Techno-economic and environmental assessment of microwave-assisted catalytic pyrolysis

of biomass

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Abstract

The conversion of abundant under-utilized forest residues into biofuels is a promising strategy for transitioning the energy structure and for decarbonizing the transportation sector. As one of the emerging thermo-chemical conversion technologies, microwave-assisted catalytic pyrolysis (MACP) is able to efficiently convert solid biomass into valuable products, including bio-oil (~36 wt%), biochar (~28 wt%) and non-condensable gas (NCG) (~36 wt%). As well as resolving technical obstacles, MACP was also assessed for its economic and environmental impact, at a systematic level, for the purpose of commercialization. The work described in this study involved a techno-economic assessment (TEA) and a life cycle assessment (LCA) based on process integration. This was used to evaluate the economic feasibility and environmental impact of a hypothetical MACP system for the co-production of biofuel and biochar from forest residues in British Columbia (BC). The minimum selling price (MSP) of MACP biofuel was shown to be \$1.01/L, indicating that MACP biofuel was still not priced competitively to petroleum fuels. The on-site utilization of NCG and integration of an upgrading process helped achieve self-sufficiency in heat and hydrogen supply, but raised concerns about high capital costs. Sensitivity analysis suggested that future research efforts should focus on improving the process performance and reducing the capital investment to bring down the MSP. However, LCA results suggested that an MACP system could potentially make a considerable contribution to reducing greenhouse gas (GHG) emissions of transportation fuels. The cradle-to-gate (CTG) carbon intensity (CI) of MACP biofuel was shown to be -57.6 g CO₂-eq/MJ, indicating that a carbon-negative system could be achieved with a GHG emission reduction of 162% compared to petroleum fuels. The key reasons were the green electricity mix and carbon sequestration of co-product biochar. The dominant iii

influence was shown to be biomass-to-biofuel conversion step which accounted for 47.3% of the GHG emissions produced. Besides, the conversion efficiencies and location specific parameters also had significant impacts on the CI of MACP derived biofuels.

Lay Summary

Although British Columbia (BC) is rich in forest resources, the abundant residues derived from logging operations, which have no merchantable value, are regarded as wildfire risks. However, this "problem" could be turned into an "opportunity", by converting forest residues to biofuels which would avoid direct emissions from otherwise possible forest fires, while helping decarbonize the transportation sector.

Microwave-assisted catalytic pyrolysis (MACP) is an efficient thermo-chemical conversion technology that can be used to convert the solid biomass into valuable products (liquid, solid and gas). Science recent research has been focused on resolving technical obstacles, there has been little work on assessing its economic and environmental impacts at the systematic level for the purpose of commercialization. This study performed the first integrated economic and environmental assessment of the MACP system to reveal its economic and environmental benefits and to provide insights for future research as well as investment.

Preface

The study presented in this dissertation is an original work completed by the author, Hui Zhu under the supervision of Prof. Xiaotao Bi and Prof. Jack Saddler. The author, Hui Zhu contributed to the literature review, research proposal, data collection, model development, results analyses and thesis writing, with suggestions from the two co-supervisors.

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Table of Contents

Abstrac	et	iii
Lay Sur	mmary	v
Preface		vi
Table of	f Contents	vii
List of 7	Гables	X
List of I	Figures	xii
List of S	Symbols	xiv
List of A	Abbreviations	XV
Acknow	vledgements	, xviii
Dedicat	ion	xix
Chapter	r 1 Introduction	1
1.1	Background	1
1.2	Microwave-assisted catalytic pyrolysis (MACP)	2
1.3	Economic and environmental assessment of MACP	4
1.3	.1 Techno-economic assessment (TEA) of MACP	4
1.3	.2 Life cycle assessment (LCA) of MACP	8
1.4	Research question and objectives	10
1.5	Structure of thesis	11
Chapter	r 2 Process Description of MACP System	13
2.1	Feedstock collection	15
2.2	Feedstock transportation	15
		vii

2.3 Co	nversion	
2.3.1	Biomass pretreatment	16
2.3.2	MACP conversion	17
2.3.3	Bio-oil upgrading	
2.3.4	Hydrogen production	
2.3.5	NCG combustion	
Chapter 3 G	lobal Warming Impact of MACP System	25
3.1 LC	A model	
3.1.1	Goal and scope definition	
3.1.2	Life cycle inventory analysis (LCI)	
3.1.3	Life cycle impact assessment (LCIA)	
3.1.4	Interpretation	
3.2 Re	sults and discussion	
3.2.1	Carbon intensity of MACP biofuel	
3.2.2	Sensitivity analysis	
3.2.2	1 Influencing parameters	
3.2.2	2 Impacts of plant location	
3.2.2	3 Impacts of system expansion and allocation methods	
3.2.2	4 Electricity for microwave pyrolysis or electric vehicle (EV)	
3.3 Co	nclusion	
Chapter 4 T	EA of MACP System	42
4.1 TE	A model	
4.1.1	Cost estimation	44
		viii

List of Tables

Table 2.1: Properties of forest residue feedstock [47] 1	3
Table 2.2: Energy consumption in feedstock collection 1	5
Table 2.3: Energy consumption in biomass pretreatment	7
Table 2.4: Major parameters used in modeling the MACP reactor	8
Table 2.5: Major parameters used in bio-oil upgrading	2
Table 2.6: Major parameters used in steam reforming for hydrogen production	3
Table 3.1: Life cycle GHG emissions of MACP biofuel 2	9
Table 3.2: Contribution of individual process to the GHG emissions 24	9
Table 3.3: Sensitivity analysis of carbon intensity of MACP biofuel 33	3
Table 4.1 Cost factors for estimating depreciable capital cost (DepC) [95]	4
Table 4.2 Calculation of the total capital investment (TCI) [95]	6
Table 4.3 Estimation of feedstock transportation cost 4'	7
Table 4.4 Estimation of operating cost 4	8
Table 4.5 Economic assumptions for DCFROR model	9
Table 4.6 Capital investment breakdown	1
Table 4.7 Operating cost breakdown	3
Appendices	
Table A.1: Reported TEA studies on pyrolysis of biomass	0
Table A.2: Reported LCA studies on pyrolysis of biomass	1
Table B.1: Process emission factors (BC, 2020, AR5-100 year)	2

Table B.2: Electricity mix profile and fuelcycle GHG emissions for electricity generation in	
Alberta and British Columbia	83
Table C.1: Chemical Engineering Plant Cost Index (CEPCI) [99]	84
Table C.2: Estimation of capital costs	85
Table C.3: The 10-year project life DCFROR model spreadsheet (million \$)	86
Table C.4: The 20-year project life DCFROR model spreadsheet (million \$)	87

List of Figures

Figure 1.1: Life cycle stages and system boundary for pyrolysis of biomass
Figure 2.1: Process flow diagram of MACP system with mass and energy balance 14
Figure 3.1: The system boundary of MACP biofuel
Figure 3.2: Life cycle GHG emissions of MACP biofuel
Figure 3.3: Potential mechanisms of soil GHG emissions in response to biochar amendment. The
red line and blue line represent the positive and negative regulations, respectively. (Adapted
from He et al. [85])
Figure 3.4: Sensitivity analysis of carbon intensity of MACP biofuel
Figure 3.5: Electricity mix in British Columbia (left) and Alberta (right)
Figure 3.6: Life cycle GHG emissions of MACP biofuel using Alberta electricity mix
Figure 3.7: Sensitivity analysis of carbon intensity of MACP biofuel using Alberta electricity
mix
Figure 3.8: Life cycle GHG emissions of MACP biofuel using different allocation methods 38
Figure 3.9: Two pathways of electricity consumption for biofuel production and charging EV. 40
Figure 4.1 Typical economic analysis procedure 42
Figure 4.2 Basic framework for estimation of capital cost and operating cost
Figure 4.3: Total capital investment and installed equipment costs
Figure 4.4 Annual operating costs (left) and distribution of feedstock delivered cost (right) 53
Figure 4.5: Sensitivity analysis of MSP of MACP biofuel
Figure 4.6: Average large industrial electricity prices in major cities in Canada (left: taken from
[102])
xi

Figure 4.7: (a) MSP of MACP biofuel in different regions of Canada and (b) Change of MSP	
compared to Vancouver baseline	58
Figure 4.8: Impacts of BC carbon tax and technology advancement on fuel prices	60

List of Symbols

C_1	Base Equipment Cost at Base Capacity
C_2	New Equipment Cost at Design Capacity
C _p	Specific Heat of Water
МС	Biomass Moisture Content
п	Capacity Exponent
Q_1	Base Capacity
Q_2	Design Capacity
Q_{p}	Enthalpy for Pyrolysis
$\mathcal{Q}_{\mathrm{mw}}$	Microwave Electricity Consumption
T_0	Room Temperature
Т	Reaction Temperature
α_1	Conversion Efficiency from Electricity to Microwave
α_2	Conversion Efficiency from Microwave to Dielectric Heat
$\Delta H_{ m vap}$	Specific Enthalpy of Water Vaporization
\$	US Dollar
€	Euro

List of Abbreviations

AB	Alberta
BC	British Columbia
CAGR	Compounded Annual Growth Rate
CCA	Capital Cost Allowance
CEPCI	Chemical Engineering Plant Cost Index
CFP	Catalytic Fast Pyrolysis
CI	Carbon Intensity
CO ₂ -eq	CO ₂ Equivalent
СР	Catalytic Pyrolysis
CTG	Cradle-To-Gate
DBEPS	Distributed Biomass Energy Production System
DCFROR	Discounted Cash Flow Rate of Return
DepC	Depreciable Capital Cost
DSC	Differential Scanning Calorimetry
EPA	Environmental Protection Agency
EV	Electric Vehicle
FCI	Fixed Capital Investment
FDP	Feedstock Delivery Point
FOC	Fixed Operating Cost
FP	Fast Pyrolysis

FR	Forest Residue
GDP	Gross Domestic Product
GGE	Gallon Gasoline Equivalent
GHG	Greenhouse Gas
GHSV	Gas Hourly Space Velocity
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global Warming Potential
HHV	Higher Heating Value
HTS	High Temperature Shift
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LTS	Low Temperature Shift
MACP	Microwave-Assisted Catalytic Pyrolysis
MACRS	Modified Accelerated Cost Recovery System
MAP	Microwave Assisted Pyrolysis

MSP	Minimum Selling Price
NCG	Non-Condensable Gas
NDepC	Non-Depreciable Cost
NPV	Net Present Value
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
OC	Operating Cost
PSA	Pressure Swing Adsorption
S/C	Steam to Carbon Molar Ratio
SC	Start-up Cost
SP	Slow Pyrolysis
TCI	Total Capital Investment
TEA	Techno-Economic Assessment
TGA	Thermogravimetric Analysis
TIC	Total Installed Cost
TPEC	Total Purchased Equipment Cost
TSA	Timber Supply Area
VOC	Variable Operating Cost
WC	Working Capital
WHSV	Weight Hourly Space Velocity

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Chapter 1 Introduction

1.1 Background

During the Covid-19 pandemic, renewables including solar, wind, bioenergy, etc., were the only energy source for which demand increased in 2020, while consumption of all other traditional fuels declined as reported by International Energy Agency (IEA) [1]. The key economies that cover 70% of global GDP and emissions have pledged to achieve net zero by 2050 or 2060, where the policies are facing transitions to supporting advanced technologies with lowest possible costs rather than simply providing subsidies [1,2]. The pathways to achieve net zero are recognized to be challenging, but will bring huge social and economic benefits [1]. In 2016, the first national climate plan, namely Pan-Canadian Framework on Clean Growth and Climate Change, was first developed as an important first step for Canada to achieve its Paris Agreement target in a practical and affordable way [3]. In December of 2020, a strengthened climate plan, i.e. "A Healthy Environment and a Healthy Economy", was announced by the Government of Canada to reduce the pollution and create good jobs so as to support a healthier economy and environment [4]. With the actions taken together, Canada is working towards the 2030 Paris Agreement emissions reduction target as well as the net-zero emissions target by 2050 [5].

With an urgent need for eliminating the dependence on fossil fuels and switching to clean and sustainable resources, biomass feedstock, including agricultural residues, forest residues, algae, municipal solid waste, sewage sludge, etc., has been considered as a clean and renewable resource to produce heat, power, fuels, materials and chemicals [6,7]. As the home to 9% of the world's forests and 36% of the world's certified sustainably managed forests, Canada is rich in forest

resources. Up to 40% of total land area in Canada is made up by forest land and British Columbia (BC) constitutes 18% of Canada's total forest area [8,9]. The abundant forest residues from logging operations with no merchantable value are regarded as wildfire risks and are burnt as part of the forestry management strategy in BC, leading to emissions and pollution without any utilization [10]. Since biofuel is the only alternative to petroleum-based transportation fuel compatible with the existing infrastructure, it is considered as one of the most promising ways for energy structure transition to decarbonizing the transportation sector. As described in the CleanBC plan, switching to cleaner fuels is regarded as a transition step for conventional vehicles to reduce greenhouse gas (GHG) emissions [11]. The BC Provincial Renewable and Low Carbon Fuel Standard requires continuous reductions in the carbon intensity of fuels, from 10% by 2020 to 20% by 2030, which stimulates the increase of the renewable fuels supply to meet the increased demand [11]. The combination of feedstock availability and policy support is therefore unique for converting forest residues to biofuels in BC.

1.2 Microwave-assisted catalytic pyrolysis (MACP)

Pyrolysis is one of the most widely studied thermo-chemical conversion pathways of biomass which shows a good adaptability for different types of feedstocks. The reactions typically occur at a medium temperature range (300~900 °C), under atmospheric pressure and in the absence of oxygen, which efficiently converts biomass feedstock into three-phase products that are non-condensable gas (NCG), bio-oil and biochar [12].

In conventional pyrolysis, heat transfer takes place through conduction, convection and radiation by heat carriers or heated reactor surfaces. Microwave pyrolysis introduces energy into the system via electromagnetic waves, which are absorbed by biomass particles or microwave absorbers and then converted into heat for local heating [13]. Therefore, microwave pyrolysis has several advantages, such as selective and volumetric heating, higher heating efficiency, better product characteristics and higher level of safety and automation [14–18]. Direct heating mode can be used for biomass with good dielectric properties. But more generally, hybrid heating mode with addition of microwave absorbers is used to increase local heating rate and tune pyrolysis reactions. Indirect heating mode is also used with heat transfer from high temperature microwave-heated surfaces to biomass particles.

With an aim to increase the reaction selectivity toward target products, catalysts such as zeolites, metal oxides, carbonaceous materials, clays, etc., are introduced into microwave-assisted catalytic pyrolysis (MACP) system. Based on the interaction between catalysts and biomass derivatives, the catalytic configurations can be classified into *in-situ*, *ex-situ* and hybrid. The catalyst is well mixed with biomass particles in *in-situ* configuration where biomass decomposition and vapors upgrading take place simultaneously, leading to modification of both bio-oil and biochar. The *ex-situ* configuration requires a separately controlled reactor located downstream of the microwave pyrolysis reactor for vapors upgrading, which shows better flexibility to tune bio-oil composition. The hybrid mode refers to dual bed, layered bed, *in-situ* and *ex-situ* in series, etc., with unique and more complicated configurations.

Bio-oil derived from pyrolysis typically shows low heating value, low stability, high viscosity and high acidity, mainly due to the abundant oxygenated compounds. MACP has the potential to reduce the oxygenated compounds, leading to a better bio-oil product with more desirable

properties. Particularly, *in-situ* MACP can catalyze the reactions at the catalyst and biochar surfaces, such as re-polymerization, condensation, etc., therefore improving bio-oil and biochar quality at the same time.

1.3 Economic and environmental assessment of MACP

As an emerging technology that can efficiently convert biomass feedstock into valuable products, MACP needs to be researched to solve the technical obstacles as well as to be assessed for its economic and environmental impacts at the systematic level for the purpose of commercialization. Techno-economic assessment (TEA) and life cycle assessment (LCA) are two commonly used tools to assess the economic feasibility and overall environmental impacts of technologies. TEA and LCA can also help identify the "hotspots" in the production processes and understand the impacts of important parameters through sensitivity analyses.

1.3.1 Techno-economic assessment (TEA) of MACP

The key outcomes of TEA are production cost, including capital investment and operating cost, and minimum selling price (MSP) of target products estimated by discounted cash flow analysis [19]. The main product from biomass pyrolysis is bio-oil which can be further upgraded into transportation fuels. The pyrolysis technology evolves from conventional carbonization or slow pyrolysis (SP) for charcoal production to fast pyrolysis (FP), catalytic pyrolysis (CP) and microwave-assisted catalytic pyrolysis (MACP) with a focus on bio-oil production by improving the bio-oil yield and upgradability.

Up to now, the majority of the studies on MACP have been focused on improving performance and solving the technical issues that could largely influence the economic performance of MACP system. Several attempts to develop continuous MACP systems have been made to improve the process efficiency and assist the process scale-up [20,21]. However, data on the economic performance of MACP systems is still scarce, mainly due to the lack of understanding of largescale reactor configurations and performance as well as the lack of detailed process design for large-scale plants. So far, the only study of TEA on large-scale centralized MACP system was reported by Yang et al. [22]. The results showed the MSP of biofuel could be as low as \$3.78/gallon (~\$1.00/L) among different scenarios with process heat integration and/or sales of biochar and surplus H_2 for credits. This agreed with the price range for biofuels from different pyrolysis pathways in peer-reviewed literatures as shown in Table A.1 [23-27]. The concept of small distributed MACP system was also proposed [28-30], which might offer a potential near-term solution to overcome the issues of centralized MACP systems (e.g. technical scalability, high capital investment, high feedstock transportation cost, etc.). This would make good use of regional biomass supply while providing extra income to farmers for the development of a local, sustainable bioeconomy. As microwave pyrolysis also shows the potential to improve biochar quality, a comparative TEA of biochar production between conventional and microwave pyrolysis was reported by Haeldermans et al. [31]. The results indicated that the MSP of biochar was between €436/tonne and €863/tonne in conventional pyrolysis, as it is a simpler and more established technology, and between \notin 564/tonne and \notin 979/tonne in microwave-assisted pyrolysis. This suggested that microwave pyrolysis was less economically feasible than conventional pyrolysis. However, if the improved quality of biochar by microwave pyrolysis was considered, i.e. higher surface area, pore volume and less contaminants, a 20% increase of selling price could result in an average net present value (NPV) higher than that of conventional pyrolysis.

In-situ MACP catalyzes vapor cracking reactions and reduces activation energy for pyrolysis reactions, leading to a lower temperature to initiate and sustain the reactions [32]. Some catalysts with good dielectric properties can also serve as microwave absorbers to reduce the operating cost. The catalyst in *in-situ* MACP has a relatively short lifetime because of the direct contact with solids containing inhibitory mineral matters, char and biomass. Ex-situ configuration allows catalyst to contact with pyrolysis vapor only, avoiding severe contamination of catalyst and extending the catalyst lifetime [20,23]. As the *ex-situ* configuration requires an additional catalytic reactor right after the pyrolyzer for vapor pre-upgrading, it is expected that the complexity of the ex-situ MACP system design and construction will result in higher capital cost. Although the exsitu mode can have a larger capital investment due to its complex configuration, less catalyst attrition and higher final product yield could potentially bring down the operating cost and MSP. Dutta et al. [23] compared *in-situ* and *ex-situ* CP for gasoline and diesel production, at an MSP of \$3.46/GGE (Gallon Gasoline Equivalent) and \$3.31/GGE, respectively. Thus, a similar comparison should be performed for MACP. Different heating modes should also be considered based on dielectric properties and the size of feedstock to obtain high microwave power density and efficient heat transfer, which can improve the reactor efficiency and save energy for biomass pyrolysis. So far data on the design and performance of MACP reactors and equipment costs are still limited, which prevents the proper quantification of the capital investment and operating cost of MACP.

Among the various applications of the three products, biofuel as transportation fuel attracts most attention because of the huge liquid fuel market. However, the inherent challenge lies in the high oxygen content of the original biomass feedstock. Although the catalytic reactions reduce the oxygen content in bio-oil, the resulting bio-oil still requires further upgrading (e.g. through hydrotreating and hydrocracking) before it can be used as transportation fuel. Therefore, a high yield of bio-oil along with low oxygen content should be a target for the MACP process.

Biochar is another important product from MACP with great economic potential and carbon storage benefit. Owing to the unique volumetric heating from microwave irradiation, the *in-situ* MACP can produce high quality biochar by direct interactions between catalysts and biomass solid particles. The traditional applications of biochar as solid fuel and soil amendment show relatively low economic values (<\$150/tonne as alternative of coal; <\$400/tonne for soil application). However, the improved qualities of biochar from MACP, as indicated by surface area, pore structure, functional group, nutrient content, etc. [17], can result in higher values and thus economic benefits to the MACP system. This is based on their potential for advanced applications, such as carbon-based catalyst, adsorbent, energy storage material, etc. [13,33], with a potential value of up to \$800~17,800/tonne [34,35]. With the introduction of more and more strict environmental protection legislations, it is predicted that porous carbon materials can have a global market size of \$10.15 billion by 2024 while the global demand for activated biochar will reach 5.1 million tonnes by 2024 at a compounded annual growth rate (CAGR) of 13.3% (2016–2024) [33]. Although the market size is predicted to grow rapidly, the market for biochar has not yet been fully established with technical issues remaining due to variations in biochar quality [34]. It should be noted that while it is important to continue to improve the quality of biochar, the economic value

7

of biochar also needs to be quantified in order to properly assess the economic performance of MACP system.

1.3.2 Life cycle assessment (LCA) of MACP

Life cycle assessment (LCA) can serve as a useful scientific tool to systematically quantify the carbon footprint and GHG reduction potential of biomass-derived products over the whole life cycle. From a life cycle point of view, biomass feedstocks can be considered as CO₂ neutral because they are formed through photosynthesis which converts atmospheric CO₂ and water into sugars, forming a closed CO₂ loop. Meanwhile, the atmospheric CO₂ can be sequestrated if any product containing long-term stable C (e.g. biochar) is derived from biomass. Therefore, the environmental burdens of the MACP process lie in the collection and transportation of the biomass feedstock, electricity consumption for microwave generation and operation of auxiliary units. The upstream emissions from the production of catalysts and microwave absorbers as well as all other conversion and transportation related activities also need to be considered.

Extensive LCA studies on conventional pyrolysis systems (e.g. fast pyrolysis and catalytic pyrolysis) have been conducted, as shown in Table A.2 [23,36–38]. The most commonly used functional unit for pyrolysis systems is 1 MJ or 1 kWh energy-content of the end energy product like heat, transportation fuels and electricity. A typical system boundary of pyrolysis from raw biomass to end products generally consists of three main stages, namely feedstock supply (i.e. cultivation, collection and transportation of biomass feedstock), production (i.e. pre-treatment, conversion and upgrading of primary products) and end use (i.e. product distribution and consumption), as illustrated in Figure 1.1.



Figure 1.1: Life cycle stages and system boundary for pyrolysis of biomass

Among the different impact categories, the global warming impact is the most commonly studied, and is typically reported in terms of CO₂ equivalents [19]. As a renewable fuel, liquid biofuels produced from biomass pyrolysis have very low GHG emissions ranging from 9.2 to 38.9 CO₂eq/MJ [23,36,39]. In comparison, life cycle GHG emissions of petroleum-based liquid fuels are at 93.1 g CO₂-eq/MJ based on 2005 baseline of gasoline, and at 91.9 g CO₂-eq/MJ for diesel [36]. The MACP system differs from conventional pyrolysis in several aspects, including electricity for microwave generation, improved product qualities, value-added applications of products, etc. Although additional GHG emissions are released from electricity generation, catalyst production, microwave absorber production, etc., the intensity for upgrading bio-oil can be significantly reduced so that leading to lowered GHG emissions. The overall carbon intensity of MACP system requires detailed quantification of the whole process and the products. The benefit from utilizing high-quality biochar (e.g. for soil amendment, wastewater treatment, catalyst, etc.) should be investigated in particular. It is widely speculated that biochar has the potential for long-term carbon sequestration due to its high fixed carbon content, thus generating GHG credits. Biochar is produced from renewable feedstock with a carbon content of 50% to 93% [34]. Roberts et al. [40] suggested that majority (~80%) of the carbon in biochar could be in a highly stable state in soil. Wang et al. [41] claimed that about 97% of biochar could contribute to long-term carbon sequestration in soil after a meta-analysis on stability and decomposition of biochar in soil. The potential CO₂ offset of biochar can also bring economic benefits to the MACP system leveraging climate-related policies and incentives under discussion around the world [42], such as the carbon tax and low-carbon fuel standard in Canada.

To the best of our knowledge, the environmental benefits of the MACP system have not been studied. Thus, there is an urgent need to conduct LCAs on this novel technology and to quantify the environmental benefits as part of an integrated assessment of the technology's commercialization.

1.4 Research question and objectives

Currently, most studies assessing the MACP process are at the lab scale, trying to overcome technical obstacles, such as catalyst development [43–45], products optimization [45,46], kinetics investigation [46], etc. Although several scalable prototype processes have been proposed [21], there has been limited investigations on the economic and environmental performances of large-scale processes.

According to a comprehensive literature review (see Table A.1 and Table A.2), although extensive TEA and LCA studies have been conducted for conventional pyrolysis of biomass, to the best of our knowledge, there has been only one TEA study [22] and no LCA study on MACP system.

Therefore, this study performed the first integrated economic and environmental assessment of an MACP system, better elucidating its economic and environmental benefits. The research questions were generated from two perspectives:

From the economic point of view,

- What is the cost of biofuel produced from MACP process? Is the minimum selling price (MSP) of MACP biofuel competitive with petroleum-based fuels?
- 2) What are the "hotspots" for cost reduction and which parameters have the most significant impacts on the MSP of MACP biofuels?

From the environmental point of view,

- 1) What is the carbon intensity (CI) of MACP biofuel and its potential to reduce GHG emissions?
- 2) What are the "hotspots" that release most GHG emissions over the life cycle stages?

1.5 Structure of thesis

Chapter 1 introduces the background, gives a brief literature review and presents the research objectives of this study.

Chapter 2 presents a detailed description of the proposed MACP system. Mass and energy flows of all associated processes are analyzed to generate data for LCA and TEA.

An LCA is conducted in Chapter 3 to investigate the GHG emissions of MACP system. In Chapter 4, a TEA is performed to assess the economic feasibility of MACP system. Both capital and

operating costs are estimated and minimum selling price of MACP biofuel is calculated by discounted cash flow rate of return model. A sensitivity analysis is conducted in each chapter to investigate the impacts of data uncertainties.

Chapter 5 presents the conclusions and identifies limitations of this study as well as recommends the future work to be carried out.

Chapter 2 Process Description of MACP System

A hypothetic biorefinery using microwave-assisted catalytic pyrolysis (MACP) system with a capacity of 2000 dry tonne of forest residues per day was assumed to be located in Prince George, BC, based on the availability and distribution of logging forest residues in BC [8]. The basic information of forest residue feedstock, shown in Table 2.1, was extracted from Phyllis database [47]. It should be noted that the energy balance was based on higher heating value (HHV) in this analysis. Considering the simple reactor configuration, improvement of co-product and bi-functionality of catalyst, the MACP system studied in this research was *in-situ* MACP with hybrid heating in a fluidized-bed reactor.

Property	Value	
Ultimate analysis, wt%		
Carbon	50.31	
Hydrogen	4.59	
Oxygen	39.95	
Nitrogen	1.03	
Sulphur	0.11	
Chlorine, mg/kg	400.00	
Total (with halides), wt%	100.00	
Moisture content, wt% (wet basis)	50	
Higher heating value, MJ/kg (wet basis)	10.08	

 Table 2.1: Properties of forest residue feedstock [47]

Phyllis #846 wood, forest residue

The annual operating time was assumed to be 7,884 hours based on an on-stream factor of 90%, allowing 36 days of planned and unplanned downtime per year [23]. Therefore, the annual

feedstock requirement was approximately 657,000 dry tonne per year. The MACP system in this study consisted of the following stages: feedstock collection, feedstock transportation and biomass-to-biofuel conversion, as depicted in Figure 2.1. The main product from this system was upgraded biofuel, while biochar was treated as co-product.



Figure 2.1: Process flow diagram of MACP system with mass and energy balance

2.1 Feedstock collection

The waste logging forest residues were first gathered, loaded to on-site grinder for a rough size reduction and then shuttled by medium-duty truck to delivery points. Due to lack of information on specific forest residue management, the average collection radius was assumed to be 12.5 km as suggested by Nie and Bi [48]. The moisture content and HHV of forest residues used in this study were 50 wt% (wet basis) as received and 10.08 MJ/kg (wet basis), respectively (see Table 2.1) [47]. The detailed energy consumption at this stage is listed in Table 2.2.

Equipment	Process	Fuel type	Energy consumption	Reference
Hydraulic loader	Loading onto on-site grinder	Diesel	0.82 L/dry tonne	[49]
On-site horizontal grinder	On-site grinding	Diesel	3.01 L/dry tonne	[49]
Front-end loader	Loading for transportation	Diesel	1.02 L/dry tonne	[49]
Medium-duty truck	Shuttling to delivery points	Diesel	6279 kJ/tonne-km	[50]

Table 2.2: Energy consumption in feedstock collection

2.2 Feedstock transportation

The forest residues demand for the biorefinery has to be fulfilled from Prince George timber supply area (TSA) and nearby supply blocks in Fort St. James, Vanderhoof, Bear Lake, etc., as studied by van Dyk et al. [8]. Based on the availability and distribution of forest residues, the average transportation distance was estimated to be 52.8 km within a 100 km supply radius [8]. The collected forest residues were transported by semi-trailer to the biorefinery for conversion, where the freight energy intensity was 1907 kJ/tonne-km for heavy-duty truck [50].

2.3 Conversion

In MACP system, the biomass-to-biofuel conversion mainly includes feedstock pretreatment, MACP conversion and subsequent bio-oil upgrading, as depicted in Figure 2.1. The biomass feedstock was first converted to bio-oil via MACP, with biochar and non-condensable gas (NCG) co-produced, and then upgraded to biofuel through hydroprocessing. The upgraded biofuel was regarded as the main product for blending into conventional petroleum fuels because of high demand in the current market. However, MACP also produces a significant amount of biochar, which attracts much research attention in recent years due to its carbon sequestration potential when applied for soil amendment. Therefore, biochar was treated as a co-product in this study. The on-site hydrogen production using non-condensable gases (NCG) as feedstock was integrated to the MACP system to provide hydrogen for the bio-oil upgrading, which could help make full utilization of NCG and achieve self-sufficiency in hydrogen supply. Heat integration was also considered to recover the waste heat for reduction of overall energy consumption. Due to lack of information on large-scale process design of the MACP system, some modeling input parameters at this stage were based on the lab experimental data and simulation results from NREL report on catalytic pyrolysis by Dutta et al. [23] with scaling and modification by replacing the original catalytic pyrolysis module with the MACP module. The detailed mass and energy balances are illustrated in Figure 2.1.

2.3.1 Biomass pretreatment

In the hypothetic biorefinery, collected forest residues were unloaded and sent to a dryer, where they were dried from 50 wt% moisture content as received to 10 wt% moisture content (wet basis). The latent heat of water vaporization is 2.26 MJ/kg water evaporated at its boiling point

[51]. In practice, more energy is required as suggested by different authors, ranging from 2.8 to 5 MJ/kg water evaporated from room temperature [24,36,40,52,53]. The average value of 3.54 MJ/kg water evaporated was used in this study. The heat for drying was fulfilled by combustion of a fraction of NCG. The dried forest residues were then ground to a particle size of below 5 mm [36]. The energy consumption for each unit of the modeled process is shown in Table 2.3.

Equipment	Process	Energy type	Energy consumption	Reference	
Front-end loader	Unloading	Diesel	0.42 L/dry tonne	[36]	
Auxiliary	Handling, dust collection,	Electricity	5 kWh/dry tonne	[36]	
	chip cleaning			[50]	
Grinder	Size reduction of biomass	Electricity	71.2 kWh/dry tonne	[36]	
Dryer	Drying	Heat	3.54 MJ/kg water evaporated	[24,36,40,52,53]	

Table 2.3: Energy consumption in biomass pretreatment

2.3.2 MACP conversion

After pretreatment, the dried fine biomass particles were well mixed with catalyst and sent to the microwave pyrolyzer to be converted into bio-oil, biochar and NCG. The fluidized bed reactor with nitrogen as fluidization agent was used for *in-situ* MACP system, operated at 500 °C and atmospheric pressure. The biochar was directly collected after MACP conversion, while the vapors were quickly quenched to condense and separate bio-oil from NCG to limit secondary reactions, such as cracking and repolymerization [36]. A pilot plant with *in-situ* MACP system using a bubbling fluidized bed reactor is under construction at the University of British Columbia, with a designed processing capacity of 25 kg/h. The product distribution from MACP conversion was based on our previous experiments in a lab unit [17,18,54]. Table 2.4 summarizes the major parameters used in modeling this process.
Parameter V		Reference
Catalyst consumption		
WHSV, h ⁻¹	1.1	[55]
Catalyst inventory, tonne	84.2	Calculated based on WHSV
Product yields, wt%		Pilot design
NCG	36	
Biochar	28	
Bio-oil	36	
NCG composition, vol%		[56]
CO ₂	16.5	
H_2	30.2	
СО	25.8	
CH_4	14.3	
C_2H_6	6.5	
C_4H_6	1.8	
C_mH_n	4.9	
Energy consumption		
Pyrolysis enthalpy, MJ/dry kg	1.5	[6,57]
Electricity to microwave conversion	0.9	[58]
Microwave to dielectric heat conversion	0.9	[58]
Microwave electricity consumption, MJ/dry kg	2.43	Calculated based on equation (2.1)
Power for condensation and product separation, MJ/dry kg	0.15	[23]

Table 2.4: Major parameters used in modeling the MACP reactor

There were numerous studies on catalysts used in MACP system, such as zeolites, metal oxides/salts, carbonaceous, and clays [17,18,59–62]. The *in-situ* catalytic configuration enables improvements of co-product qualities at the same time but suffers from easy deactivation of catalysts. Based on our previous experiments, potassium phosphate could act as microwave absorber to increase heating rate, as catalyst for modifying pyrolysis reactions and bio-oil product composition, and as nutrients added into biochar to improve fertilizer efficiency for soil application

[54]. Therefore, potassium phosphate was selected as the catalyst in this analysis of MACP process. The reactor design of microwave pyrolyzer is still at the early stage, therefore the weight hourly space velocity (WHSV) was based on the reactor design of bubbling fluidized bed catalytic fast pyrolysis (CFP) system. Xin et al. [63] and Iisa et al. [55] reported WHSV of 0.5 and 1.1 h⁻¹, respectively, for *in-situ* vapor upgrading. Hu et al. [64] noticed that the coke formation would decrease with increasing WHSV. Therefore, the WHSV in our bubbling fluidized bed MACP system was assumed to be $1.1 h^{-1}$. As a kind of fertilizer, potassium phosphate acted as catalyst during pyrolysis that could be fully recovered in the solid residues and serve its original function as a fertilizer, it could be assumed that there was no loss of its value. Therefore, the consumption of potassium phosphate could be excluded from the system boundary.

The energy consumption in MACP conversion is important to be assessed and has been reported by several studies but remains controversial. Zhao et al. [65] reported the electricity consumption between 0.58 to 0.65 kWh/(kg straw) for microwave pyrolysis of large-size straw bale, where the conversion efficiency of electricity to microwave energy was about 0.8. Yang et al. [22] assumed that the electricity consumption for pyrolyzing dry biomass from room temperature to the reaction temperature (480 °C) was 0.6 kWh/kg, while it could be reduced to 0.45 kWh/kg when preheating biomass to 100 °C. A recent research reported the microwave heat consumption in pyrolysis of horse manure was 5 GJ/tonne [66]. The enthalpy for pyrolysis, defined as the energy demand for raising biomass from room temperature to the reaction temperature and converting biomass into three-phase products, has been measured by different authors [6,57,67]. It includes the sensible enthalpy to heat up biomass and enthalpy of reaction to trigger and sustain the pyrolysis reactions. Daugaard and Brown [67] reported the enthalpy for pyrolysis of four different biomass in a pilot-

scale fluidized bed reactor operated at 500 °C, ranging from 0.78 ± 0.20 to 1.64 ± 0.33 MJ/dry kg. The enthalpies for two woody biomass were 1.46 ± 0.28 and 1.64 ± 0.33 MJ/dry kg, respectively. Yang et al. [57] estimated the heat required for pyrolysis of woody biomass in a screw-conveyer pyrolyzer at 550 °C, which was 1.5 MJ/(kg-daf-biomass). Adam [6] also reported that the enthalpy for pyrolysis of sycamore at 500 °C was 1.28 ± 0.11 MJ/dry kg by integrating the heat flow curve from DSC-TGA. He estimated the electrical energy required in a microwave-heated fluidized bed system to be around 3.5 to 4.2 MJ/kg and compared with those of microwave-heated fixed bed system and conventional-heated fluidized bed system, which were around 2.2 to 2.5 MJ/kg and 2.7 to 3.1 MJ/kg, respectively. It was suggested that the microwave fluidized bed system could be further optimized to minimize energy consumption. Therefore, in this study, the enthalpy for pyrolysis (Q_p) was assumed to be 1.5 MJ/dry kg. As the enthalpy of pyrolysis was reported on a dry basis, the enthalpy for heating and evaporating the moisture content should be added into the calculation [6]. The microwave electricity consumption $(Q_{\rm mw})$ for heating up and pyrolyzing biomass from room temperature (T_0) to reaction temperature (T) was thus calculated to be 2.43 MJ/dry kg biomass using the following equation:

$$Q_{\rm mw} = \frac{Q_{\rm p} + (C_{\rm p} \times (T - T_0) + \Delta H_{\rm vap}) \times MC/(1 - MC)}{\alpha_1 \alpha_2}$$
(2.1)

where specific heat of water (C_p) is 4.18 kJ/(kg·K) and specific enthalpy of water vaporization (ΔH_{vap}) is 2.26 MJ/kg water evaporated. The biomass moisture content (*MC*) was 10% (wet basis) after pretreatment. The conversion efficiencies from electricity to microwave (α_1) and from microwave to dielectric heat (α_2) were both set as 90% to represent the energy transformation in a large-scale system based on the Handbook of Industrial Microwave Heating [58]. The produced bio-oil contained high oxygen content, was thermally unstable and thus directly sent to the upgrading process. Many researches showed that the NCG from MACP contained more H₂ and light hydrocarbons (C1-C4) than that from conventional fast pyrolysis, as represented in Table 2.4, in favor of being recovered as the feedstock for steam reforming [22,56,68]. Therefore, the NCG stream was split into two sub-streams, with one as the feedstock for H₂ production and the other combusted for generating process heat.

2.3.3 **Bio-oil upgrading**

Bio-oil produced from MACP is not stable due to the high oxygen content and cannot be directly blended with conventional petroleum fuels, thus requiring catalytic upgrading by deoxygenation [36]. The upgrading process includes hydrotreating and hydrocracking, where the bio-oil is reacted with hydrogen under high pressure and temperature such that the oxygen content is reduced to below 1% while the molecular weight is adjusted into a suitable range [36]. The hydrogen demand for deoxygenation depends on the compositions of bio-oil. Anex et al. [69] reported that the required hydrogen input for bio-oil upgrading via hydroprocessing is 3-5 wt% of the bio-oil feed. Jones et al. [70] used 4.96 lb H₂/100 lb dry oil in their study. Based on the range of data from the literature, this study assumed a hydrogen requirement of 4.3 wt% of bio-oil, which could be generated from the full utilization of the NCG. The catalyst used for bio-oil upgrading was assumed to be CoMo catalyst, which is commonly used in hydrotreating [23]. Other catalysts, such as Ru/C catalyst, sulfided CoMo catalyst, NiMo catalyst, etc., are also identified to be widely used in hydroprocessing of bio-oil [36,48,70,71]. The catalyst requirement was calculated based on the design from Dutta et al. [23] as listed in Table 2.5, where a WHSV of 0.5 h⁻¹ with a 70% overdesign of solid inventory was used to consider a relatively high severity and accommodate catalyst

deactivation. The catalyst inventory was determined based on mass flow of input and WHSV using the following equation:

Catalyst inventory (tonne) =
$$\frac{\text{Mass flow of input (tonne \cdot h^{-1})}}{\text{WHSV (h}^{-1})}$$
 (2.2)

The effluent was cooled and separated into upgraded biofuel, wastewater and off-gas streams. The upgraded biofuel yield was assumed to be 65%, the highest yield from hydrodeoxygenation of pyrolysis oil reported by Wildschut et al. [71]. The off-gas containing light hydrocarbons was recovered along with NCG as feedstock for steam reforming.

Parameter	Value	Reference
Catalyst consumption		[23,72]
WHSV, h ⁻¹	0.50	
Overdesign	70%	
Solid inventory, tonne		
Hydrotreating	79.33	Calculated based on WHSV
Hydrocracking	13.73	Calculated based on WHSV
Catalyst lifetime, year	2	
H ₂ requirement, g/g bio-oil	0.043	
Product distribution, wt%		[71]
Upgraded biofuel	65.0	
Water	20.1	
Off-gas	14.9	
Power for bio-oil upgrading, MJ/kg bio-oil	0.45	[23]

Table 2.5: Major parameters used in bio-oil upgrading

2.3.4 Hydrogen production

An on-site hydrogen production unit was integrated with MACP system to produce hydrogen by steam reforming to meet the demand for bio-oil upgrading process. The feedstock for steam

reforming was part of NCG from MACP and off-gas from bio-oil upgrading. The gas mixture was mixed with steam and then fed to the steam reformer. The resulting gas mixture then underwent high temperature shift (HTS) and low temperature shift (LTS) to further increase the hydrogen yield. Hydrogen was purified by a pressure swing adsorption (PSA) unit and then sent to the hydrotreater and hydrocracker for bio-oil upgrading. A polygeneration process in a scaled system was designed by Parvez et al. [56], where the gaseous product from microwave-assisted pyrolysis was used as the feedstock for bio-hydrogen production. The simulation values based on their previous experiments were used as reference for our modeling of hydrogen production process, as given in Table 2.6 [56,68]. The steam requirement was calculated based on the NCG composition in Table 2.4 and a steam to carbon molar ratio of 3. The hydrogen yield was calculated based on their results for pine wood [56]. A typical gas hourly space velocity (GHSV) value of 4000 h^{-1} for high temperature or low temperature water gas shift reaction was used to estimate the catalyst consumption [73].

Parameter	Value	Reference
Steam to carbon molar ratio (S/C)	3	[56]
Steam requirement, g/g NCG	1.87	Calculated based on S/C
H ₂ production, g/g NCG	0.11	[56]
Catalyst consumption		
GHSV, h ⁻¹	4000	[73]
Solid inventory, tonne	6.45	Calculated based on GHSV
Catalyst lifetime, year	3	[48]
Power for H_2 production and management, $MJ/kg \; H_2$	6.9	[23]

Table 2.6: Major parameters used in steam reforming for hydrogen production

2.3.5 NCG combustion

Unlike traditional pyrolysis that is heated up by burning biochar and pyrolysis gases, MACP uses microwave from electricity to efficiently trigger and sustain the pyrolysis reaction. The additional heat demand for endothermic hydrogen production unit and biomass drying pretreatment could be fulfilled by combustion of the remaining NCG. Based on the NCG composition shown in Table 2.4, the air requirement for complete combustion was calculated to be 8.55 kg/kg NCG at 20% excess air. The heat generated was based on the HHV of NCG, which was assumed to be 12.8 MJ/Nm³ as reported by Parvez et al. [56]. The heat integration helped full utilization of waste energy produced from the system, therefore reducing the total energy consumption.

Chapter 3 Global Warming Impact of MACP System

3.1 LCA model

Life cycle assessment (LCA) is one of the most widely-used tools to comprehensively evaluate the environmental impact of bioenergy systems [74]. According to the international standard ISO 14040, an LCA study includes four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation [75].

3.1.1 Goal and scope definition

In this study, an attributional LCA was conducted to quantify the carbon intensity (CI) of MACP biofuel from forest residues in BC following ISO 14040 [75]. The functional unit was set as 1 MJ of upgraded biofuel product. The system boundary was defined as cradle-to-gate (CTG) as depicted in Figure 3.1, including feedstock collection, transportation, conversion and upgrading to refined biofuel product. The emissions from all the foreground and background processes were included in this study, but the emissions associated with construction and equipment manufacturing as well as waste disposal were excluded from the scope. In addition, the forest residues were strictly regarded as waste imposing wildfire risk based on the forestry management strategy in BC [48], and its removal from logging site would create avoided environmental burdens associated with its on-site slash burning. Although CO₂ emitted from slash burning is biogenic, incomplete combustion in the open air generates significant amount of other greenhouse gases (e.g. CH₄, N₂O, etc.) [74], much greater than those from biofuel combustion in vehicles. Similarly, tailpipe emissions include biogenic CO₂ and other greenhouse gases, but at much lower levels. Therefore, the emission difference between slash burning and tailpipe could be assigned as credits

generated from utilization of logging forest residues in MACP system as an alternative to the disposal approach. The carbon released from off-gases of NCG burning and bio-oil upgrading was considered as biogenic carbon originally from biomass feedstock since this process does not include additional fossil fuels. The system expansion method was applied to consider the utilization of co-product biochar as credits for the main product biofuel.



Figure 3.1: The system boundary of MACP biofuel

3.1.2 Life cycle inventory analysis (LCI)

This phase requires the collection of foreground and background data. The foreground data, including all the material and energy flows entering and leaving the system boundary at each stage,

were obtained based on mass and energy balance analysis in Chapter 2. The background data included emission factors of materials and utilities which could not be directly measured, therefore relied on databases in LCA software, such as GHGenius [50] and GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) [76]. To reflect the BC specificity in this case study, the Canadian-based LCA software GHGenius [50] was used as the primary data source for extracting the emission factors, where the region and target year were set as BC and 2020. The lacking information, such as production emissions of catalysts and fertilizers, were collected from GREET. The emission factors used in this analysis can be found in Appendix B.

3.1.3 Life cycle impact assessment (LCIA)

This study focused only on environmental impact on climate change represented by Global Warming Potential (GWP). The GWP factors from IPCC Fifth Assessment Report for 100-year time horizon were used for calculation, converting CO₂ (1), CH₄ (28), N₂O (265) and other greenhouse gases into CO₂ equivalent (CO₂-eq). The impact factor method was applied by multiplying the material and energy consumptions compiled in LCI with the corresponding impact factors. It should be noted that biomass was considered as CO₂ neutral because the atmospheric carbon dioxide was captured through photosynthesis during biomass growth. Therefore, the growth and utilization of biomass formed a closed CO₂ loop in a short period, during which the biogenic CO₂ in off-gases released from conversion was assigned no net global warming impact.

3.1.4 Interpretation

The results from LCI and LCIA were summarized and analyzed in interpretation phase [77]. The significant issues were identified based on the results analyses, such as dominance analysis,

sensitivity analysis, etc. The key outcome of interpretation phase was to determine the hotspots of the supply chain, identify the significant parameters, draw conclusions and make recommendations [75].

3.2 Results and discussion

3.2.1 Carbon intensity of MACP biofuel

The material and energy flows entering and leaving the system were analyzed in Chapter 2. By applying impact factors, the life cycle GHG emissions of upgraded biofuel were quantified, as shown in Figure 3.2 and listed in Table 3.1. The net emissions, i.e. carbon intensity of MACP biofuel, demonstrated that the proposed MACP system could produce upgraded biofuel with a negative carbon footprint within a cradle-to-gate (CTG) system boundary.



Figure 3.2: Life cycle GHG emissions of MACP biofuel

Process	GHG emissions	
1100035	(g CO ₂ -eq/MJ biofuel)	
Feedstock collection	4.72	
Feedstock transportation	2.30	
Conversion	6.29	
Pretreatment	0.79	
MACP	5.02	
Upgrading	0.32	
Hydrogen production	0.16	
Total (without credits)	13.32	
Credit from avoided slash burning	-21.31	
Biochar credit	-49.57	
Net emissions	-57.58	

Table 3.1: Life cycle GHG emissions of MACP biofuel

The life cycle GHG emission of MACP biofuel was -57.6 g CO₂-eq/MJ with consideration of biochar credits using system expansion method, achieving a 162% reduction compared to that of petroleum-based fuels based on 2005 baseline of gasoline (93.1 g CO₂-eq/MJ). The GHG emission for MACP biofuel production without considering credits was 13.3 g CO₂-eq/MJ as shown in Figure 3.2, where the predominant contribution was the biomass-to-biofuel conversion stage, accounting for 47.3% of the total GHG emissions. At conversion stage, the MACP process had the highest global warming impact due to the large electricity consumption for microwave heating. The improvements on conversion efficiencies could further reduce the electricity consumption and corresponding GHG emissions. The detailed contributions of individual processes to the overall GHG emissions are listed in Table 3.2.

 Table 3.2: Contribution of individual process to the GHG emissions

Contribution (%)

Feedstock collection	35.46
Loading	8.63
On-site grinding	14.12
Shuttling	12.71
Feedstock transportation	17.27
Conversion	47.28
Pretreatment	5.97
Unloading feedstock	1.97
Handling, dust collection, chip cleaning	0.26
Grinding	3.74
MACP	37.70
Microwave heating	35.50
Condensation and product separation	2.20
Upgrading	2.39
Power	1.84
Catalysts	0.55
Hydrogen production	1.22
Power	1.21
Catalysts	0.003
Total production	100.00

In the base analysis, system expansion method was applied to consider biochar credits from its mitigation of GHG emissions and displacement of conventional fertilizer. It was therefore critical to fully understand the sub-system of co-product biochar such that reasonable credits could be assigned to the main product. Biochar for soil application has been regarded as a negative emission technology achieved by carbon sequestration, effects on soil GHG emissions and reduction of fertilizer usage [78,79]. The biochar carbon sequestration relies on carbon stability of biochar, which can be determined by assessment methods, such as labile/stable carbon determination, carbon structure analysis, H/C_{org} and O/C_{org} molar ratio, biochar incubation and modelling [80–83]. The carbon content in biochar and its long-term stability in soil depend on many parameters,

such as feedstock type, conversion parameters, environmental soil conditions, etc. Based on an incubation and modelling assessment by Zimmerman [79], the C loss after 100 years was calculated to be 1.9~20% for biochar derived from woody biomass. Mašek et al. [78] reported a stable carbon content in biochar ranging from 73.4% to 79.9% with potassium doping under reaction temperature of 550~650 °C. Therefore, we assumed a typical carbon content of 50 wt% in biochar and used a conservative assumption that 80 wt% of the carbon could be long-term stable as reported by Roberts et al. [40]. A $\pm 10\%$ change was applied in sensitivity analysis, which reflected the general range of carbon content in biochar. The carbon sequestrated by biochar was then calculated to be 1.47 kg CO₂-eq/kg biochar, confirmed by another study from Windeatt et al. [84]. However, the effects of biochar application on soil GHG emissions are still controversial and vary among different case studies [85]. As depicted in Figure 3.3, biochar shows effects on soil CH₄ and N₂O emissions. It mainly influences soil CH₄ emissions via effects on microbial community of methanogens and methanotrophs, which produces and uptakes CH₄, respectively [85]. From a meta-analysis point of view, biochar application shows no significant effect on soil CH₄ emissions, although individual studies show diverse effects depending on multiple sitespecific factors like soil properties and microbial community [85–87]. Similarly, contradictory mechanisms have been proposed with respect to N₂O emissions. Increases in N₂O emissions could be attributed to denitrification induced by biochar, while decrease of soil N_2O emissions might be ascribed to improved soil aeration, changes in the activity of the nitrifiers and denitrifiers, etc. [85,88,89]. Therefore, the effects of biochar application on soil GHG emissions were ignored in the current study due to lack of fully understood mechanisms and specific field trial data. It was also recognized that biochar showed positive effects on soil fertility to increase crop yields, which has been proved by field trials [90]. In this analysis, nitrogen content in biochar (typically 0.5 wt%)

31

was considered to replace the nitrogen fertilizer, therefore creating additional credits from the avoided fertilizer production emissions [48].



Figure 3.3: Potential mechanisms of soil GHG emissions in response to biochar amendment. The red line and blue line represent the positive and negative regulations, respectively. (Adapted from He et al. [85])

As shown in Figure 3.2, the significant amount of biochar credits and credits from avoided slash burning successfully brought down the MACP biofuel carbon intensity to a negative value. One of the reasons was the relatively high yield of biochar (28 wt%) in MACP system compared to typical biochar yields (12~16 wt%) from conventional pyrolysis [39]. The negative carbon intensity of MACP biofuel was also attributed to the clean electricity mix in BC, which significantly lowered the overall GHG emissions. A detailed comparison between electricity mix of BC and Alberta can be found in the sensitivity analysis, as well as the corresponding impacts on carbon intensity of MACP biofuel.

3.2.2 Sensitivity analysis

3.2.2.1 Influencing parameters

To identify the most influencing parameters for MACP biofuel carbon intensity, a sensitivity analysis was performed by changing the parameter values by $\pm 10\%$. The resulting changes of MACP biofuel carbon intensity are listed in Table 3.3 and illustrated in Figure 3.4. By increasing distances of transportation and collection, the carbon intensity of MACP biofuel increased slightly. As the biochar credits outweighed the production emissions, the net GHG emission was very sensitive to the carbon sequestration ability of biochar instead of energy consumption in the "hotspot" MACP conversion. The bio-oil yield in MACP conversion process and biofuel yield in the upgrading process influenced the carbon intensity of MACP biofuel mainly through changing the total product output. Since the carbon intensity of MACP biofuel was negative because of the credits from biochar carbon sequestration and avoided slash burning, the unit credits assigned to per MJ biofuel would decrease with increasing production capacity. It should be noted that the key parameters could be identified via sensitivity analysis with a small change, represented by $\pm 10\%$ in this analysis [91]. However, more practical ranges and distributions of the results would require uncertainty analysis with practical distributions of input parameters collected.

			•			
Parameter	Parameter value		Carbon intensity (g CO ₂ -eq/MJ))2-eq/MJ)	
	-10%	Nominal	10%	-10%	Nominal	10%
Transportation distance (km)	47.52	52.80	58.08	-57.81	-57.58	-57.35
Enthalpy for pyrolysis (MJ/kg)	1.35	1.50	1.65	-57.93	-57.58	-57.22
Biofuel yield	58.5%	65.0%	71.5%	-64.25	-57.58	-52.12
Bio-oil yield	32.4%	36.0%	39.6%	-67.37	-57.58	-49.56
Carbon sequestration	72%	80%	88%	-52.68	-57.58	-62.47

Table 3.3: Sensitivity analysis of carbon intensity of MACP biofuel





Figure 3.4: Sensitivity analysis of carbon intensity of MACP biofuel

3.2.2.2 Impacts of plant location

Collection distance (km)

To investigate location impacts, the BC electricity mix was changed to Alberta electricity mix while other parameters remained the same. It should be noted that the "green" electricity in BC, consisting of more than 90% generation capacity from hydro, as shown in Figure 3.5, favors the electricity-intensive process operations. Alberta grid is mostly made up of fossil fuels, resulting in an impact factor (855.7 g CO₂-eq/kWh delivered) that is more than fourteen times higher than that of BC's electricity (58.6 g CO₂-eq/kWh delivered) [50].



Figure 3.5: Electricity mix in British Columbia (left) and Alberta (right)

The carbon intensity of MACP biofuel using Alberta grid was 23.5 g CO₂-eq/MJ with the consideration of credits from biochar and avoided slash burning, and 94.4 g CO₂-eq/MJ without credits. Unlike in BC, the production emissions could not be offset by sequestrated carbon from biochar and avoided burden of slash burning when using Alberta electricity mix, therefore leading to a positive carbon intensity of MACP biofuel. Because of the large consumption of electricity, the GHG emissions at the conversion stage increased significantly and became dominant, as depicted in Figure 3.6. At the same time, energy consumption for pyrolysis became the most influencing parameter as indicated by sensitivity analysis in Figure 3.7, followed by carbon sequestration ability of biochar. The carbon intensity of MACP biofuel could be reduced with the increase of liquid yields, while collection and transportation distance remained having the least impacts.



Figure 3.6: Life cycle GHG emissions of MACP biofuel using Alberta electricity mix



Change of carbon intensity (g CO2-eq/MJ)

Figure 3.7: Sensitivity analysis of carbon intensity of MACP biofuel using Alberta electricity mix

The results addressed the importance of properly selecting the location for implementing the MACP system based on regional differences in electricity grid. The differences in relative

importance of influencing parameters in BC and Alberta also suggested that focus of system improvement should be location specific. Overall, there is a great potential in the region with clean electricity supply to deploy the MACP system for biofuel production to achieve substantial environmental benefits in terms of GHG mitigation.

3.2.2.3 Impacts of system expansion and allocation methods

In a multifunctional process with more than one product, the environmental burdens of the process have to be assigned to multiple products [92]. The ISO 14041 standard [93] suggests that wherever possible, system expansion has the highest priority to be used to include the additional functions of co-products, while allocation should be avoided. When allocation cannot be avoided, the inputs and outputs of the system should be partitioned between products based on the physical relationships such as mass or energy content. If the physical relationship cannot be established or used as the basis for allocation, it can also be done based on the economic proportion [93]. It should be noted that the system expansion provides a more comprehensive picture of the consequences of the process [92], thus is practically used in governments' regulations, such as California and BC's low carbon fuel standard (LCFS).

In this study, biochar was co-produced from the MACP system and could be utilized for soil application. Therefore, the system boundary could be expanded to include the exported function of biochar and assign biochar credit to biofuel, following BC-LCFS. Through the utilization of biochar, stable carbon in biochar could be sequestrated for a long time meanwhile GHG emissions from the production of commercial fertilizer could be avoided. However, if the exported function of co-product was not considered internally, the overall environmental burdens from the

production process should be shared by the main product and the co-product and allocated based on different relationships between them, i.e. mass, energy or economic values. The results obtained from using the four different methods are compared in Figure 3.8.



Figure 3.8: Life cycle GHG emissions of MACP biofuel using different allocation methods

The system expansion was the only way to consider the credits from sub-system of co-product biochar, while allocation methods simply assigned part of the total process emissions to biofuel product. As a result, the system expansion method led to the lowest carbon intensity of biofuel product with a 162% reduction from the conventional petroleum counterpart (2005 gasoline baseline). Owing to green electricity in BC and credits from avoided slash burning, the allocation methods also resulted in negative carbon intensities of MACP biofuel, ranging from -3.2 to -5.5 g CO₂-eq/MJ, corresponding to a GHG emission reduction of 103% to 106%.

The energy content share between biofuel and biochar were 52.6% and 47.4%, with a GHG intensity of -4.2 g CO₂-eq/MJ for both of them based on energy allocation. The mass allocation method gave a carbon intensity of -3.2 g CO₂-eq/MJ for biofuel product. The value allocation method relied on the revenues of biofuel and biochar, which were \$157.1 million and \$70.8 million on an annual basis with unit prices of \$1.01/L and \$385/tonne, respectively. The detailed economic analysis is given in Chapter 4. The biofuel had a higher economic share of 68.9% and therefore a higher credit of -5.5 g CO₂-eq/MJ. The GHG intensity of MACP biofuel based on Alberta electricity mix ranged from 23.5 to 50.3 g CO₂-eq/MJ with a reduction of 75% to 46% from fossil fuels, where system expansion method resulted in the lowest carbon intensity of biofuel. Regardless of different methods to treat the co-product and locations of deployment, MACP biofuel showed a great potential for GHG emissions reduction.

3.2.2.4 Electricity for microwave pyrolysis or electric vehicle (EV)

Unlike traditional pyrolysis where heat is provided from NCG and biochar combustion, the MACP system uses electricity to generate microwave to assist pyrolysis reactions with biochar as a coproduct and NCG for hydrogen production. As a premium energy with limited supply, electricity could be directly used to power electric vehicles, rather than being used to produce MACP biofuel to replace transportation fuels in internal combustion engine vehicles (ICEV). Based on the energy balance in Chapter 2, it was found that 100 MJ electric power could assist in producing 237.2 MJ biofuel in the MACP system, which was set as the basis for comparison. As depicted in Figure 3.9, electricity has two pathways to be consumed. One is to generate microwave power in the MACP system for biofuel production, with the energy contained in biofuel further used to fuel ICEVs. The other is to directly charge electric vehicles (EV).



Figure 3.9: Two pathways of electricity consumption for biofuel production and charging EV

It should be noted that fuel economy varies significantly from different vehicle models. To make a side-by-side comparison, 2021 Hyundai Ioniq and 2021 Hyundai Ioniq Electric were chosen for comparison, with an EPA fuel economy of 1.7 gal/100 mi and 25 kWh/100 mi, respectively [94]. The results showed that 100 MJ electricity enabled the EV to travel 179 km with a GHG emission rate of 9.1 g CO₂-eq/km and emit 1.6 kg CO₂-eq in total, while 237.2 MJ biofuel could make the ICEV to travel 171 km with a GHG emission rate of -79.9 g CO₂-eq/km and total GHG emissions of -13.7 kg CO₂-eq. The results indicated that using electricity for biofuel production did not reduce the vehicle travel distance but generated great environmental benefits from MACP system. The conclusion was consistent when Alberta grid was considered in the analysis, with 23.8 kg CO₂-eq GHG emissions for EV and 5.6 kg CO₂-eq GHG emissions for biofuel powered ICEV. effectively convert waste biomass into carbon negative biofuels, contributing to decarbonization of the transportation sector.

3.3 Conclusion

This chapter conducted a life cycle assessment (LCA) of a hypothetic MACP system located in BC. The results suggested that a negative carbon footprint of biofuel could be realized through MACP system, mainly owing to clean electricity mix in BC and credits from co-product biochar and avoided slash burning. MACP biofuel achieved a 162% GHG emissions reduction compared with conventional petroleum fuels, showing great environmental benefits. A sensitivity analysis revealed the importance of selecting the right location with low-carbon intensity electricity mix as well as improving the yields of bio-oil and biofuel product. The use of system expansion and different allocation methods to treat the co-product biochar resulted in different carbon intensity of MACP biofuel product, with the system expansion method giving rise to the lowest GHG emissions. MACP biofuel production was shown to be a preferred use of electricity, which led to comparable travel distance and much more GHG emissions reduction of ICEVs compared to directly charging EVs.

Chapter 4 TEA of MACP System

4.1 TEA model

With the specific case defined as described in Chapter 2, a TEA was conducted to evaluate the economic feasibility of MACP process, starting from the estimation of capital and operating costs as shown in the detailed framework of Figure 4.2 and followed a typical procedure in Figure 4.1. It should be noted that all the costs in this study were expressed in 2019 US dollars.



Figure 4.1 Typical economic analysis procedure



Figure 4.2 Basic framework for estimation of capital cost and operating cost

4.1.1 Cost estimation

4.1.1.1 Capital investment

The estimation of capital investment began with estimating the depreciable capital cost (DepC) with the size of the process units determined by the process mass and energy flow rates. The depreciable capital cost (DepC) was divided into several categories, including direct cost, indirect cost, contractor's fee and contingency. The delivered equipment cost should be first collected and then multiplied by cost factors to estimate other components of the depreciable capital cost as shown in Table 4.1 [95]. The installation factor for individual unit, which accounted for all costs required to make the equipment operable [95], could be found in Table C.2 of Appendix C.

Capital cost	Cost factor ^a	
Direct cost		
Delivered equipment	1	
Equipment installation	f ^b	
Buildings	0.32 ^c	
Auxiliary facilities	0.55°	
Indirect cost		
Engineering	0.32 ^d	
Construction	0.34 ^d	
Contractor's fee	0.18	
Contingency	0.36	

Table 4.1 Cost factors for estimating depreciable capital cost (DepC) [95]

^a Fraction of delivered equipment cost

^b See Table C.2 for individual installation factor

^c For plant at an existing site and solid-fluid process

^d For solid-fluid process

As the basis of estimation of depreciable capital cost, the delivered equipment cost usually refers to manufacturer's quotation or is obtained from the literature. The equipment costs from literatures should be scaled from the original capacities to design capacity using the following equation [95]:

$$C_2 = C_1 \times \left(\frac{Q_2}{Q_1}\right)^n \tag{4.1}$$

where C_1 is the base equipment cost at base capacity of Q_1 and C_2 is the new equipment cost at design capacity of Q_2 . With equipment cost at one capacity and the capacity exponent *n* (also known as scaling factor) known, the cost at another capacity can be obtained. The capacity exponent *n* usually ranges from 0.5 to 0.7, with 0.6 used in this study [96,97]. Since a pilot plant of MACP is under construction at the University of British Columbia, the equipment cost for MACP conversion unit was scaled from the quotation at a base capacity of 25 kg/h, mainly including biomass feeding system, bubbling fluidized bed pyrolyzer, cyclone, condenser, heat exchanger, afterburner, auxiliaries, etc. The other equipment costs were scaled from NREL reports based on design mass flow rates in Chapter 2 [23,98]. It should be noted that the equipment costs must be corrected for inflation over time, where the Chemical Engineering Plant Cost Index (CEPCI) in Table C.1 is one of the commonly used cost indices [99]. The current year for analysis was set to be 2019 due to the most recent availability of CEPCI. The detailed reference equipment costs, base capacities, design capacity, scaled and inflation corrected costs could be found in Appendix C.

Besides depreciable capital cost (DepC), total capital investment (TCI) also consisted of nondepreciable cost (NDepC), start-up cost (SC) and working capital (WC) as shown in Table 4.2. The fixed capital investment (FCI) included depreciable capital cost (DepC) and non-depreciable cost (NDepC) as commonly defined [95].

Capital cost	Calculation
Non-depreciable cost (NDepC)	
Land cost	0.015 ^a * DepC
Site development cost	0.0249 ^b * DepC
Fixed capital investment (FCI)	DepC + NDepC
Start-up cost (SC)	0.09° * FCI
Working capital (WC)	0.2 * FCI
Total capital investment (TCI)	FCI + SC + WC

 Table 4.2 Calculation of the total capital investment (TCI) [95]

^a Average value from 0.01 to 0.02

^b For plant at an existing site and solid-fluid process

^c Average value from 0.08 to 0.09

4.1.1.2 Operating cost

The operating cost, also called production cost or manufacturing cost synonymously, includes variable operating cost (VOC) and fixed operating cost (FOC). The VOC depends on the daily productivity and corresponding market prices of materials and utilities, consisting of costs for feedstock, materials, utilities and disposal, while the FOC is fixed including labor, maintenance, tax, etc.

The feedstock delivered cost to the gate of biorefinery was calculated using Akhtari's method [100] with modification by Nie [10] to reflect a BC specific scenario, which included raw material cost, machinery cost and transportation cost. The raw material cost for forest residues in BC was assumed to be low at a price of \$3/dry tonne since they were regarded as logging wastes and were

generally burned to avoid wildfire following BC's forestry management strategy [10]. The machinery cost for collecting forest residues was \$18.41/green metric tonne based on Nie's calculation [10]. The transportation cost was for shuttling forest residues from forest stands to feedstock delivery points (FDP) and transporting to biorefinery. The estimation of transportation cost was described in Table 4.3. The overall feedstock delivered cost was estimated to be \$91.78/dry tonne.

Parameter	Forest stands to FDPs by dump truck	FDPs to biorefinery by semi-trailer	Reference
Average speed, km/h	40	60	[10]
Waiting time for loading and unloading, h	2	2	[10]
Payload, tonne	11.8	23.25	[10]
Hourly rate, \$/h	55	85	[10]
Distance, km	12.5	52.8	[8,10]
Annual feedstock transportation cost, \$/yr	16,077,013	18,062,555	Calculated

Table 4.3 Estimation of feedstock transportation cost

The estimation of VOC and FOC were summarized in Table 4.4. The costs for materials and utility were either based on market prices or taken from literatures. It should be noted that, as described in Chapter 2, the consumption of MACP catalyst could be excluded from the system boundary since the nutrients could be fully recovered in the solid residues as fertilizer, where the net cost was assumed to be zero. The lifetime of hydrotreating and hydrocracking catalysts was assumed to be 2 years [23], while it was 3 years for hydrogen production catalyst [101]. The wastewater from biorefinery generally requires more stringent treatment before discharged. Due to limited information about practical wastewater treatment in biorefinery, the cost of \$1.36/tonne was used

in this study as reported by Yang et al. [22]. The FOC consisted of labor cost, maintenance and supplies, tax and insurance and plant overhead, which remained constant regardless of production rate as listed in Table 4.4. As discussed in Chapter 3, co-product biochar utilized as soil amendment could bring significant environmental benefits to the MACP system. Therefore, the price of biochar in soil application was used in the base analysis, while the impacts of biochar's different applications were discussed in the sensitivity analysis.

Parameter	Value	Reference
Variable operating cost (VOC)		
Feedstock delivered cost, \$/dry tonne	91.78	Calculated
Materials		
CoMo catalyst, \$/kg	44.09 ^a	[23]
Steam reforming catalyst, f of H_2 produced	7.80	[23]
Utility		
Electricity, \$/kWh	0.053 ^b	[102]
Wastewater disposal, \$/tonne	1.36	[22]
Fixed operating cost (FOC)		
Labor cost, million \$/yr	3.26	[23]
Maintenance and supplies		[95]
Maintenance material	1.8% of FCI	
Operating supplies	0.75% of FCI	
Plant maintenance	4.5% of FCI	
Tax and insurance		[95]
Property taxes	2% of FCI	
Insurance	1% of FCI	
Plant overhead		[95]
Fringe benefits	22% of labor cost	
Overhead (less fringe benefits)	50% of labor cost	
Co-product revenue		
Biochar, \$/tonne	385.00°	[103]

^a Converted from \$20/lb

- ^b Industrial electricity price in Vancouver
- ^c Average of \$200-500/ton (equivalent to \$220-550/tonne)

4.1.2 DCFROR model

After cost estimation, the profitability of the process can be assessed using a discounted cash flow rate of return (DCFROR) model. The minimum selling price (MSP) of biofuel was the main output from modeling, by manipulating the selling price to find the breakeven point where net present value (NPV) of the project equaled zero. The economic assumptions were presented in Table 4.5. Although 20 years is a common assumption for project life [23,36,70,101], this study used a 10year project life which considered the relatively small scale of biorefinery compared to conventional oil refinery and hence, a shorter payback period that investors would expect. The accelerated rates for depreciation are provided from many governments to encourage investment in clean energy systems, such as MACRS (Modified Accelerated Cost Recovery System) in US. The government of Canada uses accelerated Capital Cost Allowance (CCA) Class 43.1 and 43.2 for specified clean energy systems and equipment, where the systems to convert biomass into biooil fit under one of the categories [104]. Class 43.2 provides a 50% rate per year where it is halved to 25% for the first year, as shown in Table C.3 of Appendix C. The DCFROR modeling was performed in Excel with VBA code to find the breakeven point by iteration. The detailed spreadsheet can be found in Appendix C.

Parameter	Assumption		
Internal rate of return (IRR)	10%		
Project life	10 years		

Table 4.5 Economic assumptions for DCFROR model

Plant operating time	7884 h/yr		
Plant financing by equity /debt	40% / 60% of TCI		
Interest rate for debt financing	6.5%		
Term for debt financing	5 years		
Salvage value	0		
Depreciation schedule	CCA Class 43.2		
Income tax rate	26%		
Construction period	3 years		
	year 1: 30%, year 2: 50%, year 3: 20%		
Start-up time	3 months		
During start-up			
Revenue	50% of normal		
Variable operating cost (VOC)	75% of normal		
Fixed operating cost (FOC)	100% of normal		

4.2 **Results and discussion**

4.2.1 Cost estimation

Figure 4.3 illustrated the detailed TCI and installed equipment cost. The installed equipment cost dominated the TCI, accounting for 36.6%. In this study, hydrogen production showed the highest contribution (21%) to the installed equipment cost, which indicated a high capital expense required to utilize the NCG and make the system self-sufficient in hydrogen. As a mature process, on-site hydrogen production is commonly recognized as a high capital cost operation in the upgraded biofuel production system [22,23,39,70]. Jones et al. [70] reported a 28% contribution of hydrogen generation process to the TCI of a fast pyrolysis plant, and updated to 17.89% in their 2013 report [39]. Based on total installed cost (TIC) breakdown results from Dutta et al. [23], hydrogen plant was found to account for 23.72% and 21.04% for *in-situ* and *ex-situ*, respectively. Yang et al. [22] also noticed the largest share from hydrogen production, up to 41% to 64% of TIC for different scenarios. Since bio-oil contains high oxygen content which requires additional treatment, it is not

surprising that bio-oil upgrading process requires high capital expenses. Compared to conventional fast pyrolysis or catalytic pyrolysis conversion stage that contributed 30% to 60% of total installed cost (TIC), MACP conversion process showed a relatively lower capital cost requirement (14.16%), which agreed with the results of 12-20% from the only TEA study on MACP system by Yang et al. [22]. Therefore, MACP technology showed a potential in capital cost reduction. However, it should be noted that the reference capacity (25 kg/h) of pilot plant was very low, which resulted in great uncertainties in cost estimation when scaling up the process. The capital cost estimation of MACP conversion must be updated with the development of MACP reactor design and larger-scale demonstration plant deployment. The detailed contribution of each component in TCI can be found in Table 4.6.



Figure 4.3: Total capital investment and installed equipment costs

Table 4.6 Capital investment breakdown

Capital cost	Value (million \$)	Contribution
Depreciable cost (DepC)		
Direct cost		
Total installed cost (TIC)	174.77	36.59%
Buildings	28.03	5.87%
Auxiliary facilities	48.17	10.08%
Indirect cost		
Engineering	28.03	5.87%
Construction	29.78	6.23%
Contractor's fee	15.77	3.30%
Contingency	31.53	6.60%
Non-depreciable cost (NDepC)		
Land cost	5.34	1.12%
Site development cost	8.87	1.86%
Fixed capital investment (FCI)	370.28	77.52%
Start-up cost	33.33	6.98%
Working capital	74.06	15.50%
Total capital investment (TCI)	477.66	100.00%

The annual operating cost was estimated to be \$135.24 million as shown in Figure 4.4 and the detailed breakdown was in Table 4.7. Widely recognized as the largest cost contributor [28,39,70,101], the feedstock delivered cost was responsible for the majority of total operating cost, accounting for 44.59% at an annual cost of \$60.30 million. Although waste biomass could be obtained at a very low merchantable value, the challenges lay in collection and transportation of widely scattered waste biomass with low bulk density, which contributed significant operating cost as illustrated in Figure 4.4. Early in 2008, Ruan et al. [28] proposed small distributed biomass energy production systems (DBEPS) based on microwave assisted pyrolysis (MAP), which could offer a near-term solution to cut down feedstock-related costs and bring economic benefits to local farmers. The cost reduction of feedstock is undoubtedly a complicated problem that requires a

better waste management strategy either from government's regulation or from market development. The utility cost had a 22.01% contribution to the total operating cost, due to the large consumption of electricity for microwave generation. The reduction of electricity price and increase of energy efficiencies could help further reduce the utility cost. The material cost was significantly reduced owing to the utilization of potassium phosphate as MACP catalyst whose nutrients and associated values could be recovered in the solid product. The fixed operating cost (FOC), including labor cost, maintenance and supplies, tax and insurance and plant overhead, was mainly based on the fixed capital investment (FCI), which also contributed a large portion of total operating cost.



Figure 4.4 Annual operating costs (left) and distribution of feedstock delivered cost (right)

Table 4.7 Operating cost breakdown
Operating cost	Value (million \$/yr)	Contribution
Variable operating cost (VOC)		
Feedstock delivered cost	60.30	44.59%
Materials		
Hydrotreating catalyst	1.75	1.29%
Hydrocracking catalyst	0.30	0.22%
Steam reforming catalyst	0.07	0.05%
Utilities	29.77	22.01%
Wastewater treatment	0.23	0.17%
Fixed operating cost (FOC)		
Labor cost	3.26	2.41%
Maintenance and supplies		
Maintenance material	6.67	4.93%
Operating supplies	2.78	2.05%
Plant maintenance	16.66	12.32%
Tax and insurance		
Property taxes	7.41	5.48%
Insurance	3.70	2.74%
Plant overhead		
Fringe benefits	0.72	0.53%
Overhead (less fringe benefits)	1.63	1.20%
Total operating cost	135.24	100.00%

4.2.2 Minimum selling price

Based on the economic assumptions in Table 4.5, the minimum selling price (MSP) of MACP biofuel was calculated to be \$1.01/L, which was more than double of gasoline price at about \$0.5/L [101]. The detailed DCFROR model spreadsheet could be found in Table C.3 of Appendix C. So far, there is only one TEA study available on microwave pyrolysis by Yang et al. [22], who reported the MSP of target product jet fuels as \$3.78-4.78/gallon (\$1.00-1.26/L) based on different scenarios for the co-products and solvents used for the hydrogenation reaction. A literature review was also conducted on TEA studies of pyrolysis of biomass, including conventional fast pyrolysis,

catalytic pyrolysis and novel microwave pyrolysis. The results in Table A.1 showed that the MSP ranged from \$0.46-1.73/L [22–27,39,70,105]. It should be noted that the economic assumptions varied from different studies, such as project life, acceptable internal rate of return (IRR), interest rate, depreciation schedule, etc. The variation in those assumptions has impacts on MSP in different degrees and makes it difficult to compare results from different studies. For example, some TEA studies assumed a 20-year project life, while some used 30 years. In our analysis, we assumed a relatively shorter project life for a small scale biorefinery, while the MSP could be reduced to \$0.96/L if the project life was assumed to be 20 years (see Table C.4 for detailed DCFROR model spreadsheet). The impacts of other economic consumptions were further discussed in the sensitivity analysis.

4.2.3 Sensitivity analysis

4.2.3.1 Influencing parameters

As uncertainties exist in the data from both process design and cost estimation, a sensitivity analysis is necessary to test the robustness of the results and to identify the most influencing parameters for further improvement.



Figure 4.5: Sensitivity analysis of MSP of MACP biofuel

As illustrated in Figure 4.5, a sensitivity analysis was performed by changing the nominal values by $\pm 10\%$. The results indicated that the most influencing parameters were associated with capital investment and conversion efficiencies. The increase of liquid yields in MACP conversion and upgrading process could significantly reduce the MSP of MACP biofuel. Therefore, research efforts should be made to increase the conversion efficiencies so as to improve the economic benefit. The fixed capital investment (FCI) also showed a significant impact on MSP of MACP biofuel. Since biochar shared 28 wt% in products of MACP conversion, its revenue had a moderate influence on MSP of MACP biofuel at a change of $\pm 4.51\%$. Although MACP conversion consumed a great amount of electricity for microwave power generation, parameters related to electricity, i.e. price and consumption, had less impacts on MSP of MACP biofuel. Other parameters associated with operating cost and economic assumptions showed little impact.

4.2.3.2 Impacts of plant location

The regional differences are mainly embodied in electricity structure and corresponding market price. Although the impacts from electricity price were assessed in last section, the price in different provinces of Canada can vary more than 10% as shown in Figure 4.6. Therefore, it was necessary to investigate the regional electricity impacts on MSP of MACP biofuel.



Figure 4.6: Average large industrial electricity prices in major cities in Canada (left: taken from [102])

The MSPs of MACP biofuel in different regions were shown in Figure 4.7, where it could be as low as \$0.96/L with the lowest electricity price in Winnipeg and as high as \$1.15/L in Toronto with the highest electricity price. As recognized in the last section, despite the large consumption of electricity in MACP system, electricity price had only minor impact on biofuel MSP, as shown in Figure 4.5. The highest variation of MSP was found to be 13.61% resulting from a significant increase (71.12%) of electricity price from Vancouver to Toronto. Although electricity price was not a significantly influencing parameter, investors still should avoid choosing a location with a very high electricity price and high carbon intensity.



Figure 4.7: (a) MSP of MACP biofuel in different regions of Canada and (b) Change of MSP compared to Vancouver baseline

4.2.3.3 Applications of biochar

As an important co-product from MACP process, biochar shows great potential for many applications. This study used its soil application as the baseline, which considered the carbon sequestration of biochar for environmental benefits as discussed in Chapter 3. Energy application as a solid fuel to replace coal and as activated carbon for adsorption applications are two other common applications of biochar. The former represents the lower-value application of biochar,

while the latter represents the higher-value application. If the biochar is used as solid fuel to replace coal, the price of biochar should be estimated based on the market price of wood pellets which is currently sold as a renewable solid fuel. The bulk price was about CA\$120/tonne, equivalent to CA\$6.7/GJ with a HHV of 18 GJ/tonne as quoted by the supplier [106]. With a relatively higher HHV of 27.04 MJ/kg, the price of biochar as an alternative solid fuel was estimated to be \$136.3/tonne. As the co-product revenue was reduced, it resulted in an increased MSP of main product biofuel at \$1.31/L. The market price of activated carbon varies a lot due to the different characteristics and specific applications. Alhashimi and Aktas [34] conducted a meta-analysis to compare biochar and activated carbon from environmental and economic aspects, and reported a wide price range from \$0.8 to \$17.8 per kg. As biochar from MACP system didn't undergo an activation process, it could be regarded as a precursor of activated carbon. Even if \$0.8/kg was used as the price of biochar, which was a conservative assumption, the MSP of MACP biofuel could be significantly reduced to \$0.52/L, comparable to conventional petroleum fuels. The coproduction of value-added biochar and liquid biofuel should thus be considered, which would bring the flexibility to the biorefinery to seek the highest economic and environmental benefits.

4.2.3.4 Impacts of policy support

To encourage the development of low-carbon technologies, BC has implemented carbon tax since 2008 [107]. The carbon tax has been rising at CA\$5 per tonne annually, except in 2020, where the annual increase was frozen at the 2019 level (CA\$40 per tonne) as part of pandemic relief policies. In April 2021, BC's carbon tax increased from CA\$40 to CA\$45 per tonne and is scheduled to rise to CA\$50 per tonne in 2022 [107]. Starting in 2023, the BC government will be forced to double the annual increase in order to harmonize with the federal rate of CA\$65 per tonne, and then triple

it in 2024 to a total of CA\$80 per tonne. The CA\$15 per tonne increase will continue annually until BC's carbon tax matches the 2030 target of CA\$170 per tonne. Figure 4.8 showed the impacts of carbon tax on petroleum price and MSP of MACP biofuel following Nie's method [101]. Benefited from negative carbon intensity, the MSP of MACP biofuel would continuously decrease with the rising of carbon tax. Petroleum fuel would encounter huge pressure with the increased penalty. As illustrated in Figure 4.8, it was predicted that the MACP biofuel would be priced competitively to petroleum fuels before 2026 under current carbon tax schedule. Furthermore, if a 1% annual cost reduction was considered to be achieved by technology advancement, the breakeven point could be achieved as early as 2025. The results emphasized the importance of policy support in low-carbon innovations to transition away from fossil fuels and achieve global net-zero target.



Figure 4.8: Impacts of BC carbon tax and technology advancement on fuel prices

4.3 Conclusion

The capital investment and operating cost of proposed MACP system were estimated in this chapter and MSP of MACP biofuel was calculated to be \$1.01/L via DCFROR model. The current price was not competitive to conventional petroleum fuels, thus requiring further technology improvement and policy support to bridge the price gap. In particular, the key parameters were identified as fixed capital investment (FCI), liquid yields in MACP conversion and upgrading process. The negative carbon intensity and co-product revenue from value-added applications of biochar could potentially make MACP biofuel economically competitive to petroleum fuels. The co-production of MACP biofuel and biochar could bring flexibility to biorefinery from both economic and environmental perspectives.

Chapter 5 Conclusions and Future Work

5.1 Conclusions

Forest residues from logging operations are abundant in British Columbia (BC), which has no merchantable values and imposes wildfire risks. As a promising strategy to decarbonize the transportation sector, liquid biofuel is the only alternative to petroleum-based liquid fuel compatible with the existing infrastructure and has been promoted by BC government via the lowcarbon fuel standard regulations. Therefore, in order to make good use of the under-utilized biomass resource, conversion of forest residues to liquid biofuels becomes attractive from both supply and demand points of view. MACP as an emerging technology can efficiently convert biomass into target products with improved qualities (e.g. lower oxygen content in bio-oil, better structured biochar, etc.) due to its unique volumetric local heating and *in-situ* catalytic vapour upgrading. A techno-economic assessment (TEA) and a life cycle assessment (LCA) were therefore conducted to investigate the economic feasibility and environmental benefit of utilizing abundant forest residues in BC based on MACP technology and to identify the key economic and environmental issues for future improvement. The key findings are listed below:

1) An LCA of a hypothetic MACP system located in BC revealed that a negative carbon footprint of MACP biofuel could be realized, mainly owing to clean electricity mix in BC and carbon sequestration of co-product biochar. With the credit from biochar, MACP biofuel achieved a 162% GHG emissions reduction compared with conventional petroleum fuels, showing great environmental benefits. A sensitivity analysis revealed the importance of selecting the right location with low-carbon electricity mix as well as improving the yields of bio-oil and biofuel

product. The use of system expansion and different allocation methods to treat the co-product biochar resulted in different carbon intensity of MACP biofuel product, with the system expansion method giving the lowest GHG intensity of biofuel product. MACP biofuel production was shown to be a good application of electricity, which led to comparable travel distance and much more GHG emissions reduction of biofuel powered ICE vehicles compared to the direct use of electricity for electric vehicles.

2) Based on estimated capital investment and operating cost of proposed MACP system, the MSP of MACP biofuel was calculated to be \$1.01/L via DCFROR model, suggesting that it was not competitive with conventional petroleum fuels, thus requiring further technology improvement and policy support to bridge the price gap. The key parameters influencing biofuel MSP were identified as fixed capital investment (FCI), liquid yields in MACP conversion and upgrading process. The co-production of MACP biofuel and biochar could bring both economic and environmental flexibility to the biorefinery.

5.2 Limitations and future work

Although the proposed MACP system has shown the potential for high GHG emissions reduction, uncertainties exist in data quality and methodology. Thus, the following issues need to be addressed in the future work:

 Since MACP is still under development at lab and pilot scales, performance data has been obtained from scaling the inventory data measured at lab or pilot scale to estimate the actual performance of the integrated commercial process, regional variations of feedstock supply, product distribution and use, etc. This has inevitably introduced high uncertainties to the modeling results. One approach is to collect additional data to derive probability distributions for the key model variables, such that a Monte Carlo simulation can be performed to probabilistically examine these uncertainties.

- 2) The MACP process analyzed in this study consists of assumptions such as simplified supply chain, theoretical electric energy consumption for MACP reactor, products distribution used for the design of a pilot unit, hypothetic on-site bio-oil upgrading and hydrogen production processes, all of which have not been tested in a commercial integrated MACP process. The use of assumptions is inevitable in the process synthesis and analysis at the early stage of MACP development. However, a more comprehensive study using real process design and process performance data should be carried out in the future to update the results from the current analysis.
- 3) In the current study, the estimation of capital cost relies on literature data and quotes for a pilot design. In the future, quotes from manufacturers for specific units of a commercial plant should be used for economic analysis. The operating cost regarding materials, manpower, and the associated upstream supply chains also needs to be revisited (e.g. to account for economies of scale).
- 4) It is widely recognized and proved from this study that the use of system expansion and allocation methods could give significant variation in LCA results. Therefore, it is important to apply the most suitable method following the local standards and specific purpose of the

study. The system boundaries also vary among different studies. In the current study, e.g. emissions associated with the manufacturing of building equipment materials are excluded in the system boundary. It is thus important in the future study to examine the sensitivity of the modeling results to the variation of system boundary.

- 5) A centralized system requires long distance transportation of forest residues, resulting in high biomass supply cost and emissions associated with fuel consumption. Scenarios based on distributed MACP systems are worth examining to see whether such distributed systems can reduce the biofuel production cost and increase GHG emission mitigation.
- 6) Biochar is shown to contribute significantly to GHG sequestration and cost reduction. However, there are high uncertainties on biochar price and environmental stability. Further improvement on biochar performance could be carried out in the future based on a comprehensive literature review and laboratory test of biochar produced from the MACP reactor.

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Appendices

Appendix A Literature review

Product	Feedstock	Technology	Capacity	Capital cost	Operating cost	MSP	Reference
Trouter	I Clustock	reemong,	(dry tonne/day)	(million \$)	(million \$/yr)	(\$/L)	Reference
Gasoline and diesel	Hybrid poplar	Fast pyrolysis	2000	303/188	-	$0.54^{a}/0.46^{b}$	[70]
Naphtha and diesel	Com stover	Fast pyrolysis	2000	287/200	109/123	0.82 ^c /0.56 ^d	[24]
	Com stover		2000	911/585	-	$1.73^{e}/0.90^{f}$	[24]
Gasoline and diesel	Woody biomass	Fast pyrolysis	2000	700	-	0.90	[39]
Gasoline and diesel	Corn stover	Fast pyrolysis	2000	429	84	0.68	[26]
Gasoline and diesel	Forest residues	Fast pyrolysis	2000	427	154	1.65	[27]
Gasoline and diesel	Hybrid poplar	Catalytic pyrolysis	2000	457	142	0.97	[25]
Gasoline and diesel	Woody biomass	in-situ/ex-situ catalytic pyrolysis	2000	546/590	109/103	0.91/0.87	[23]
Gasoline and diesel	Woody biomass	in-situ/ex-situ catalytic pyrolysis	2000	-	-	1.11/1.13	[105]
Jet	Hybrid poplar	Microwave-assisted catalytic pyrolysis	1000	286/183/175/292	53/48/52/56	1.00/1.16/1.26/1.16 ^g	[22]

Table A.1: Reported TEA studies on pyrolysis of biomass

^a For a stand-alone "nth" plant

^b For an integrated plant co-located with an existing refinery

^c For hydrogen production scenario

^d For hydrogen purchase scenario

^e For first-of-a-kind hydrogen production scenario

^f For first-of-a-kind hydrogen purchase scenario

^g For scenarios with different hydrogenation solvent, heat integration and co-product treatment

Feedstock	Target products	Technology	Functional unit (FU)	System boundary	Location	Life cycle GHG emissions (g CO2-eq/FU)	Reference	
Forest residues	Gasoline and diesel	Fast pyrolysis	1MJ of fuel	Well_to_wheel	US	Gasoline: 39/Diesel: 39	[38]	
Porest residues	Gasonne and dieser	T ast pyrorysis	1km ^a	wen-to-wheel	0.5.	Gasoline: 117/Diesel: 98	[20]	
Corn stover	Gasoline and diesel	Fast pyrolysis	1km ^a	Well-to-wheel	U.S.	Gasoline: 37/Diesel: 15	[37]	
Woody biomass	Gasoline and diesel	Fast pyrolysis	1MJ of fuel	Well-to-wheel	U.S.	18.9	[39]	
Forest residues	Gasoline and diesel	Fast pyrolysis	1MJ of fuel	Well-to-wheel	U.S.	Gasoline: 33.8/Diesel: 34.0	[36]	
Hybrid poplar	Gasoline and diesel	Fast pyrolysis	1MJ of fuel	Well-to-wheel	Spain	Gasoline: 39.41/Diesel: 39.13	[108]	
Oil palm empty	Die eil	Foot munchasia	ling of his sil	Wall to meduat	Malavaia	1160	[100]	
fruit bunch	D10-011	Fast pyrorysis	TKg OI DIO-OII	wen-to-product	Malaysia	4400	[109]	
Dland fandataals	Casalina and diasal	in-situ catalytic pyrolysis	1ML of fuel	Wall to wheel	116	Gasoline: 9.2/Diesel: 9.3	[22]	
Blend feedstock ^b	Gasonne and dieser	ex-situ catalytic pyrolysis	TMJ OF TUEL	wen-to-wheel	0.3.	Gasoline: 10.2/Diesel: 10.3	[23]	
Woody biomass	Gasoline and diesel	ex-situ catalytic pyrolysis	1MJ of fuel	Gate-to-gate	U.S.	-19.8	[72]	

Table A.2: Reported LCA studies on pyrolysis of biomass

^a Traveled by a light-duty vehicle

^b 45% pulpwood, 32% wood residues, 3% switchgrass, and 20% construction and demolition waste

Appendix B Emission factors

	-
Process	Emission factor
Feedstock collection	
Diesel for on-site processing ^a (kg CO2-eq/MJ diesel)	1.35E-01
Medium duty truck ^b (kg CO2-eq/tonne-km)	5.67E-01
Feedstock transportation	
Heavy duty truck ^c (kg CO2-eq/tonne-km)	1.82E-01
Conversion	
Pretreatment	
Diesel for loader ^a (kg CO2-eq/MJ diesel)	1.35E-01
Electricity ^d (kg CO2-eq/kWh)	5.86E-02
MACP conversion	
Electricity (kg CO2-eq/kWh)	5.86E-02
Catalyst ^e (kg CO2-eq/kg)	1.19E+00
Biochar C sequestration (kg CO2-eq/kg)	-1.47E+00
Fertilizer displaced ^f (kg CO2-eq/kg nutrient)	-3.55E+00
Upgrading	
Electricity (kg CO2-eq/kWh)	5.86E-02
CoMo catalyst ^g (kg CO2-eq/kg)	8.67E+00
Hydrogen production	
Electricity (kg CO2-eq/kWh)	5.86E-02
Ni catalyst ^h (kg CO2-eq/kg)	9.50E-01
Avoided burden of slash burning (kg CO2-eq/dry kg FR)	-2.01E-01

Table B.1: Process emission factors (BC, 2020, AR5-100 year)

^a [50] Equip Emis Factors - Wheeled loader - Diesel; ^b [50] Freight Emissions - Medium Duty Truck - Petrol diesel; ^c
[50] Freight Emissions - Heavy Duty Truck - Petrol diesel; ^d [50] BC electricity mix; ^e [76] Potassium phosphate; ^f
[50] Fertilizer - Nitrogen; ^g [76] Co/Mo/Al₂O₃; ^h [76] Mo/Ni/Al₂O₃

	Coal	Fuel Oil	Gas Boiler	Wind	Solar	Biomass	Hydro	Total
Alberta								
Power generation ^a (GJ)	117.28	0.32	84.59	18.33	0.09	2.46	7.42	230.51
Contribution to grid mix (%)	50.88	0.14	36.70	7.95	0.04	1.07	3.22	100.00
GHG emissions ^b (g CO2-eq/kWh delivered)	1196.94	1233.02	661.86	4.08	3.93	27.19	46.88	855.74
British Columbia								
Power generation ^a (GJ)	0.00	0.83	5.90	3.66	0.03	15.21	247.22	272.84
Contribution to grid mix (%)	0.00	0.30	2.16	1.34	0.01	5.57	90.61	100.00
GHG emissions ^b (g CO2-eq/kWh delivered)	1078.51	838.31	562.14	4.04	3.90	23.66	46.88	58.56

Table B.2: Electricity mix profile and fuelcycle GHG emissions for electricity generation in Alberta and British Columbia

^a [50] Power Gen; ^b [50] Elec Emissions

Appendix C Economic assessment

Year	CEPCI	Year	CEPCI
2000	394	2010	551
2001	394	2011	586
2002	396	2012	585
2003	402	2013	567
2004	444	2014	576
2005	468	2015	557
2006	500	2016	542
2007	525	2017	567.5
2008	575	2018	603.1
2009	521	2019	607.5

 Table C.1: Chemical Engineering Plant Cost Index (CEPCI) [99]

Process	Base capacity	Base purchased equipment cost/\$	Installed cost/\$	Installation factor (f)	Current capacity	Scaled purchased equipment cost	Scaled installed cost	Scaling factor	Base year	Current year	Scaled purchased equipment cost in 2019\$	Scaled installed cost in 2019\$	Reference
Pretreatment	550 dry tonne/day	2,255,061	5,570,000	2.47	2000 dry tonne/day	4,892,813	12,085,248	0.6	2003	2019	7,393,990	18,263,155	[98]
MACP conversion	25 kg/h	95,256	190,512	2.00	2000 dry tonne/day	12,377,120	24,754,239	0.6	2019	2019	12,377,120	24,754,239	Pilot design
Condensation and product separation	6.56 kg/s	12,173,913	22,400,000	1.84	6.48 kg/s	12,087,858	22,241,659	0.6	2011	2019	12,531,354	23,057,692	[23]
Upgrading	6.56 kg/s	18,786,127	32,500,000	1.73	6.48 kg/s	18,653,332	32,270,264	0.6	2011	2019	19,337,711	33,454,241	[23]
Hydrogen production	0.88 kg/s	36,412,526	70,640,300	1.94	0.28 kg/s	18,245,106	35,395,506	0.6	2011	2019	18,914,508	36,694,146	[23]
Wastewater treatment	2.70 kg/s	7,238,690	17,155,696	2.37	6.01 kg/s	11,702,485	27,734,890	0.6	2011	2019	12,131,843	28,752,467	[23]
Auxiliary utilities	2000 dry tonne/day	4,724,929	9,449,857	2.00	2000 dry tonne/day	4,724,929	9,449,857	0.6	2011	2019	4,898,283	9,796,567	[23]

Table C.2: Estimation of capital costs

Year	-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed capital investment (equity)	44.43	74.06	29.62										
Debt	85.98	143.30	57.32										
Loan payment				73.98	73.98	73.98	73.98	73.98					
Interest	5.59	15.27	19.98	19.98	16.47	12.74	8.76	4.52	0.00	0.00	0.00	0.00	0.00
Loan principal	85.98	234.87	307.45	253.45	195.94	134.70	69.47	0.00	0.00	0.00	0.00	0.00	0.00
Start-up			13.33										
Working capital			29.62										
Revenue													
Biofuel sales				137.50	157.14	157.14	157.14	157.14	157.14	157.14	157.14	157.14	157.14
Biochar sales				61.97	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82
Total annual revenue				199.47	227.96	227.96	227.96	227.96	227.96	227.96	227.96	227.96	227.96
Operating cost													
Variable operating cost				86.65	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42
Fixed operating cost				42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81
Total annual operating cost				129.46	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24
Depreciation				89.02	133.53	66.76	33.38	16.69	8.35	4.17	2.09	1.04	0.52
CCA Class 43.2				25.00%	37.50%	18.75%	9.38%	4.69%	2.34%	1.17%	0.59%	0.29%	0.15%
Net revenue				-39.00	-57.28	13.23	50.59	71.52	84.38	88.55	90.64	91.68	92.20
Loss forward				0.00	-39.00	-96.27	-83.04	-32.46	0.00	0.00	0.00	0.00	0.00
Taxable income				-39.00	-96.27	-83.04	-32.46	39.06	84.38	88.55	90.64	91.68	92.20
Income tax				0.00	0.00	0.00	0.00	10.16	21.94	23.02	23.57	23.84	23.97
Cash flow	-44.43	-74.06	-72.57	-3.98	18.74	18.74	18.74	8.59	70.79	69.70	69.16	68.89	68.75
Discounted factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39
Annual present value	-53.76	-81.46	-72.57	-3.61	15.49	14.08	12.80	5.33	39.96	35.77	32.26	29.22	26.51
Net present value			0.00										
Accumulative discounted cash flow	-53.76	-135.23	-207.80	-211.42	-195.93	-181.84	-169.04	-163.71	-123.75	-87.99	-55.72	-26.51	0.00

Table C.3: The 10-year project life DCFROR model spreadsheet (million \$)

Note: Net revenue = Total annual revenue - Total annual operating cost - Interest - Depreciation; Taxable income = Net revenue + Loss forward; Income tax = Max (0, taxable income) \times Tax rate; Cash flow = Total annual revenue - Total annual operating cost - Loan payment - Income tax.

Year	-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed capital investment (equity)	44.43	74.06	29.62										
Debt	85.98	143.30	57.32										
Loan payment				42.77	42.77	42.77	42.77	42.77	42.77	42.77	42.77	42.77	42.77
Interest	5.59	15.27	19.98	19.98	18.50	16.93	15.25	13.46	11.55	9.52	7.36	5.06	2.61
Loan principal	85.98	234.87	307.45	284.67	260.40	234.56	207.04	177.73	146.51	113.27	77.86	40.16	0.00
Start-up			13.33										
Working capital			29.62										
Revenue													
Biofuel sales				112.12	128.14	128.14	128.14	128.14	128.14	128.14	128.14	128.14	128.14
Biochar sales				61.97	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82
Total annual revenue				174.09	198.96	198.96	198.96	198.96	198.96	198.96	198.96	198.96	198.96
Operating cost													
Variable operating cost				86.65	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42
Fixed operating cost				42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81
Total annual operating cost				129.46	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24
Depreciation				89.02	133.53	66.76	33.38	16.69	8.35	4.17	2.09	1.04	0.52
CCA Class 43.2				25.00%	37.50%	18.75%	9.38%	4.69%	2.34%	1.17%	0.59%	0.29%	0.15%
Net revenue				-64.37	-88.31	-19.97	15.09	33.57	43.83	50.03	54.27	57.62	60.59
Loss forward				0.00	-64.37	-152.68	-172.65	-157.55	-123.98	-80.15	-30.12	0.00	0.00
Taxable income				-64.37	-152.68	-172.65	-157.55	-123.98	-80.15	-30.12	24.15	57.62	60.59
Income tax				0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.28	14.98	15.75
Cash flow	-44.43	-74.06	-72.57	1.86	20.96	20.96	20.96	20.96	20.96	20.96	14.68	5.97	5.20
Discounted factor	1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39
Annual present value	-53.76	-81.46	-72.57	1.69	17.32	15.74	14.31	13.01	11.83	10.75	6.85	2.53	2.01
Net present value			0.00										
Accumulative discounted cash flow	-53.76	-135.23	-207.80	-206.11	-188.79	-173.05	-158.73	-145.72	-133.89	-123.14	-116.29	-113.76	-111.75

Table C.4: The 20-year project life DCFROR model spreadsheet (million \$)

Note: Net revenue = Total annual revenue - Total annual operating cost - Interest - Depreciation; Taxable income = Net revenue + Loss forward; Income tax = Max (0, taxable income) \times Tax rate; Cash flow = Total annual revenue - Total annual operating cost - Loan payment - Income tax.

Year	11	12	13	14	15	16	17	18	19	20
Fixed capital investment (equity)										
Debt										
Loan payment										
Interest	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Loan principal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Start-up										
Working capital										
Revenue										
Biofuel sales	128.14	128.14	128.14	128.14	128.14	128.14	128.14	128.14	128.14	128.14
Biochar sales	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82	70.82
Total annual revenue	198.96	198.96	198.96	198.96	198.96	198.96	198.96	198.96	198.96	198.96
Operating cost										
Variable operating cost	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42	92.42
Fixed operating cost	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81	42.81
Total annual operating cost	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24	135.24
Depreciation	0.26	0.13	0.07	0.03	0.02	0.01	0.00	0.00	0.00	0.00
CCA Class 43.2	0.07%	0.04%	0.02%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Net revenue	63.46	63.59	63.66	63.69	63.71	63.72	63.72	63.72	63.72	63.72
Loss forward	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Taxable income	63.46	63.59	63.66	63.69	63.71	63.72	63.72	63.72	63.72	63.72
Income tax	16.50	16.53	16.55	16.56	16.56	16.57	16.57	16.57	16.57	16.57
Cash flow	47.22	47.19	47.17	47.16	47.16	47.16	47.16	47.16	47.16	47.16
Discounted factor	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
Annual present value	16.55	15.04	13.66	12.42	11.29	10.26	9.33	8.48	7.71	7.01
Net present value										
Accumulative discounted cash flow	-95.20	-80.17	-66.50	-54.08	-42.79	-32.53	-23.20	-14.72	-7.01	0.00

Note: Net revenue = Total annual revenue - Total annual operating cost - Interest - Depreciation; Taxable income = Net revenue + Loss forward; Income tax = Max (0, taxable income) \times Tax rate; Cash flow = Total annual revenue - Total annual operating cost - Loan payment - Income tax.