ASSESSING COMMUNITY BIOENERGY DEVELOPMENT POTENTIAL IN NORTHERN AND REMOTE INDIGENOUS COMMUNITIES

A Thesis Submitted to the College of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements for the Degree of Master of Science
In the Department of Geography and Planning
University of Saskatchewan
Saskatoon

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ABSTRACT

Many rural and remote Indigenous communities in northern Canada's boreal forest zone are not connected to the continental energy grid or are 'end-of-line' communities and suffer from energy insecurity due to unreliable energy supplies and high energy costs. Biomass, a significant renewable energy source, holds potential for addressing the energy insecurity of these northern communities. Though different tools and techniques have been used to assess bioenergy potential in different parts of the world, a detailed framework, and step-by-step processes for assessing bioenergy potential in remote northern communities based on local socio-economic and environmental settings are limited. Hence, the purpose of this research is to assess community bioenergy potential (CBP) by advancing an assessment framework in a northern context. This study focuses on Southend, a Peter Ballantyne Cree Nation (PBCN) community in north-east Saskatchewan, to investigate the potential for community bioenergy development from forest residues. By applying an integrated framework of CBP assessment, this study provides a comprehensive evaluation of bioenergy potential in Southend, considering all the technical, economic, environmental, and sustainability aspects crucial to assess in the early stages of community energy planning. Using spatial tools and energy conversion models, available biomass resources and their energy potential have been estimated under various scenarios. The results reveal a significant biomass resource base in Southend, yielding an estimated 132,617 odt of forest residues annually. Energy production potential varies across scenarios, with gasification technology offering the highest output at 329,022 MWh, benefiting from the high conversion efficiency and high heating value of biomass. Biomass availability within 20 km of the community and 5 km of roads is deemed sufficient to operate bioenergy facilities exceeding community needs. The study also evaluates the environmental benefits of bioenergy, particularly its potential to reduce GHG emissions. The results emphasize the importance of using high-efficient conversion technologies not only to maximize energy yields but also to minimize environmental impacts. Overall, by prioritizing efficient conversion technologies and optimizing biomass supply-demand dynamics, Southend can strengthen community energy security and contribute to Canada's goal of emission reduction as a global climate change mitigation initiative for a resilient future.

Keywords: Biomass, Community energy, Energy potential, Forest residue, Indigenous community, Northern Canada.

ACKNOWLEDGEMENTS

First and foremost, I am profoundly grateful to Almighty Allah for providing me with the strength, health, and perseverance to complete this thesis. I acknowledge everyone without whose support this dissertation would have been impossible. I extend my heartfelt gratitude to my supervisor, Dr. Bram Noble, Professor and Vice Dean of Research, Scholarly, and Artistic Work at the College of Arts and Science, University of Saskatchewan. His unwavering support, insightful guidance, and academic expertise were invaluable in shaping this research. I am beyond grateful to Professor Greg Poelzer, Co-Director; and Jackie Martin, Project Manager of the Community Appropriate Sustainable Energy Security (CASES) partnership at the University of Saskatchewan for their technical and logistic support, which were crucial for the successful completion of this research. A special thanks and gratitude go to Dr. Tayyab Shah, Geospatial Research Manager at the University of Saskatchewan's Canadian Hub for Applied and Social Research (CHASR), for his exceptional cooperation, technical support, and GIS training, all of which were instrumental in the development and completion of this research. I would also like to extend my gratitude to Omar Farag, Senior Projects Lead of QUEST Canada; Dr. Kirby Calvert, Team Lead; Rebecca Jahns, Coordinator of Collaborative Mapping and Stakeholder Engagement of Co-Mapping Solutions Inc.; and Silas Asante, Graduate student of Geography at the University of Saskatchewan, for their collaborative engagement in this research work. Finally, I gratefully acknowledge Mitacs Canada, CASES, and the Department of Geography and Planning, University of Saskatchewan, for providing funding grants that made this research and my Master's study program in Geography possible.

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LIST OF ABBREVIATIONS

CAD	Canadian Doller
CBP	Community Bioenergy Potential
CEP	Community Energy Planning
CO_2	Carbon Di-oxide
CRE	Community Renewable Energy
CST	Combustion Steam Turbines
EA	Environmental Assessment
ECCC	Environment and Climate Change Canada
ENRC	Environment and Natural Resources Canada
EROI	Energy Return on Investment
EUBIA	European Biomass Industry Association
GCC	Gasification Combined Cycle
GHGs	Greenhouse Gases
GIS	Geographic Information System
HCE	High Conversion Efficiency
HE	High Efficiency
HHV	High Heating Value
IEA	International Energy Agency
INAC	Indigenous and Northern Affairs Canada
LCA	Life Cycle Assessment
LCE	Low Conversion Efficiency
LE	Low Efficiency
LHV	Low Heating Value
MLTC	Meadow Lake Tribal Council
MW	Megawatt
NRC	Natural Resources Canada
ODT	Oven Dry Tons
PBCN	Peter Ballantyne Cree Nation
RE	Renewable Energy
SDGs	Sustainable Development Goals

CHAPTER 1

INTRODUCTION

In the quest for sustainable and resilient energy solutions, the harnessing and development of renewable energy (RE) resources have emerged as a promising avenue, particularly in regions characterized by remoteness. Remote communities living in the Circumpolar North usually stand at the intersection of unique socio-economic and environmental challenges because of geographic isolation and global climate change, and often grapple with energy insecurity owing to limited energy infrastructure and high costs (Rakshit *et al.*, 2019; MacKay *et al.,* 2021; Holdmann *et al.*, 2022). Across northern Canada and Alaska alone, there are approximately 280 remote communities, mostly Indigenous, that are not connected to the North American power grid or natural gas distribution network (Leonhardt *et al.,* 2023). Most of these communities are exposed to extreme cold weather while also suffering from energy poverty (Rezaei and Dowlatabadi, 2016; Karanasios and Parker, 2018; Buss *et al.*, 2021). These off-grid communities usually rely on imported diesel fuel for power generation, which is expensive, has an impact on the environment and air quality, and also contributes to global climate change (Mercer *et al.*, 2020; Buss *et al.*, 2022; Leonhardt *et al.*, 2022). Even in many northern grid-connected communities, energy infrastructure is aging and operating at or near capacity, with electricity and home heating costs 6-10 times higher than the national average (Lovekin, 2021).

Access to affordable and clean energy, as well as strengthening local energy security, is thus vital for the socio-economic development and overall well-being of these northern and remote Indigenous communities. Community renewable energy (CRE) is emerging as a sustainable means of providing clean energy and transitioning remote communities towards a low-carbon and secure energy future (Menghwani *et al.,* 2022; Leonhardt *et al.,* 2023; McMaster *et al.,* 2023). Hence, the development of CRE based on the available local resources is assumed to be a potential solution to the energy security challenges facing northern communities (Buss *et al.,* 2021; Leonhardt *et al.,* 2022; McMaster *et al.,* 2024). CRE also has the potential to offer decentralized solutions, creating opportunities for local ownership and alleviating energy insecurity (Stefanelli *et al.,* 2019; Leonhardt, 2021). CRE usually emphasises the process of planning, establishing, and potentially running a local energy project in an open and participatory manner while ensuring local benefits. It can address energy security challenges by minimising energy conflicts and their socio-economic and environmental consequences (Hoicka *et al.,* 2021). At the same time, CRE can empower communities to engage with energy transformation and planning, boost local economies, and increase resilience against climate change (Bullock *et al.,* 2020; Coy *et al.,* 2021; Leonhardt *et al.,* 2022; Menghwani *et al.,* 2023).

Many Indigenous communities across the Circumpolar North are located in the boreal forest zone and surrounded by large, forested areas (Buss *et al.,* 2021; Menghwani *et al.,* 2022). In Canada, for instance, approximately 70% of Indigenous communities are positioned in the forest regions that are rich in biomass (NRC, 2021). So, there is high potential to use this vast resource to produce local bioenergy, which can help meet the energy needs of northern communities (Buss *et al.,* 2021; Menghwani *et al.,* 2022). Biomass is considered a carbon-neutral fuel and one of the largest sources of RE, where energy can be produced from forest resources and by-products (e.g., timber, wood chips, and forest residues: leftover trees, slashes, and sawmill waste) (Thakur, 2011; Sobamowo and Ojolo, 2018; Saratale *et al.,* 2019; Buss *et al.,* 2021). The exploration of sustainable bioenergy options tailored to the specific needs and environmental conditions of northern and remote Indigenous communities holds the promise of fostering energy autonomy, community resilience, and economic empowerment (Zurba and Bullock, 2020; Buss *et al.,* 2021; Menghwani *et al.,* 2023).

Though the development of community bioenergy presents a potential opportunity to address northern energy insecurities, communities often lack an energy plan that provides estimations of potential biomass resources, resource capacities to meet local energy demands, feedstock supply chains, site selection for infrastructure development, opportunities, and challenges (Poelzer *et al.,* 2016; Potvin *et al.,* 2017; Sigurdson *et al.,* 2020). Moreover, identification of the optimal energy conversion technologies and opportunity areas for maintaining sustainable feedstock supply is also a vital need (Paulo *et al.,* 2015; Zetterholm *et al.,* 2020). Forest resources also have significant economic and ecological values, and overexploitation for bioenergy development can have significant negative consequences for the local ecosystem and environment (Gonzalez-Salazar *et al.,* 2016; Titus *et al.,* 2021). To ensure reliable energy supply by maintaining sustainable exploitation of forest resources aligned with the principles of environmental conservation, the application of forest residues and by-products is a promising option for community energy production in the North, yet there is limited research focused on community bioenergy potential (CBP) estimations from forest residues in Canadian northern contexts.

It is therefore essential to conduct comprehensive assessments of the bioenergy development potential of forest residues and by-products near northern communities, with consideration for local socio-economic and environmental contexts. To ensure the sustainable exploitation of biomass resources and while pursuing bioenergy as a reliable energy supply in the future, it is essential to assess the CBP; this requires well-structured and strategic approaches for reliable estimations of available biomass resources and energy potential to inform the early stages of community energy planning. Though many authors have used different tools and techniques to assess biomass energy potentials in different parts of the world, the majority of scholarly attention has been focused at the regional to national scale: e.g., eastern Ontario, Canada (Calvert and Mabee, 2015), Cameroon (Mboumboue and Njomo, 2018), Columbia (Gonzalez-Salazar *et al.,* 2014), the Czech Republic (Safarik *et al.*, 2022), India (Yadwad *et al.,* 2012; Dabas *et al.*, 2023), Iran (Shorabeh *et al.*, 2021), Mexico (Morales-Maximo *et al.,* 2021), and Nigeria (Jekayinfa *et al.*, 2020), or urban-centric (Thakur, 2011; Bao *et al.,* 2020; Morales-Maximo *et al.,* 2021; Twumasi *et al.,* 2022), with relatively limited attention to northern contexts. Even so, there is limited applied research focused on developing and testing frameworks and methods for the estimation of CBP in northern boreal communities based on local socio-economic and environmental settings, which is crucial to strengthening energy security, mitigating global climate change, and contributing to energy sustainability at the local level.

1.1 Purpose and Objectives

The purpose of this research is to assess the bioenergy potential of forest residues for the development of CRE in northern and remote Indigenous communities. The specific objectives of the research are as follows, to:

a) Explore the state of scholarship on current approaches to CBP assessment and advance a conceptual framework for CBP in the northern context.
b) Apply the conceptual framework to assess CBP for a Peter Ballantyne Cree Nation (PBCN) community, northern Saskatchewan, as a case study application.
c) Identify the technical challenges and constraints of CBP assessment and development in the north.

1.2 Research Scope and Significance

This study aims to assess the bioenergy potential of forest residues focusing on their utilization for community based RE initiatives in northern and remote Indigenous communities in Canada and the global north, by recognizing their unique socio-cultural and environmental contexts. To achieve the intended goal, the research scope involves a comprehensive analysis of available forest biomass, including residues from logging and processing activities, to evaluate their viability for bioenergy production, exploring technological and economic feasibility within the specific context, and understanding the potential benefits and challenges of adopting an energy transition.

The significance of this research lies in its potential to address energy security challenges facing northern and remote Indigenous communities and to contribute to the global discourse on sustainable and local energy transitions. The research will address the critical gaps in the case of energy transition through CRE development, as described earlier. Though a vast volume of research is conducted on bioenergy development and its potential, most of the scholarly research is focused on a specific national or regional context, where a significant number of studies are conducted on bioenergy crops and forest resources, which can create competition for land use, food production, and other commercially valuable products. These studies are even not aligned with informing CBP assessments in the North. This research, however, is focused on the estimation of bioenergy potential from forest residues and by-products to meet the energy needs of northern communities while keeping in mind overexploitation and sustainable use of forest resources. The findings of this study will help advance practical methods and approaches for assessing bioenergy potential in remote communities in the boreal zone and similar regions of the world and empower Indigenous communities for energy self-sufficiency and socio-economic development, which can contribute broadly to achieving sustainable development goals (SDGs).

1.3 Thesis Structure

This thesis is presented in six chapters and adopts a traditional thesis format. Chapter one, the current chapter, presented the background and context of the research, the aims and objectives of the study, and its scope and significance considering the scholarly contribution. Chapter two discusses a broad area of scholarship within the existing academic literature on community energy potential and planning with respect to remote Indigenous communities in Canada and the Circumpolar North. Northern energy insecurity, the role of community energy in the energy transition, the potential of bioenergy development in northern communities, and different assessment types and factors are explored. This chapter advances a conceptual framework for assessing CBP in the northern context. Chapter three outlines the study area and the methodology used to assess the community's local bioenergy potential. The results are presented in Chapter four, providing a detailed analysis of CBP in the study region. In Chapter five, the research findings are interpreted and discussed by comparing them with existing literature. This chapter highlights the high-level summary of the research results, key takeaways and findings of the research, and their implications from a broad scholarly perspective. The thesis concludes with Chapter six, providing a summary of key findings, the challenges and limitations, suggestions for future research directions, and possible ways to address the raised issues.

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Insecurity in Northern Remote Communities

Globally, many rural and remote communities are suffering from energy insecurity. In Canada, for instance, remote Indigenous communities are faced with enduring energy insecurity challenges, especially in the provincial and territorial North (Huang *et al*., 2016; Rakshit *et al.*, 2019; MacKay *et al.*, 2021; McMaster *et al*., 2024) (Figure 2.1). Approximately 250 off-grid communities exist in Canada, of which 170 are Indigenous and rely on diesel generators or trucked-in liquefied natural gas as a primary source of energy for home heating and electricity (ECCC, 2016). But the energy security of these communities is not stable; seasonal fuel supplies can be limited, energy costs are high, and power outages are common (Mercer *et al.*, 2020; Lovekin, 2021; Leonhardt *et al.,* 2022). Moreover, emissions from diesel combustion have harmful consequences for human health (e.g., respiratory illness) and the local environment (e.g., atmospheric pollution) and contribute cumulatively to global climate change (Mboumboue and Njomo, 2018; Buss *et al*., 2022). In some cases, diesel generation also limits the community's ability to thrive and grow due to the limited output of generators, as well as complicated energy governance and decision-making processes controlled by central utilities (Bullock *et al.*, 2020; McMaster *et al*., 2023).

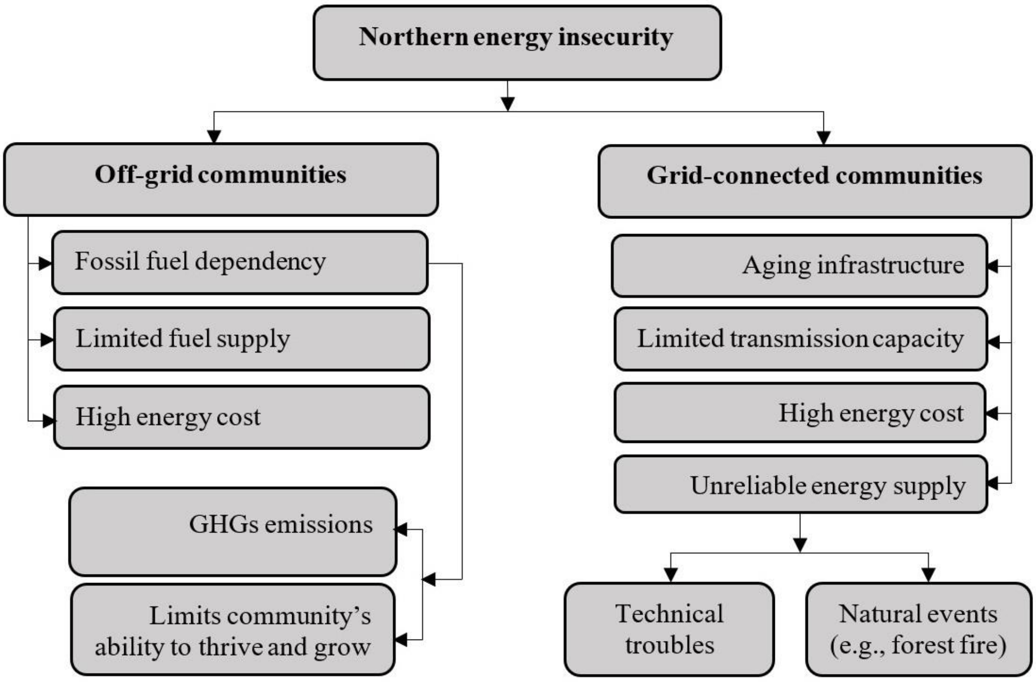


Figure 2.1 Major causes and consequences of northern energy insecurity (author's construction).

However, many northern grid-connected communities are also reported to be suffering from energy insecurity (Huang *et al.,* 2016; Hoicka *et al.,* 2021; Armagan, 2023). Due to the cold weather conditions, the heating loads of communities are very high, and communities without access to the natural gas distribution system often heat buildings via electricity, which leads to high energy expenses (Sigurdson *et al.*, 2020; Asante *et al.*, 2023). Further, the power supply is not always reliable because of limited grid capacity or the aging of transmission infrastructure (Lovekin, 2021). With long transmission distances or end of the grid locations, communities can experience higher than normal technical troubles and outages. In bad weather, a forest fire, or any other problem with the grid, a community may frequently be without power for several hours or days, often relying on either forest wood or diesel generators for their backup energy needs (Sigurdson *et al.,* 2020; Asante *et al.,* 2023). The energy insecurities of these communities pose significant and multifaceted challenges, impacting overall community well-being, economic stability, and sustainability; such challenges also serve as major drivers for energy transitions for strengthening energy security and sustenance.

2.2 Community Energy and Energy Transition

Community energy refers to the generation, distribution, and consumption of energy at the local level, wholly owned and controlled by the communities or through a partnership with commercial or public sector partners (Leonhardt, 2021; Bauwens *et al.,* 2022). It is a bottom-up energy initiative with community participation and benefit sharing where residents engage in energy planning and often operate community-led renewable energy and energy supply projects, such as solar panels, wind turbines, or biomass facilities (Gall, 2018; Hoicka *et al.*, 2021). The development of CRE also helps communities to adopt new technologies, ultimately advancing energy transition and empowering communities to engage with energy transformation and planning (Coy *et al.,* 2021; Leonhardt *et al.*, 2022; McMaster *et al.,* 2023). It can also help to decentralize energy infrastructure and ownership by offering power generation close to where power will be used, while ownership remains in the hands of the community (Gui *et al.*, 2018; Stefanelli *et al.,* 2019; Leonhardt, 2021).

Energy transition refers to the global to local movement away from conventional, fossil fuel-based energy systems to more sustainable and renewable energy sources (Pena *et al.,* 2022). The development of CRE can thus enhance energy transitions, strengthen energy security challenges, mitigate global climate change by reducing greenhouse gas (GHG) emissions, and achieve the SDGs, especially SDG7 (affordable clean energy), SDG11 (sustainable cities and communities), and SDG13 (climate action). CRE can also help achieve Canada's goal of reducing GHGs emissions by 40–45% by 2030 as part of a climate change mitigation effort (ECCC, 2022). Overall, CRE is considered a pivotal component of community wellbeing and mitigation and adaptation to climate change. It can also have direct, indirect, induced, and co-benefits, as well as monetary and non-monetary value. For instance, the development of CRE in Indigenous communities can promote local control and encouragement of energy sovereignty, strengthen energy security and resilience against climate change, and support processes of reconciliation with Indigenous peoples (Karanasios and Parker, 2018; Hoicka *et al.,* 2021). Beyond strengthening energy security and environmental advantages, CRE can also bring social and economic benefits to the local area, such as job creation, skill acquisition**,** community development, and a sense of shared responsibility (Karanasios and Parker, 2018; Sigurdson *et al.,* 2020; Coy *et al.,* 2021; Hanna *et al.,* 2024). Furthermore, CRE helps to move away from a centralized energy system and promote a more distributed and resilient energy infrastructure, especially in rural and remote regions.

2.3 Bioenergy Potential in the Circumpolar North

Bioenergy is energy produced from renewable biological sources, such as biomass. Biomass is usually known as matter derived from living organisms or plant material that can be turned into fuel to supply heat and electricity (Banerjee, 2023). Globally, it ranks fourth as an energy source, provides approximately 14% of the world's energy needs, and is considered one of the largest sources of RE, with the potential to reduce dependency on fossil fuels (Vaillancourt *et al.,* 2019; Buss *et al.,* 2022). Thiyagarajan *et al.* (2021) identify biomass as a carbon-neutral or low-carbon fuel because the plants used for biomass absorb approximately the same amount of carbon-dioxide (CO_2) while growing as that released when the biomass is burned. Vegetation (e.g., trees, plants, brush) that are the source of biomass for energy, capture almost the same amount of CO_2 through photosynthesis while growing as is released when that biomass is burned, which can make biomass a carbon-neutral energy source (Slamersak *et al.,* 2022; Malico and Goncalves, 2024).

A wide variety of biomass is reported to be used in bioenergy production, including woody biomass (e.g., wood and wood residues), energy crops (e.g., maize, sweet sorghum, etc.), agricultural residues (e.g., straw or corn stover), animal manure, and municipal and household organic wastes (Tursi, 2019; Pavlas *et al.,* 2020; Balcioglu *et al.,* 2023). Among them, forest-based woody biomass is the focus of this study, which can be used as a fuel directly or processed into pellet fuel or other forms of fuel. The woody biomass is usually made up of various components, the most important of which are carbohydrates and lignin (Tursi, 2019). Generally, this category includes the whole tree from the forest, bark, and leaves of woody shrubs both above and below ground, trees and root residues, mill residues, dead or dying trees, stumps, tree trimmings, construction and demolition debris, packaging wastes, and harvesting residues (branches and tops generated during the logging operation) (Thakur, 2011; Batidzirai *et al.,* 2012; Zurba and Bullock, 2020; Malico and Goncalves, 2024). To ensure sustainable exploitation of forest resources and avoid competition for woody biomass to other commercially valuable products (e.g., furniture, pulp, and paper, construction materials, etc.), biomass harvesting for energy production will often on forest biomass residues and logging leftovers (e.g., roots, bark, branches, leaves, stumps, tops, rejected logs, and offcuts, etc.) (Sobamowo and Ojolo, 2018; Mansuy *et al.,* 2020; Tolessa, 2023).

2.3.1 Biomass availability and potentials in the Circumpolar North

Boreal forests, extending across the northern latitudes, hold immense potential to produce woody biomass. There are many Indigenous communities living in the boreal forest zones of Siberia, Alaska, and Northern Canada, offering a significant potential for using these biomass resources as a RE source (Wells *et al.,* 2020). For instance, over 600 Indigenous communities (70% of Canada’s Indigenous communities) have lands and traditional territories in Canada’s boreal forest, an area rich in biomass (Axelrod, 2017; Zurba and Bullock, 2020; Buss *et al.,* 2021; NRC, 2021). These communities are geographically well positioned to tap into this vast biomass resource to produce bioenergy and meet their local energy needs (Mansuy *et al.,* 2020; Buss *et al.,* 2021). Developing a bioenergy plant is suitable not only to provide reliable clean energy and reduce energy poverty in northern and remote Indigenous communities, but also to help with infrastructure development, skill acquisition, strengthening the local economy by creating employment opportunities, and improving public health and the environment (Pavlas *et al.,* 2020; Bullock *et al.,* 2020; Menghwani *et al.,* 2023).

Bioenergy development in Canada also has potential to be beneficial to Indigenous communities in similar ways to other natural resource developments, such as forestry and other types of energy projects (Zurba and Bullock, 2018). According to Natural Resources Canada, bioenergy accounts for approximately 6% of Canada’s total energy supply, and the Government of Canada prioritizes bioenergy systems research and development (NRC, 2018). Canada is reported to have the largest amount of biomass per capita in the world and approximately 6.5% of the world’s bioenergy potential, with 9% of the world’s forests (Buss *et al.,* 2021). Sustainable forestry practices can thus ensure a continuous supply of forest resources for energy production without compromising the ecological integrity of these vital ecosystems (Kumar *et al.*, 2021). A holistic approach, combining ecological considerations, technological advancements, and community involvement, is imperative to unlock the potential of biomass in the unique and fragile ecosystems of the Circumpolar North.

2.3.2 Energy content of the dominant boreal trees

The energy content of biomass refers to the amount of energy stored within a given quantity of biomass or organic matter. It usually varies depending on the types and species of biomass, its chemical composition, and moisture content (Barrette *et al.*, 2015). The boreal forest of Canada as well as the Circumpolar North typically characterizes forested land with a greater dominance of Jackpine and black and white spruce (Berry, 2023). The calorific value (MJ/kg) of the different components of these boreal species is listed in Table 2.1. The heating value of the different components of these species ranges from 18.78 to 21.56 MJ/kg (Table 2.1), which is considered a high heating value (HHV). The HHV of raw biomass generally ranges from 15–20 MJ/kg (Chen, 2015), while the heating values of agricultural residues range from 14–19 MJ/kg and coal from 17–30 MJ/kg (MAFRA, 2011).

Table 2.1 Calorific value (MJ/Kg) of the tree components growing in boreal forest of Canada.

Species	Stump	Steam	Top	Bark	Foliage	Branches	Mean
Jack pine	19.95	19.44	21.23	21.30	21.43	21.37	20.79
White spruce	19.83	19.02	21.56	19.83	20.56	21.14	20.32
Black spruce	19.20	18.78	21.56	19.48	20.87	20.68	20.09

Source: Barrette *et al.* (2015)

2.3.3 Bioenergy conversion technologies

Upgrading raw biomass to higher-grade fuels is achieved by different methods, broadly classified as thermochemical, biochemical, and physicochemical conversion (Adams *et al.*, 2018). The available conversion technologies for biomass and their corresponding products from the required feedstock are listed in Table 2.2. It is suggested from the literature that, among the conversion technologies, direct combustion and gasification are widely used, where indirect combustion cogeneration of heat and power has the lowest environmental impacts and minimal expenses (Balcioglu *et al.*, 2023). In this process, biomass can be directly burned in boilers to generate heat or steam, which can be further used for electricity generation through steam turbines (Tursi, 2019; Banerjee, 2023). In gasification, combustible solids biomass is converted into a gaseous fuel mixture with small quantities of char and condensable compounds, which can offer high energy conversion efficiencies (Chen *et al.*, 2020; Banerjee, 2023).

Table 2.2 Available biomass conversion technologies and their corresponding products.

Process	Technology	Feedstock	End products
Thermo-chemical conversion	Combustion	Agricultural residues, woody residues, animal wastes	• Steam • Process heat • Electric energy
	Pyrolysis	Agricultural residues, woody residues	• Pyrolysis oil • Producer gas • Char
	Gasification	Agricultural residues, woody residues	• Steam • Process heat • Electric energy
	Liquefaction	Agricultural residues, algal biomass	• Fertilizer/biofuel • Syngas • Liquid fuels
Biochemical conversion	Anaerobic digestion	Animal wastes, sewage sludge	• Liquid fuels • Biogas • Electric energy
	Fermentation	Agricultural residues, sugars, starch	• Liquid fuels (bioethanol)
Physicochemical conversion	Esterification or transesterification	Vegetable oils, animal fats, waste oils	• Liquid fuels • Glycerol

Sources: Adams *et al.* (2018), Tursi (2019), Banerjee (2023)

2.4 Bioenergy Potential Assessment

The assessment of bioenergy potential involves evaluating the available biomass resources and their capacity for energy production by considering technical, regulatory, environmental, and economic factors. It’s a crucial step in the early stages of energy planning to grasp energy sustainability. To enable systematic evaluation of bioenergy potential, different assessment types and approaches have been reported in the literature and are discussed below.

2.4.1 Types of bioenergy potentials

2.4.1.1 Theoretical potential

Theoretical potential refers to the maximum amount of biomass theoretically available for energy production under ideal conditions. It provides an estimate of the theoretical upper limit of energy production that could be achieved if all available biomass resources were utilized optimally (Hassan *et al.*, 2019; Picirelli de Souza *et al.*, 2021). This type of assessment usually takes into consideration the total available biomass, its energy content, and the efficiency of conversion technologies (EUBIA, 2023). Assessments of theoretical potential are valuable for informing energy policy, planning, and research efforts, helping to understand the maximum contribution that bioenergy could make while considering environmental and social sustainability (Batidzirai *et al.,* 2012; Gonzalez-Salazar *et al.,* 2014). However, it should be noted that the actual achievable bioenergy potential may be significantly lower due to practical constraints, economic viability, and environmental considerations.

2.4.1.2 Technical potential

Technical potential is the fraction of theoretical potential available for energy production under existing technological possibilities and constraints (Batidzirai *et al.,* 2012; Gonzalez-Salazar *et al.,* 2016). It usually describes the practical contribution to the theoretical energy potential considering the availability of biomass resources while taking into account other applications, community values and regulatory restrictions, conversion technologies and efficiencies, ecological and environmental considerations, and economic criteria (Picirelli de Souza *et al.,* 2021). This type of assessment gives a holistic overview of bioenergy potential estimation in energy planning and is widely used (e.g., Clabert and Mabee, 2014; Mboumboue and Njomo, 2018; Shorabeh *et al.,* 2021; Deka *et al.,* 2023; Tolessa, 2023). The technical potential of bioenergy usually considers the determination of the biomass resource potential, energy production potential of available biomass, economic potential, and ecological and environmental potential, which are discussed below.

a. **Resource potential** refers to the availability of biomass or forest resources that can be sustainably harvested for bioenergy production without depleting the source or causing environmental harm, while also considering other applications (e.g., food, fibre, wood, etc.), community values, and regulatory restrictions (Picirelli de Souza *et al.,* 2021). Assessing biomass resource potential is crucial for developing sustainable and efficient bioenergy systems and varies depending on the geographical location, climatic conditions, land availability, and using behaviour, e.g., agricultural practices (Jekayinfa *et al.,* 2020). It usually involves evaluating the availability of biomass feedstocks, understanding the environmental impact of their extraction or cultivation, and ensuring that the harvesting practices are in line with long-term ecological and social considerations (Titus *et al.,* 2021).

b. **Energy potential** or energy production potential, refers to the amount of energy that can be generated from the available biomass resources. It usually depends on a number of factors, including the availability of biomass feedstocks, biomass types and their energy content, conversion technologies, and technological efficiencies (Bello, 2005; Gonzalez-Salazar *et al.,* 2014). Technology choice and the advancements of biomass conversion methods (e.g., combustion, gasification, anaerobic digestion, etc.) play a crucial role in determining the energy production potential. Advances in these technologies are reported to improve production efficiency, reduce environmental impacts, and make biomass a more competitive and viable option for meeting energy demands (Weldemichael and Assefa, 2016; Antar *et al.*, 2021; Tshikovhi and Motaung, 2023).

c. **Economic potential** considers economic profitability criteria, e.g., competition with fossil fuels or existing energy supply (Thorenz *et al.*, 2018; Picirelli de Souza *et al.*, 2021; EUBIA, 2023). Assessing economic potential usually involves exploration of several factors that contribute to the economic viability of bioenergy, including market conditions, technological advancements, feedstock supply costs, infrastructure development and maintenance costs, and policy aspects (Picirelli de Souza *et al.*, 2021). Usually, financial aspects (e.g., cost-supply and energy price) are taken into consideration to evaluate the economic potential, and typically, techno-economic analysis, net energy balance, market analysis, and cost-supply analysis are performed (Wang *et al.*, 2018).

d. **Ecological or environmental potential** involves evaluating the environmental impact and sustainability of bioenergy production and utilization and considering ecological criteria, e.g., loss of biodiversity or habitat destruction (EUBIA, 2023). Environmental potential usually considers various ecological factors (e.g., land use, biodiversity preservation, ecosystem services, carbon footprint, GHGs emission mitigations, etc.) to determine the overall environmental benefits and drawbacks associated with bioenergy systems (Weldemichael and Assefa, 2016; Picirelli de Souza *et al.*, 2021). Environmental potential is typically assessed using a combination of methods that consider various aspects of the bioenergy production and utilization lifecycle, including life cycle assessment (LCA), carbon footprint analysis, GHG emission and mitigation potential, land use change analysis, biodiversity assessment, energy return on investment (EROI), and analysing regulatory restrictions (Laganiere *et al.*, 2017; Wang *et al.*, 2018; Sadaghiani *et al.*, 2022).

2.4.2 Approaches and methods of bioenergy potential assessment

To enable systematic evaluation of bioenergy potential, different assessment approaches and methodologies have been reported in the literature (Table 2.3). Based on the objectives of each study and the data requirements, the methodologies of bioenergy assessment can be broadly classified into three main approaches: (a) resource-focused assessment, (b) demand-driven assessment, and (c) integrated assessment, each of which is performed by using different tools and techniques presented in Figure 2.2. Nonetheless, Figure 2.3, depicts the approaches of bioenergy potential assessments along with their respective end outputs.

Table 2.3 Bioenergy potential assessment approaches and tools highlighted in recent literature.

Types of approaches	**Tools/Methods**	**Material/Feedstock**	**Country**	**References**
Resource-focused	GIS-based	Forest and crop residues	Nigeria	Ukoba *et al.* (2023)
		Agricultural residues	India	Dabas *et al.* (2023)
		Energy crops and agricultural residues	Turkey	Senocak and Goren (2022)
		Mixed biomass	China	Ma *et al.* (2022)
		Mixed biomass	Iran	Shorabeh *et al.* (2021)
	Statistical	Mixed residual biomass	Ethiopia	Tolessa (2023)
		Forest-residues	Louisiana	Twumasi *et al.* (2022)
		Forest residues	Mexico	Morales-Maximo *et al.* (2021)
		Agro-forestry residues	Brazil	Picirelli de Souza *et al.* (2021)
		Forest and agricultural residues	Nigeria	Jekayinfa *et al.* (2020)
		Forest resources	Cameroon	Mboumboue and Njomo (2018)
		Mixed biomass	Columbia	Gonzalez-Salazar *et al.* (2014)
		Forest resources, agricultural residues, and animal manure	India	Deka *et al.* (2023) Yadwad *et al.* (2012)
	Both GIS and statistical	Agricultural residues	Indonesia	Papilo *et al.* (2017)
Demand-driven	Cost-supply	Mixed biomass	Lithonia	Kukharets *et al.* (2023)
		Agricultural and forest residues	Nigeria	Sobamowo and Ojolo (2018)
		Household waste, energy crops, agricultural residues	UK	Welfle *et al.* (2014)
	Energy system modelling and simulation	Forest, agricultural, and grassland residues	China	Nie *et al.* (2022)
		Energy crops	Netherlands	Daioglou *et al.* (2019)
Integrated	GIS and yield simulation model	Energy crops	China	Bao *et al.* (2020)
	Statistical and energy system modelling	Agriculture and forest residues	China	Gao *et al.* (2016)
	GIS-based, cost-supply	Forest, grassland, crops residues	Canada	Clabert and Mabee (2014)

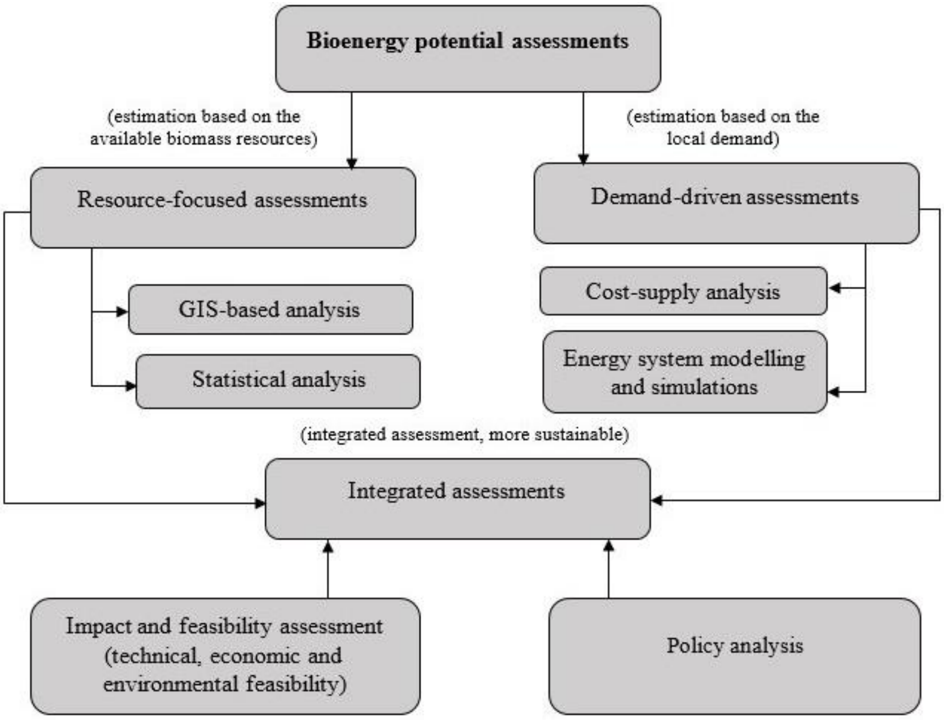


Figure 2.2 Bioenergy potential assessments: types of approaches and methods (author's construction).

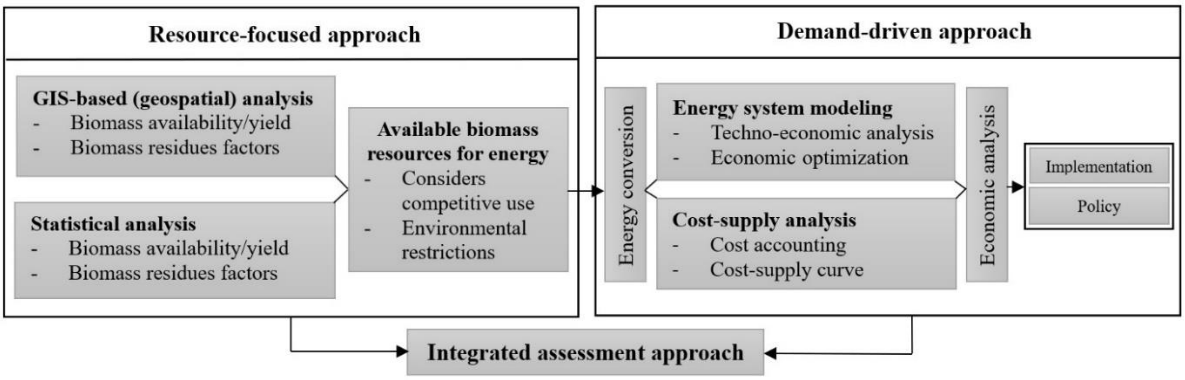


Figure 2.3 Approaches of bioenergy potential assessments and end output (author's construction).

2.4.2.1 Resource-focused assessments

Resource-focused assessments investigate the total bioenergy resource base for energy conversion considering competition between different uses of the resources (Figure 2.3). These assessment approaches typically estimate the theoretical or technical potential of biomass for energy conversion (Picirelli de Souza *et al.*, 2021). Resource-focused assessments can be performed either using geospatial (GIS-based) (Shorabeh *et al.*, 2021; Senocak and Goren, 2022; Dabas *et al.*, 2023) or statistical analysis of land use and yield data (Gonzalez-Salazar *et al.*, 2014; Jekayinfa *et al.*, 2020; Twumasi *et al.*, 2022) (Table 2.3), as described below.

a. **GIS-based (geospatial) analysis** combines spatially explicit data and land use to assess biomass resources potential. The data sets used can be classified into geo-data and statistical data, which can be collected from georeferenced information such as land use and land cover maps and data obtained from GIS and include datasets on elevation, forest type and density, protected areas, water bodies, etc. (Senocak and Goren, 2022). The advantage of this type of analysis is the ability to evaluate the distribution of biomass and its impacts at a local and regional level (Bharti *et al.*, 2021). Moreover, the yields of energy crops can be estimated based on crop growth models that use spatially explicit data on climate, soil type, and crop management (Batidzirai *et al.*, 2012; Senocak and Goren, 2022). It is a cost-effective way to gather information and analyse land use and land cover changes on a large economic, regional, and global scale, and the resulting patterns can be studied by comparing images obtained at different times (Papilo *et al.*, 2017). Overall, this type of assessment method is transparent, varying levels of data details can be aggregated, and it can help estimate the biomass resources in remote and vast areas. Reproduction of the results by communities is, however, difficult because the use of GIS software and spatially explicit data can be labour-intensive and highly complex, which does not necessarily provide more accurate results (Gonzalez-Salazar *et al.*, 2014).

b. **Statistical analysis usually** relies on statistical data to estimate the availability of biomass resources for energy conversion and other uses. The data sets typically used for statistical analysis include agriculture and forest production, cultivated areas, harvested volumes or total yield, residue to crop ratios, demographic and economic dynamics, socio-economic developments, technological trends, etc. (Picirelli de Souza *et al.*, 2021; Safarik *et al., 2022*). The advantages of this type of assessment include simplicity, transparency, reproducibility, and low cost. However, it offers limited considerations for macro-economic impacts and environmental and social aspects (Gonzalez-Salazar *et al.*, 2014). In addition, data unavailability in vast resources and remote areas is a hindrance to this technique. To overcome this issue, Papilo *et al.* (2017) used both GIS and statistical techniques in their study (Table 2.3), where geospatial techniques were used to estimate the growth in the stock of biomass and productivity, and statistical models were used to estimate the agricultural residues of available biomass crops.

2.4.2.2 Demand-driven assessments

A demand-driven approach analyses the cost competitiveness of biomass-based energy systems and estimates the biomass required to meet energy security or renewable energy quota’s targets. (Batidzirai *et al.*, 2012; Picirelli de Souza *et al.*, 2021). These types of studies typically focus on economic potential (Figure 2.3) and are performed by energy system modelling (Daioglou *et al.*, 2019; Nie *et al.*, 2022), and cost-supply analysis (Welfle *et al.*, 2014; Sobamowo and Ojolo, 2018; Kukharets *et al.*, 2023) (Table 2.3), as described below.

(a) Cost-supply analysis typically combines bottom-up bioenergy technical estimates with cost accounting evaluations of the costs of biomass production, feedstock supply, transportation, and conversion, and the results are normally expressed as cost-supply curves (Calvert and Mabee, 2014). Cost-supply analysis is simple, transparent, reproducible, and cheap. It helps to estimate the energy production and associated costs and is essential to understanding the market feasibility and overall potentiality of bioenergy development. However, it does not allow the matching of demand and supply through prices, and thus competition is not accurately modelled (Batidzirai *et al.*, 2012). Another disadvantage is that there are limited possibilities for accounting for environmental or social limitations (Gonzalez-Salazar *et al.*, 2014).

(b) Energy system modelling simulates the behaviour of energy markets and the competitiveness of biomass energy systems through the application of economic optimization (Nie *et al.*, 2022). In this method, bioenergy system efficiency (technological efficiency) is compared with fossil fuel or other renewable energy to evaluate economic prospects (Picirelli de Souza *et al.*, 2021). Energy system models also help to explore different decarbonization pathways with different time horizons and scopes and provide long-term forecasts (Fodstad *et al.*, 2022). The benefits of this assessment include the suitability of evaluating costs and the effectiveness of policies. However, it lacks validation of land availability and agricultural yields, and it uses economic correlations based on expert judgment (Batidzirai *et al.*, 2012).

2.4.2.3 Integrated assessments

Integrated assessment combines both resource-focused and demand-driven assessment components (Figure 2.3). This type of assessment can provide a holistic assessment of energy potential and offers the possibility to evaluate multiple sustainability aspects (Gonzalez-Salazar *et al.*, 2014; Picirelli de Souza *et al.*, 2021). Different authors have used different tools and techniques for the integrated assessment of bioenergy potential, based on the objective of the study and other contextual factors. For instance, Calvert and Mabee (2014) used both geospatial and cost-supply analyses in their study to analyze the biomass resource potential in eastern Ontario, Canada. Again, some integrated assessments consist of different models and tools and combine information on economic, energy, and climate variables across different scientific disciplines, time scales, and spatial scales while allowing the modelling of multi-dimensional scenarios with a large variety of assumptions for different parameters (e.g., population growth, economic growth, food consumption, environmental aspects, etc.) (Gao *et al.,* 2016; Daioglou *et al.,* 2019). An integrated assessment can also incorporate impact and feasibility assessments and policy analysis, which include the technical, economic, and environmental feasibility of bioenergy development on certain aspects, such as water scarcity, food security, biodiversity, climate change, and employment (Batidzirai *et al.,* 2012). For instance, Fischer *et al.* (2009) evaluate the social, environmental, and economic implications of bioenergy developments on transportation, fuel security, climate change, feedstock prices, and land use change-albeit at broad national scales. An integrated assessment can provide a holistic overview of bioenergy potential and can be adopted in northern community contexts.

2.5 Bioenergy Potential Assessment in the Circumpolar North

In recent years, several studies have been conducted highlighting the prospects and barriers of community bioenergy as well as CRE development in northern Canada (Rakshit *et al.,* 2019; Zurba and Bullock, 2020; Buss *et al.,* 2021, 2022; Leonhardt *et al.,* 2022; Menghwani *et al.,* 2023); Alaska (Holdmann *et al.,* 2022; Menghwani *et al.,* 2022); and different Northern European countries (Stolarski *et al.,* 2020). For instance, Zurba and Bullock (2020) explore the implications of bioenergy development for the social wellbeing of Indigenous peoples in Canada, while the GHGs mitigation potential of wood-based bioenergy development assessed by Buss *et al.* (2022) found that replacing diesel fuel with bioenergy can save equivalent to 32,166 tons of CO_2 emissions over 100 years. The challenges and key barriers of bioenergy development in the northern Indigenous communities across Canada were also explored by Buss *et al.* (2021) and Menghwani *et al.* (2023), with both identifying the high initial investment costs of bioenergy projects, the logistical and operational challenges of developing a sustainable wood supply chain in remote locations, and the limited opportunities for community leadership of bioenergy projects as among the key barriers to transition. The complexities of energy transition in remote Indigenous communities are similarly highlighted in Hill First Nation in Ontario, where Rakshit *et al.* (2019) emphasize the necessity of integrating Indigenous values in energy planning. Leonhardt *et al.* (2022) thus emphasize the necessity of government instruments to support community energy transition in the North, (e.g., financial support, feed-in tariffs, grid services, and fiscal incentives). McMaster *et al.* (2023) further highlight the importance of strengthening local capacity to develop community energy in the North, focusing on Gwich'in communities in the Northwest Territories of Canada, emphasizing community relationships to share skills and resources and to build local socio-technical capacity for energy transitions.

There is also some, but limited, research highlighting bioenergy potential as a CRE resource in the North. For instance, Thakur (2011) estimates the potential of power generation from forest residues in Alberta, using techno-economic models for the assessment of power generation costs and optimum power plant size using forest residues as feedstock. In eastern Ontario, Canada, Calvert and Mabee (2014) explored a spatial analysis of biomass resources, using and integrating multiple land cover resource maps to estimate biomass resource availability. The authors also estimated the bioenergy production potential and biomass supply-cost curves for different cities in the study region. The same authors, in 2015, investigated land use conflicts and figured out the resource-based bioenergy potential in eastern Ontario by using GIS-based methods (Calvert and Mabee, 2015). In northern Alberta, the utilization of harvested and fire-impacted forest residues for community bioenergy and their prospects, in terms of both the economic and environmental perspectives of the Cold Lake First Nations, were assessed by Mansuy *et al.* (2020). In this study, the authors used remote sensing data for biomass resource estimation and a scenario-based approach to assess economic and environmental prospects. Bioenergy potential in different northern European countries, including Denmark, Germany, Estonia, Finland, Latvia, Lithuania, Poland, Sweden, and Norway, have also been estimated by Stolarski *et al.* (2020), where resource-based bioenergy potential was estimated using statistical tools and techniques. None of these studies, however, with the exception of the Cold Lake Alberta study, focus on local CBP assessment in the northern, remote, and Indigenous community context, where energy insecurities are most pressing and where CRE solutions are vital to long-term community well-being.

2.5.1 Framework for CBP assessment in the north

Based on the lessons learned from the review of state-of-the-art bioenergy potential assessment approaches and drawing on the critical factors of bioenergy potential assessments synthesized in the literature (Table 2.4), a conceptual framework is proposed for approaching CBP assessment in the northern context (Figure 2.4). The proposed framework integrates both resource-focused and demand-driven analysis, along with consideration of northern environmental, socioeconomic, policy, data constraints, and different influential factors. It is intended that the proposed integrated framework will help to provide a holistic overview of

CBP assessment, which can contribute to RE transition as well as reliable and sustainable energy supply for northern and remote rural communities.

Table 2.4 Critical factors of bioenergy potential assessment as identified in recent scholarship.

Key drivers/Factors	**Requirement for potential assessment**
Availability of biomass resources	- Mapping and projection of biomass resources - Determine the density, size, ages, etc. for resource estimation
Types and classification of biomass and choice of biomass for bioenergy	- Classify the potential biomass for harvest - Determine energy content of the species - Avoid commercially valuable biomass
Laws and regulations	- Identify applicable federal and provincial laws - Avoid legally restricted zones and species for harvest
Biodiversity, wildlife, and ecosystem	- Exclude threatened species for bioenergy production - Avoid conservation areas and minimize land degradation
Ecological sensitive and protected areas	- Proper planning for the protection of natural habitat - Exclude ecologically sensitive zones
Land use	- Determine land use type to avoid agricultural and other competition for land. - Consider local and traditional values of land use
Climate change and natural events	- Impact of CO_2 fertilization effects, temperature change, changes in precipitation, and water availability - Extreme climatic events and forest fires
Biomass demand for competition with food, feed, fiber, and other biomaterials	- Proper choice of biomass resources to avoid competition - Use of biomass wastes and residues
Use of residues and biproducts	- Choice of quality residues and leftovers - Accounting for competing applications of residues - Biodiversity thresholds for residue removal
Biomass demand	- Estimation of local energy demand - Projection of socio-economic trends (e.g., population, households, economic growth, etc.)
Technological consideration	- Choice of biomass conversion and efficient technology - Consider emissions and other relevant factors
Cost of bioenergy production	- Cost estimation for yield harvesting to energy production - Consider cost-supply dynamics - Influence of market demand, local trade policy, etc.
Environmental and sustainability aspects	- Emission factors - Sustainability aspects of bioenergy operations

Sources: Batidzirai *et al. (2*012); Gonzalez-Salazar *et al.* (2014); Rakshit *et al.* (2019)

The first step of the proposed framework is to estimate the potential of biomass resources, which is basically a resource-focused estimation to provide an understanding of how much available resource exists and can be used for bioenergy production. GIS-based techniques are assumed to be helpful and adaptable for assessing biomass resource potential in the North.

Though geospatial analysis may not be able to provide an accurate estimation of local CBP, it can provide insight into available and potential biomass resources over vast lands and in areas in the North with limited data by analysing land cover classifications, which can be used to determine bioenergy potentials (Papilo *et al.,* 2017; Shorabeh *et al.,* 2021; Senocak and Goren, 2022; Dabas *et al.,* 2023). As there is often limited biomass data (e.g., forest types, species) available for many northern and remote community locations and peripheral forest lands, geospatial analysis may be helpful to identify and estimate the available biomass resources that have potential for bioenergy production. In the case of biomass resource estimations, either commercial, non-commercial, or both forest zones can be considered, and then for harvesting purposes, biomass can be classified into different categories (e.g., young, mature, old, and very old), and young trees need to be excluded from the estimation by following sustainable forest biomass harvesting guidelines stated in Titus *et al.* (2021). It should also be mentioned here that, in practice mature, old, and very old species are being harvested commercially by the timber supply companies operating in the boreal region (Asante *et al.*, 2023).

Since we know that forest resources in the North are of economic and ecological significance, and overexploitation has significant negative consequences, the use of forest residues and by-products can first be considered for bioenergy production. In the case of commercial forest cut-blocks, the application of slashes, and residues of logging operations and timber processing can be promising for bioenergy production and can be estimated. At the same time, it can reduce competition among the uses of forest resources and help generate clean energy by following the principle of circular economy (Casau *et al.*, 2022). Again, for biomass resource estimation in non-commercial forest zones, the approximate ratio of the generated forest residues from clear-cut harvesting of that specific area or the areas of similar geographical settings can be applied (Asante *et al.*, 2023). Besides dead and forest fire-impacted trees, trimming residues from highways and transmission lines can along with be considered.

In the biomass resource estimations, however, either in commercial or non-commercial forest zones, applicable laws and policies must always be analysed to avoid regulatory restrictions, if there are any, and threatened, endangered species, and ecologically sensitive zones need to be excluded (Long *et al.*, 2013). It can help to determine an accurate approximation of harvestable biomass resources by avoiding federal or provincial laws. Another important consideration of biomass resource estimation is to aggregate local knowledge and values to avoid land use competition, which at the same time can help to estimate harvestable biomass resources with confidence and enhance community acceptance of community energy development (Colmenares-Quintero *et al.*, 2020; Hoicka et al., 2021; Fournier *et al.*, 2023). By considering all the above-mentioned aspects, the total harvestable forest areas, and the potential biomass resources and/or residues can be estimated in the north.

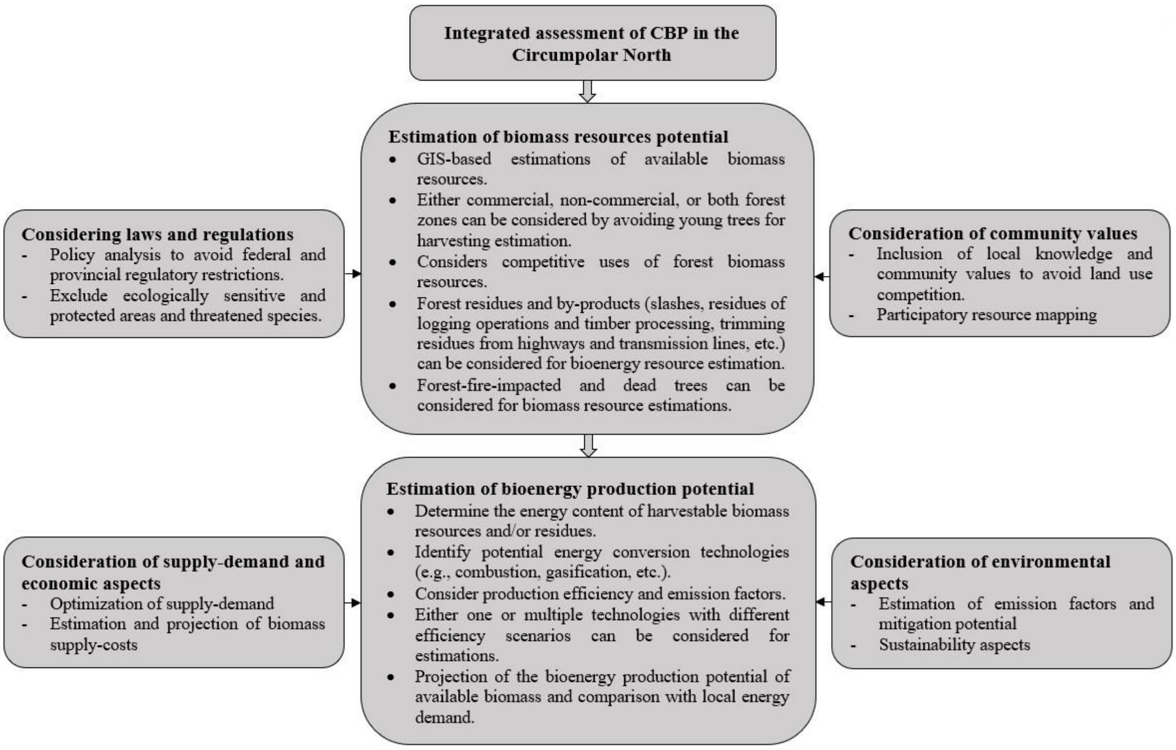


Figure 2.4 Proposed integrated framework of CBP assessment in the north (author's construction).

The second step of the proposed framework, however, is to estimate the energy production potential of available biomass resources and optimize resources to supply adequate feedstock for bioenergy production based on local energy demand and subsequent costs, which is in fact a demand-driven approach of bioenergy potential assessment. Moreover, sustainability aspects of bioenergy development based on biomass resource availability and GHG mitigation potential are integrated into this framework for a holistic assessment of CBP by considering all the technical, economical, and environmental aspects. It should be noted that, to estimate the energy production potential, the energy content of the biomass resources and potential bioenergy conversion technology need to be determined (Tshikovhi and Motaung, 2023). Based on the literature and the feasibility of heat and electricity production, the combustion and gasification techniques are found to be suitable for northern communities given the type of biomass resources available and the importance of both heat and power to community energy security. While different components of the dominant boreal species are reported to have high energy content, though it depends on various natural factors (Barrette *et al.*, 2015).

In the case of energy conversion technology selection, production efficiency and emissions factors need to be taken into consideration (Chen *et al.,* 2020), and either one or multiple technologies with different efficiency scenarios can be generated for estimations. If the periphery of the community has plenty more biomass resources than the local energy demand, biomass resources need to be optimized further based on the required feedstock supply and demand. To do so, community energy demand needs to be determined, which can be performed either by collecting energy consumption records from energy providers (in the case of grid-connected) or estimated based on the total population, number of households, and energy use types. Future projections of energy demand can also be incorporated to understand whether the available biomass can meet the local energy needs and provide a reliable energy supply in the future. Moreover, the required biomass supply and relevant cost determination also need to be considered for estimations, which help to project the feedstock supply cost and determine the resource supply from low-cost zones. Overall, it will help to determine the local energy demand and cost estimation, which are important to incorporate for reliable energy supply and sustainable energy transitions.

Though both cost-supply analysis and energy system modelling are helpful to understand the economic potential and future projections, simple cost-benefit analysis can be adopted because reliable energy supply is the main target in northern communities (Huang *et al.,* 2016; Sigurdson *et al.,* 2020; Asante *et al.,* 2023) and there is limited market competition like in urban settings. Energy system modelling, however, requires a vast data set and work in different dimensions to simulate the behavior of energy markets and the competitiveness of biomass energy systems (Fodstad *et al.,* 2022; Nie *et al.,* 2022). The estimation of biomass supply and associated costs by developing cost-supply curves can thus help to determine the best-suited options for feedstock supply for bioenergy development and potential estimations. Furthermore, environmental and sustainability aspects of bioenergy development are being integrated into the potential assessment. The greenhouse gas (GHG) emissions, mitigation potential, and approximate sequestration period can be determined to project the net atmospheric benefit of bioenergy development by using available assessment tools. Again, the sustainability aspect of bioenergy development is incorporated into the assessment framework to determine the sufficiency of biomass resources to provide a reliable energy supply for sustainable energy transition.

CHAPTER 3

STUDY AREA AND METHODS

The study area for this research was Southend, a Peter Ballantyne Cree Nation (PBCN), community in North-East Saskatchewan (Figure 3.1). PBCN is a First Nations band government, occupies around 51,000 km^2 of land, and consists of 8 communities: Denare Beach, Deschaumbault Lake, Kinoosao, Pelican Narrows, Prince Albert, Sandy Bay, Southend, and Sturgeon Landing (PBCN, 2022). The total population of the communities is about 11,572, the majority of whom live in the traditional territory, where traditional hunting and gathering are key livelihoods (INAC, 2021). Except for Kinoosao, all PBCN communities are connected to the northern transmission grid of Saskatchewan’s electricity network, which is reported to be characterized by aging infrastructure and frequent outages caused by seasonal storm events (wind, ice), lightning strikes, and wildfire (Sigurdson *et al.*, 2020). However, the communities in northern Saskatchewan are not connected to the province’s natural gas distribution network, therefore heating for residential buildings uses electricity, supplemented by wood stoves, and community buildings by propane (Sigurdson *et al.*, 2020; Asante *et al.*, 2023). Though the price of electricity in PBCN communities is the same as for all other non-urban areas of the province (SaskPower, 2023), because of high electricity use for space heating, energy costs are high compared to other parts of the province. On average, households' utility bills in the PBCN communities are reported to be about $800-1000 CAD per month (Hung *et al.*, 2016).

3.1 Study Area

Southend is located between 56°20′0″N and 103°14′0″W (Figure 3.1) in the boreal shield ecozone, the largest ecozone in Canada, covering almost 20% landmass of the country (Bell, 2002). This zone is characterized by forested land with a dominance of jack pine and black and white spruce, and is home to black and grizzly bear, wolf, lynx, moose, barren-ground and woodland caribou, coyote, among many other wildlife species (Berry, 2023). Southend is situated at the southern end of Reindeer Lake, the ninth largest lake in Canada (Evans, 2014), and is accessed by an all-season gravel road, approximately 222 km north of La Ronge, the nearest service center.

The population of Southend is reported at 1052, with the land occupied at approximately 37.64 km^2 and a population density of approximately 28 persons per km^2 (Statistics Canada, 2021). Cree is the mother tongue of the residents, though almost all residents speak English. In

Southend, residents can attend a community school from kindergarten to grade 12 (PBCN, 2022). Fishing, outfitting, the Nobel Bay mine, and private business are the main economic activities in Southend. Fishing is a key livelihood, and the immense lake supports commercial fishing for many different species. Community members usually spend leisure time through different recreational activities, including fishing, hockey, cross-country skiing, swimming, hiking, boating, and dog sledding (PBCN, 2022).

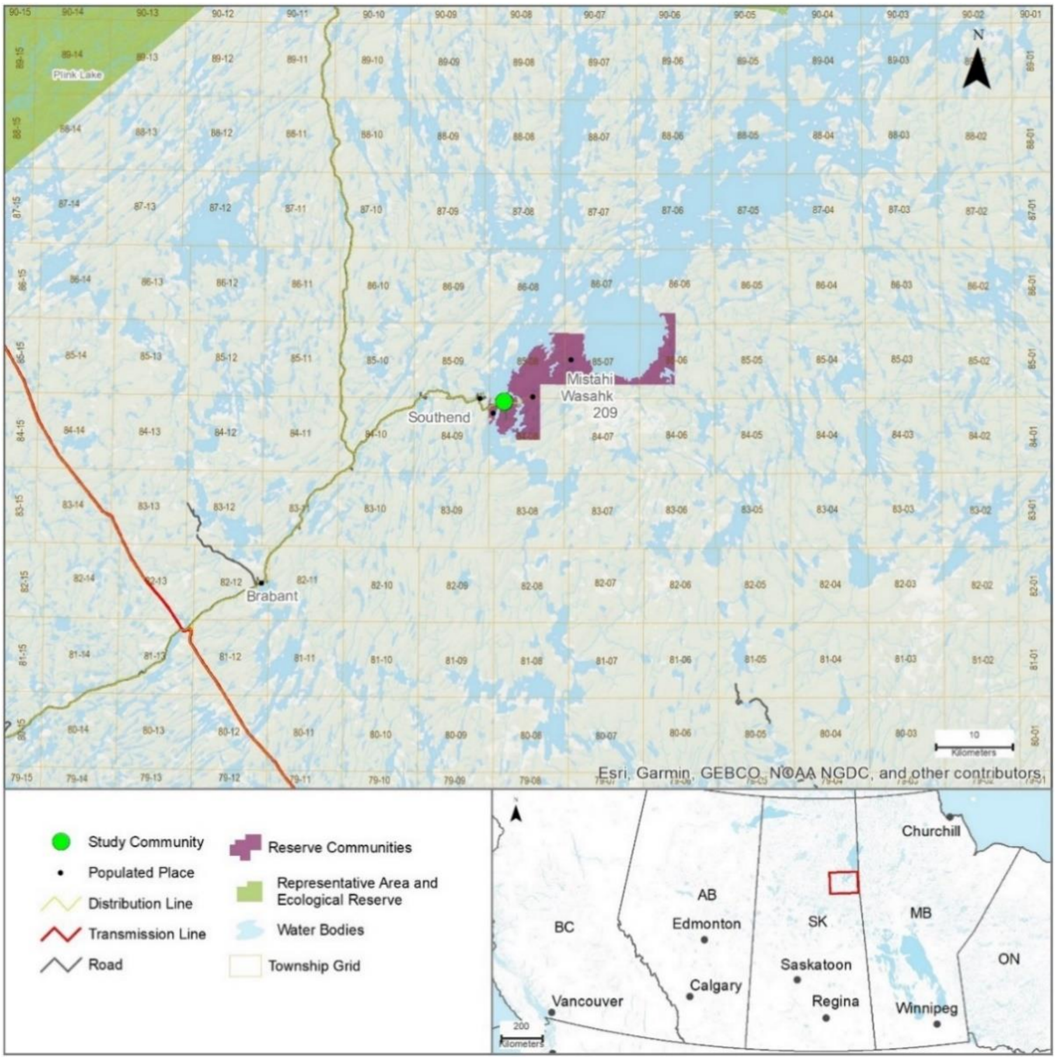


Figure 3.1 Southend, Saskatchewan.

3.1.1 Weather and climate

The community experience a sub-arctic climate characterised by long, cold winters and short, mild summers. Weather and climate of this region exhibit distinct seasonal variations (Figure 3.2) and are influenced by the northern geographic location (Weather Atlas, 2023). Winter conditions in Southend typically last from November to April, and temperatures often drop below freezing with average monthly temperatures ranging from -20 ˚C to -30˚C (Figure 3.2a),

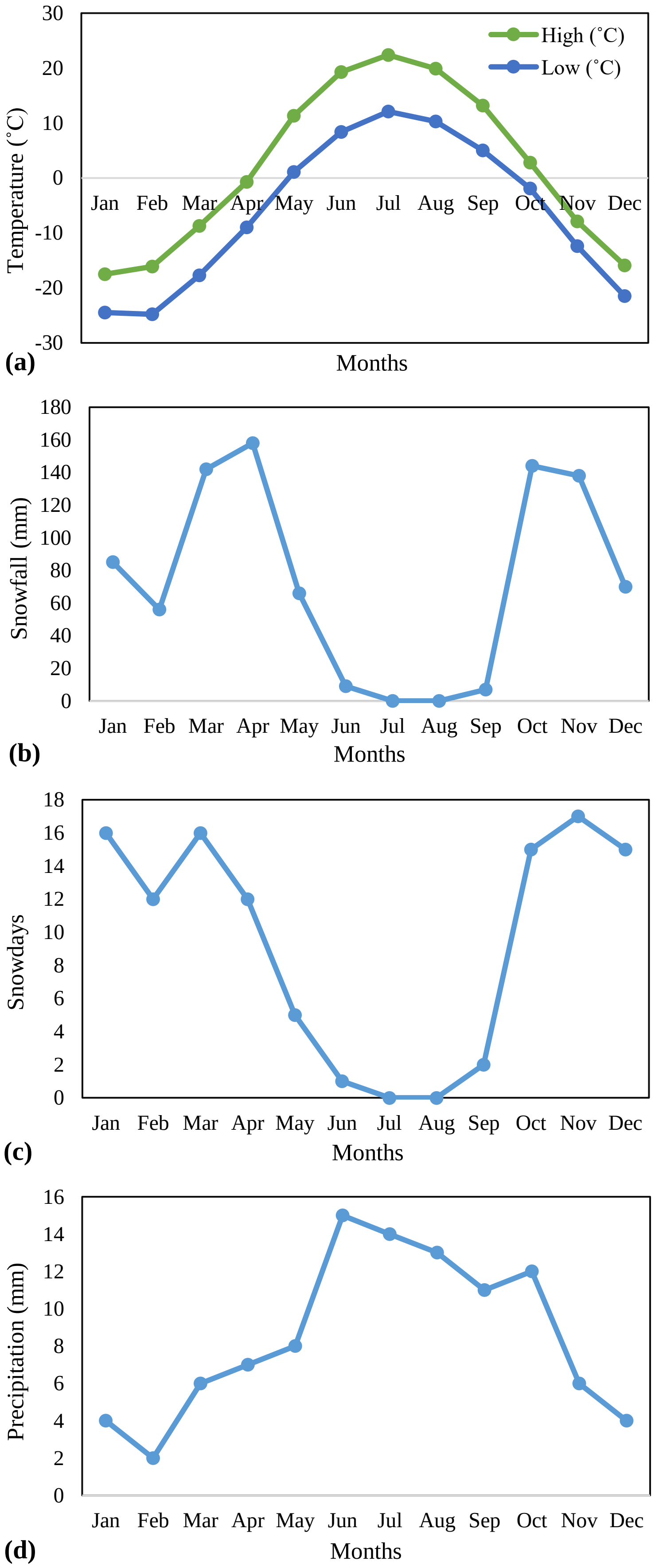


Figure 3.2 Seasonal variation of weather and climatic variables in Southend (Data source: ENRC, 2023).

with occasional temperatures below -40˚C (ENRC, 2023). Relative humidity is at its maximum in December and February, making the air much cooler. Heavy snowfall is common, and the region is covered in a thick blanket of snow throughout the winter season (Figure 3.3). The highest amount of snowfall usually occurs in April, with an average snowfall of 158 mm (Figure 3.2b), whereas the maximum number of snowy days is reported in the month of November (Figure 3.2c). Compared to winter, the average precipitation of Southend is higher in the summer season, and June is the wettest month (Figure 3.2d). The community typically experience severe weather conditions such as blizzards and heavy snowstorms during the winter, which can result in reduced visibility, hazardous road conditions, transportation and communication disruptions, and a hampering of electricity transmission.

Figure 3.3 Snowy conditions in Southend. Saskatchewan, in November 2022 (author's own captured).

3.1.2 Energy use and consumption

The community is connected to the Saskatchewan Power Corporation's (SaskPower) northern transmission grid; power disruptions are reported to be very frequent, with outages sometimes lasting for several hours to days during severe storm or fire events, with residents relying on firewood and imported propane fuel (Asante *et al.*, 2023). As the communities do not have access to natural gas, residential buildings are heated using electricity, which means increased electricity consumption, and thus higher energy costs, especially in the winter months (Figure 3.4). The highest electricity consumption in 2020, for example, was 1,123.81 MWh in December, while the lowest was 309.86 MWh in June (Figure 3.4). Residents living in the community claim that because of high electricity bills they often cannot afford groceries, ultimately affecting their health and wellbeing (Maxwell, 2019).

There is also significant wood stove usage in the communities to help offset electricity use for heating (and sometimes cooking), and the band provides firewood to elders (Sigurdson *et al.*, 2020). However, burning of firewood for space heating sometimes causes fire incidents and threatens life and property (Figure 3.5). Large commercial and public or community buildings are heated using propane-fired boilers, typically delivered from a distributor in La Ronge. Transportation and preservation of imported fuel is challenging, requires high costs and causes increased GHG emissions. Overall, the community is energy insecure, and is paying high costs for their energy needs. Given Southend's location in the boreal forest zone, the community has expressed interest in exploring local bioenergy options to reduce high energy expenses and strengthen local energy security.

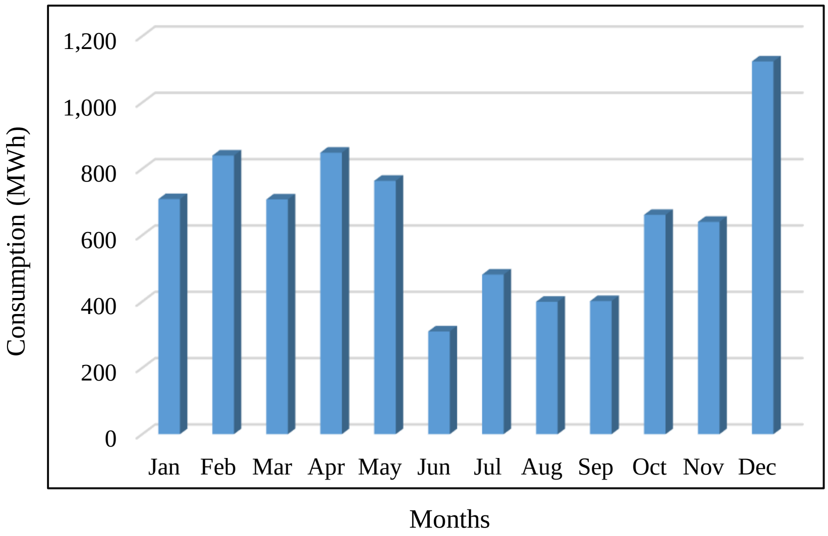


Figure 3.4 Monthly average electricity consumption (MWh) for the community of Southend, in 2020 (Data source: SaskPower).

Figure 3.5 Residential fire incident caused by a woodstove, captured during a community visit in June 2023 (author's own captured).

3.2 Methods

Both qualitative and quantitative data were used in this research, collected mainly from secondary data sources including remote sensing images and literature. Primary data collected through a community engagement workshop and participatory mapping exercise to identify areas of biomass resource potential and exclusion zones (e.g. culturally significant sites, regulatory land use restrictions, etc.), were drawn from a previous engagement exercise with the community (see Asante *et al.*, 2023), and also informed the mapping inputs for this research. ArcGIS (version 10.8) software was used for mapping and geospatial analysis of potential biomass resources around the community, enabling the visualization of resource hotspots and the estimation of potential biomass resources. Statistical analyses of quantitative data, models, and graphical presentation were done using Microsoft Excel.

To assess the CBP of Southend, the proposed integrated framework for bioenergy potential assessment adopted. The technical flowchart illustrated in Figure 3.6 depicts the step-by-step research design and is described below.

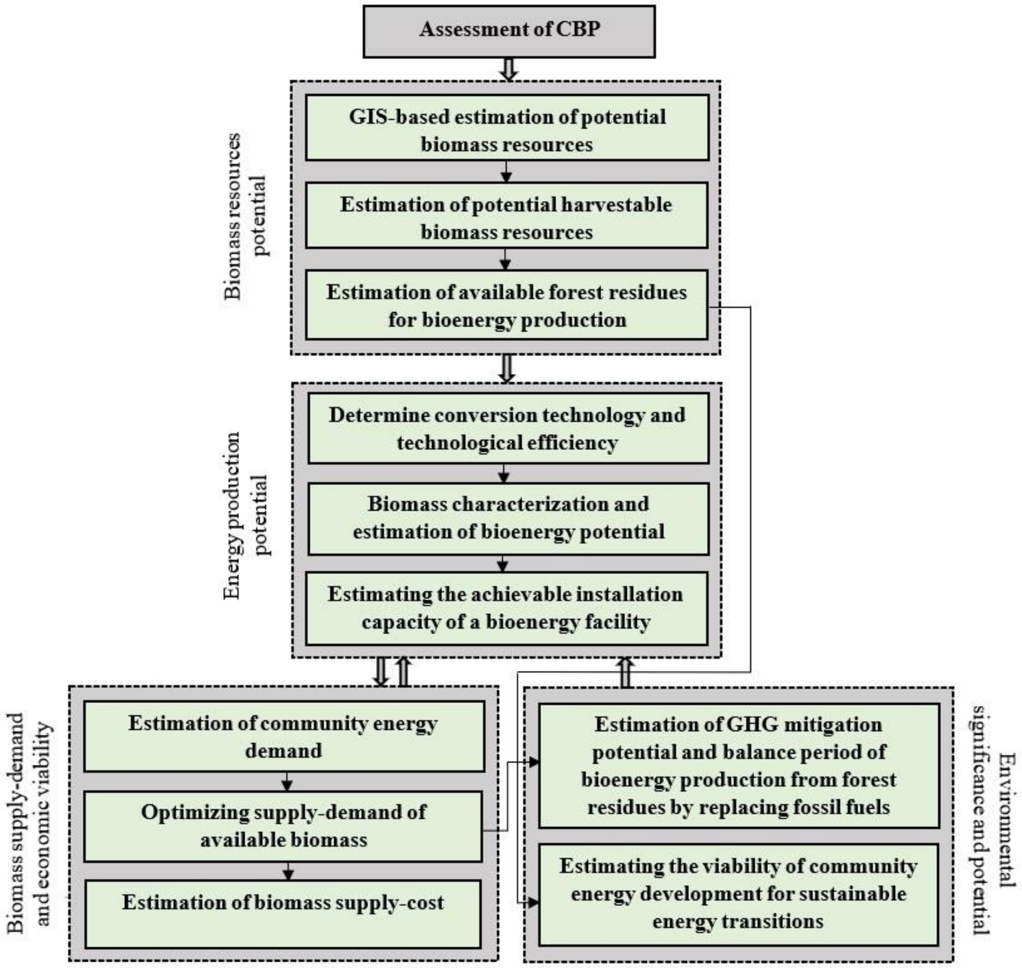


Figure 3.6 Community bioenergy potential technical assessment framework (author’s construction).

3.2.1 Estimation of potential biomass resources

Geospatial techniques were used to assess potential biomass resources within a 50-km boundary of Southend, defined as the local area of biomass supply. This was tempered by township grid zones for ease of resource estimations, resulting in the assessment area extending up to 65 km east and west (Figure 3.1). In the initial phase of the assessment, the upland forest cover raster layer (30m x 30m) was extracted from the generalized land cover classification data of the Ministry of Environment of Saskatchewan, followed by the layer of potential tree species (e.g., jack pine, white spruce) that are mature (75–125 years), old (126–200 years), and very old (above 200 years) (Saskatchewan State of the Environment, 2019). It is noted that mature, old, and very old tree species are harvested commercially by the timber supply companies operating in boreal regions (Asante *et al.*, 2023). To ensure the accuracy of the biomass availability assessment, legally inaccessible zones, restricted and regulatory areas, protected locations, and their designated buffers have been taken into consideration and then excluded from the estimation of the biomass resource base by following the methodologies outlined in Asante *et al.* (2023). The biomass resource base was further refined to estimate the potential harvestable biomass resources by considering community concerns through community engagement and participatory mapping workshops (Asante *et al.*, 2023), ensuring that local knowledge of the area, land uses that would conflict with biomass harvesting, and community concerns were integrated into the assessment and delineation of available biomass resources for harvesting. The harvestable biomass area was further examined to estimate the availability of forest residues generated for bioenergy production by following the methodology outlined by Mansuv *et al.* (2020) for bioenergy estimations in Cold Lake First Nation, Alberta, whereby 18 odt/ha is considered for forest residue yield from clear-cut harvest, and the annual allowable harvestable quota is considered 1.2% of the available biomass.

3.2.2 Estimation of bioenergy production potential

The energy production potential of biomass depends on the application of conversion technology and the heating value of biomass (Tshikovhi and Motaung, 2023). Based on the literature, among the available conversion technologies thermochemical conversion process through simple combustion and gasification are widely used for bioenergy production. The Meadow Lake Tribal Council's (MLTC) bioenergy centre in northern Saskatchewan, for example, is one of the province's first carbon-neutral energy infrastructures, with a capacity of 6.6 MW of power generation fuelled by the burning of biomass sawmill residuals through direct combustion, powering approximately 5,000 homes (MLTC Bioenergy Centre, 2020).

Combustion is thus considered a viable technology for installation in Southend, owing to similar geo-environmental settings. Simple combustion steam turbines (CST) are renowned for their simplicity for bioenergy production with minimal expenses (Balcioglu *et al.,* 2023). Meanwhile, gasification combined cycle (GCC) is a more advanced technology that converts solid biomass into gaseous fuel, which is further used to produce electricity. It is known for its high energy conversion efficiencies and low emissions (Chen *et al.*, 2020; Banerjee, 2023). Therefore, both technologies, and their high and low conversion efficiencies, are considered in this research for the estimation of energy production potential in the study region.

Energy content as well as the calorific value or heating value of biomass depends on several factors, including moisture content, species types, composition of the biomaterials, and environmental and climatic factors (Clarke *et al.*, 2011; Barrette *et al.*, 2015). Therefore, it is difficult to determine the exact energy content of the estimated biomass residues in the study area, and thus both high and low heating values are considered for estimation purposes. By considering both the technological efficiency and energy content of biomass, the following scenarios were adopted and assessed: (a) high conversion efficiency (HCE) and high heating value (HHV); (b) high conversion efficiency (HCE) and low heating value (LHV); (c) low conversion efficiency (LCE) and high heating value (HHV); and (d) low conversion efficiency (LCE) and low heating value (LHV). It was assumed ins all scenarios that available biomass resources would be processed at the bioenergy facility to generate electricity.

Considering the above assumptions and scenarios, an energy conversion factor was used to estimate the energy production potential of biomass residues per ton. Table 3.1 illustrates the conversion capacity factors used, derived from literature, to multiply the annual harvestable biomass residues in the study area against the different scenarios. The installation capacity (MW) of a bioenergy facility for the study area was then estimated by dividing the estimated energy potential per ton (MWh) by approximate operating hours. It was assumed that the facility will operate at 90% hours of its capacity (i.e., 328.5 days per year or 7,884 hours of operation), allowing 10% time offline throughout the year for maintenance or other factors.

Table 3.1 Applied capacity factors in energy conversion model.

Items	**HHV**	**LHV**	**References**
HCE-ST (MWh/t)	2.111	1.667	Caputo *et al.* (2005)
LCE-ST (MWh/t)	1.056	0.833	Caputo *et al.* (2005)
HCE-GCC (MWh/t)	2.481	1.958	Searcy and Flynn (2009)
LCE-GCC (MWh/t)	1.847	1.458	Searcy and Flynn (2009)

3.2.3 Assessing biomass supply-demand and economic viability

To estimate the community energy demand, household electricity consumption data for one year has been collected from SaskPower. Based on the community electricity demand, the required installation capacity of a bioenergy facility is estimated as follows [equation 3.1]:

$$Installation\ capacity\ (MW) = \frac{Annual\ electricity\ consumption\ (MWh)}{Probable\ operation\ hours\ of\ bioenergy\ facility\ (h)} \ldots\ldots\ldots\ldots\ldots (3.1)$$

Available biomass resources were further optimized to identify adequate biomass supply to meet community energy demand. Different availability and accessibility scenarios were considered based on Asante *et al.* (2023), including (a) a preference for harvesting resources closer to the community (i.e., distance of the harvestable resource base from the community), (b) accessibility of biomass resources for road access (i.e., distance of the harvestable resource base from existing roads), and (c) preference and accessibility (i.e., both distance of the harvestable resource base from the community and distance from existing roads).

Based on the required biomass availability, a supply-cost model was estimated for a 30 km service area from the community and 5 km from the existing road infrastructure (see Asante *et al.*, 2023). The supply-cost model was built based on Calvert and Mabee (2014), and based on the following assumptions: (a) biomass from the forest is sorted and bundled at the roadside and transported to the facility at 50% moisture content in a 40-ton truck; (b) average trucking speed is considered to be 60 km/h; and (c) any further processing like chipping and drying is considered to be performed at the facility site. Model inputs regarding the biomass supply-costs are present in Table 3.2. The data was exported to Excel, where supply-cost curves were generated by inputting the distance and yield values into the supply-cost model. It should be mentioned here that, due to a lack of sufficient data, slope is not being considered in this analysis as a factor impacting driving distance and costs. Moreover, recent fuel prices and inflation are not also considered in estimating transportation costs.

Table 3.2 Biomass supply-cost model inputs.

Operations	Feedstock cost factors	References
Total harvesting cost of biomass residues* ($/odt)	20.50	Calvert and Mabee (2014)
Loading and unloading ($/odt)	6.00	Richardson *et al.* (2011); Alam *et al.* (2012); Calvert and Mabee (2014)
Transportation costs ($/odt-km)	0.18	Calvert and Mabee (2014)

**Here, total harvesting costs includes felling, bundling, skidding, and processing (e.g., chipping)*

3.2.4 Assessing environmental significance and potential

To assess the environmental potential of community bioenergy development, the GHG mitigation potential of bioenergy from harvested forest residues is estimated as a substitute for fossil fuel-based energy. In Saskatchewan, almost 81% of electricity is produced from fossil fuels, and the electricity sector produces the second highest amount of GHG emissions across Canada (Canada Energy Regulator, 2024). SaskPower, the major electricity producer in the province, typically relies on natural gas (43%) and coal (30%) to generate electricity, though they also produce electricity from renewable sources, including wind (15%), hydro (7%), and others (5%) (SaskPower, 2024). Therefore, both coal and natural gas are being considered as substitutes to estimate the GHG mitigation potential of bioenergy for Southend.

Table 3.3 Model parameters used in the greenhouse gases mitigation calculator.

Model parameter	Description
Feedstock	Harvest residues (woody debris, e.g., branches, treetops, bark, etc.),
Feedstock transformation	Wood chips
Mean annual temperature	-1 ˚C (based on the weather and climate data of Southend)
Place of use	Local market (within Canada)
Transportation mode	Truck
Distance for travel	20 km (high efficiency), 30 km (low efficiency)
Energy conversion	Electricity and heat
Bioenergy system efficiency	75% (high), 26% (low)
Fossil fuel replaced	Coal, Natural gas
Fossil fuel system efficiency	Coal: 80% (high), and 33% (low), Natural gas: 85% (high), and 45% (low)

To estimate the GHG mitigation potential of bioenergy, a GHG calculator developed by Natural Resources Canada was used (https://apps-scf-cfs.rncan.gc.ca/calc/en/bioenergy-calculator). Based on the methodology developed by Laganiere *et al.* (2017), this tool made it possible to estimate the GHG balance period and uncertainty phases when bioenergy from harvested forest residue is used as a substitute for fossil fuel. The results are presented in best- and worst-case scenarios for a 100-year periods and start at year 0, with the production and utilization of bioenergy sourced from a sustainably managed forest. The parameters of the model inputs are present in Table 3.3. Different assumptions and scenarios based on the conversion efficiency, i.e., high bioenergy system efficiency with high fossil fuel (coal and natural gas) system efficiency, high bioenergy system efficiency with low fossil fuel (coal and natural gas) system efficiency, low bioenergy system efficiency with high fossil fuel (coal and natural gas) system efficiency, and low bioenergy system efficiency with low fossil fuel (coal and natural gas) system efficiency, have been tested in this study over a 100-year timeframe to examine the GHG balance period as well as the net atmospheric emission reduction potential of biomass energy from harvested forest residues.

The potential of community bioenergy development in Southend was further assessed to evaluate the feasibility of a sustainable biomass supply for energy production. Based on the harvestable biomass resources availability, probability of the biomass harvesting tenure was calculated by following [equation 3.2]:

$$\textit{Biomass harvesting tenure (yr)} = \frac{Residues\ of\ total\ harvestable\ biomass}{Residues\ of\ annual\ harvestable\ biomass} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

CHAPTER 4

RESULTS

4.1 Available Biomass Resources

Figure 4.1 shows the theoretically available biomass resource base in the study region. The theoretically available biomass resource base is that portion of forested land that is not deemed “legally inaccessible” forest area (i.e., ecologically protected areas, transmission lines and road rights-of-way, reserve communities, mining blocks), and accounting for water bodies (e.g., wetlands, lakes, rivers, streams). Within the study region, approximately 919,779 ha of land are characterized as forested, and 362,083 ha are non-forested land. Among the forested land, the biomass resource base is approximately 663,858 ha (Table 4.1).

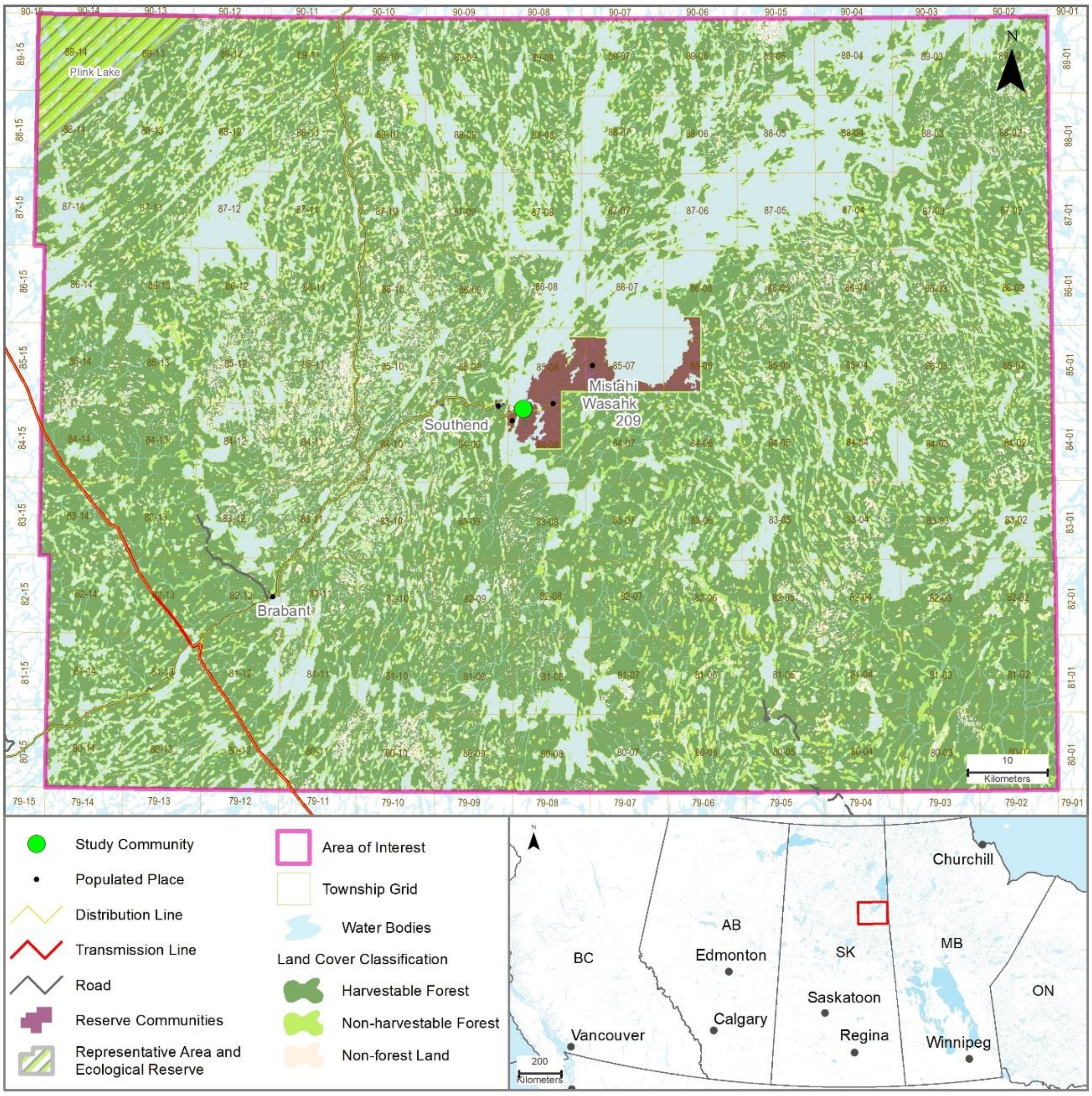


Figure 4.1 Theoretical biomass resources in the study area.

Table 4.1 Non-forested land, forested land, inaccessible forested land, and theoretically available biomass resource base in the study area.

Classification	Areas (ha)
Non-forested land	362,083
Forested land	919,779
Legally inaccessible forest areas	255,921
Theoretical biomass resources for harvest	663,858

The theoretically available biomass resource base was further assessed to delineate areas of community concern, such as areas of land use competition or areas of cultural significance, that may not be permissible for biomass harvesting. The delineation of these areas serves to strike a balance between the utilization of natural resources for local energy production and the preservation of vital cultural and ecological elements. Local community workshops we conducted (see Asante *et al.,* 2023), identifying several locations where biomass harvesting would be considered for inappropriate, including traditional medicinal and food (wild rice) gathering areas, local hunting areas and active trapline areas, fishing areas, rocky area, pictograph areas, wildfire zones, and campsites. Figure 4.2a highlights the noted areas where biomass harvesting would be deemed inappropriate owing to their ecological value, or cultural, historical, or recreational importance for the community. Considering these restricted areas, the biomass resource base in the study area for local bioenergy production was further refined (Figure 4.2b). The estimations of the refined harvestable biomass with community considerations are presented in Table 4.2.

Table 4.2 Forest area classification following identification of community areas of concern.

Classification	Area (ha)
Non-forested land	362,083
Harvestable forest trees area within regulatory, legally inaccessible zones and areas of community concern	305,813
Harvestable forest trees outside regulatory, legally inaccessible zones, and areas of community concern	613,966

Forest trees have significant economic (timber, building material) and ecological value; therefore, it may not always be desirable to harvest forest trees for bioenergy. To avoid the competition of using forest resources for bioenergy production with other uses, this assessment focused only on forest residues available from harvested trees. Table 4.3 presents the estimation of forest residues that would be generated from harvestable forest trees. Results show that the total residue from harvestable forest trees is 11,051,393 oven dry tons (odt).

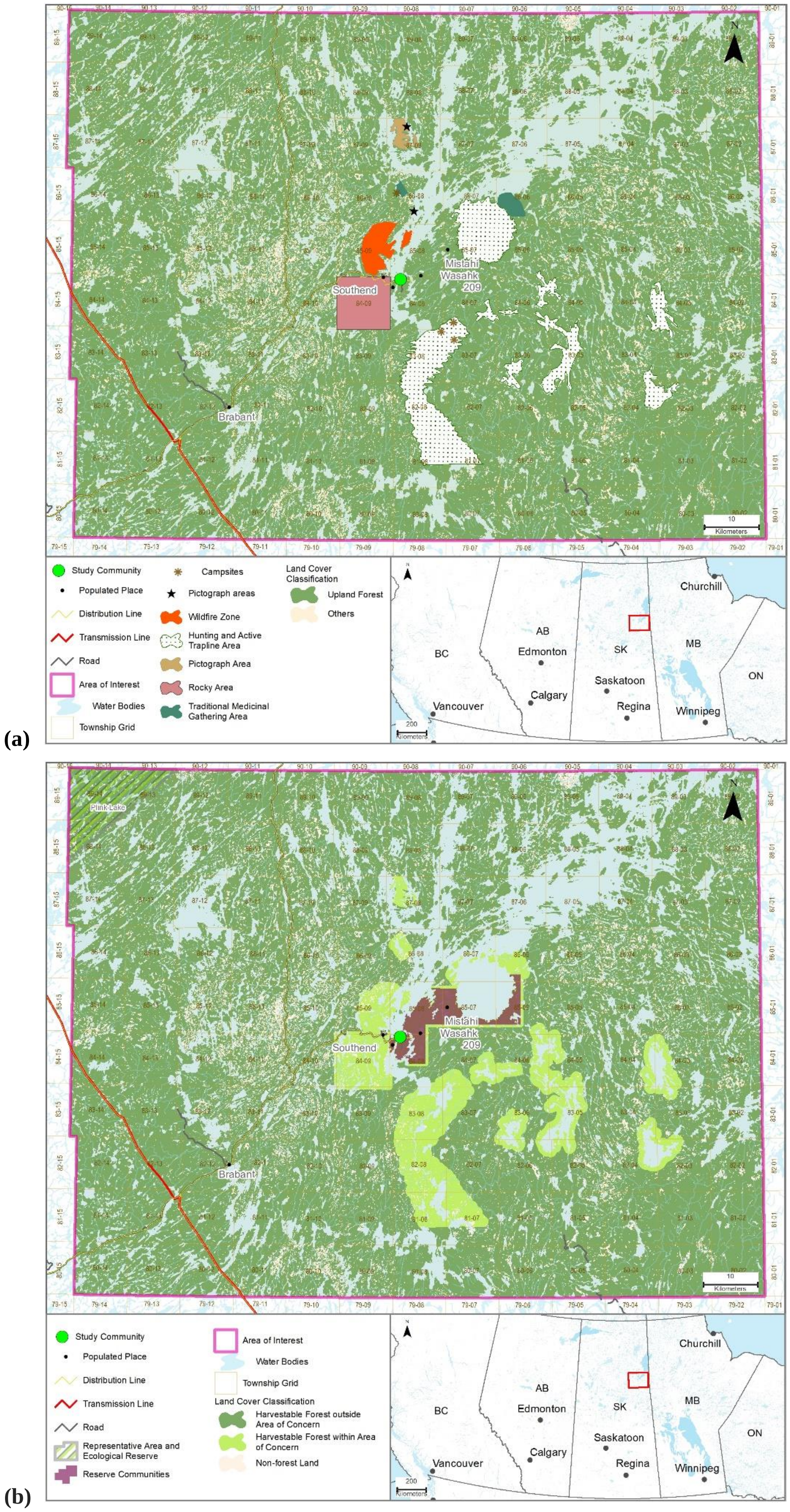


Figure 4.2 Community areas of concern (a) and potentially harvestable biomass (b).

By considering an annual harvest rate of 1.2%, based on the Cole Lake First Nation, Alberta, bioenergy harvesting operation, residues generated from the harvestable forest trees would be 132,617 odt per annum (Table 4.3). This residue is next used to estimate harvest needs for bioenergy production.

Table 4.3 Estimation of forest residue availability based on harvestable forest trees outside regulatory, legally inaccessible zones, and community concern areas.

Forest harvest parameter	Values
Residue from clear-cut harvest (odt/ha)	18
Annual harvested rate (%)	1.2
Total residue from harvestable forest trees (odt)	11,051,393
Annual residue from harvestable forest trees (odt)	132,617

4.2 Energy Production Potential

Energy potential is estimated in different technological efficiency and heating value scenarios, i.e., high conversion efficiency (HCE) and high heating value (HHV); high conversion efficiency (HCE) and low heating value (LHV); low conversion efficiency (LCE) and high heating value (HHV); and low conversion efficiency (LCE) and low heating value (LHV) (Table 4.4). The results indicate the variations in energy production potential under these different scenarios based on the combination of conversion efficiency and heating value for both combustion and gasification technologies. The highest energy potential is observed in gasification combined cycle technology, with high conversion efficiency and a high heating value, reaching 329,022 MWh. Conversely, the lowest potential is found for the simple combustion steam turbine technology, with a low conversion efficiency and low heating value, yielding 110,470 MWh (Table 4.4).

Table 4.4 Estimation of energy potential based on the potential biomass residues.

Energy production potential	Unit	Value
combustion steam turbine (CST)		
High conversion efficiency and high heating value	MWh	279,821
High conversion efficiency and low heating value	MWh	221,072
Low conversion efficiency and high heating value	MWh	140,043
Low conversion efficiency and low heating value	MWh	110,470
gasification combined cycle (GCC)		
High conversion efficiency and high heating value	MWh	329,022
High conversion efficiency and low heating value	MWh	259,644
Low conversion efficiency and high heating value	MWh	244,943
Low conversion efficiency and low heating value	MWh	193,355

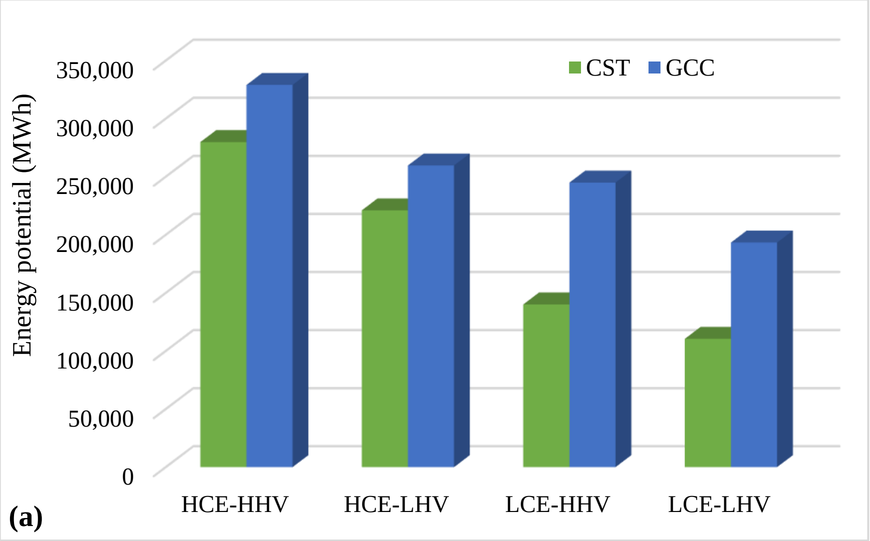
4.2.1 Estimation of installation capacity

The installation capacity of the two bioenergy facility types (combustion steam turbine, gasification combined cycle plant technology) is further estimated to predict the maximum power output each type of bioenergy facility could generate, considering biomass supply availability. These estimations indicate the feasibility of developing and implementing a bioenergy facility and the necessary steps in the early phase of energy planning. Table 4.5 presents the estimated installation capacity based on the potential biomass residues. Assuming a bioenergy facility operating at 90% hours of its capacity in a year (7,884 hours of operation in a year), the results show that a maximum 41.73 MW and 35.49 MW bioenergy plant can be operated by using the available biomass resources in the study area, with highly efficient GCC and CST, respectively (Table 4.5).

Table 4.5 Estimation of the installation capacity of bioenergy facility based on the potential biomass residues.

Installation capacity	**Unit**	**Value**
combustion steam turbine (CST)		
High conversion efficiency and high heating value	MW	35.49
High conversion efficiency and low heating value	MW	28.04
Low conversion efficiency and high heating value	MW	17.76
Low conversion efficiency and low heating value	MW	14.01
gasification combined cycle (GCC)		
High conversion efficiency and high heating value	MW	41.73
High conversion efficiency and low heating value	MW	32.93
Low conversion efficiency and high heating value	MW	31.07
Low conversion efficiency and low heating value	MW	24.52

The comparison among the potential energy output and installation capacity for bioenergy power generation using combustion steam turbine and gasification combined cycle technology under various conditions of conversion efficiency and heating value is illustrated in Figure 4.3. These results provide insights into the performance and capacity of both technologies under different scenarios. Results show that, in every case, maximum energy output can be generated from gasification technology compared to combustion steam turbine. This suggests that installing gasification technology holds significant promise for maximizing energy generation potential of the available biomass residues. Moreover, conversion efficiency is another important factor, which can help get the maximum energy output for the application of either of these technologies.



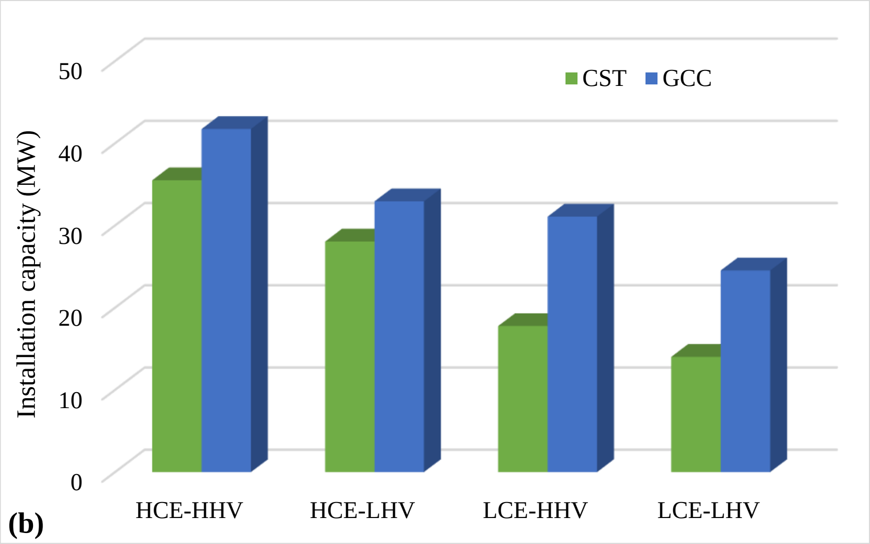


Figure 4.3 Comparison of (a) energy potential and (b) the installation capacity of bioenergy facility between steam turbine and gasification technology.

4.3 Community Energy Demand and Optimizing Biomass Supply

The estimation of community energy demand was performed by analysing household-level energy consumption data for the community. Table 4.6 presents the summary of monthly household electricity consumption (MWh) of Southend in 2020. The total annual electricity consumption of the community is approximately 7886.43 MWh. To meet this energy demand, it is projected that a 1.0 MW bioenergy facility operating at 90% operation hours capacity of a year (i.e., operating 7,884 hours per year) could generate the required electricity. This estimation provides crucial insight to the potential of harnessing bioenergy resources to meet the energy needs of Southend. Based on this estimation, it can be assumed that there is sufficient biomass resource available to feed a community-based biomass power plant in

Southend; this would be nearly 41 and 35 times higher than the local demand if using HHV and highly efficient gasification or combustion technology, respectively (Table 4.5). The anticipated electricity generation from the bioenergy facility would surpass local demand, under the assumed biomass harvesting conditions, conversion, and technology assumptions.

Table 4.6 Monthly average electricity consumption (MWh) in 2020 of Southend.

Months	Electricity consumptions (MWh)
January	708.90
February	840.09
March	707.80
April	848.79
May	763.88
June	309.86
July	481.31
August	399.25
September	401.36
October	661.26
November	640.12
December	1123.81
Total	**7886.43**

Data source: Data provided by SaskPower based on a data sharing agreement with CASES, University of Saskatchewan.

Results show a significant amount of biomass resources within the study area. As such, the resource base was reassessed to optimize the economic costs of harvesting of biomass, assuming a bioenergy plant located in the community of Southend. Available biomass resources are thus optimized under different availability and accessibility scenarios: harvesting close to the community; harvesting close to the road network; harvesting close to the community *and* close to the road network.

4.3.1 Distance from the community

Energy potential was reassessed by considering the availability of harvestable biomass resources close to the community as preferred to meet the local energy demand. Resource availability was assessed at increasing distances from Southend in all directions: 0–10 km, 10–20 km, 20–30 km, 30–40 km, and >40 km (Figure 4.4). The aspiration to optimize biomass resources is that, though moving biomass resources away from the community may allow for larger quantities of biomass, increased distance can lead to higher transportation costs, including fuel and logistics expenses. Another important consideration was the level of community engagement in resource collection and management practices. It's noted that increasing distances may reduce community involvement, which could have implications for sustainability and social acceptance of bioenergy project. Community engagement is essential for the successful implementation and long-term viability of bioenergy project, as it ensures local support and participation in the management of biomass resources.

The results of the assessment indicate that sufficient amounts of biomass resources are available within 20 km of Southend to provide the required forest residue for power production, with the exception of a low-efficient CST and LHV scenario (Table 4.7), which highlight the viability of local resource utilization for sustainable energy generation.

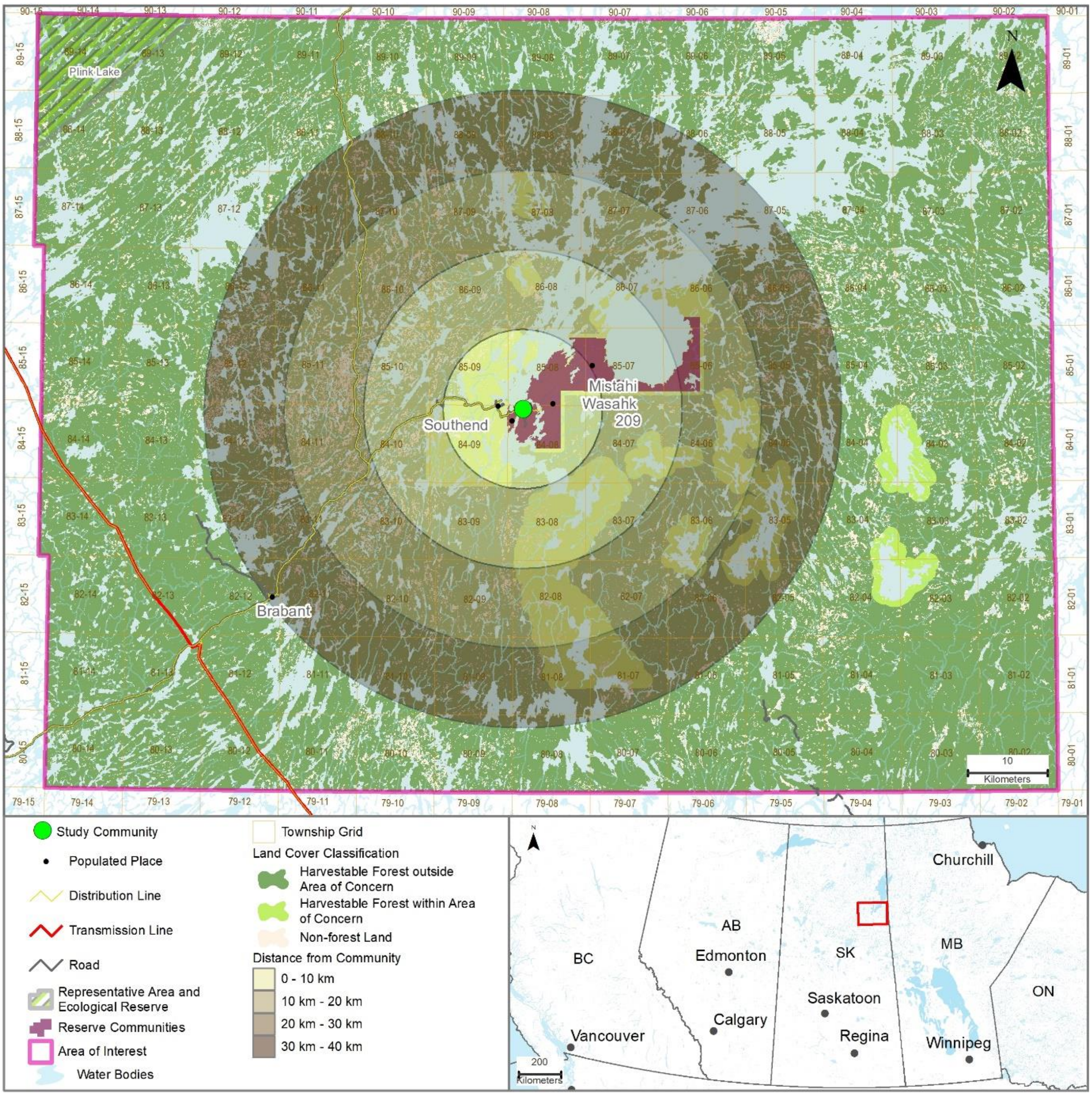


Figure 4.4 Harvesting zones at increasing distances from the community.

Table 4.7 Estimation of energy potential based on increasing distances from the community.

Scenario	**Unit**	**Distance from the community (km)**				
		0-10	**10-20**	**20-30**	**30-40**	**>40**
Total harvestable biomass	odt	82,269	616,270	1,252,104	1,906,946	7,193,804
Annual harvestable biomass	odt	987	7,395	15,025	22,883	86,326
combustion steam turbine (CST)						
Energy potential (HCE-HHV)	MWh	2,083	15,604	31,703	48,284	182,147
Energy potential (HCE-LHV)	MWh	1,646	12,328	25,047	38,147	143,905
Energy potential (LCE-HHV)	MWh	1,043	7,809	15,867	24,165	91,160
Energy potential (LCE-LHV)	MWh	822	6,160	12,516	19,062	71,909
Installed capacity (HCE-HHV)	MW	0.26	1.98	4.02	6.12	23.10
Installed capacity (HCE-LHV)	MW	0.21	1.56	3.18	4.84	18.25
Installed capacity (LCE-HHV)	MW	0.13	0.99	2.01	3.07	11.56
Installed capacity (LCE-LHV)	MW	0.10	0.78	1.59	2.42	9.12
gasification combined cycle (GCC)						
Energy potential (HCE-HHV)	MWh	2,449	18,348	37,278	56,774	214,174
Energy potential (HCE-LHV)	MWh	1,933	14,480	29,419	44,806	169,026
Energy potential (LCE-HHV)	MWh	1,823	13,659	27,752	42,266	159,443
Energy potential (LCE-LHV)	MWh	1,439	10,782	21,907	33,364	125,863
Installed capacity (HCE-HHV)	MW	0.31	2.33	4.73	7.20	27.17
Installed capacity (HCE-LHV)	MW	0.25	1.84	3.73	5.68	21.44
Installed capacity (LCE-HHV)	MW	0.23	1.73	3.52	5.36	20.22
Installed capacity (LCE-LHV)	MW	0.18	1.37	2.78	4.23	15.96

4.3.2 Distance from the road network

Energy potentials were further reassessed by considering the availability of harvestable biomass resources closer to the existing road infrastructures. To perform this assessment, resource estimations as well as the energy potential were performed based on the increasing distances from the road network, ranging from 0–0.5 km, 0.5–1 km, 1–5 km, 5–10 km, 10–15 km, 15–20 km, 20–25 km, 25–30 km, 30–40 km, and >40 km on both sides of the existing available roads (Figure 4.5).

Results suggest that the availability of biomass resources within 5 km of the existing road network of the study area would be sufficient to the residues required for community bioenergy production, under all assumptions, from high conversion efficiency and HHV to low conversion efficiency and LHV of biomass (Table 4.8). The road network is an important factor in the accessibility of biomass resources for harvesting and transportation. Results indicate considerable potential for biomass availability closer to the existing roads, which at the same time provides opportunities for resource harvesting and reduces transportation time and costs.

Table 4.8 Estimation of energy potential based on increasing distances from the road infrastructure.

Scenario	**Unit**	**Distance from the road (km)**									
		0-0.5	**0.5-1**	**1-5**	**5-10**	**10-15**	**15-20**	**20-25**	**25-30**	**30-40**	**>40**
Total harvestable biomass	odt	80,260	86,214	625,104	716,925	705,328	674,157	636,890	510,679	1,003,970	6,011,867
Annual harvestable biomass	odt	963	1,035	7,501	8,603	8,464	8,090	7,643	6,128	12,048	72,142
combustion steam turbine (CST)											
Energy potential (HCE-HHV)	MWh	2,032	2,183	15,828	18,153	17,859	17,070	16,126	12,930	25,421	152,220
Energy potential (HCE-LHV)	MWh	1,606	1,725	12,505	14,341	14,109	13,486	12,740	10,216	20,083	120,261
Energy potential (LCE-HHV)	MWh	1,017	1,093	7,921	9,085	8,938	8,543	8,071	6,471	12,722	76,182
Energy potential (LCE-LHV)	MWh	802	862	6,249	7,166	7,050	6,739	6,366	5,105	10,036	60,095
Installed capacity (HCE-HHV)	MW	0.26	0.28	2.01	2.30	2.27	2.17	2.05	1.64	3.22	19.31
Installed capacity (HCE-LHV)	MW	0.20	0.22	1.59	1.82	1.79	1.71	1.62	1.30	2.55	15.25
Installed capacity (LCE-HHV)	MW	0.13	0.14	1.00	1.15	1.13	1.08	1.02	0.82	1.61	9.66
Installed capacity (LCE-LHV)	MW	0.10	0.11	0.79	0.91	0.89	0.85	0.81	0.65	1.27	7.62
gasification combined cycle (GCC)											
Energy potential (HCE-HHV)	MWh	2,389	2,567	18,611	21,344	20,999	20,071	18,961	15,204	29,890	178,985
Energy potential (HCE-LHV)	MWh	1,886	2,026	14,687	16,845	16,572	15,840	14,964	11,999	23,589	141,255
Energy potential (LCE-HHV)	MWh	1,779	1,911	13,855	15,890	15,633	14,942	14,116	11,319	22,252	133,247
Energy potential (LCE-LHV)	MWh	1,404	1,508	10,937	12,543	12,340	11,795	11,143	8,935	17,565	105,184
Installed capacity (HCE-HHV)	MW	0.30	0.33	2.36	2.71	2.66	2.55	2.41	1.93	3.79	22.70
Installed capacity (HCE-LHV)	MW	0.24	0.26	1.86	2.14	2.10	2.01	1.90	1.52	2.99	17.92
Installed capacity (LCE-HHV)	MW	0.23	0.24	1.76	2.02	1.98	1.90	1.79	1.44	2.82	16.90
Installed capacity (LCE-LHV)	MW	0.18	0.19	1.39	1.59	1.57	1.50	1.41	1.13	2.23	13.34

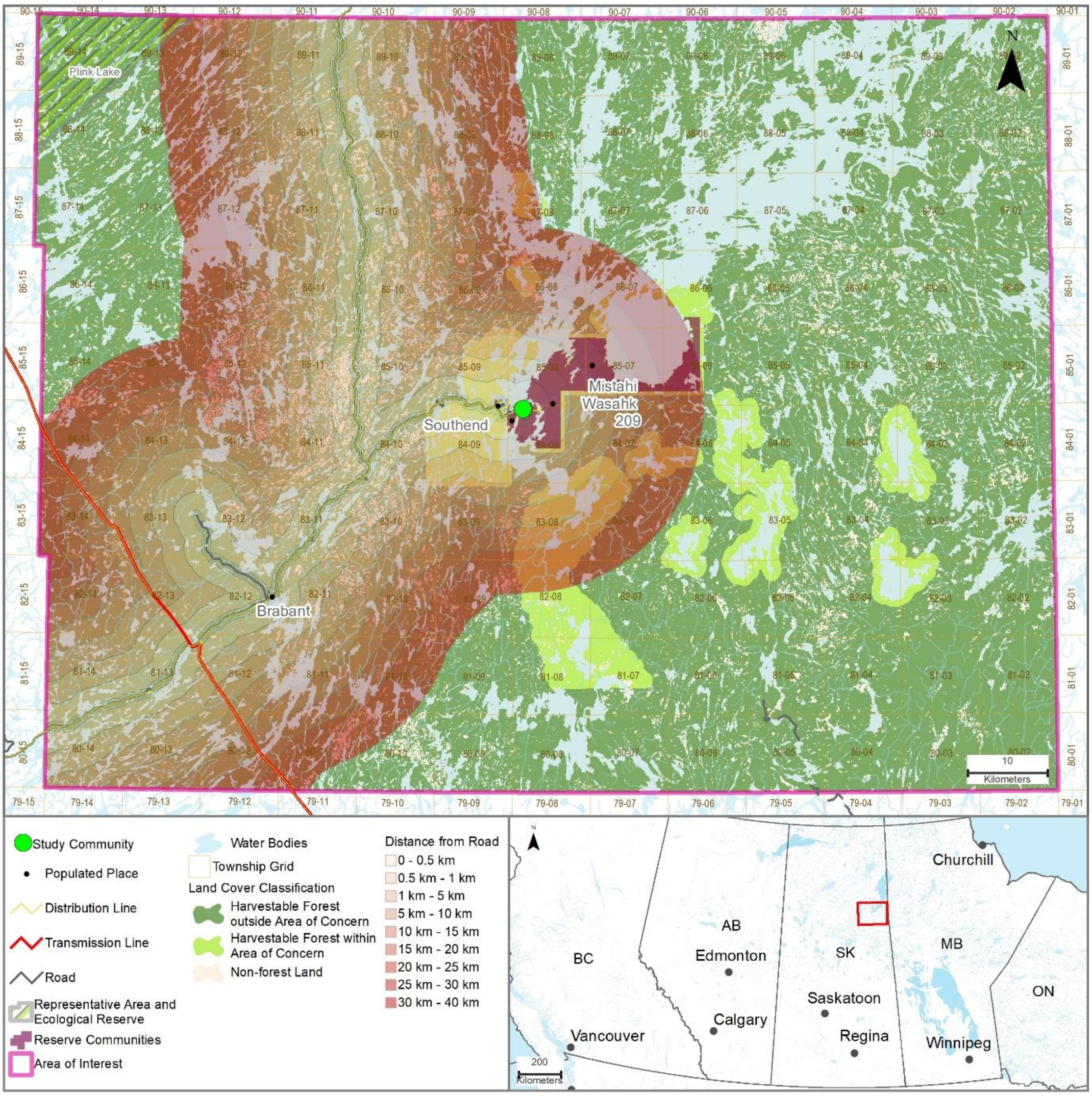


Figure 4.5 Availability of biomass resources at increasing distances from the road network.

4.3.3 Distances from both the community and road network

Next, energy potential based on an optimization scenario of availability and accessibility of biomass resources close to the community *and* the existing road network was assessed. To perform this assessment, resource estimations as well as energy production potential were performed based on the increasing distances from both the community and the existing road network, based on four distinct categories: highly optimal (most accessible), medium optimal (moderately accessible); least optimal (less accessible), and outside optimal (not feasible for easy access) (Figure 4.6).

Results indicate that the availability of harvestable biomass resources within the highly optimal zones around Southend would be sufficient to acquire the required forest residue for energy production, except under the scenario of low conversion efficiency of CST and HHV, and low conversion efficiency of CST and LHV in biomass cases (Table 4.9). Biomass available in the highly optimal zones might not be enough to meet the community energy demand, instead both of these scenarios require that biomass is harvested up to the medium-optimal zones. The results collectively indicate that Southend possesses substantial local availability of accessible biomass resources for local energy production that is sufficient to meet community energy needs.

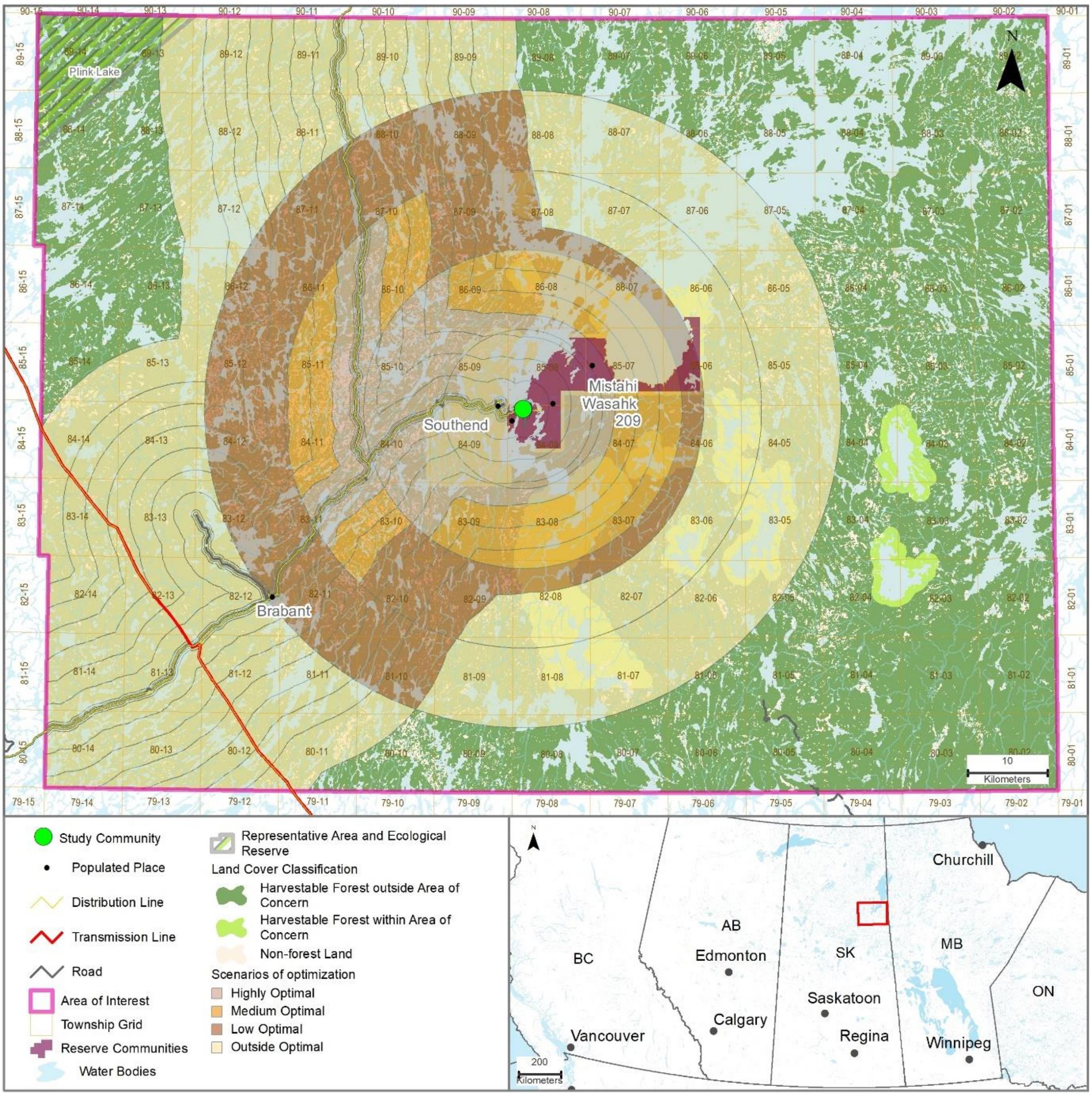


Figure 4.6 Availability and accessibility of biomass resources at specific distances to the community and from the road infrastructure.

Table 4.9 Estimation of energy potential based on increasing distances from both the community and the road network.

Scenario	**Unit**	**Optimization categories**			
		Highly optimal	**Medium optimal**	**Low optimal**	**Outside of optimal**
Total harvestable biomass	odt	563,473	551,758	1,334,785	3,997,084
Annual harvestable biomass	odt	6,762	6,621	16,017	47,965
combustion steam turbine (CST)					
Energy potential (HCE-HHV)	MWh	14,267	13,971	33,797	101,206
Energy potential (HCE-LHV)	MWh	11,272	11,037	26,701	79,958
Energy potential (LCE-HHV)	MWh	7,140	6,992	16,914	50,651
Energy potential (LCE-LHV)	MWh	5,632	5,515	13,343	39,955
Installed capacity (HCE-HHV)	MW	1.81	1.77	4.29	12.84
Installed capacity (HCE-LHV)	MW	1.43	1.40	3.39	10.14
Installed capacity (LCE-HHV)	MW	0.91	0.89	2.15	6.42
Installed capacity (LCE-LHV)	MW	0.71	0.70	1.69	5.07
gasification combined cycle (GCC)					
Energy potential (HCE-HHV)	MWh	16,776	16,427	39,739	119,001
Energy potential (HCE-LHV)	MWh	13,239	12,964	31,362	93,915
Energy potential (LCE-HHV)	MWh	12,489	12,229	29,584	88,591
Energy potential (LCE-LHV)	MWh	9,859	9,654	23,353	69,933
Installed capacity (HCE-HHV)	MW	2.13	2.08	5.04	15.09
Installed capacity (HCE-LHV)	MW	1.68	1.64	3.98	11.91
Installed capacity (LCE-HHV)	MW	1.58	1.55	3.75	11.24
Installed capacity (LCE-LHV)	MW	1.25	1.22	2.96	8.87

4.3.4 Biomass supply-cost

The estimations of biomass supply-cost are further performed to evaluate the economic viability of biomass feedstock, assess the costs associated with biomass supply for energy production, and present them through the supply-cost curves (Figure 4.7). The relationship between the quantity of biomass supply and the associated costs is illustrated by plotting the estimated delivered costs against the annual aggregate supply of biomass, considering the availability of biomass up to a 30 km radius from the community (Figure 4.7a) and within 5km from the existing roads (Figure 4.7b). Results show a strong association between the biomass supply and delivery costs, suggested for 31.9 $/t and 27.4 $/t from 30 km and 5 km distances, respectively. Notably, the costs per ton exhibit an upward trend with an increasing amount of biomass supply. The influencing factors behind this trend are primarily associated with collection and transportation costs and distances from the community and roads. As the supply extends further, transportation costs increase, contributing to the overall increase in delivery costs. Therefore, it is crucial to consider geographical proximity in community energy planning.

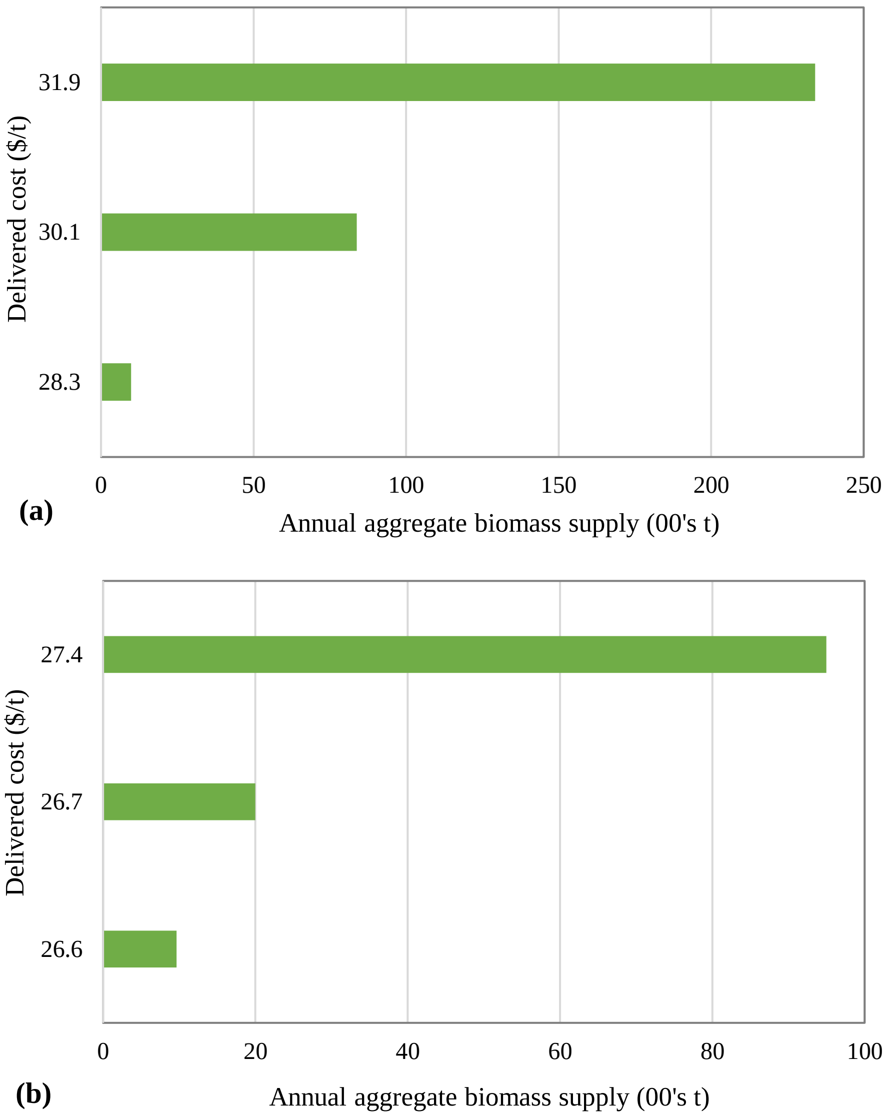


Figure 4.7 Biomass supply-cost curve based on the required biomass availability and distance from the (a) community and (b) existing road network.

4.4 Environmental Significance and Potentials of Bioenergy

The GHG mitigation potential of bioenergy by replacing fossil fuels (i.e., coal-generated electricity; natural gas) are shown below, based on the GHG calculator developed by Natural Resources Canada (NRC). Different assumptions, considering conversion efficiency, were tested in a 100-year timeframe for bioenergy versus coal (Figure 4.8) and for bioenergy versus natural gas (Figure 4.9) to examine the GHG balance period as well as the net atmospheric benefits or losses of bioenergy development from harvested forest residues as a substitute for coal and natural gas. It should be noted that here a positive value represents a net source of CO_2 (carbon emission), while a negative value represents a net benefit to the atmosphere (carbon sequestration).

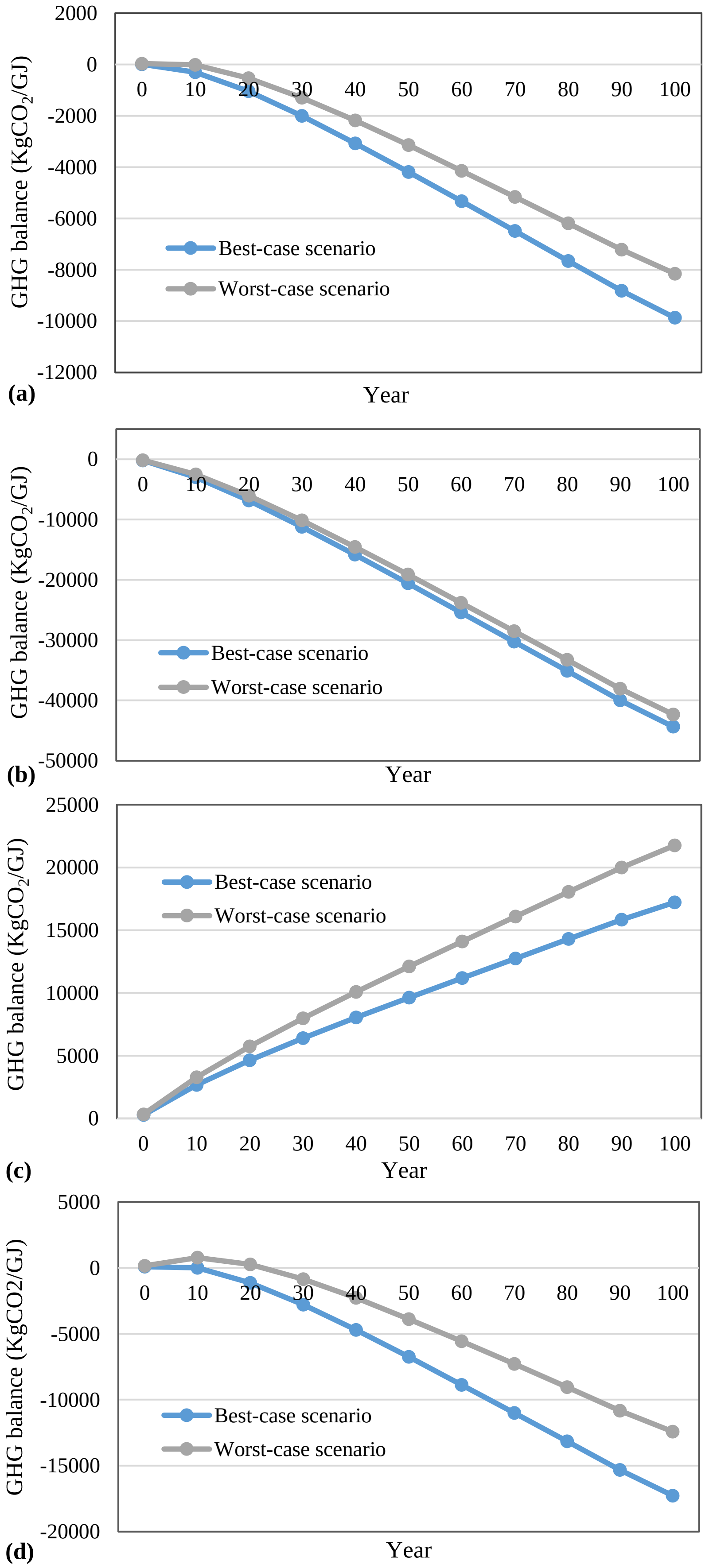


Figure 4.8 GHG mitigation potential of bioenergy by replacing coal in different scenarios: (a) biomass HE, coal HE (b) biomass HE, coal LE (c) biomass LE, coal HE and (d) biomass LE, coal LE.

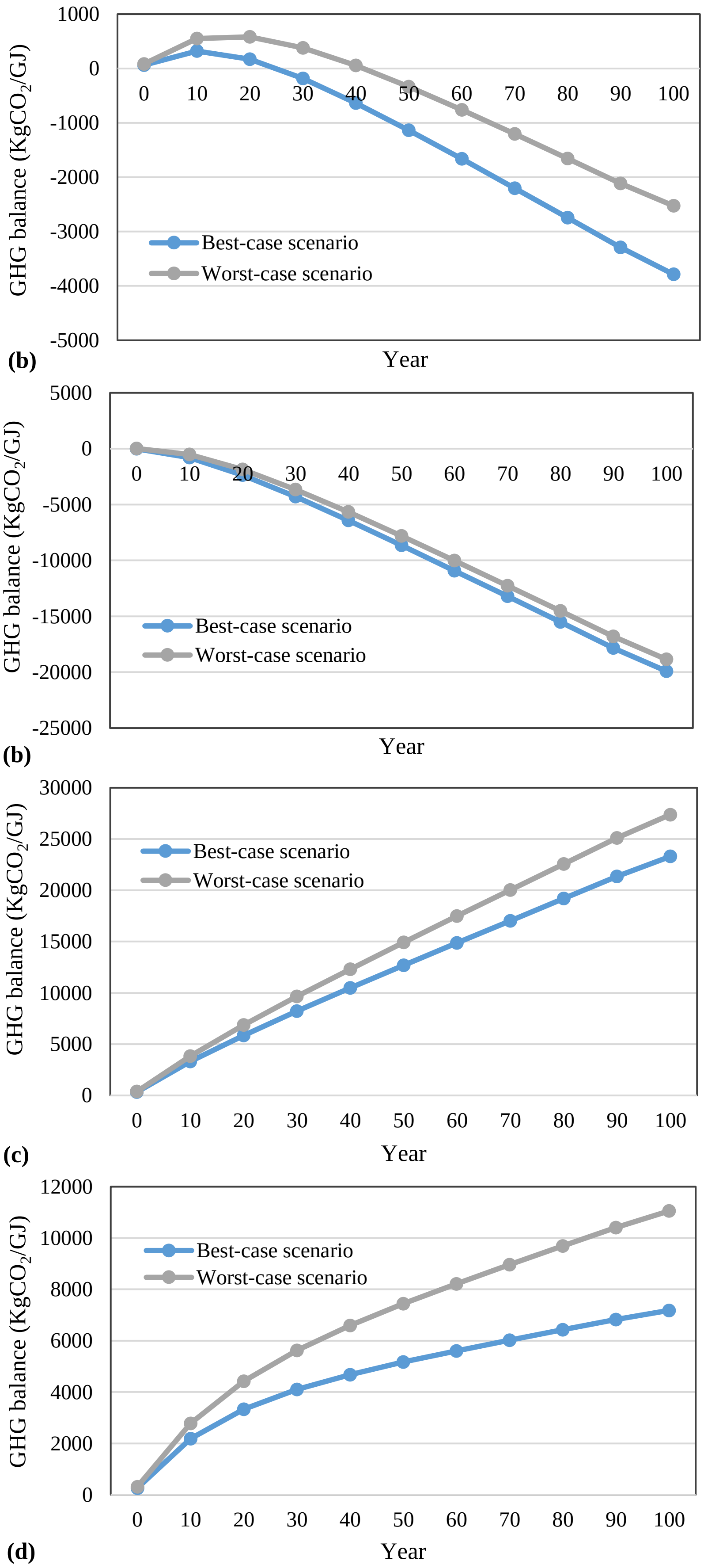


Figure 4.9 GHG mitigation potential of bioenergy by replacing natural gas in different scenarios: (a) biomass HE, gas HE (b) biomass HE, gas LE (c) biomass LE, gas HE and (d) biomass LE, gas LE.

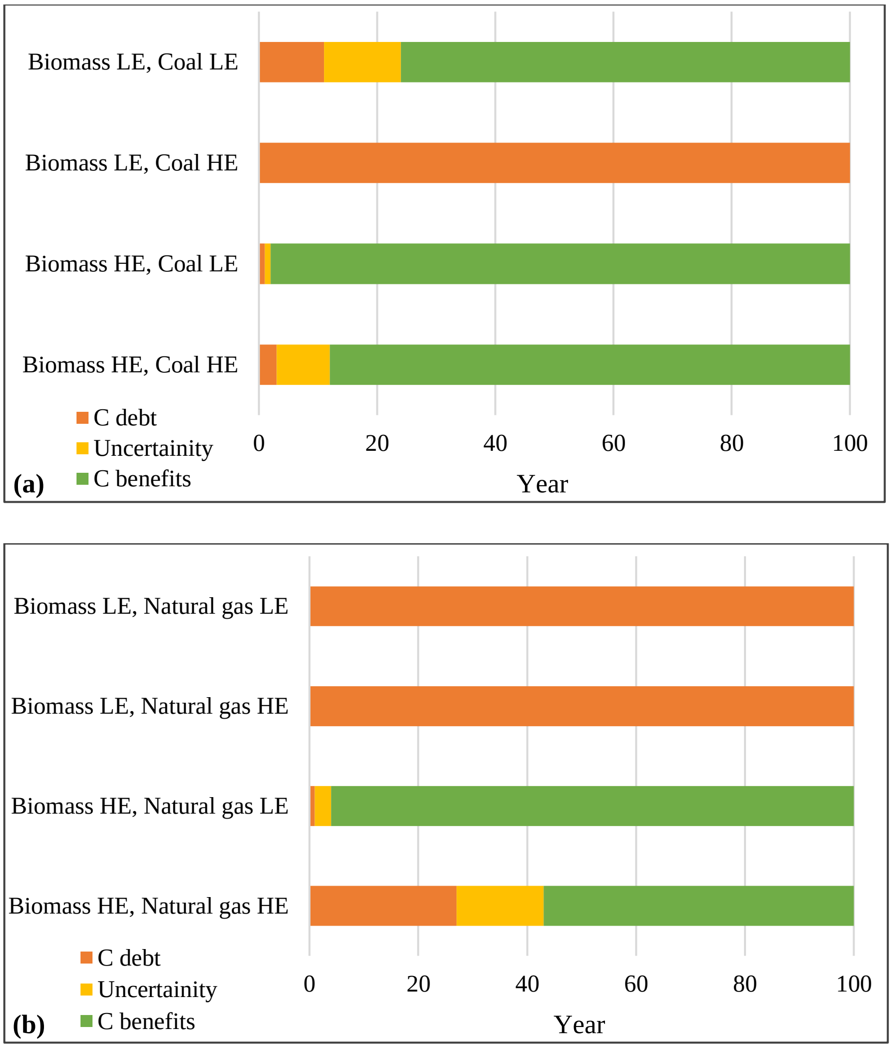


Figure 4.10 The uncertainty phases of bioenergy by replacing (a) coal, and (b) natural gas to produce electricity in a 100-year timeframe under different efficiency scenarios. *C debt* is the period do not provide any atmospheric benefits, *Uncertainty* is unclear if atmospheric benefits have started or not, and *C benefits* is bioenergy development generates, atmospheric benefits (GHG) in all cases.

Estimations indicate that a net benefit to the atmosphere can be achieved in the cases of high conversion efficiency of both biomass and coal (Figure 4.8a), high conversion efficiency of biomass and low conversion efficiency of coal (Figure 4.8b), and even low conversion efficiency of both biomass and coal (Figure 4.8d). A net CO_2 emission is found to be achieved with the low biomass conversion efficiency against the higher conversion efficiency of coal energy (Figure 4.8c).

Again, in the case of replacing natural gas with biomass, results illustrate that a net benefit to the atmosphere can be achieved when highly efficient (HE) biomass is replaced by either highly efficient natural gas (Figure 4.9a) or low efficient (LE) natural gas (Figure 4.9b). In contrast, in cases where low-conversion-efficient biomass technology is replaced with either highly efficient natural gas (Figure 4.9c) or even low-efficient natural gas (Figure 4.9d), a net CO_2 emission can occur. These results emphasize the critical importance of considering the efficiency of conversion technologies in achieving desired environmental outcomes.

The results also illustrate the GHG balance period, which is found to have been achieved at different time periods and influenced by technological efficiencies (Figure 4.10). Quick carbon sequestration or atmospheric benefit is found to be achieved in almost 2 years in the case of high conversion efficiency of biomass and low conversion efficiency of coal. The GHG balance period as well as the net atmospheric benefits will be assumed to start after 10 and 20 years in the case of replacing, HE coals by HE biomass, and LE coal by LE biomass, respectively (Figure 4.10a). Again, in cases of replacing natural gas with biomass energy, the quick GHG balance period is found to be achieved by 4 years in the scenarios of replacing LE natural gas by HE biomass (Figure 4.10b). A net benefit to the atmosphere is also found to be achieved after approximately 43 years in the cases of replacing HE natural gas by HE biomass (Figure 4.10b). Overall, these findings emphasize the importance of considering conversion efficiency in energy production strategies to effectively mitigate GHG emissions and foster environmental sustainability.

4.5 Viability of Community Bioenergy Development

Southend is exploring reliable energy sources that can help ensure both energy security and a sustainable community. Table 4.10 presents the availability of harvestable biomass residues in Southend and the approximate harvesting tenure. Results found that the availability of locally accessible biomass resources can be harvested for an approximate duration of 83 years to support community energy production, which presents a viable opportunity for community bioenergy development in Southend.

Table 4.10 Availability of harvestable biomass residues in Southend.

Items	Total residue of harvestable forest trees (odt)	Annual residue of harvestable forest trees (odt)	Harvesting probability (year)
Biomass availability in the entire 50 km study region	11,051,393	132,617	83.34
Biomass availability up to 30 km distances from the community	1,252,104	15,025	83.34
Biomass availability up to 5 km distances from the existing roads	625,104	7,501	83.34

At the same time, it can be expected that, within this time period, re-planted trees in the commercially managed forest will grow into mature trees to harvest again. It should be noted that, according to Natural Resources Canada, trees grown in natural forests usually take 40 to 100 years to mature (NRC, 2020). The local biomass resource base can not only ensure long-term energy security in Southend, but also align with sustainable practices by allowing ample time for replanting and regeneration of forests. The community stands to benefit from a strategic approach to biomass utilization that can meet the current energy demands while at the same time ensuring the replenishment of forest resources for future generations. Moreover, the potential to balance generated GHG emissions and achieve overall atmospheric benefits further underscores the viability of biomass energy within Southend's energy portfolio. Southend possesses a tremendous potential for community energy development, paving the way towards achieving energy sustainability and fostering a greener, more resilient future for the community.

CHAPTER 5
DISCUSSION

The results of this research provide insight to the availability and potential of biomass resources for bioenergy production and community energy development in Southend, as well as the implications of the proposed framework for bioenergy potential assessment. The community has substantial biomass resources available for bioenergy production, and the available electricity generation from a local bioenergy facility based on this resource could surpass local demand, significantly. Results indicate that the biomass resource available within a 50-km boundary of Southend, is 41 and 35 times higher than the local demand, when assuming high energy content and high conversion efficiency of gasification and combustion technology, respectively. The optimization assessment shows that more than sufficient biomass resources can be harvested to meet energy demands within 20 km of Southend and within 5 km of existing road infrastructure. These findings emphasize the resource feasibility of implementing a biomass power plant in Southend to address the community's energy challenges. The abundance of biomass resources, coupled with the estimated electricity generation capacity, positions bioenergy as a viable and sustainable option for meeting community’s local energy demand and fostering a more sustainable and self-reliant energy infrastructure in Southend.

In addition, the results demonstrate a practical application of the assessment framework, which offers a structured approach to evaluating the viability of bioenergy projects in their early stages – even in regions of sparse data to support such assessments. By integrating factors such as biomass resource availability and technological, economic, and environmental considerations, the assessment framework enables stakeholders to make informed decisions regarding the adoption of bioenergy solutions. This framework not only streamlines the assessment process but also facilitates the sustainable aspects of community energy development. It is assumed that the framework can guide to assess the feasibility of bioenergy development in the early stages of community energy planning in similar circumstances and in other remote northern communities. The key takeaways and findings of the research and their implications from a broader scholarly perspective are discussed below.

5.1 Challenges and Data Constraints

Doing research in northern Indigenous communities presents unique challenges that need to be addressed carefully and sensitively. Because of cultural protocols, languages, traditions, and worldviews, meaningful engagement in research is important, which requires respect of knowledge systems, maintaining ethical considerations, and building trust and relationships with the community members for shared decision-making. Though the framework (Figure 2.4) is developed and conceptualized based on the northern context for assessing CBP, its application in this northern context reveals considerable constraints. Data accessibility is one of the key constraints, because of the limited past studies and records and the lack of comprehensive databases, especially for land use characteristics, available biomass resources, and species types and characteristics in the northern boreal forest. Geospatial techniques such as GIS have been thus applied in gathering biomass information in northern boreal forests. GIS allows for the integration of various remote sensing data sources, such as satellite imagery, enabling the assessment of biomass distribution over large and remote areas (Papilo *et al.*, 2017), and thus former authors also applied this technique in assessing biomass resources in remote areas in the Circumpolar North (Wulder *et al.*, 2008; Hall *et al.*, 2010; Calvert and Mabee, 2014; Mansuy *et al.*, 2020).

Data constraints were faced in every stage of this research, not only for assessing biomass availability and resource estimation but also for estimating energy production potential – owing to uncertainty as to the specific nature and type of bioenergy technology to be development and lack of local data on the energy content of biomass residues. For instance, the energy production potential of biomass is primarily dependent on the application of conversion technology, its efficiency, and the heating value of biomass (Tshikovhi and Motaung, 2023). Several technologies, e.g., combustion, gasification, pyrolysis, etc., are available and widely used for converting woody biomass into bioenergy (Tursi, 2019; Banerjee, 2023). Even the quality as well as the energy content of biomass are dependent on the species types and moisture content of biomass depending on local climatic factors (Barrette *et al.,* 2015; Antar *et al.,* 2021), which is uncertain to determine. Similar challenges have also been faced in estimating biomass supply-demand and cost estimation because of the uncertain and undetermined labour cost, biomass harvesting and carrying costs to roads, and transport to the facility site.

5.2 Bioenergy Potential Assessment Under Uncertainty

To tackle the above uncertainty and data constraints, scenario-based assumptions were used in the assessment application. In some cases, an estimation protocol was performed by following research or assessments in similar settings. For instance, because of the lack of locally available data the estimation of forest residue from harvested trees in the study area was based on a scenario informed by operations at Cold Lake First Nations in northern Alberta. Data from Cold Lake First Nations was used as the basis to inform the assessment owing to the similar method of forest harvesting activities (i.e., clear-cutting), available data on annual allowable harvestable quota, comparable species within the boreal region, and available pre-feasibility studies from Cold Lake First Nation on forest residue generated from harvestable forest trees for wood-based bioenergy production (Mansuy *et al.*, 2020). Energy production potential was then estimated by considering both high and low efficiency of two different, yet widely used technologies (i.e., combustion and gasification), and the HHV and LHV of biomass cases, to provide a range of possibilities to inform the early stages of community energy planning based on biomass opportunities. With no data on supply-costs for biomass harvesting in the study area, resource supply optimization was explored by considering biomass availability and energy potential at increasing distances from the community and road infrastructure. The GHG mitigation potential of bioenergy was assessed by following similar scenario-based approaches, focused on bioenergy as a replacement fuel for coal and natural gas in higher and lower efficiency cases.

In the face of uncertainty and data constraints, this research illustrates that a scenario-based approach can play an important and informative role for community energy planning (CEP) in the North. Arguably, at the early stages of CEP, when the focus of attention is on pre-feasibility assessment, a scenario-based approach may indeed be the best alternative for biomass resource assessments and energy potential studies under uncertain conditions. Although not previously applied in the northern CEP context, other organizations engaged in energy planning in other contexts have also successfully applied such approaches to explore possible future scenarios (Benedict, 2017). Similarly, under uncertain economic, environmental, and technological conditions, Ilbahar *et al.* (2023) highlighted the value of a scenario-based approach in their research, where they ranked different sustainability scenarios for effective energy planning. Their work illustrates how considering multiple future scenarios can aid in understanding the potential impacts of various factors and in making informed decisions. Overall, the scenario-based approach adopted and demonstrated in this research is a valuable approach for CBP assessment under uncertain and undetermined conditions at the early stages of CEP. By presenting multiple scenarios, communities can gain insights into the range of energy supply options and their associated risks and opportunities, which can help to develop strategies that are resilient across different technology and energy use scenarios.

5.3 Necessities of Appropriate Technology Choice

Technology choice is vital to achieving maximum production efficiency and both economic and environmental benefits in energy conversion. Results of this research show that the estimated energy production potential of harvestable biomass residues in Southend varies considerably based on the conversion efficiency and energy content of biomass in both combustion and gasification technologies, with the highest production potential observed in gasification scenarios. As the energy content of biomass residues depend on uncontrolled natural factors, an appropriate technology choice can thus help to achieve maximum energy production. Application of a low-efficient conversion technology will produce a low energy yield and, at the same time, burn more feedstock and waste resources. This leads to a higher demand for biomass feedstock, potentially clearing more forest land, or needing to harvest biomass at increasing distances from the community thus costing more money for harvesting and transportation and reducing the economic potential or cost savings of local energy (Popp *et al.,* 2014; Wu *et al.,* 2018; Blair and Mabee, 2020).

Environmental emissions also vary depending on the applied conversion technology, and the application of different techniques emits pollutants in different concentrations (Chen *et al.,* 2020). Table 5.1 presents the emission data of the major pollutants released during power generation by combustion and gasification technology in the 1 kWh life cycle.

Table 5.1 Comparing emissions of power generation through different energy conversion technology.

Parameters	**Combustion (kg/kWh)**	**Gasification (kg/kWh)**
CO_2	7.48×10^{-2}	4.70×10^{-2}
CO	2.50×10^{-4}	8.30×10^{-5}
CH_4	5.29×10^{-5}	4.71×10^{-5}
SO_x	3.26×10^{-3}	2.58×10^{-4}
NO_x	3.04×10^{-3}	1.11×10^{-4}
PM	2.24×10^{-4}	3.37×10^{-4}

Source: Chen *et al.* (2020)

Modern biomass conversion technologies use advanced filtration systems for emission reduction and are designed to prevent energy loss as well (Chandra *et al.,* 2023). Inefficient or low-efficient conversion processes, however, usually result in higher emissions and released unburn shoots (Yu *et al.,* 2021), thus undermining the environmental benefits of using bioenergy as a renewable energy source. It is also not economically viable or good from a sustainability perspective. This research illustrates the importance of careful consideration of the up-front investment costs of bioenergy technology against not only energy production potential but also required harvesting distances from the community and the immediate to long-term emissions reduction goals at the early stages of CBP assessment and CEP.

5.4 Biomass Supply-Demand, Opportunities, and Cost Factors

There is a substantial amount of biomass resources available near Southend – much more than required to meet basic community energy needs. Results suggest that utilization of these resources for bioenergy production can not only meet local community energy demand but also create an opportunity for the community to earn revenue through energy sharing with other PBCN communities or by providing power to the northern grid. Based on resource availability, and depending on community goals and aspirations, the development of a community bioenergy facility in Southend could strengthen energy autonomy, boost the local economy, and create employment opportunities, much like the success witnessed at the Meadow Lake Tribal Council (MLTC) bioenergy centre. The MLTC's operation of a 6.6 MW bioenergy facility, fed by sawmill residues and fully Indigenous owned, has not only bolstered economic prospects but also provided employment to the nine Indigenous communities associated with the MLTC (MLTC Bioenergy Centre 2020). The centre, at the same time, meets the energy demand of the MLTC communities and adds a substantial amount of electricity to the Saskatchewan power grid. The energy sharing concept is also implemented successfully in many countries in Europe and Australia, where communities produce energy from renewable sources and share surplus energy with the participating communities (Olivero *et al.,* 2021; Gjorgievski *et al.,* 2023; Rozite *et al.,* 2023; Ahmed *et al.,* 2024). The local production and exchange of energy can not only help to strengthen the energy security of the communities, but also help to address the challenges facing power systems today, including insufficient transmission capacity, grid congestion, power loss, etc. (Rozite *et al.,* 2023). For instance, recently, the International Energy Agency (IEA) estimated that grid losses contribute to the emission of one gigatons of CO_2, which accounts for nearly 3% of the total global energy-related CO_2 emissions (IEA, 2023). Localized, community-based renewable energy generation and sharing can thus help to reduce these losses from long transmission and achieve sustainable energy transitions.

Optimization of biomass resource supply with demand is also critical to the viability of bioenergy in northern communities. For Southend, the results of this research indicate that the community can collect their required biomass feedstock within 5 km of the existing road or within 20 km from the community. Though harvesting closer to the community is mostly preferred, considering accessibility, the road network is crucial to cost-effectively transporting biomass resources (Havimo *et al.*, 2017). In some areas, biomass may not be practical to harvest because of limited accessibility, even though it is close to a community with substantial harvestable biomass. This implication is not like other renewable energy developments or resources, such as solar or wind, where the primary concern lies in resource availability; bioenergy solutions pose unique challenges due to collection and transportation (Guaita-Pradas *et al.*, 2019; Al-Addous *et al.*, 2020). This highlights the nuanced nature of CBP assessment within the context of community energy planning in the North.

Simple biomass supply-cost analysis suggests a direct association between the cost of biomass supply and the quantity supplied. This escalation in costs with increasing supply is attributed to expenses associated with biomass collection, harvesting, and transportation to a single facility. Similar findings by Calvert and Mabee (2014) and Shadbahr *et al.* (2021) on forest biomass supply chains in Ontario and Quebec validate these observations. The cost for biomass feedstock supply, as well as energy production costs, also depend on the conversion technology – for example, low-efficient technology requires burning more biomass to produce the required energy. For instance, results from this study showed that in scenarios of low-efficient technology and low energy content (Table 4.7), Southend may be compelled to extend their biomass harvesting zone by an additional 10 km from the community to meet energy needs. This not only necessitates increased forest clearing and emissions both from biomass burning and vehicles, but also amplifies biomass supply costs due to extended transportation distances. Therefore, it is crucial to consider not only the geographical proximity of the biomass resource, but also accessibility and technological efficiency when assessing CPB in CRE planning and feasibility studies.

5.5 Emission Factors and Sustainability Aspects

Finally, the GHG mitigation potential of bioenergy production from forest residues, as a replacement for fossil fuels, illustrates the importance of conversion efficiency in determining whether environmental benefits will be achieved. Notably, in this research, scenarios with high conversion efficiency of biomass exhibit net atmospheric benefits, emphasizing the need for technological advancements to maximize efficiency. Conversely, cases where biomass conversion efficiency is low may lead to increased CO_2 emissions compared to fossil fuel alternatives, highlighting the importance of technological optimization. Maier *et al.* (2019) also note the importance of conversion efficiency as a key influencing factor of environmental emissions, based on a life cycle assessment of forest-based bioenergy production in British Columbia. Poor efficiency as well as low energy conversion rates are reported to be linked to soot emissions because of incomplete combustion of biomass (Yu *et al.*, 2021). The delineation of GHG balance periods also provides valuable insight of the temporal dynamics of atmospheric benefits. Results indicate that carbon sequestration is observed in scenarios with high biomass conversion efficiency, indicating the potential for rapid environmental gains. However, it is essential to consider the lag time before achieving net atmospheric benefits, particularly in scenarios with lower conversion efficiencies. These findings emphasize the pivotal role of conversion efficiency in bioenergy production as well as the necessity of using highly efficient techniques and the efforts for continuous technological innovation to maximize environmental benefits and foster sustainability.

Again, results of this research suggest that the substantial amount of biomass availability offers a promising opportunity to establish community bioenergy in Southend. The long-term viability of biomass utilization would be reinforced by the ample time available for replanting and forest regeneration, as stated in Natural Resource Canada (2020) and Saskatchewan State of the Environment (2019). By adopting a strategic approach to biomass utilization, Southend can ensure energy security while simultaneously promoting sustainable practices and safeguarding forest resources for future generations. Furthermore, the alignment of community bioenergy development with GHG emission reduction goals underscores its significance in fostering a greener, more resilient future for the community. The potential to achieve overall atmospheric benefits further enhances the appeal of community bioenergy within Southend's energy portfolio, positioning it as a key driver of energy sustainability.

CHAPTER 6

CONCLUSIONS

In conclusion, this study explored the potential of community bioenergy development in northern and remote Indigenous communities, with a focus on the case study of Southend. The application of the proposed integrated framework offers a comprehensive assessment of CBP in Southend and provides valuable insights into its overall viability and the challenges and opportunities associated with transitioning towards sustainable energy solutions. The results indicate a significant biomass resource base in Southend, with ample potential for bioenergy production to meet local energy demands. It was determined that approximately 919,779 hectares of forested land are available within the study boundary, yielding an estimated 132,617 odt of forest residues, annually. This substantial resource could support the operation of a biomass power plant capable of generating electricity to meet and even surpass the community's demand.

The assessment of energy production potential revealed promising results that varied with varying scenarios using different technologies, their conversion efficiencies, and the energy content of biomass residues. The highest energy potential was observed with gasification technology (329,022 MWh) when considering the high conversion efficiency and high heating value of biomass. By comparing with the community energy demand, it was assumed that there are substantial resources available, and the sufficient biomass can be harvested within 20 km of Southend and within 5 km of existing road infrastructure. By prioritizing high-efficiency conversion technologies and considering factors such as biomass quality and energy content, communities can maximize energy yields while minimizing environmental impacts. Additionally, the results underscore the importance of optimizing biomass supply-demand dynamics and considering factors such as geographical proximity and transportation costs to ensure the economic viability of bioenergy projects.

Furthermore, the environmental significance of bioenergy development was evaluated, showcasing its potential to mitigate GHG emissions and contribute to long-term atmospheric benefits. By replacing fossil fuels with biomass-derived energy, Southend could contribute to Canada’s goal of emissions reduction, particularly when employing highly efficient conversion technologies. Again, the viability of community energy development in Southend was underscored by the longevity of biomass resources, which could sustain energy production for approximately 83 years. This extensive timeframe aligns with sustainable forest management practices, ensuring the replenishment of resources for future generations while meeting current energy needs.

In essence, the findings suggest the immense potential of community bioenergy development in Southend, offering a pathway towards energy sustainability, economic development, and environmental stewardship. By leveraging abundant biomass resources and adopting strategic approaches to technology deployment and supply-chain optimization, communities can enhance energy security, foster local economic growth, and contribute to global efforts to mitigate climate change. Successful implementation, however, will require collaborative efforts between community stakeholders, policymakers, and industry partners to overcome technical, financial, and regulatory challenges. It is also essential to continue the ongoing research to further refine this research result and address the highlighted challenges. Overall, this study contributes significant insights to the field of community energy as a practical initiative for advancing sustainable energy solutions, and the assessment approach can be a valuable tool for guiding decision-making in the early stages of community energy planning in other northern and remote Indigenous communities.

6.1 Limitations

Though this study provides a valuable insight into the step-by-step processes of assessing community bioenergy development potential in northern and remote Indigenous communities by using a case study application, it has considerable limitations that should be interpreted with caution. Due to the unavailability of precise data regarding northern forest biomass resources, harvestable biomass resources and the approximation of residues were estimated based on the remote sensing data, which is not exact but a probable estimation. Again, because of the lack of data on forest species type and uncertain technological considerations, energy production potential was estimated using scenario-based approaches, which inherently introduce uncertainties and may not precisely reflect real-world conditions. These estimations provide valuable insights but may not fully capture the complexity and variability of actual energy production scenarios and may not be exact. Moreover, in the supply-cost analysis, transportation costs were estimated based on assumptions, including the use of straight roads for transportation. Due to a lack of sufficient data, slope is not being considered, which may not accurately reflect the actual transportation routes and challenges faced in remote areas and their impact on driving distance and costs. Furthermore, the lack of recent data necessitated the use of cost estimates derived from past literature, which may not align perfectly with current expenses. While these estimates offer a starting point for analysis, they should be interpreted with caution due to potential discrepancies with real-world costs. Overall, the findings of this study may be limited in their generalizability due to the specific context of the case study area and the assumptions made throughout the analysis.

6.2 Recommendations and Future Research Directions

Despite the limitations, this study's efforts advanced a practical understanding of community bioenergy development in remote regions. Future research efforts could focus on addressing data gaps, refining modelling techniques, and conducting in-depth studies to improve the accuracy and reliability of energy potential assessments and cost estimations. The following recommendations thus have been made for guiding future research and advancing sustainable energy solutions in northern and remote Indigenous communities.

a. Resource estimations have been performed based on the remote sensing data and by following the assumptions of similar past studies. In-depth and comprehensive studies regarding forest tree species, their types, height, etc. may provide more accurate estimations.
b. Meaningful engagement and integrating traditional knowledge are important while performing research with Indigenous communities to address the data gaps. Therefore, it is recommended to prioritize meaningful engagement with the communities, respecting their knowledge systems, cultural protocols, and traditional practices, and integrating traditional knowledge into bioenergy assessment and development projects.
c. In uncertain conditions, energy potential was estimated in different scenarios and cases, which provides a rough estimation of the energy potential of the estimated biomass residues. Hence, more in-depth, distinct studies are recommended for a better understanding of each of the different technologies and their efficiencies and emission factors. Moreover, it is recommended to conduct research and development to improve the efficiency of bioenergy conversion technologies, thereby increasing energy output while reducing environmental impact and costs.
d. The findings of this study illustrate the substantial availability of biomass resources, which is much more than the community needs. Therefore, it is recommended to explore the opportunities of energy sharing with nearby communities, possible challenges, and policy aspects to maximize resource utilization and foster sustainable energy transitions. Moreover, it is also recommended to develop and implement guidelines for sustainable

biomass harvesting practices by considering ecological, cultural, and socio-economic considerations.

e. Cost-supply analysis was performed under hypothetical assumptions, and the transportation costs were estimated according to the expenditures mentioned in past literature, which may not reflect current expenses. Therefore, it is recommended to explore an in-depth analysis of cost-supply based on the existing harvesting and transportation costs and other expenditures.
f. The GHG mitigation potential of bioenergy is estimated as a substitute for coal and natural gas, which gives a generalized idea regarding the net atmospheric emissions or benefits of bioenergy development. It is recommended to conduct comprehensive assessments of the emissions and environmental impacts of different bioenergy conversion technologies for a clear understanding of the eco-friendly technologies for bioenergy conversion. Moreover, it is suggested to conduct longitudinal studies and environmental assessment (EA) to monitor the long-term impacts of community bioenergy development on the local ecosystem and the environment.

It is expected that, by addressing these recommendations in future research, scholars and practitioners can contribute to advancing energy sustainability based on the available biomass resources in northern and remote Indigenous communities, which can help foster energy security, economic prosperity, and environmental stewardship.

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