constructed to address the identified lacks. Our study considers some common forest management practices and realistic assumptions, such as selective harvest of mature wood plantations, which takes into consideration the forest type, age, and structure. Also, the whole forest landscape (347 million ha) is considered to provide a more accurate estimate of the carbon density and carbon sequestration rate. Additionally, climate change is assessed based on both the CO_2 emissions and the resultant increase in the average temperatures.

Furthermore, the environmental impacts of the hypothetical bioelectricity process are assessed in detail by performing the life cycle assessment (LCA). This ensures some clarity related to the growing use of biomass for energy. The LCA study considers a variety of transportation distances to perform the sensitive analysis of the electricity production from biomass.

2.6 Life Cycle Assessment (LCA) of Bioelectricity Process

As the use of biomass for energy grows, doubts concerning bioenergy's efficacy as a way to reduce greenhouse gas (GHG) emissions and reliance on fossil fuels arise. The LCA approach can reveal these environmental and energy performances, but the results can vary even for seemingly equivalent bioenergy systems. Differences arise from various factors, including raw material type and management, conversion technologies, end-use technologies, system boundaries, and the energy system against which the bioenergy chain is evaluated (Wang, Zhang, Chang, & Pang, 2021).

There are two types of LCA: attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA). ALCA estimates a product's proportion of global environmental burdens, whereas CLCA estimates how the global environmental burdens are affected by the production and use of the product (Ekvall, 2019). The LCA performed in this study falls under the category of CLCA simply because the study examines the impact of biomass electricity on climate change. Table 2.4 presents a list of recent LCA studies on bioelectricity.

Table 2.4: Recent LCA studies on biomass energy.

Feedstock	**Case Study**	**Boundaries**	**LCA method**	**Country**	**Reference**
Forest waste	Electricity generation	Cradle-to-grave	IPCC	Sweden, 2018	(Porsö, Hammar, Nilsson, & Hansson, 2018)
Woody biomass (raw)	Electricity generation	Cradle-to-grave	CML	EU, 2019	(Yi et al., 2018)
Woody biomass (raw)	Medium or large-scale heat generation	Cradle-to-gate	IPCC	China, 2019	(Liu, Zhu, Zhou, & Peng, 2019)
Woody biomass (industrial waste)	Small-scale heat generation	Cradle-to-grave	ReCiPe	Portugal, 2019	(Quinteiro et al., 2019)
Agricultural waste	Pellet Production	Cradle-to-gate	Eco-indicator 99	Poland, 2019	(Żelazna et al., 2019)
Woody	Electricity generation	Cradle-to-gate	TRACI	Canada, 2015	(Cleary &

biomass (raw)					Caspersen, 2015)

2.6.1 Impact Assessment

The LCIA target the environmental impact of the bioelectricity process by considering the following impact categories: Global warming, respiratory effects, fossil fuel depletion, eutrophication, carcinogenics, acidification, ecotoxicity, smog, and non-carcinogenics (Briones-Hidrovo et al., 2021).

The environmental impact of a hypothetical bioelectricity process is assessed using TRACI 2.1 method. TRACI 2.1 is the only method developed using parameters consistent with the North American regions. However, the most widely used LCIA method is ReCiPe, followed by the Intergovernmental Panel on Climate Change (IPCC) assessment method, as seen in **Figure 2.6**. IPCC stands out for being the leading method for the climate change category (Barros, Salvador, Piekarski, de Francisco, & Freire, 2020). Both TRACI 2.1 and IPCC assess the global warming potential (GWP) over a 100-year time horizon (Boschiero, Cherubini, Nati, & Zerbe, 2016). Table 2.5 and Figure 2.6 present some of the commonly used impact assessment methods and the number of occurrences in the literature studies.

Table 2.5: Uses of various LCIA methods and locations.

Method	Use	Location	Reference
IPCC	-Studies climate change	Global	(Barros et al., 2020)
TRACI	-Midpoint-oriented method -Developed using input parameters consistent with US locations -Uses a 100- year time frame	United States Canada	(Martin-Gamboa, Marques, Freire, Arroja, & Dias, 2020)
ReCiPe	- Mainly to assess the impacts of primary energy sources (main non-renewable sources) -Improvement of Eco-indicator 99	Europe	(Martin-Gamboa et al., 2020)
VDI	- Mainly to assess the impacts of primary energy sources (main non-renewable sources)	Europe	(Martin-Gamboa et al., 2020)
CML	-Uses various impact categories such as eutrophication, ionization radiation, aquatic ecotoxicity, land use, and human toxicity	Europe	(Mohan, 2018)
IMPACT 2002+	-Method aggregates the intermediate impacts in four categories of impacts: Impact on human health, Impact on the ecosystem quality, Impact on climate change, and Impact on resource depletion	Europe	(Perilhon, Alkadee, Descombes, & Lacour, 2012)
ILCD	-Uses midpoint indicators for the assessment	Europe	(Sala, Pant, Hauschild, & Pennington, 2012)
Eco-indicator 99	-Uses three categories to evaluate the environmental impact of a product: ecosystem quality, depletion of non-renewable resources, and human health	Europe	(V. Singh, Dincer, & Rosen, 2018)

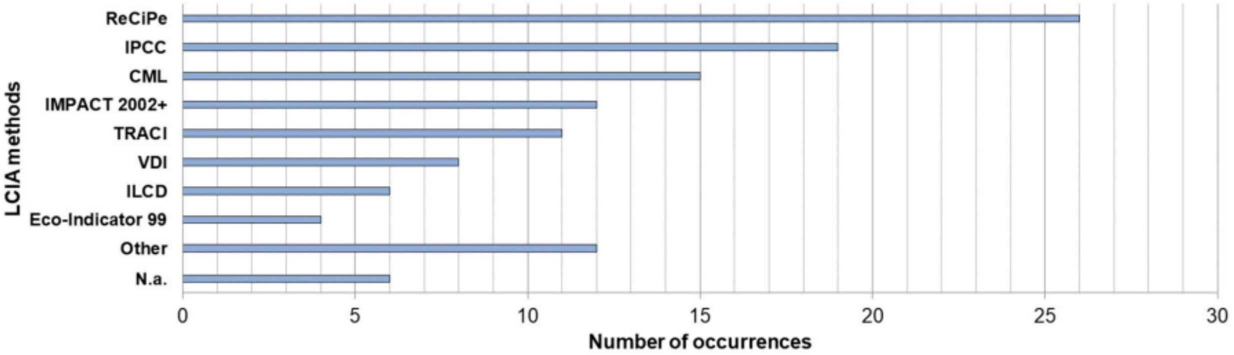

Figure 2.6: Common LCA methods.

Additionally, the research will investigate the global warming potential (GWP) of various energy sources including hydro, nuclear, solar, wind, natural gas, crude oil, coal, and biomass. The comparison will be based on the environmental consequences of producing 1 kWh of end-use electricity from each source. This research will provide a comprehensive understanding of the energy sector issues.

Chapter 3: Methodology

The methodology followed in this study are discussed below following the order of the objectives of the thesis.

3.1 Objective 1: Quantification of the carbon dioxide emissions

The first goal in this thesis study was to quantify and compare the CO_2 emissions produced by biomass and coal combustion. Literature data for carbon intensities, combustion and processing efficiencies, processing losses, and the CO_2 emissions incurred in the supply chain were compared for the two sources. The steps followed to address objective 1 are shown in Figure 3.1 below.

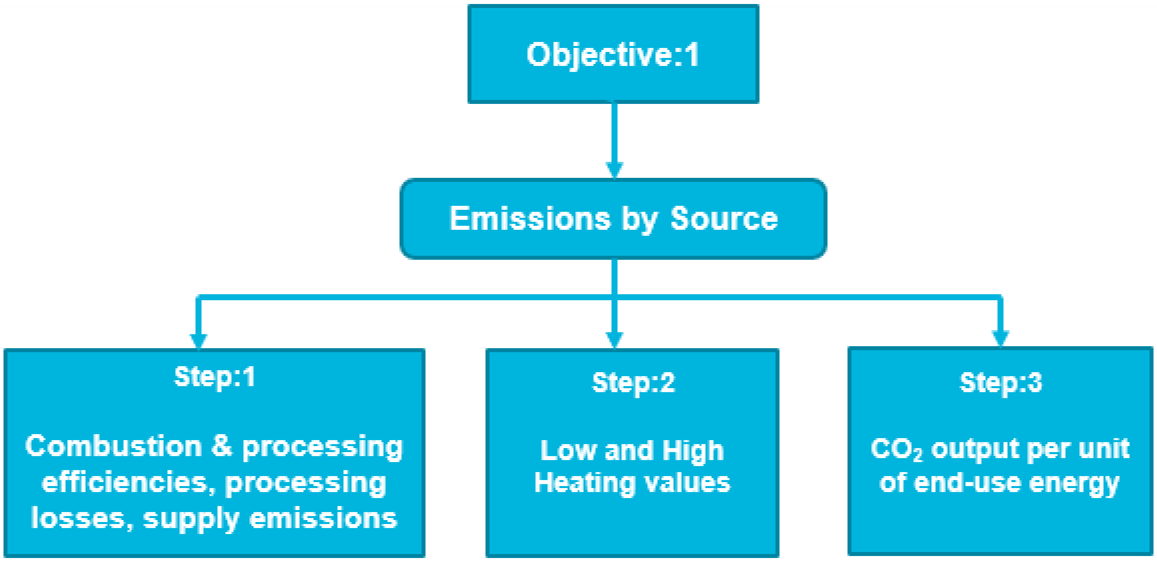

Figure 3.1: Steps followed to determine emissions from biomass and fossil fuels (objective 1).

3.1.1 Step 1: Combustion and processing efficiencies

This step involves comparing the combustion and processing efficiencies, carbon intensities, and carbon intensities of the supply chains for biomass and the conventional route for the production of electricity using fossil fuels. The reported literature results for the processing losses, combustion and processing efficiencies were compared in order to determine the suitability of using biomass or coal to generate electricity.

3.1.2 Step 2: Determination of resource amount and energy output

The heating values reported from the literature for the two energy sources are examined. The biomass's lower and higher heating values are reported to be 45% on an average for resources containing 20% moisture content (MC), respectively. The lower and higher heating values for coal are reported at 35.6% and 2.5% MC by weight. The comparison determines the source which gives more energy per kg of biomass or coal and the amount of the resource required per unit of energy.

3.1.3 Step 3: Carbon dioxide emissions per unit energy produced

The CO_2 output is quantified per gigajoule, GJ of the end-use energy from biomass and coal. The emissions from biomass combustion are calculated based on lower heating values (LHV), which signifies the worst-case scenario.

3.2 Objective 2: Dynamic analysis of carbon dioxide emissions

3.2.1 Software and Model Structure

The study uses En-ROADS, a climate simulation model consisting of a system of differential equations representing the carbon cycle, stocks of greenhouse gases (GHGs), radiative and heat balance of the Earth. With En-ROADS, one can explore dynamics in global energy supply, land use, transportation, carbon removal, and global mean surface temperature. This software was obtained from Dr. John Sterman, the director of the Massachusetts Institute of Technology (MIT) system dynamic group.

The software is extensively used to track the carbon cycle, which combines the stocks of carbon in fossil fuels, the atmosphere, terrestrial biomass and soils, and ocean bodies. The stocks include carbon flux from the atmosphere to biomass by net primary production. In contrast, the carbon in biomass returns to the atmosphere through litterfall and tree mortality. Carbon is also lost from both biomass and dead organic matter by fire. Additionally, carbon in the soil stock is transferred to the atmosphere through the activity of decomposers and other heterotrophs (Sterman et al., 2018).

3.2.2 Constant parameters used in these simulations

The simulation assumes typical combustion efficiencies for wood are approximately 25%, compared to 35% for coal (Sterman et al., 2018). Also, the processing losses (in energy content) for the wood pellet supply chain are on the order of approximately 27% if biomass is used in the drying process (Röder, Whittaker, & Thornley, 2015), compared to losses of roughly 11% for coal (IEA, 2020). These parameters are kept constant when performing simulations for either biomass or coal. The objective is addressed following the steps shown in Figure 3.2 below.

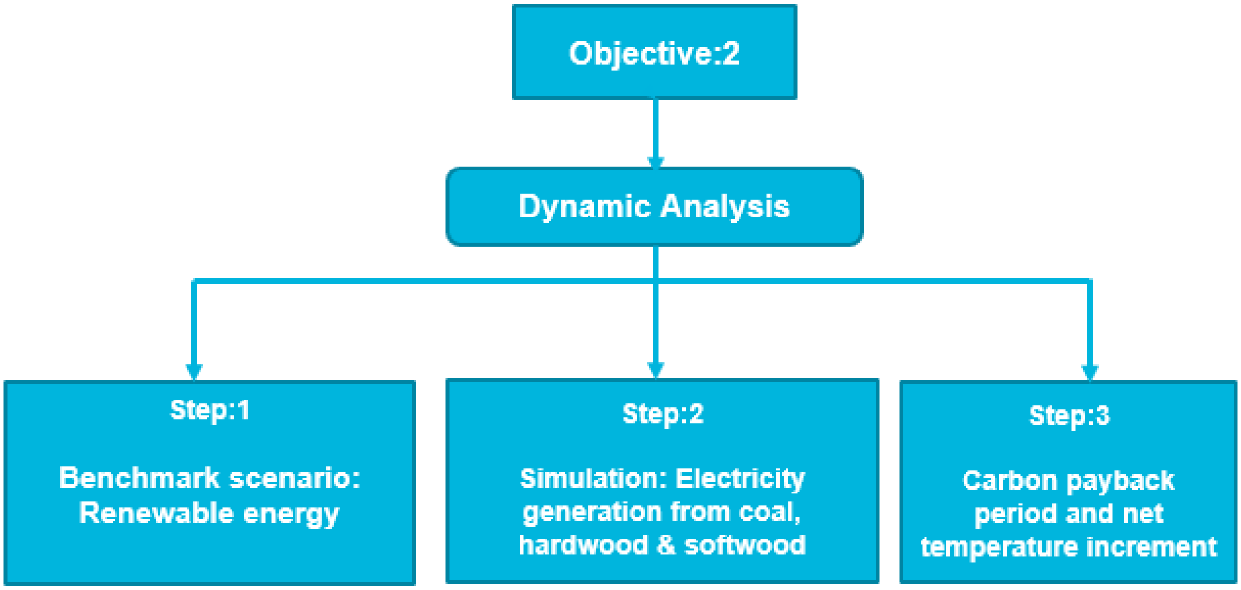

Figure 3.2: Steps followed for the dynamic analysis of electricity generation using biomass and coal (Objective 2).

3.2.3 Step 1: Electricity from Renewable Energy Sources

A benchmark scenario of producing electric power from renewable sources, including hydro, solar, geothermal etc. has been simulated. The result for this scenario was used as a reference when accessing alternative routes (biomass and coal route) for electricity. Table 3.1 shows the scenario parameters for generating electricity from renewable sources (zero-carbon energy).

Table 3.1: Scenario parameters for the generation of electricity from renewable sources.

Parameter	**Value/Level**	**Units**
Zero-carbon end-use energy	$\rho_C^B=\rho_{SC}^B=0$	tC/GJ
Renewable (tax/subsidy)	Highly subsidized	D'less
Renewable tax/subsidy start year	2021	D'less
Renewable tax/subsidy stop year	2100	D'less
Carbon Price	250	$/ton CO_2
Years to achieve initial carbon price	1	Yr.
Energy efficiency of new transport	Highly increased	D'less
Energy efficiency of new transport (start year,2021)	5, max.	%
Electrification of new transport-road and rail, air, and water	100	%
Energy efficiency of new building and industry	5, max.	%/yr.
Rate of building and retrofitting	20, max.	%/yr.
Deforestation	Highly reduced, -5	%
Methane and other gases (reduce/increase)	Highly reduced, -85	%
Afforestation · *Percent available land used for afforestation*	40	%/yr.
· *Time to secure land for afforestation*	1	Yr.
· *Afforestation planting time*	1	Yr.
Population-lowest growth, 2100	9.1	billion

Table 3.1: Scenario parameters for the generation of electricity from renewable sources (Continued).

Parameter	**Value/Level**	**Units**
Economic Growth · *Long-term economic growth*	0.5	%/yr.
· *Near-term economic growth (GDP per person)*	1.7	%/yr.
Level of Technology · *BECCS* · *Direct air capture* · *Mineralization* · *Agricultural soil carbon* · *Biochar*	Medium 50	%

3.2.4 Step 2: Electricity from hardwood, softwood, and coal

The scenario tests the feasibility of using coal to produce end-use electricity. Also, scenarios involving the utilization of the two types of biomass plantations (softwood & hardwood) are run. The comparison is made based on the intensity of CO_2 emissions and the carbon payback period. Tables 3.2, 3.3, and 3.4 show the scenario parameters used in the calculations to produce electricity from hardwood, softwood and coal, respectively.

Table 3.2: Scenario parameters for the hardwood species.

Parameter	**Value/Level**	**Units**
Hardwood	4,962	Mmt/yr.
Carbon intensity of the biofuel, ρ_C^B	0.027	tC/GJ
Carbon intensity of biomass supply chain, ρ_{SC}^B	0.0012	tC/GJ
Bioenergy (tax/subsidy)	Highly increased	D'less
Deforestation	3.57	%
Afforestation		
· *Percent available land used for afforestation*	40	%/yr.
· *Time to secure land for afforestation*	1	Yr.
· *Afforestation planting time*	50	Yrs.
Population-lowest growth, 2100	9.1	billion
Economic Growth		
· *Long-term economic growth*	0.5	%/yr.
· *Near-term economic growth (GDP per person)*	1.7	%/yr.
Level of Technology · *BECCS* · *Direct air capture* · *Mineralization* · *Agricultural soil carbon* · *Biochar*	Medium 50	%

Table 3.3: Scenario parameters for the softwood species.

Parameter	**Level**	**Units**
Softwood	4,956	Mmt/yr.
Carbon intensity of the biofuel, ρ_C^B	0.027	tC/GJ
Carbon intensity of biomass supply chain, ρ_{SC}^B	0.0012	tC/GJ
Bioenergy (tax/subsidy)	Highly increased	D’less
Deforestation	6.74	%
Afforestation		
· *Percent available land used for afforestation*	40	%/yr.
· *Time to secure land for afforestation*	1	Yr.
· *Afforestation planting time*	30	Yrs.
Population-lowest growth, 2100	9.1	billion
Economic Growth		
· *Long-term economic growth*	0.5	%/yr.
· *Near-term economic growth (GDP per person)*	1.7	%/yr.
Level of Technology		
· *BECCS*	Medium	
· *Direct air capture*	50	%
· *Mineralization*		
· *Agricultural soil carbon*		
· *Biochar*		

Table 3.4: Scenario parameters for coal.

Parameter	**Value/Level**	**Units**
Coal	3,570	Mmt/yr.
Carbon intensity of fossil fuel, ρ_C^F	0.025	tC/GJ
Carbon intensity of fossil fuel supply chain, ρ_{SC}^F	0.0015	tC/GJ
Coal (tax/subsidy)	40	$/tce
Coal tax subsidy start year	2021	D'less
Coal tax/subsidy stop year	2100	D'less
% Reduction in coal utilization start year	2021	D'less
Population	9.1	billion
Economic Growth · *Long-term economic growth(GD per person)*	0.5	%/yr.
· *Near-term economic growth (GDP per person)*	1.7	%/yr.
Level of Technology · *BECCS* · *Direct air capture* · *Mineralization* · *Agricultural soil carbon* · *Biochar*	Medium 50	%

3.2.5 Step 3: Determination of carbon payback period and temperature change

The CO_2 emissions from renewable sources, coal, hardwood, and softwood to produce end-use electricity are quantified, and their respective carbon payback periods are determined. The carbon payback period estimates the time it takes to offset the CO_2 emitted when a source is employed to produce electricity. In order to estimate the payback period, the difference between the total carbon flux from biomass and soil to the atmosphere and the Net Primary Production, NPP is determined. Sterman et al. (2018) reported that the carbon fluxes from biomass and soil are modelled using the land use model, whereas the NPP of a region is modelled using a variant of the Richards growth model (Richards, 1959). And based on the carbon sequestration rate of the biomass, the time it takes to absorb all the CO_2 emitted by biomass can then be determined. Additionally, the software uses the Intergovernmental Panel on Climate Change (IPCC) equation of temperature increase, which gives the temperature change when the CO_2 concentration increases to calculate the impact on climate change (Houghton et al., 2001).

3.3 Objective 3: Life Cycle Assessment (LCA) of Bioelectricity Process

The dynamic analysis carried out in the previous objective does not account for the biomass transportation to the pellet site and power plant and other related matters. Therefore, a Consequential Life Cycle Assessment (CLCA) is performed to account for the transportation distance as part of assessing the environmental impacts of producing bioelectricity from softwood biomass. The ecoinvent v3.8 database in openLCA software was used for this part of the work to develop the bioelectricity process.

Furthermore, the global warming potentials (GWPs) of various energy sources, including hydro, nuclear, solar, wind, natural gas, and crude oil, are investigated to understand their environmental consequences better. The comparison is based on the environmental impacts of producing 1 kWh of end-use electricity from each source. LCA is performed in the order shown in Figure 3.3 below.

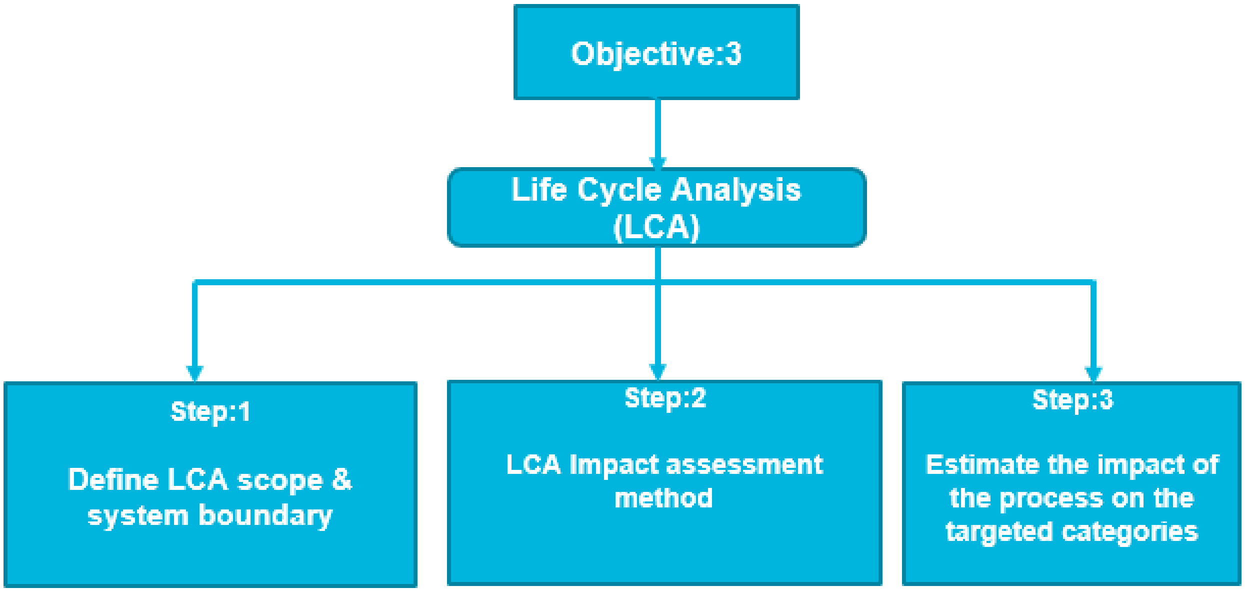

Figure 3.3: Steps followed for the Life Cycle Analysis (LCA) for electricity generation from biomass and coal (objective 3).

3.3.1 Step 1: LCA system description

3.3.1.1 Functional Unit for the LCA

The net GHG emissions and environmental impacts of the LCA scenario are assessed using a functional unit of 1 kilowatt-hour of electricity (kWh) generated at the combustion/gasification site.

3.3.1.2 System boundary and description

The study examines one hypothetical bioenergy chain based on the direct combustion of biomass to produce electricity. A reference system that uses coal to produce electricity is also considered for comparison purposes. The LCA system boundary is shown in Figure 3.4 below. The approach used here is a “cradle to gate” boundary conditions.

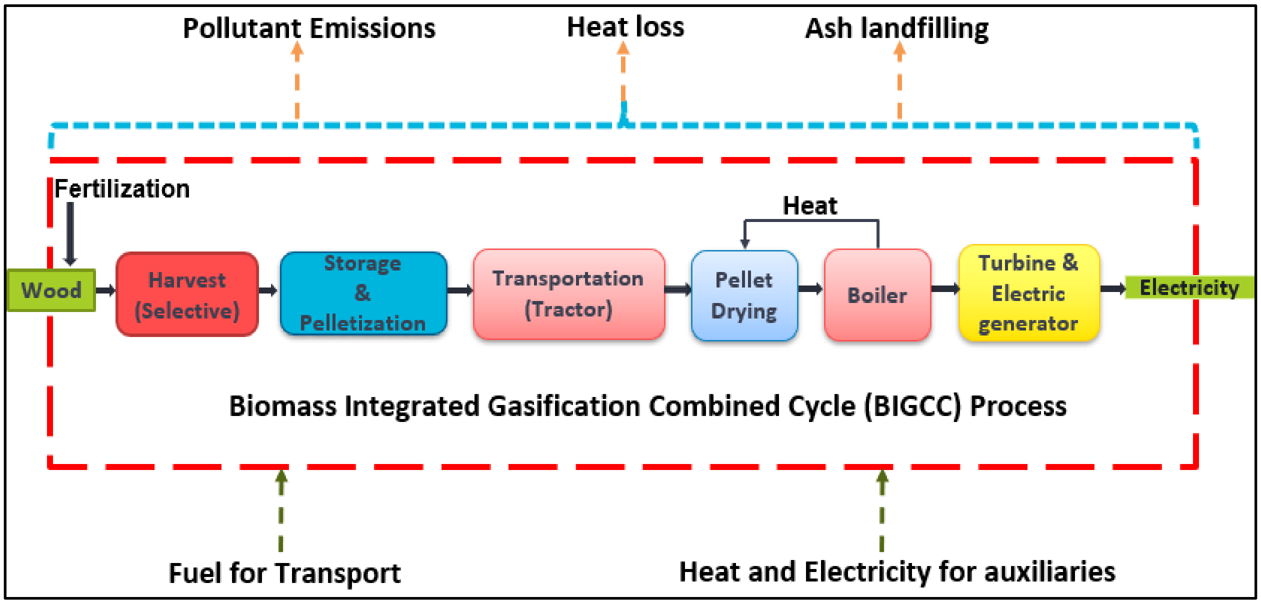

Figure 3.4: LCA system boundary.

3.3.1.2.1 Assumptions for the LCA

1. **Gasification technology** is chosen because it is considered the best available bio-CHP technology for small energy plants because of **high power-to-heating ratios and overall efficiencies.**
2. A **loss of 2%** during transportation and the stocking phase is considered.
3. The pellets are assumed to enter the power plant with an average **moisture content of 47%.**
4. The drying step before gasification decreases the **moisture content to around 20%.** Also, the heat overproduced during gasification is used for drying.
5. It is assumed that **15%** of the **wood inputs** are burned to supply heat to dry the remaining biomass (Cleary & Caspersen, 2015).

3.3.2 Step 2: LCA data inventory

The data reported by Natural Resource Canada (NRC) for the Canadian boreal forest and the data obtained from calculations performed in the second objective are used as LCA input data. In addition, literature data are used to complement the results for the dynamic analysis, and the Ecoinvent v3.8 database is used for the background process. The inputs inventories and the output flows for the LCA study are given in the appendixes section.

3.3.3 Step 3: Life Cycle Impact Assessment (LCIA)

The LCIA of the bioelectricity process is performed by considering the following impact categories: Global warming, respiratory effects, fossil fuel depletion, eutrophication, carcinogenics, acidification, ecotoxicity, smog, and non-carcinogenics. The study uses TRACI 2.1 method to perform the impact assessment (Barros et al., 2020; Martin-Gamboa et al., 2020). TRACI 2.1 utilizes the amount of the chemical emission or resource used and the estimated potency of the stressor. The estimated potency is based on the best available models and data for each impact category. For some impact categories (e.g., ozone depletion potentials, global warming potentials), there is international consensus on the relative potency of the chemicals listed. For other impact categories, the relative potency may depend on models related to chemical and physical principles and/or experimental data.

The location of the emission or resource employed is important to the effectiveness of the stressor in several impact categories, and the practitioner is advised to keep the location with each stressor. Individual stressors in these circumstances have a potency factor at each of the locations, rather than a single potency factor. The calculations should then be carried out at each location before being added together to determine the overall impact of the study. For instance, if the impact category (i) has a fate factor (F), and potency factor (P), then the site-specific analysis is calculated as follows

$$I^i = \sum_s \sum_x \sum_m F^i_{xms} \, P^i_{xms} M_{xms} \tag{1}$$

Where:

I^i = the potential impact of all chemicals (x) for a specific impact category of concern (i), F^i_{xms}= the fate of chemical (x) emitted to media (m) at site (s) for impact category (i), P^i_{xms} = the potency of chemical (x) emitted to media (m) at site (s) for impact category (i), M_{xms}= the mass of chemical (x) emitted to media (m) at site (s).

There are numerous occasions where the site-specific location is not used. For some effect categories, for example, location has little influence on fate, transit, or potency, hence only one characterization factor is presented for global use (e.g., global climate change, stratospheric ozone depletion). When the precise locations of emissions are unknown for a study, the more site-generic US average characterization variables may be applied. In this case, the generalized equation with respect to location would be:

$$I^i = \sum_{xm} CF^i_{xm} \times M_{xm} \tag{2}$$

Where:

I^i = the potential impact of all chemicals (x) for a specific impact category of concern (i), CF^i_{xm}= the characterization factor of chemical (x) emitted to media (m) for impact category (i), M_{xm}= the mass of chemical (x) emitted to media (m).

Chapter 4: Results and Discussions

4.1 Objective 1: Quantification of the carbon dioxide emissions

Our study aims to determine the feasibility of replacing coal with biomass to produce electricity. The use of lignocellulosic biomass as a source of energy should consider several factors, including the forest type, composition of tree species, age, structure, and the harvesting practice. This will ensure the right and mature plantation with a significant biomass yield is employed to generate energy. The lignocellulosic biomass yield varies from one species to the other, and since the risks of climate change limit the harvest of the forest cover, it would be appropriate to maximize the utilization of the plantation that gives a significant amount of biomass without increasing the net amount of GHG emissions.

CO_2 output of biomass was calculated based on producing 1 GJ of end-use energy. This was adopted in order to compare the final results with the literature values reported by Volker-Quaschning, 2022. The weight of biomass is given per cord, which is a unit used to measure the volume of wood. The total usable energy that can be obtained from biomass was calculated using the heating values (Higher and lower heating values). The higher heating value (HHV) gives the gross energy produced on complete combustion of biomass, whereas the lower heating value (LHV) is the energy obtained after energy losses used to vaporize water. The results for biomass's CO_2 emissions were calculated using the LHV in order to examine the maximum CO_2 output of wet wood from its natural setting.

The net usable energy from the combustion of softwood and hardwood species were computed at an assumed boiler efficiency of 90%, a typical boiler efficiency for the best bioenergy boilers (Vakkilainen, 2017). In addition, the average carbon contents were assumed to be 48.5% and 51.5% for the hardwood and softwood, respectively (Shao et al., 2022; William Strauss, 2012).

Based on the corresponding carbon contents of the wood species, the ultimate CO_2 output was calculated using the molecular mass ratio between caron and carbon dioxide (12 kg C/44 kg CO_2). Tables 4.1 and 4.2 below summarize the amount of biomass, the effect of the moisture content (MC), and the CO_2 output associated with the use of different plant species (softwood and hardwood) to produce a unit of end-use energy.

Table 4.1: Biomass and CO_2 emissions per unit of end-use energy for a variety of hardwood species.

Species	**Density** (kg/m^3)	**Weight** (kg/cord)	**Energy (at 20% MC)** (GJ/cord)	**Energy (at 45% MC)** (GJ/cord)	**HHV (at 20% MC-air dried)** (MJ/kg)	**HHV (at 45% MC-air dried)** (MJ/kg)	**CO_2 Output (LHV)** (kg/GJ)
Hardwood							
Hickory	815.3	1962	29.23	20.46	19.41	17.78	111.1
East Hophornbeam	804.1	1935	28.80	20.16	19.63	17.78	111.1
Beech	708.0	1704	25.32	17.72	19.54	17.75	111.3
Yellow Birch	695.2	1673	24.90	17.43	19.40	17.77	111.2
White Ash	695.2	1673	24.90	17.43	19.40	17.77	111.2

Table 4.2: Biomass and CO_2 emissions per unit of end-use energy for a variety of softwood species.

Species	**Density (kg/m^3)**	**Weight (kg/cord)**	**Energy (at 20% MC) (GJ/cord)**	**Energy (at 45% MC) (GJ/cord)**	**HHV (at 20% MC-air dried) (GJ/kg)**	**HHV (at 45% MC-air dried) (GJ/kg)**	**CO_2 Output (LHV) (kg/GJ)**
Softwood							
Jack Pine	502.9	1210	18.04	12.63	19.42	17.81	117.8
Hemlock	467.7	1125	16.78	11.74	19.42	17.81	117.8
Black Spruce	467.7	1125	16.78	11.74	19.42	17.81	117.8
White Pine	421.3	1014	15.09	10.56	19.40	17.77	118.1
Balsam Fir	421.3	1014	15.09	10.56	19.40	17.77	118.1

The data in Tables 4.1 and 4.2 show that there are significant differences in the densities between the hardwood and softwood species. Most hardwood species have higher lignocellulosic biomass compared to their softwood counterparts. However, the plant's maturity is an important factor that needs to be taken into consideration, as hardwood species take a longer time than softwood to reach their full potential. In contrast, softwood plantations consist of short rotational plants, which give significantly large amounts of biomass over a short period of time. Also, their rate of carbon sequestration is faster than in hardwood plantations. Thus, they are preferable species from which lignocellulosic biomass can be sourced (Kovacs, Haight, Moore, & Popp, 2021; Navarro-Cerrillo et al., 2022).

The other important factor that should be considered when using biomass for energy is the moisture content (MC) of the lignocellulosic biomass. As evident in Tables 4.1 and 4.2, the MC plays a significant role in determining the density and the heat content of a wood species. The amount of energy derived from a wood species depends on the moisture content of the biomass. Also, it is apparent that the energy content of different species at 20% MC is relatively higher than the energy output at 45% MC. This is because the presence of water hinders combustion and results in higher CO_2 emissions (Cesprini et al., 2020). The carbon intensity of biomass energy process provides the basis for considering such a process over the conventional fossil route. The need to quantify emissions resulting from the use of biomass for energy production has also to be considered.

Tables 4.1 and 4.2 show that the CO_2 emissions from softwood species are slightly higher than in hardwood. On average, the carbon content of the hardwood species is significantly lower than the softwood, hence resulting in slightly lower emissions when combusted. Although the softwood species are carbon-intensive, their rate of growth and sequestration is much faster than hardwood species (Lunguleasa, Dumitrascu, & Ciobanu, 2020). Sterman et al. (2018) reported that the carbon sequestration rate for softwood is usually high at the initial stages, then reaches the maximum at approximately 30 years, whereas hardwood plantation matures at roughly 50 years (Sterman et al., 2018). The benefit of accelerated sequestration is that it shortens the time it takes for the plant to grow and increases the carbon uptake from the atmosphere.

Furthermore, the transient state (the period before CO_2 emissions is sequestered) usually is substantially longer in hardwood species, which leads to the accumulation of CO_2 in the atmosphere, thus global warming (Bentsen, 2017). Replanting the forest plantation with a fast-growing species could help increase the net primary production (NPP). This is a promising technique of offsetting the carbon debt (IEA, 2020; IPCC, 2018). It needs to be stressed that the underlying point being made here is that detailed studies on the effect of harvesting biomass for energy generation must take into account the impact on carbon sequestration and thus carbon accumulation in the atmosphere.

When comparing the CO_2 emissions that result from biomass and coal combustion, there is no clear difference as the emissions are relatively similar. On average, hardwood and softwood at 45% MC emit 111.2 and 117.9 kg CO_2/GJ, respectively. The calculated biomass's CO_2 outputs agree with the literature value of 109.6 kg CO_2/GJ reported by Volker-Quaschning, (2022). On the other hand, the emissions from coal are estimated to be around 120.8 kg CO_2/GJ (William Strauss, 2012). Sterman et al. (2018) reports that the fundamental difference between wood and coal lies in the combustion efficiency and processing losses. First, even after drying, wood pellets have more moisture than coal. Drying pellets reduces moisture content and improves combustion efficiency but at the expense of lowering the processing efficiency because some biomass energy is used to provide heat for drying (Knutel, Gaze, Wojtko, Dębowski, & Bukowski, 2022; Paczkowski et al., 2021).

Second, the processing losses for wood are more than for coal. The losses for the wood result from biomass harvest, chipping, and during the transportation from the forest to the pellet mill and power plant. In contrast, coal processing losses arise from transportation losses, dust, and oxidation of coal stocks along the supply chain (IEA, 2020; Sterman et al., 2018). In order to determine the feasibility of using biomass or coal for energy production, a comprehensive dynamic analysis of all carbon fluxes needs to be done. Such analysis estimates the resultant increase in the CO_2 concentration in the atmosphere, the related temperature rise and the carbon payback period (the time it takes to offset the CO_2 emitted.

4.2 Objective 2: Dynamic analysis of carbon dioxide emissions

4.2.1 Effect of Carbon Capture and Storage (CCS) technologies

The second objective of this thesis was to investigate the carbon imbalances of the atmospheric carbon cycle. While analyzing the CO_2 emissions from renewable energy sources, biomass, and coal, the carbon capture and storage (CCS) technology was found to have a great impact on the dynamic of the carbon flux. Therefore, the level of CCS technology must be defined correctly to avoid errors in the final outcomes. The Global CCS Institute identifies Canada as one of the five nations (Australia, Norway, the United Kingdom, and the United States) that are leaders in creating an enabling environment for the commercial deployment of CCS. These five nations have taken significant steps to reduce CO_2 emissions by CCS (Ian Havercroft, 2018).

Global ambition aimed to avoid the worst effect of climate change was confirmed by enacting the Glasgow Agreement (Tobin & Barritt, 2021). The agreement seeks to keep global temperature increase from pre-industrial levels below 1.5°C, which will require rapid cuts in fossil fuel consumption (Sterman et al., 2018). To reach the Glasgow Agreement's goals, CCS will need to be deployed at an unprecedented rate, capturing, transporting, and storing between 0.2 and 6 billion tons of CO_2 per year (Ian Havercroft, 2018).

The efforts to remove carbon dioxide from the air with new technologies that enhance natural removals or manually sequester and store carbon. Carbon dioxide removal technologies include direct air capture, bioenergy with carbon capture and storage (BECCS), mineralization, agricultural soil carbon, and biochar. These are the commonly used techniques to reduce the concentration of carbon in the atmosphere, including the CO_2 emissions from bioenergy. The effect of different levels of technology was tested on the emissions that result from the combustion of biomass (softwood plantation) to produce 0.2 EJ of end-use electricity**,** and the results are shown in Figure 4.1.

As mentioned previously, En-ROADS software was used to perform the dynamic analysis of the carbon flows from biomass to the atmosphere. The land-use model determines the total carbon flux from biomass and soil to the atmosphere, and the NPP is modelled using the Richards growth model (Sterman et al., 2018). The net emission is the difference between the total carbon flux to the atmosphere and the NPP. In order to run the simulation, softwood plantation was used as the feedstock for the bioelectricity process, and the rate of deforestation to produce 0.2 EJ of electricity was calculated to be 6.74%. Other input parameters include biomass processing efficiency of 25%, biomass's carbon intensity of 0.027 tC/GJ, and the carbon intensity of biomass supply chain of 0.0012 tC/GJ (Bello Ould-Amer, Galán Martín, Feijoo Costa, Moreira Vilar, & Guillén Gosálbez, 2020; Röder et al., 2015). These constant parameters are literature-reported values consistent with bioenergy processes.

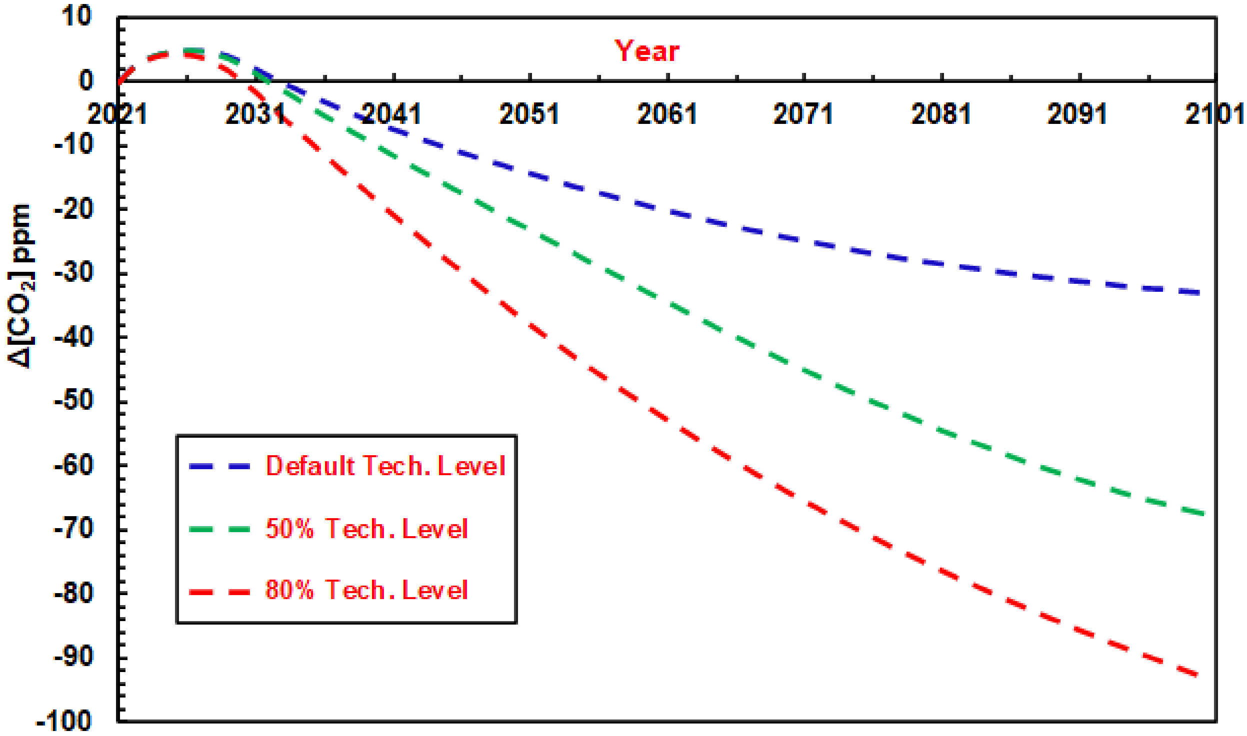

Figure 4.1: Effects of CCS technologies on the dynamic of the biomass (softwood plantation carbon level in the atmosphere).

From Figure 4.1, it is apparent that the advancement of CCS technologies significantly reduces the accumulation of CO_2 in the atmosphere. This is demonstrated by the decrease in the breakeven period as the level of technology advances from low (default Tech. Level) to high (80% Tech. Level). Therefore, the level of CCS technology is a critical factor when analyzing the consequential emissions from the use of biomass or coal for electricity production. This study adopted mid-level technology to perform dynamic analysis of carbon fluxes, although Canadian CCS technology is close to the upper quartile (Index score of 71) of the globally established CCS technologies (Ian Havercroft, 2018).

Furthermore, Canadian CCS projects sequester up to 6.4 million tons per annum (Mtpa) of CO_2 as part of the efforts to meet the objectives of the Glasgow agreement. This is a combined capacity of the four different projects, including the SaskPower Project in Saskatchewan, Quest in Alberta, Spectra's Fort Nelson in British Columbia, and the Alberta Carbon Trunk Line (ACTL) in Alberta. These projects play an important role in helping Canada meet its greenhouse gas (GHG) emissions reduction targets. Under the United Nations Framework Convention on Climate Change (UNFCCC), Canada agreed to reduce emissions to 30% below 2005 levels by 2030 (Doluweera, Hahn, Bergerson, & Pruckner, 2020; Drever et al., 2021).

4.2.2 Dynamic Analysis of the carbon fluxes

Figure 4.2 shows the results for a set of scenarios using parameters estimated for renewable energy sources, coal, and biomass (hardwood and softwood) using the En-ROADS climate simulator software. All scenarios examine a 0.2 EJ of end-use electric energy generated from renewable energy sources and wood pellets; offsetting 0.2 EJ of end-use electricity produced from coal.

Scenario 0 (S0) used renewable sources of energy, such as solar, wind and geothermal, to produce electricity. In this scenario, both the carbon intensity and supply chain emissions of biomass and coal were set to zero as it was assumed that all the electricity is produced from zero-carbon sources. Also, the rate of deforestation was reduced to its minimum level, and the government subsidy for this process was set to its maximum level. Additionally, the annual economic growth for all scenarios was set to 1.7%, which was Canada's pre-covid economic growth (Nam, 2019).

In our study lignocellulosic biomass from Canadian boreal forest was assumed to be the feedstock for the bioelectricity route. In scenario 1 (S1), the input parameters include 4956 million metric tons (Mmt) of softwood biomass per year, which represents a sustainable deforestation rate of 6.74% (calculated). Biomass processing efficiency of 25%, the carbon intensity of 0.027 tC/GJ, and the carbon intensity of biomass supply chain of 0.0012 tC/GJ from the literature were used to design the biomass route (Röder et al., 2015). Additionally, for all the biomass scenarios, the percent of available land used for afforestation was assumed to be 40%, which represents nearly the percentage of the land covered by forest in Canada (Miura, Amacher, Hofer, San-Miguel-Ayanz, & Thackway, 2015).

In scenario 2 (S2), hardwood plantation was assumed to be the source of biomass, and the amount to be harvested per year was calculated to be 4962 Mmt. This represents an annual deforestation rate of 3.57% (calculated). The literature values for the processing efficiency, carbon intensity, and the carbon intensity of the biomass supply chain were the same as in S1. Scenario 3 (S3) utilized coal (fossil source) as the energy source to produce 0.2 EJ of electricity. The input parameters include 3570 Mmt of coal, and a carbon tax of $40 per ton of carbon (tc) was considered (Fried, Novan, & Peterman, 2021; Jagers, Lachapelle, Martinsson, & Matti, 2021; Schaufele, 2018). The literature reported data for the processing efficiency of 35%, carbon intensity of 0.025 tC/GJ, and the fossil fuel supply chain emission of 0.0015 tC/GJ were used to run the simulation for this scenario (Sterman et al., 2018). The literature data were used since they are practical parameters for the conventional fossil fuels power plants. Figure 4.2 presents the results for the change in the atmospheric CO2 concentration when renewable energy sources, hardwood, softwood, and coal, are employed to produce 0.2 EJ of the end-use electricity.

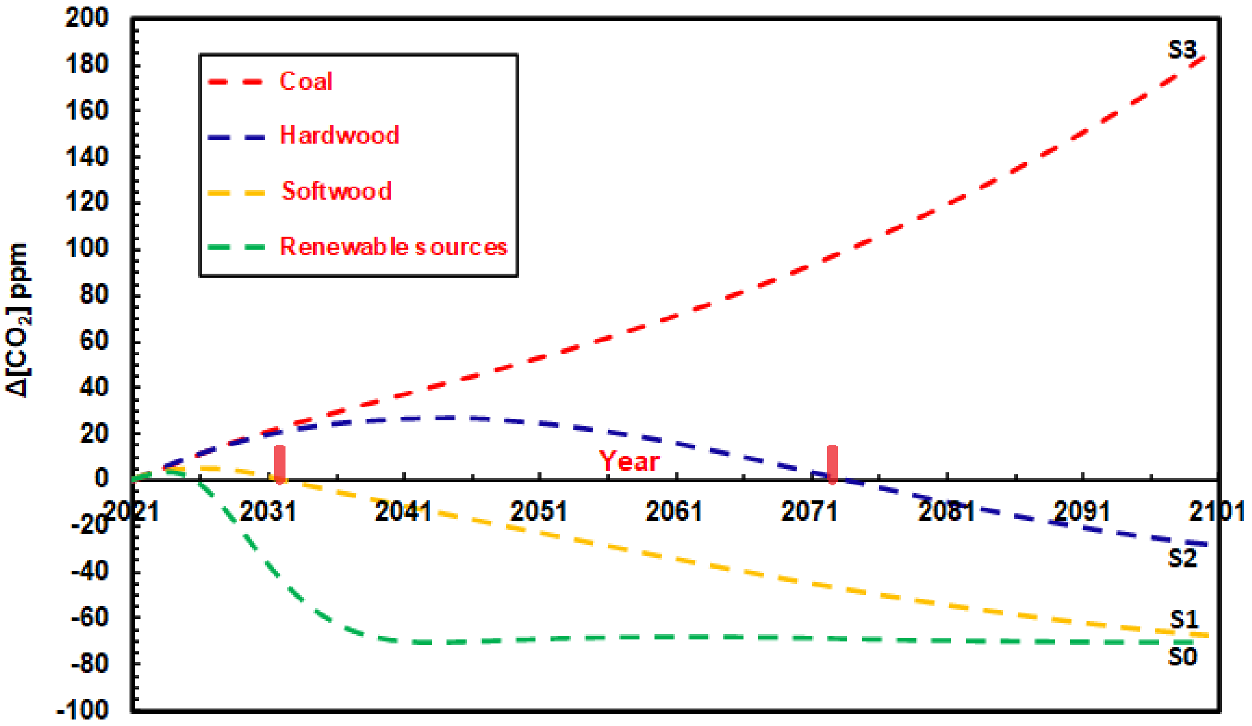

Figure 4.2: Change in atmospheric CO_2 concentration resulting from generation of 0.2 EJ of electricity from renewable sources (S0), softwood (S1), hardwood (S2), and coal (S3).

Scenario 0 presents a benchmark showing how atmospheric CO_2 levels would change if 0.2 EJ of end-use energy from coal was replaced with zero-carbon energy from solar, wind, or geothermal (and assuming zero emissions from the supply chain). Using a zero-carbon alternative to replace 0.2 EJ of end-use energy from coal preserves 75 GtC of fossil carbon in the ground, permanently lowering atmospheric CO_2 by about 70 ppm. These results agree with the literature findings reported by Sterman et al. (2018), where the use of renewable energy results in an immediate and permanent lowering of the atmospheric CO_2 concentration.

Scenario 1 shows a realistic case with projected combustion efficiency and supply chain emissions for softwood pellets, assuming a selective harvest of 6.74% of the softwood biomass. The initial impact of bioenergy use results in a 4.8 ppm increase in atmospheric CO_2 because the production and combustion of wood produce more CO_2. However, regrowth slowly transfers carbon from the atmosphere to biomass and soil carbon stocks, resulting in a carbon debt payback period of 11 years. Sterman et al. (2018) carried out a similar study and the resultant carbon payback period from the use of softwood plantation for electricity was determined to be 8 years. The disparity between these results can be reduced if our process is optimized. The optimization may involve the utilization of the jack pine, a softwood species that gives a large harvest for biomass. In addition, afforestation planting time and the amount is another optimization parameter that could further reduce the carbon debt payback period for the softwood species.

Scenario 2 is the same as S1 except that a hardwood plantation (sustainable deforestation of 3.57%) is employed to produce 0.2 EJ of end-use bioelectricity. As evident from Figure 4.2, the immediate impact of producing bioenergy from hardwood leads to an adverse increase in atmospheric carbon levels to around 26.6 ppm. However, replanting the forest helps alleviate the accumulation of carbon after a payback time of 53 years, which agrees with the literature value of 52 years reported by Sterman et al. (2018). The payback period is significantly higher than softwood plantations since hardwood species take a long time to mature, and the rate of carbon sequestration is very low at the early stages of growth.

Scenario 3 depicts a case with known combustion and supply chain emissions for coal. As noticeable in Figure 4.2, the impact of using fossil resources to produce 0.2 EJ of end-use electricity is a consequential accumulation of CO_2 in the atmosphere. Furthermore, the concentration of CO_2 keeps rising even after a decade and does not come to a breakeven point. Hence, the use of coal harms the environment, and it results in emissions that can never be repaid, thus causing climate change. This finding confirms the literature claims that the use of coal results in adverse environmental effects as the CO_2 emissions cannot be offset (Ravilious, 2020; Sterman et al., 2018).

As mentioned earlier, the combustion and processing efficiencies for wood in electricity production are lower than for coal. As a result, the initial impact of replacing coal with wood is an increase in the atmospheric CO_2 concentration. At this transient state, the atmospheric CO_2 levels are higher than they would have been if bioenergy had not been used, hence causing an increase in the global average temperatures and climate change (Sterman et al., 2018). However, this carbon debt is offset after regrowth, and the process could be enhanced further to reduce the payback period if the forest is replanted with a fast-growing softwood species. In addition, sustainable forest management should be enforced to ensure that forest is harvested and regenerated in a sustainable manner.

4.2.3 Temperature Change due to CO2 emissions

Figure 4.3 displays the resultant temperature increases under all scenarios. The climate simulator En-ROADS software was used to simulate the temperature changes related to the change in the atmospheric CO_2 concentration. The software uses the land use model and the Richards growth model to determine the net change in CO_2 concentration in the atmosphere. Subsequently, IPCC's equation of temperature increase is used to estimate the resultant change in temperature from the pre-industrial temperature level (1850-1900).

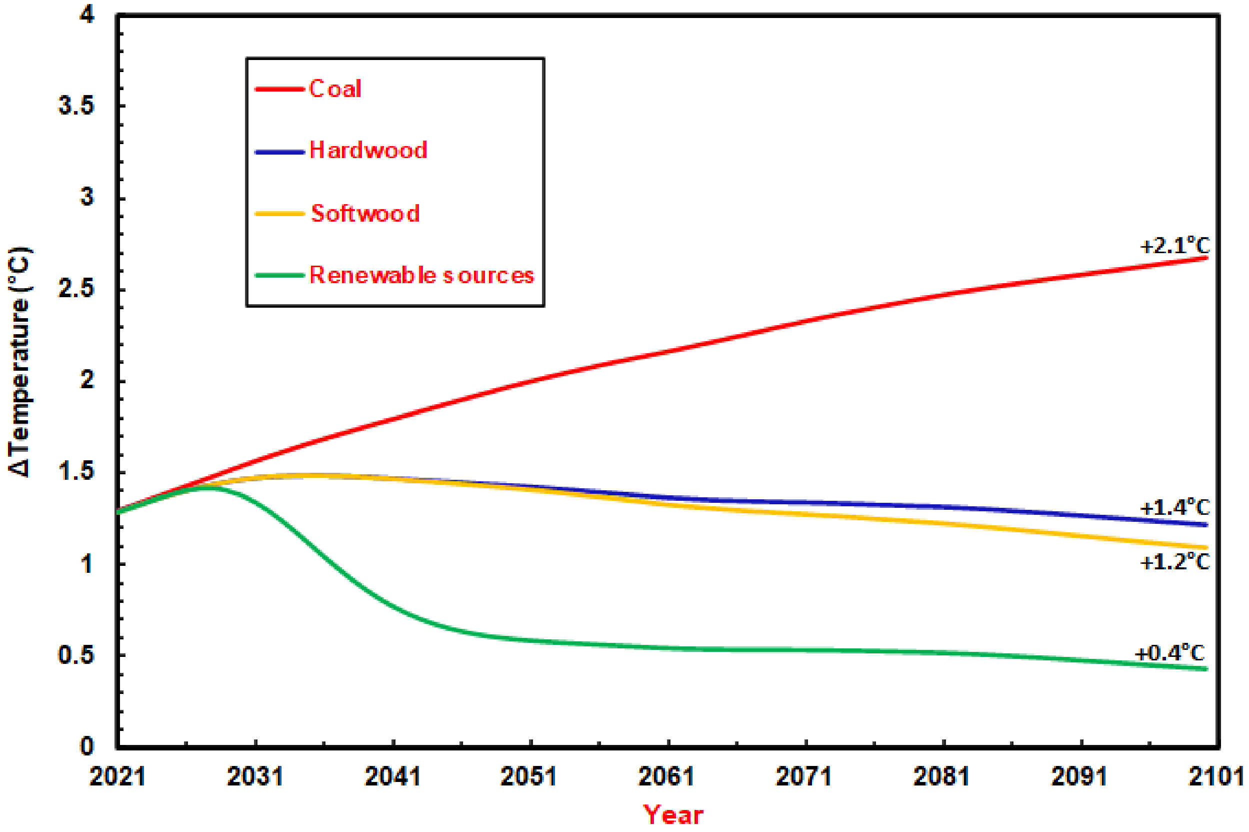

Figure 4.3: Temperature change due to CO_2 emissions.

As noticeable from Figure 4.3, the temperature rise averages 0.4°C when renewable sources, such as solar, wind, and geothermal, are used to produce electricity. Renewable sources would be the best sources to employ for electricity generation. However, the sustainability of some sources (wind and solar photovoltaic (PV)) have not yet been addressed (J. Ge, Shen, Zhao, & Lv, 2022; Mauree et al., 2019; WNA, 2021). The use of biomass results in an average temperature increase of 1.2°C and 1.4°C for softwood and hardwood, respectively. The use of coal results in a consequent temperature rise, which averages 2.1°C for the period studied. Saberali et al. (2022) reported that the rate of warming had been 0.18°C per decade since 1981 (Saberali, Shirmohammadi-Aliakbarkhani, & Nasrabadi, 2022). This implies that the average temperature rise in eight decades will be approximately 1.5°C, which falls within the range of global warming over the studied period through 2100.

Contrary to the Glasgow agreement, which set the average global temperature to 1.5°C above the pre-industrial level, the use of coal poses a risk of severe climate change as the average temperature increase exceeds the target. In contrast, biomass utilization for electricity seems to be a feasible process as far as climate change is concerned. The average temperature increases are well below 1.5°C, which is the IPCC average global warming temperature target. Therefore, substituting coal for wood, especially softwood, is a better route that reduces CO_2 emissions, thus limiting climate change.

4.3 Objective 3: Life Cycle Assessment (LCA) of Bioelectricity Process

4.3.1 Impact Assessment

This section determines the environmental performance of biomass-based combined heat and power (CHP) plant. The process is assumed to use gasification technology to produce 1 kWh of electricity. The environmental impact of a hypothetical bioelectricity process was performed using the ecoinvent v3.8 database in openLCA software and the impact was assessed using the TRACI 2.1 method. The method was adopted because it was developed using parameters consistent with the North American regions. Thus, it is popularly used in North American regions, including Canada. The following impact potentials were assessed according to the TRACI 2.1: fossil fuel depletion, carcinogenics, eutrophication, acidification, global warming, ozone depletion, respiratory effects, ecotoxicity, smog and non-carcinogenics.

The sensitivity analysis was performed to evaluate the impact of changing the wood pellet delivery distance. This ensures that the emissions involved in the process of transporting the biomass to the pellet facility and power plant are taken into account. The sensitivity analysis was carried out at different ranges of distances from 50 km to 2,000 km, and the results are reported in Table 4.3 below.

Our LCA study assumed softwood biomass to be the feedstock since it was found to be the most suitable wood species to use for electricity generation. The simulation also employs gasification technology to convert biomass into end-use electricity. The gasification technology is reported to be the best available bio-CHP for small energy plants due to high power-heating ratios and high efficiencies (Cleary & Caspersen, 2015).

Biomass transportation from the forest to the pellet site and power plant was assumed to be by road. A loss of 2% during the transportation is considered, and the pellets are assumed to enter the power plant at 47% MC. Before the pellets are combusted, the MC is decreased to 20% by drying, and 15% of the wood inputs are burned to supply heat to dry pellets (Naryanto et al., 2020; Oveisi et al., 2018; Situmorang, Zhao, Yoshida, Abudula, & Guan, 2020).

Table 4.3: Impact of 1 kWh of electricity from the forest biomass system (Calculated using TRACI 2.1).

	Impact Result					
Impact Category	**Units**	**50 km**	**100 km**	**200 km**	**500 km**	**2000 km**
Fossil fuel depletion	MJ surplus	7.60 x 10^{-2}	9.10 x 10^{-2}	1.21 x 10^{-1}	2.11 x 10^{-1}	6.60 x 10^{-1}
Carcinogenics	CTUh	1.34 x 10^{-8}	1.38 x 10^{-8}	1.47 x 10^{-8}	1.73 x 10^{-8}	3.02 x 10^{-8}
Eutrophication	kg Neq	1.50 x 10^{-4}	1.50 x 10^{-4}	1.70 x 10^{-4}	2.20 x 10^{-4}	4.80 x 10^{-4}
Acidification	kg SO2eq	1.12 x 10^{-3}	1.16 x 10^{-3}	1.25 x 10^{-3}	1.51 x 10^{-3}	2.80 x 10^{-3}
Global warming	kg CO2eq	4.83 x 10^{-2}	5.53 x 10^{-2}	6.94 x 10^{-2}	1.12 x 10^{-1}	3.22 x 10^{-1}
Ozone depletion	kg CFC-11eq	8.14 x 10^{-9}	9.81 x 10^{-9}	1.32 x 10^{-8}	2.32 x 10^{-8}	7.34 x 10^{-8}
Respiratory effects	kg PM2.5 eq	9.94 x 10^{-5}	1.00 x 10^{-4}	1.10 x 10^{-4}	1.50 x 10^{-4}	3.00 x 10^{-4}
Ecotoxicity	CTUe	9.83 x 10^{-1}	1.04 x 10^{0}	1.14 x 10^{0}	1.47 x 10^{0}	3.08 x 10^{0}
Smog	kg O3eq	2.48 x 10^{-2}	2.60 x 10^{-2}	2.83 x 10^{-2}	3.52 x 10^{-2}	6.98 x 10^{-2}
Non-carcinogenics	CTUh	2.24 x 10^{-7}	2.25 x 10^{-7}	2.29 x 10^{-7}	2.38 x 10^{-7}	2.86 x 10^{-7}

The results clearly show the impact categories (namely, fossil fuel depletion, carcinogenics, eutrophication, acidification, global warming, ozone depletion, respiratory effects, ecotoxicity, smog and non-carcinogenics) are substantially dependent on biomass procurement distance as the impacts increase as the transportation distance increases. Clearly et al. (2015) studied the LCA for a live Atikokan biomass power plant, and the outcome showed that the process was a net emitter of CO_2. The impact assessment was performed for a biomass delivery distance of 27 km, which was replicated in our study, and the result corroborated the literature findings. Based on these results, it is reasonable to conclude that the bioelectricity process contributes to CO_2 emissions, which could cause global warming. Therefore, plant managers must prioritize localized biomass sources to avoid the dangers of long-distance biomass distribution when planning biomass procurement strategies.

Nonetheless, the impact contributions at each stage of the bioenergy life cycle show that ensuring the pellets are perfectly dried to a lower MC before they are combusted, lowering emissions during gasification and producer gas combustion, and impacts from biomass processing would result in the biggest gains in environmental performance.

4.3.2 Emissions by Fuel type

Figure 4.4 shows the results for the global warming potential (GWP) for different fuel types. The analysis was carried out on the bases of producing 1 kWh of the end-use electricity from various energy sources (biomass, coal, natural gas, crude oil, hydro, geothermal, and wind). This part of the study used the ecoinvent v3.8 database in openLCA software to assess the environmental impact of using different energy sources to produce 0.2 EJ of end-use electricity. Also, GWP for both biomass and coal were studied at an assumed transportation distance of 100 km.

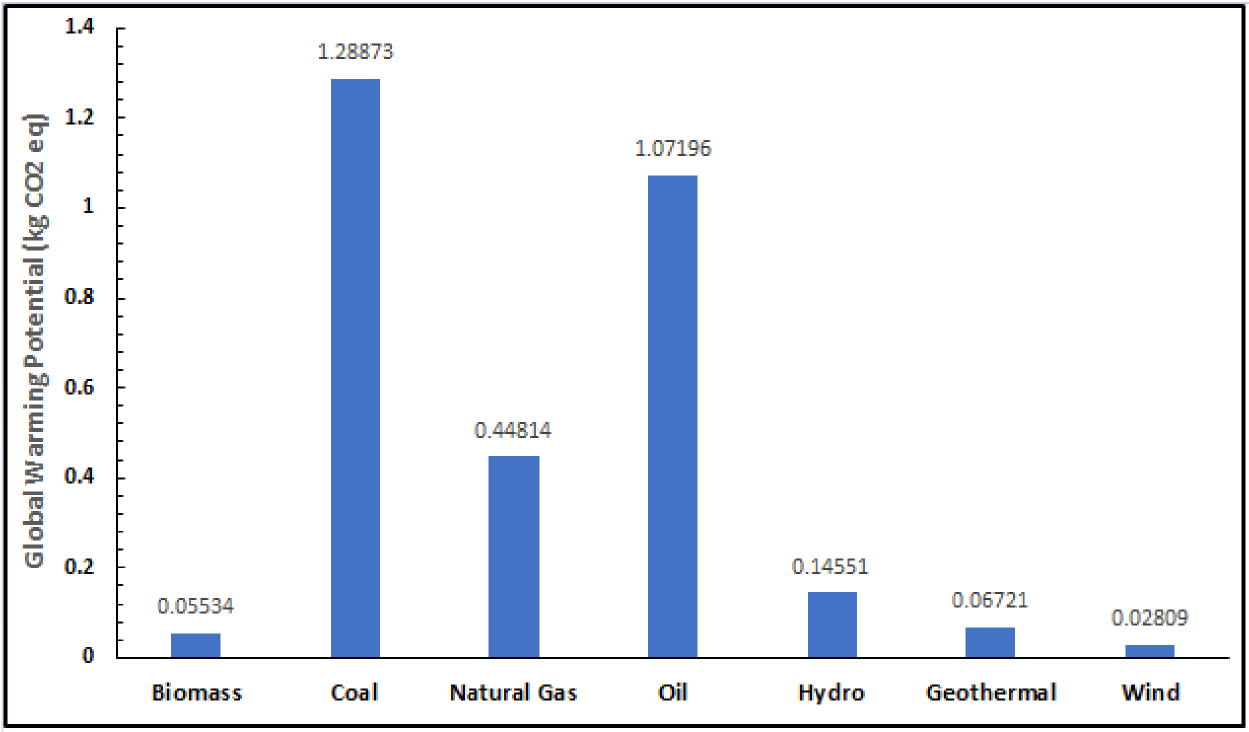

Figure 4.4: Global warming potential from various energy sources.

As evident in Figure 4.4, the coal-fired plant has the highest GHG emissions intensities on a lifecycle basis. Overall, fossil resources are the leading emitters, with coal having the highest emissions at 1.289 kg CO_2eq, followed by crude oil, which emits 1.072 kg CO_2eq, then natural gas with an emission amounting to 0.4881 kg CO_2eq. On the other hand, biomass emits around 0.055 kg CO_2eq when used to produce 1 kWh of end-use electricity. The results agree with the literature values for a similar study carried out by Clearly et al. (2018), where the emissions from coal were found to be 1.147 kg CO_2eq, and the emissions from biomass were determined to be approximately 0.040 kg CO_2eq.

Overall, hydro, geothermal, and wind were found to contribute to CO_2 emissions. However, their emissions were significantly low compared to fossil fuels. The emissions from these sources can also be attributed to fossil fuels because electricity generation systems consume fossil fuels directly and indirectly in the many activities of the whole energy chain (Ebhota & Tabakov, 2018; Kalair, Abas, Saleem, Kalair, & Khan, 2021; Rashad & Hammad, 2000).

Renewable and alternative energy sources are generally referred to as "clean" energy since they emit substantially less carbon dioxide than fossil fuels, although they have an environmental impact. Bioenergy production, for example, produces emissions that may have a negative influence on the environment: Moreso, the production of bioenergy conflicts with the acreage of food crops and the food supply chain. Therefore, the utilization of energy crops may remedy the loopholes since they do not compete with food or food-related crops, and they do not interfere with valuable resources such as forests or other timberlands (Malico, Pereira, Gonçalves, & Sousa, 2019; Situmorang et al., 2020).

Additionally, hydropower generation releases lower carbon emissions than fossil fuel. However, damming water to build reservoirs for hydropower floods valleys, disrupting local ecosystems and livelihoods (Flecker et al., 2022; Mayeda & Boyd, 2020; Moran, Lopez, Moore, Müller, & Hyndman, 2018). As mentioned earlier, the possibility of growing wind and solar photovoltaic (PV) use for power production requires consideration of their long-term viability (Dutta, Chanda, & Maity, 2022; Guaita-Pradas, Marques-Perez, Gallego, & Segura, 2019; Razmjoo et al., 2021). Nuclear energy has considerably lower lifecycle emissions than fossil fuel-based generation systems. It is reported that when averaging the results of different studies, nuclear energy's 30 tons CO_2eq/GWh emission intensity is found to be 7% that of natural gas and only 3% that of coal-fired power plant (Bersano, Segantin, Falcone, Panella, & Testoni, 2020). Other factors, such as safety, are also important when dealing with nuclear energy. A meltdown at a nuclear power plant is extremely unlikely, but the consequences would be disastrous if it happens. Concerns about the dangers of operating nuclear power facilities have actually limited nuclear energy expansion (Baron & Herzog, 2020; Buongiorno, Corradini, Parsons, & Petti, 2019;

Goswami, Rahman, & Chowdhury, 2022).

In conclusion, the use of renewable energy sources to generate electricity leads to less emissions than biomass and fossil sources, hence making them preferred sources to be employed to produce energy. However, issues related to sustainability and catastrophic accidents remain to be a problem. In order to satisfy energy needs, the utilization of biomass for electricity has proved to be a promising route that can reduce the carbon footprint. Therefore, an energy mix that combines biomass and renewable energy sources could provide an alternative way of limiting the CO_2 emissions resulting from the energy sector.

Chapter 5: Conclusions and recommendations for future work

5.1 Conclusions

Our study has proved that biomass use for electricity generation leads to emissions during harvest, processing, transportation, and combustion. Our dynamic analysis also revealed that the first impact of displacing coal with wood is an immediate increase in the CO_2 concentration in the atmosphere, which peaks at 4.8 ppm and 26.6 ppm for softwood and hardwood plantations, respectively. However, the carbon debt incurred is repaid if the harvested land is allowed to regrow. Our analysis found that it takes 11 years for the softwood to reach the breakeven point, whereas, for the hardwood counterpart, it takes 53 years to offset the CO_2 emitted.

Although the carbon debt is repaid, there are still chances of experiencing climate change because of the CO_2 accumulated before it is sequestered. This is evident as the average temperature increase associated with the use of softwood was determined to be 1.2°C and 1.4°C for the hardwood species. Though the resultant average temperature rise is below the average global warming target (1.5°C), there could still be a chance of registering high temperatures if the regrowth and harvest are not done sustainably. Therefore, sustainable forest management practices should be enforced to ensure no overlap in the atmospheric carbon cycle. In addition, plant managers must prioritize localized biomass sources when planning biomass procurement strategies to reduce CO_2 emissions that result from transportation.

The LCA results also indicated that the bioelectricity process is a net emitter of CO_2, and there is a need for caution when employing biomass for electricity generation. In order to limit emissions, softwood plantation is a preferred choice to use for bioelectricity because it grows faster, and the rate of carbon sequestration is very high at the early stages of growth. The softwood plantation matures faster than hardwood, which has a slow growth, and the carbon sequestration rate is quite low. Additionally, sustainable forestry entails that the biomass should be selected based on the forest type, age, and structure of the forest and selective harvesting is the most preferred method of harvesting biomass because it considers all the factors laid out by sustainable forestry.

The LCA analysis proved that renewable energy sources would be the most efficient to use for electricity. They have substantially low CO_2 emissions compared to their fossil fuels counterparts. However, there are a lot of challenges facing their implementation. For instance, biomass is a better alternative, but it poses a loophole of interfering with the food crops and food-related supply chain. The sustainability of using wind and solar for electricity are being addressed rapidly as they are much cleaner as they do not have any direct emissions. Nuclear energy seems to be a suitable alternative for electricity generation, but the dangers of nuclear waste disposal and exposure limits the expansion of nuclear power.

In conclusion, the use of biomass for electricity production is a better route than using coal. But it has to be done sustainably to avoid imbalances in the carbon cycle that may lead to the accumulation of CO_2 in the atmosphere. Conventional routes using fossil resources to generate electricity has the advantage of higher heating values but has no sequestration capacity leading to accumulation. This route can continue only if afforestation is stepped up to offset the CO_2 emissions resulting from power generation.

5.2 Future work

Our study has found that biomass could provide an alternative energy source that might help reduce CO_2 emissions. The emissions that result from the bioelectricity process could further be reduced if the process is optimized by employing jack pine to produce electricity, as it is the softwood species that renders substantial biomass. Optimization can be enhanced by increasing the afforestation and the level of Carbon Capture and Storage (CCS) technology to hasten the rate of carbon sequestration. This will ensure that the carbon payback period is shortened, thus reducing the accumulation of CO_2 in the atmosphere. Furthermore, there is a need to incorporate metabolic engineering to test the feasibility of the bioelectricity process. This can be conducted by adopting values predicted from the perspective of metabolic engineering as the possible biomass yield. Additionally, it is recommended to conduct the sensitivity analysis of the LCIA. The inclusion of these practices will tremendously improve the suitability of the bioelectricity process and eventually limit the risks of climate change.

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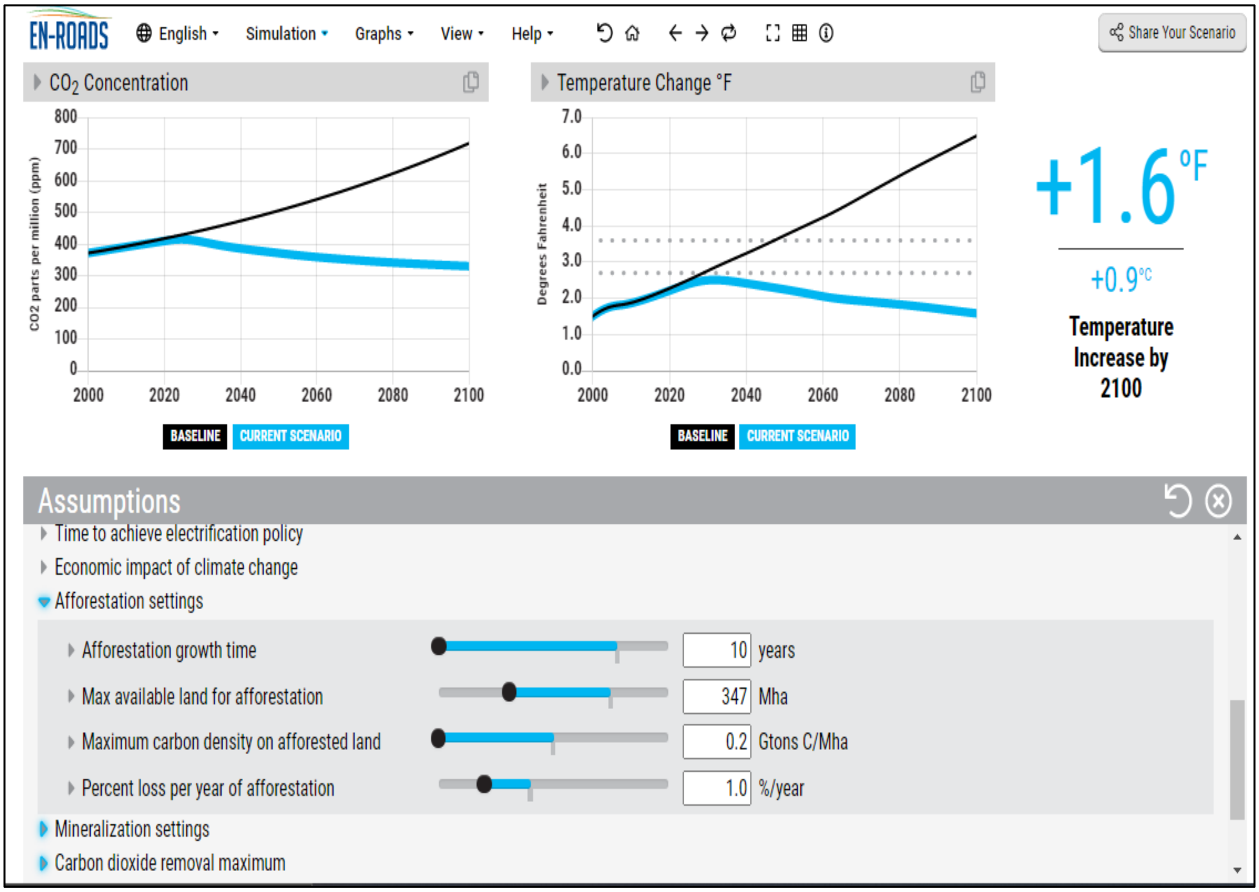
Appendix



Afforestation growth time 10 years

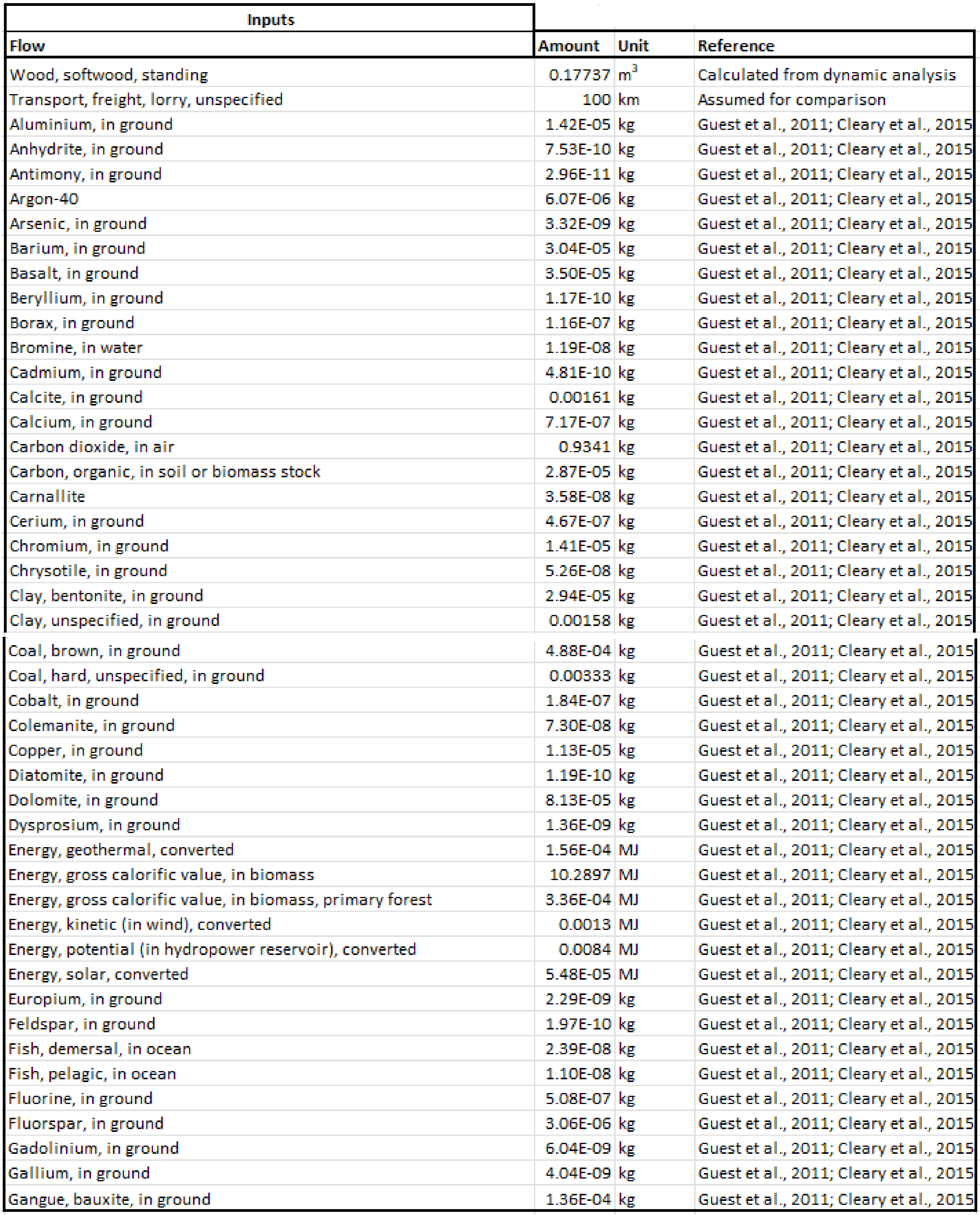
Max available land for afforestation 347 Mha

Maximum carbon density on afforested land 0.2 Gtons C/Mha

Percent loss per year of afforestation 1.0 %/year

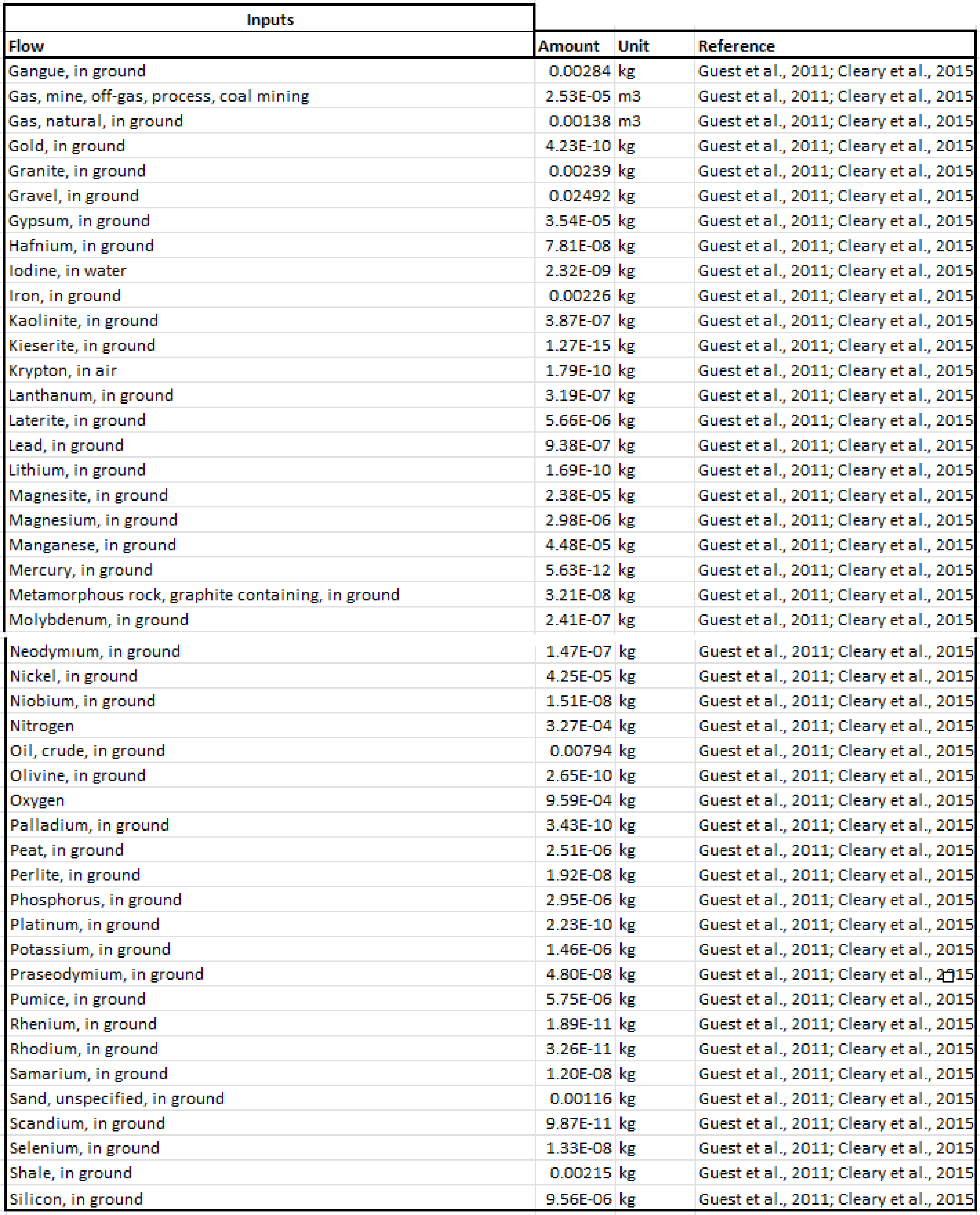
Figure A.1: En-ROADS software interface.

Table A.1: Inventories data used to model BIGCC plant.



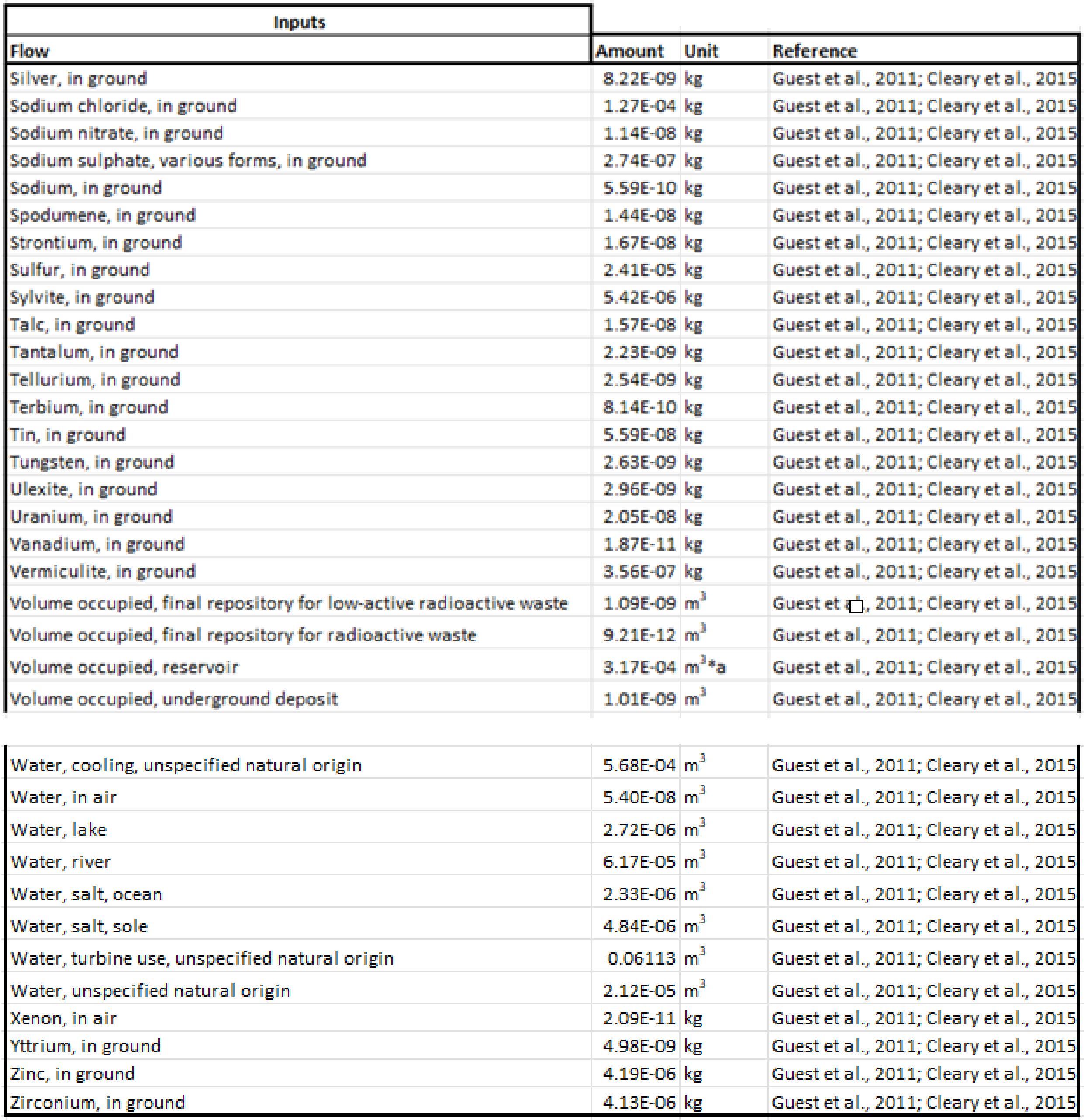
Inputs			
Flow	**Amount**	**Unit**	**Reference**
Wood, softwood, standing	0.17737	m^3	Calculated from dynamic analysis
Transport, freight, lorry, unspecified	100	km	Assumed for comparison
Aluminium, in ground	1.42E-05	kg	Guest et al., 2011; Cleary et al., 2015
Anhydrite, in ground	7.53E-10	kg	Guest et al., 2011; Cleary et al., 2015
Antimony, in ground	2.96E-11	kg	Guest et al., 2011; Cleary et al., 2015
Argon-40	6.07E-06	kg	Guest et al., 2011; Cleary et al., 2015
Arsenic, in ground	3.32E-09	kg	Guest et al., 2011; Cleary et al., 2015
Barium, in ground	3.04E-05	kg	Guest et al., 2011; Cleary et al., 2015
Basalt, in ground	3.50E-05	kg	Guest et al., 2011; Cleary et al., 2015
Beryllium, in ground	1.17E-10	kg	Guest et al., 2011; Cleary et al., 2015
Borax, in ground	1.16E-07	kg	Guest et al., 2011; Cleary et al., 2015
Bromine, in water	1.19E-08	kg	Guest et al., 2011; Cleary et al., 2015
Cadmium, in ground	4.81E-10	kg	Guest et al., 2011; Cleary et al., 2015
Calcite, in ground	0.00161	kg	Guest et al., 2011; Cleary et al., 2015
Calcium, in ground	7.17E-07	kg	Guest et al., 2011; Cleary et al., 2015
Carbon dioxide, in air	0.9341	kg	Guest et al., 2011; Cleary et al., 2015
Carbon, organic, in soil or biomass stock	2.87E-05	kg	Guest et al., 2011; Cleary et al., 2015
Carnallite	3.58E-08	kg	Guest et al., 2011; Cleary et al., 2015
Cerium, in ground	4.67E-07	kg	Guest et al., 2011; Cleary et al., 2015
Chromium, in ground	1.41E-05	kg	Guest et al., 2011; Cleary et al., 2015
Chrysotile, in ground	5.26E-08	kg	Guest et al., 2011; Cleary et al., 2015
Clay, bentonite, in ground	2.94E-05	kg	Guest et al., 2011; Cleary et al., 2015
Clay, unspecified, in ground	0.00158	kg	Guest et al., 2011; Cleary et al., 2015
Coal, brown, in ground	4.88E-04	kg	Guest et al., 2011; Cleary et al., 2015
Coal, hard, unspecified, in ground	0.00333	kg	Guest et al., 2011; Cleary et al., 2015
Cobalt, in ground	1.84E-07	kg	Guest et al., 2011; Cleary et al., 2015
Colemanite, in ground	7.30E-08	kg	Guest et al., 2011; Cleary et al., 2015
Copper, in ground	1.13E-05	kg	Guest et al., 2011; Cleary et al., 2015
Diatomite, in ground	1.19E-10	kg	Guest et al., 2011; Cleary et al., 2015
Dolomite, in ground	8.13E-05	kg	Guest et al., 2011; Cleary et al., 2015
Dysprosium, in ground	1.36E-09	kg	Guest et al., 2011; Cleary et al., 2015
Energy, geothermal, converted	1.56E-04	MJ	Guest et al., 2011; Cleary et al., 2015
Energy, gross calorific value, in biomass	10.2897	MJ	Guest et al., 2011; Cleary et al., 2015
Energy, gross calorific value, in biomass, primary forest	3.36E-04	MJ	Guest et al., 2011; Cleary et al., 2015
Energy, kinetic (in wind), converted	0.0013	MJ	Guest et al., 2011; Cleary et al., 2015
Energy, potential (in hydropower reservoir), converted	0.0084	MJ	Guest et al., 2011; Cleary et al., 2015
Energy, solar, converted	5.48E-05	MJ	Guest et al., 2011; Cleary et al., 2015
Europium, in ground	2.29E-09	kg	Guest et al., 2011; Cleary et al., 2015
Feldspar, in ground	1.97E-10	kg	Guest et al., 2011; Cleary et al., 2015
Fish, demersal, in ocean	2.39E-08	kg	Guest et al., 2011; Cleary et al., 2015
Fish, pelagic, in ocean	1.10E-08	kg	Guest et al., 2011; Cleary et al., 2015
Fluorine, in ground	5.08E-07	kg	Guest et al., 2011; Cleary et al., 2015
Fluorspar, in ground	3.06E-06	kg	Guest et al., 2011; Cleary et al., 2015
Gadolinium, in ground	6.04E-09	kg	Guest et al., 2011; Cleary et al., 2015
Gallium, in ground	4.04E-09	kg	Guest et al., 2011; Cleary et al., 2015
Gangue, bauxite, in ground	1.36E-04	kg	Guest et al., 2011; Cleary et al., 2015

Table A.1: Inventories data used to model BIGCC plant (Continued).



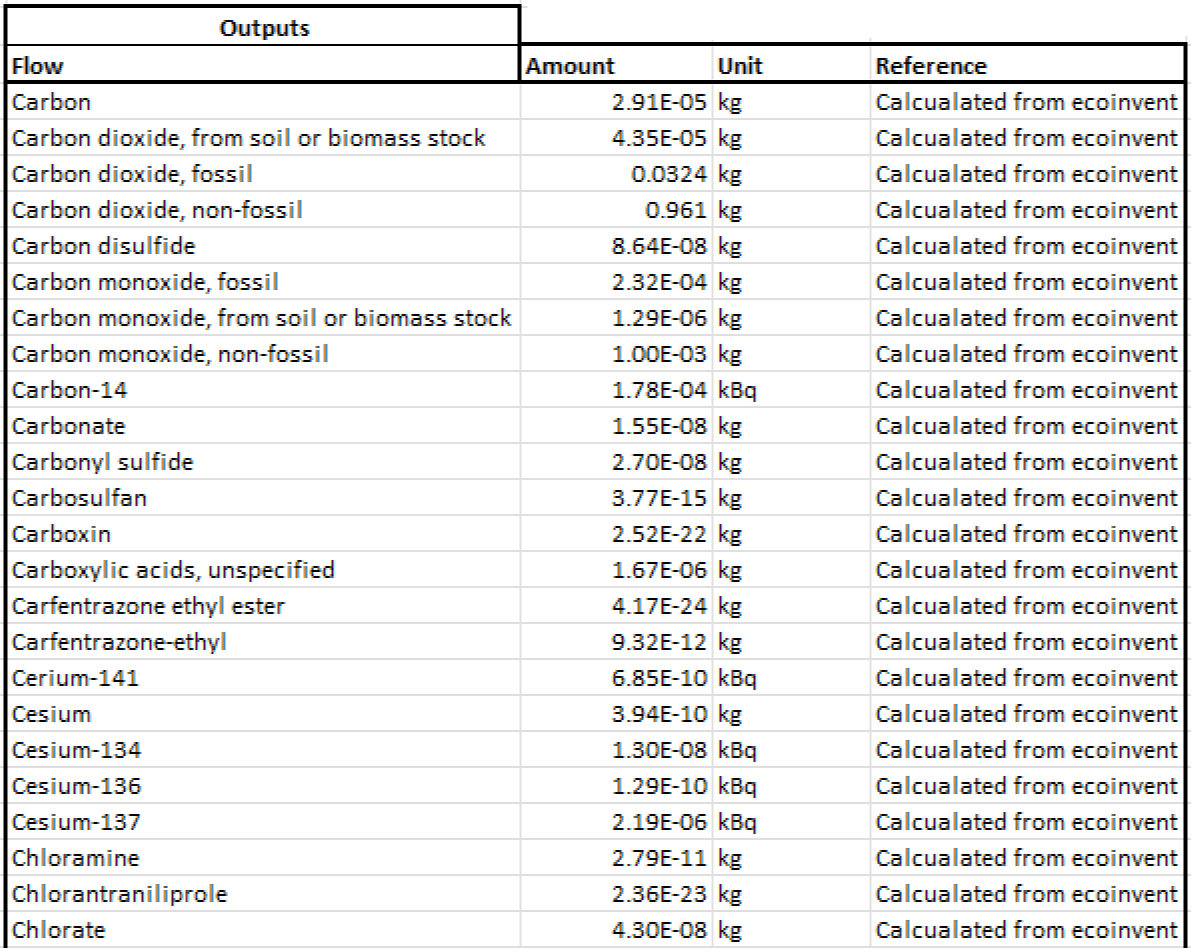
Inputs			
Flow	**Amount**	**Unit**	**Reference**
Gangue, in ground	0.00284	kg	Guest et al., 2011; Cleary et al., 2015
Gas, mine, off-gas, process, coal mining	2.53E-05	m3	Guest et al., 2011; Cleary et al., 2015
Gas, natural, in ground	0.00138	m3	Guest et al., 2011; Cleary et al., 2015
Gold, in ground	4.23E-10	kg	Guest et al., 2011; Cleary et al., 2015
Granite, in ground	0.00239	kg	Guest et al., 2011; Cleary et al., 2015
Gravel, in ground	0.02492	kg	Guest et al., 2011; Cleary et al., 2015
Gypsum, in ground	3.54E-05	kg	Guest et al., 2011; Cleary et al., 2015
Hafnium, in ground	7.81E-08	kg	Guest et al., 2011; Cleary et al., 2015
Iodine, in water	2.32E-09	kg	Guest et al., 2011; Cleary et al., 2015
Iron, in ground	0.00226	kg	Guest et al., 2011; Cleary et al., 2015
Kaolinite, in ground	3.87E-07	kg	Guest et al., 2011; Cleary et al., 2015
Kieserite, in ground	1.27E-15	kg	Guest et al., 2011; Cleary et al., 2015
Krypton, in air	1.79E-10	kg	Guest et al., 2011; Cleary et al., 2015
Lanthanum, in ground	3.19E-07	kg	Guest et al., 2011; Cleary et al., 2015
Laterite, in ground	5.66E-06	kg	Guest et al., 2011; Cleary et al., 2015
Lead, in ground	9.38E-07	kg	Guest et al., 2011; Cleary et al., 2015
Lithium, in ground	1.69E-10	kg	Guest et al., 2011; Cleary et al., 2015
Magnesite, in ground	2.38E-05	kg	Guest et al., 2011; Cleary et al., 2015
Magnesium, in ground	2.98E-06	kg	Guest et al., 2011; Cleary et al., 2015
Manganese, in ground	4.48E-05	kg	Guest et al., 2011; Cleary et al., 2015
Mercury, in ground	5.63E-12	kg	Guest et al., 2011; Cleary et al., 2015
Metamorphous rock, graphite containing, in ground	3.21E-08	kg	Guest et al., 2011; Cleary et al., 2015
Molybdenum, in ground	2.41E-07	kg	Guest et al., 2011; Cleary et al., 2015
Neodymium, in ground	1.47E-07	kg	Guest et al., 2011; Cleary et al., 2015
Nickel, in ground	4.25E-05	kg	Guest et al., 2011; Cleary et al., 2015
Niobium, in ground	1.51E-08	kg	Guest et al., 2011; Cleary et al., 2015
Nitrogen	3.27E-04	kg	Guest et al., 2011; Cleary et al., 2015
Oil, crude, in ground	0.00794	kg	Guest et al., 2011; Cleary et al., 2015
Olivine, in ground	2.65E-10	kg	Guest et al., 2011; Cleary et al., 2015
Oxygen	9.59E-04	kg	Guest et al., 2011; Cleary et al., 2015
Palladium, in ground	3.43E-10	kg	Guest et al., 2011; Cleary et al., 2015
Peat, in ground	2.51E-06	kg	Guest et al., 2011; Cleary et al., 2015
Perlite, in ground	1.92E-08	kg	Guest et al., 2011; Cleary et al., 2015
Phosphorus, in ground	2.95E-06	kg	Guest et al., 2011; Cleary et al., 2015
Platinum, in ground	2.23E-10	kg	Guest et al., 2011; Cleary et al., 2015
Potassium, in ground	1.46E-06	kg	Guest et al., 2011; Cleary et al., 2015
Praseodymium, in ground	4.80E-08	kg	Guest et al., 2011; Cleary et al., 2015
Pumice, in ground	5.75E-06	kg	Guest et al., 2011; Cleary et al., 2015
Rhenium, in ground	1.89E-11	kg	Guest et al., 2011; Cleary et al., 2015
Rhodium, in ground	3.26E-11	kg	Guest et al., 2011; Cleary et al., 2015
Samarium, in ground	1.20E-08	kg	Guest et al., 2011; Cleary et al., 2015
Sand, unspecified, in ground	0.00116	kg	Guest et al., 2011; Cleary et al., 2015
Scandium, in ground	9.87E-11	kg	Guest et al., 2011; Cleary et al., 2015
Selenium, in ground	1.33E-08	kg	Guest et al., 2011; Cleary et al., 2015
Shale, in ground	0.00215	kg	Guest et al., 2011; Cleary et al., 2015
Silicon, in ground	9.56E-06	kg	Guest et al., 2011; Cleary et al., 2015

Table A.1: Inventories data used to model BIGCC plant (Continued).



Inputs			
Flow	**Amount**	**Unit**	**Reference**
Silver, in ground	8.22E-09	kg	Guest et al., 2011; Cleary et al., 2015
Sodium chloride, in ground	1.27E-04	kg	Guest et al., 2011; Cleary et al., 2015
Sodium nitrate, in ground	1.14E-08	kg	Guest et al., 2011; Cleary et al., 2015
Sodium sulphate, various forms, in ground	2.74E-07	kg	Guest et al., 2011; Cleary et al., 2015
Sodium, in ground	5.59E-10	kg	Guest et al., 2011; Cleary et al., 2015
Spodumene, in ground	1.44E-08	kg	Guest et al., 2011; Cleary et al., 2015
Strontium, in ground	1.67E-08	kg	Guest et al., 2011; Cleary et al., 2015
Sulfur, in ground	2.41E-05	kg	Guest et al., 2011; Cleary et al., 2015
Sylvite, in ground	5.42E-06	kg	Guest et al., 2011; Cleary et al., 2015
Talc, in ground	1.57E-08	kg	Guest et al., 2011; Cleary et al., 2015
Tantalum, in ground	2.23E-09	kg	Guest et al., 2011; Cleary et al., 2015
Tellurium, in ground	2.54E-09	kg	Guest et al., 2011; Cleary et al., 2015
Terbium, in ground	8.14E-10	kg	Guest et al., 2011; Cleary et al., 2015
Tin, in ground	5.59E-08	kg	Guest et al., 2011; Cleary et al., 2015
Tungsten, in ground	2.63E-09	kg	Guest et al., 2011; Cleary et al., 2015
Ulexite, in ground	2.96E-09	kg	Guest et al., 2011; Cleary et al., 2015
Uranium, in ground	2.05E-08	kg	Guest et al., 2011; Cleary et al., 2015
Vanadium, in ground	1.87E-11	kg	Guest et al., 2011; Cleary et al., 2015
Vermiculite, in ground	3.56E-07	kg	Guest et al., 2011; Cleary et al., 2015
Volume occupied, final repository for low-active radioactive waste	1.09E-09	m^3	Guest et al., 2011; Cleary et al., 2015
Volume occupied, final repository for radioactive waste	9.21E-12	m^3	Guest et al., 2011; Cleary et al., 2015
Volume occupied, reservoir	3.17E-04	m^3*a	Guest et al., 2011; Cleary et al., 2015
Volume occupied, underground deposit	1.01E-09	m^3	Guest et al., 2011; Cleary et al., 2015
Water, cooling, unspecified natural origin	5.68E-04	m^3	Guest et al., 2011; Cleary et al., 2015
Water, in air	5.40E-08	m^3	Guest et al., 2011; Cleary et al., 2015
Water, lake	2.72E-06	m^3	Guest et al., 2011; Cleary et al., 2015
Water, river	6.17E-05	m^3	Guest et al., 2011; Cleary et al., 2015
Water, salt, ocean	2.33E-06	m^3	Guest et al., 2011; Cleary et al., 2015
Water, salt, sole	4.84E-06	m^3	Guest et al., 2011; Cleary et al., 2015
Water, turbine use, unspecified natural origin	0.06113	m^3	Guest et al., 2011; Cleary et al., 2015
Water, unspecified natural origin	2.12E-05	m^3	Guest et al., 2011; Cleary et al., 2015
Xenon, in air	2.09E-11	kg	Guest et al., 2011; Cleary et al., 2015
Yttrium, in ground	4.98E-09	kg	Guest et al., 2011; Cleary et al., 2015
Zinc, in ground	4.19E-06	kg	Guest et al., 2011; Cleary et al., 2015
Zirconium, in ground	4.13E-06	kg	Guest et al., 2011; Cleary et al., 2015

Table A.2: Outputs for the bioelectricity process.



Outputs			
Flow	**Amount**	**Unit**	**Reference**
Carbon	2.91E-05	kg	Calcualated from ecoinvent
Carbon dioxide, from soil or biomass stock	4.35E-05	kg	Calcualated from ecoinvent
Carbon dioxide, fossil	0.0324	kg	Calcualated from ecoinvent
Carbon dioxide, non-fossil	0.961	kg	Calcualated from ecoinvent
Carbon disulfide	8.64E-08	kg	Calcualated from ecoinvent
Carbon monoxide, fossil	2.32E-04	kg	Calcualated from ecoinvent
Carbon monoxide, from soil or biomass stock	1.29E-06	kg	Calcualated from ecoinvent
Carbon monoxide, non-fossil	1.00E-03	kg	Calcualated from ecoinvent
Carbon-14	1.78E-04	kBq	Calcualated from ecoinvent
Carbonate	1.55E-08	kg	Calcualated from ecoinvent
Carbonyl sulfide	2.70E-08	kg	Calcualated from ecoinvent
Carbosulfan	3.77E-15	kg	Calcualated from ecoinvent
Carboxin	2.52E-22	kg	Calcualated from ecoinvent
Carboxylic acids, unspecified	1.67E-06	kg	Calcualated from ecoinvent
Carfentrazone ethyl ester	4.17E-24	kg	Calcualated from ecoinvent
Carfentrazone-ethyl	9.32E-12	kg	Calcualated from ecoinvent
Cerium-141	6.85E-10	kBq	Calcualated from ecoinvent
Cesium	3.94E-10	kg	Calcualated from ecoinvent
Cesium-134	1.30E-08	kBq	Calcualated from ecoinvent
Cesium-136	1.29E-10	kBq	Calcualated from ecoinvent
Cesium-137	2.19E-06	kBq	Calcualated from ecoinvent
Chloramine	2.79E-11	kg	Calcualated from ecoinvent
Chlorantraniliprole	2.36E-23	kg	Calcualated from ecoinvent
Chlorate	4.30E-08	kg	Calcualated from ecoinvent