# Applications of Equilibrium Modeling and Game Theory in Biomass Supply Chain Management

Zahra Vazifehkoorabbasloo

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By: **Zahra Vazifehkoorabbasloo**

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complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

______________________________ Chair
Dr. John Xiupu Zhang

______________________________ Examiner
Dr. Chun Wang

______________________________ Examiner
Dr. Jun Yan

______________________________ Examiner
Dr. Sang Hyeok Han

______________________________ External Examiner
Dr. Saeed Zolfaghari

______________________________ Supervisor
Dr. Fereshteh Mafakheri

______________________________ Supervisor
Dr. Chunjiang An

Approved by ______________________________
Chair of Department or Graduate Program Director

November 7th, 2023

Date of Defence

Dr. Mourad Debbabi, Dean
Gina Cody School of Engineering and Computer Science

# Abstract


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**Zahra Vazifehkoorabbasloo**

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The increasing attention towards renewable energies as solutions to environmental problems and future energy security has made biomass-based energy an attractive option. Biomass energy not only reduces dependence on fossil fuels but also helps mitigate environmental impacts. Effective biomass supply chain management is essential for bioenergy production, covering the entire process from feedstock harvesting to energy conversion facilities. Despite its advantages, biomass-based energy faces challenges such as low energy density, seasonal availability, and variable costs. Moreover, inefficient interactions and conflicting interests among supply chain participants hinder its development.

To address these challenges, efficient decision-making structures and coordination among supply chain entities are crucial. This PhD thesis focuses on coordination in biomass supply chains using game theoretical tools, which are well-suited for addressing conflicting objectives. The research encompasses three main attempts:

1. Evaluation of the impact of power distribution on supply chain efficiency through game theoretic modeling, considering various leadership schemes.
2. Assessment of the role of government incentives using game theoretic analysis to determine the most effective approach for incentivizing biomass development.
3. Design of game theoretic contract approaches for coordinating biomass supply chains while considering environmental impacts, including revenue sharing and quantity discounts.

Non-cooperative approaches, particularly Stackelberg game and equilibrium models, are emphasized within the game theoretic framework. A case study of northern Canadian communities is proposed to validate the feasibility of replacing diesel with bioenergy for heat and electricity consumption.

Preliminary work on modeling supply chains with different leaders using Stackelberg games has shown promising results, demonstrating the dominant role of communities in supply chain efficiency. The outcomes of this research have been published in peer-reviewed journals, including Sustainable Cities and Society and Clean Technologies and Environmental Policy. Additionally, a coordinated approach involving quantity discounts and revenue sharing has been proposed to evaluate the economic and environmental impact of bioenergy development. This approach has shown potential for improved economic performance and significant reductions in environmental impact. By employing game theory and coordination strategies, this thesis contributes to the understanding and optimization of biomass supply chains, promoting sustainable energy systems and addressing the challenges faced in the bioenergy sector.

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# Chapter 1

# Introduction

The global energy landscape is undergoing a transformative shift, with an increasing emphasis on renewable sources to meet the ever-growing demand for power. Among these renewable sources, biomass stands out as a highly accessible and versatile option that can be utilized in various industries, including transportation and electricity generation (Ansarinasab et al., 2021). Biomass not only helps reduce dependence on fossil fuels but also offers a cost-effective energy solution for remote communities, thereby fostering economic growth and job creation (Maier et al., 2019). The utilization of biomass spans a wide range, from small-scale stoves used for cooking in residential buildings to large-scale power plants employed for space heating in factories. In the Canadian context, where there is an extensive forest land spanning 347 million hectares (Mupondwa et al., 2017), biomass plays a crucial role in the production of renewable energy, accounting for a significant share of 23% (NRCan, 2020). Recognizing the immense potential of biomass, it becomes imperative to efficiently manage the entire bioenergy generation process, from the initial harvesting of feedstock to its ultimate conversion into usable energy (Müller et al., 2011). A well-coordinated biomass supply chain plays a pivotal role in optimizing resource utilization, thereby bolstering bioenergy generation and supporting sustainable development.

This research focuses on the coordination of bioenergy supply chain as a viable alternative to diesel fuel in northern Canadian communities. The objective is to investigate and analyze the various aspects involved in achieving seamless coordination throughout the supply chain. The findings presented in this study are compiled across chapters 3 to 5, highlighting the results gathered during this PhD program. Finally, the conclusion encapsulates the key insights gained from this research, while also offering valuable directions for future studies in this domain. Through this endeavor, the aim is to contribute to the advancement of efficient bioenergy utilization and further enhance the sustainable development of energy systems.

## 1.1 Problem Statement

The biomass supply chain is a complex network involving three main echelons: suppliers, preprocessors, and conversion facilities. Within this framework, biomass suppliers undertake the tasks of collecting and harvesting of feedstock, preprocessors are responsible for preprocessing, and wholesaling biomass to the conversion facilities for heat and energy production, catering to the needs of end users (Vazifeh et al., 2021). However, the decentralized nature of decision-making within this supply chain often leads to conflicts and challenges among the various players (Yue and You, 2014), necessitating a thorough exploration of coordination approaches through supply chain management.

In reality, the autonomy of each entity in the biomass supply chain gives rise to independent decision-making based on individual benefits. This decentralized decision-making environment often leads to clashes and competitions among the players, posing significant obstacles to the stability of the channel. Consequently, it becomes crucial to address the following key challenges using game theory concepts:

1. Determining the dominant player or leader who can strategically leverage the first-mover advantage to influence and guide other participants in the supply chain.
2. Understanding the mechanisms through which dominant players can employ incentives and persuasive tactics to motivate other parties to align their decisions with the dominant players' preferences.
3. Identifying effective incentive structures that can drive the development of bioenergy within the supply chain, considering factors such as payoff structures, rewards, and penalties.
4. Designing a mechanism that compels supply chain participants to adopt decisions similar to those made in a centralized supply chain, thereby aligning the channel's objectives and achieving coordination.

To tackle these crucial inquiries, it is imperative to conduct an extensive exploration of coordination approaches in supply chain management. Game Theory emerges as the most suitable methodology for illustrating decision-making in situations involving multiple interdependent parties, where each party's choice impacts the overall outcome. Leveraging the principles and tools of game theory, particularly the Stackelberg game, this research endeavors to harmonize the objectives of individual members in the supply chain with the collective goals of the entire system. This harmonization is anticipated to drive heightened efficiency, enhanced stability, and the promotion of sustainable bioenergy generation within the biomass supply chain.

This research endeavor will delve into the concept of coordination within the biomass supply chain, employing advanced game theory techniques as the fundamental framework for decision optimization. The subsequent sections will explore the problem statement, motivations, objectives, and basic assumptions.

## 1.2 Objectives/Problems

The primary aim of this doctoral research is to enhance efficiency and achieve economies of scale in the biomass supply chain through the application of game theoretic modeling. The specific focus of this study is the adoption of biomass as an alternative source for electricity generation in Quebec's northern communities. The choice of this case study is motivated by the pressing concerns surrounding energy security and resilience in these isolated regions, where reliance on diesel fuel for electricity generation is the sole option (NEB, 2016). To address the coordination challenges outlined in the problem statement, the following objectives have been established as the key objectives of this study:

1. Investigating the impact of decision-making power distribution on the efficiency of the biomass supply chain using game theoretic modeling. By employing this approach, we aim to identify the optimal strategies and decision-making processes that can lead to improved overall efficiency within the supply chain.
2. Assessing the effectiveness of various governmental incentives on the performance of the supply chain through game theoretic modeling. This objective involves analyzing the influence of different incentive structures on the behavior and decision-making of the supply chain participants, to identify the most effective incentives for achieving desired outcomes.
3. Developing a game theoretic contract framework that effectively coordinates the biomass supply chain. By designing a contract framework grounded in game theory principles, we aim to establish a mechanism that encourages cooperation, aligns the interests of different parties, and promotes efficient decision-making throughout the supply chain.

By pursuing these objectives, this study aims to contribute to the advancement of coordination strategies within the biomass supply chain, particularly in the context of Quebec's northern communities. Through the application of game theoretic modeling and the development of contract frameworks, we seek to enhance the efficiency, effectiveness, and sustainability of biomass-based electricity generation, ultimately leading to greater energy security and resilience in these communities.

## 1.3 Limitations/ Assumptions

The present research has a primary limitation concerning the type of biomass that is investigated. This study focuses exclusively on forest residues as the chosen biomass source, while other types of biomasses, such as agricultural residues, are not considered. This limitation stems from the lack of reliable data available for other biomass types within the Northern Quebec region. Moreover, in implementing an effective game theoretic approach to coordinate the biomass supply chain, several key assumptions can be identified:

- Rational decision-making: Supply chain members, acting as rational players, are assumed to optimize their individual objective functions. However, due to conflicting interests, they are not expected to share information with members in other echelons of the supply chain.
- Knowledge of strategies and payoffs: Each participant possesses knowledge of the strategies employed by others relative to their own strategies. Additionally, they are aware of the associated payoffs for any potential solution or decision.
- Formation of coalitions: Within each echelon of the supply chain, players, acting as rational entities, have the capability to form coalitions and engage in collective action. By doing so, they can leverage the benefits derived from economies of scale to improve the overall efficiency and effectiveness of the supply chain.

These assumptions provide a foundational basis for the application of game theory in coordinating the biomass supply chain. By considering rational decision-making, strategic knowledge, and coalition formation, the aim is to develop a comprehensive game theoretic model that addresses the coordination challenges inherent in the biomass supply chain, specifically focusing on forest residues in the context of Northern Quebec.

## 1.4 Thesis Overview (Outline of Thesis)

The structure of this thesis is outlined as follows. Chapter 2 offers an extensive review of pertinent literature, focusing on modeling techniques and methodologies relevant to the research. In Chapter 3, we delve into our study on the Game-theoretic Modeling and Analysis Approach for Biomass Supply Chain Coordination. This chapter establishes the foundational model for our research and investigates the identification of the optimal leader within the supply chain. Chapter 4 is dedicated to our investigation of the Coordination of Bioenergy Supply Chains under Government Incentive Policies. Here, we assess the impact and effectiveness of various government supports and incentives on the performance and coordination of the supply chain. Moving on to Chapter 5, we present our research on the Contract-based Enviro-Economic Coordination of Wood Pellet Supply Chains. This chapter explores the design and implementation of contract frameworks aimed at enhancing coordination and efficiency within the supply chain. Finally, in Chapter 6, we conclude our research work, providing a comprehensive summary of our findings, highlighting the contributions made, and offering insights into potential future research directions. Through this structured approach, we aim to present a cohesive and comprehensive examination of the coordination of biomass supply chains, utilizing game theory principles, government incentives, and contract-based frameworks.

# Chapter 2

# Literature Review

The literature on modeling and coordination approaches using game theory in the biomass and bioenergy supply chain is extensive and valuable. Game theory serves as a powerful framework for comprehending the strategic interactions among diverse stakeholders in this complex domain. It enables the analysis of decision-making processes through problem-modeling platforms in both cooperative and non-cooperative game approaches, providing insights into incentives and coordination mechanisms within the biomass and bioenergy supply chain. The subsequent subsections delve into an exploration of the aforementioned area.

## 2.1 Non-cooperative Games

In terms of modeling, game theory offers various techniques to capture the interactions and interdependencies among different actors in the supply chain. One commonly used approach is the non-cooperative game, where each player maximizes their own utility or profit independently. This allows researchers to analyze the behavior and strategies of individual stakeholders, such as biomass producers, bioenergy manufacturers, distributors, and consumers. By considering factors such as pricing, quantity decisions, and resource allocation, game theory models can provide insights into the dynamics of the supply chain and identify potential conflicts or inefficiencies. In scenarios where it is presumed that every player is aware of the equilibrium strategies employed by other participants, and where no player benefits from altering their strategy independently, it is possible to derive Nash equilibria as introduced by J. Nash in 1951. Nash equilibrium stands as a cornerstone principle within game theory, encapsulating the steady result of strategic interplay amid numerous participants. It signifies a scenario wherein no individual player is motivated to independently diverge from their selected strategy, considering the strategies opted for by all other participants. In a Nash equilibrium, each player's strategy is considered optimal, considering the strategies of others. It is a self-enforcing state where players have reached a balance, and any unilateral change would not lead to a better outcome for the deviating player.

Nash equilibrium has been widely studied across various fields, from economics to political science and biology, providing valuable insights into strategic decision-making and predicting likely outcomes in complex systems (L. Wang, T. Watanabe, 2016) (M. Chern, Y. Chan, J. Teng, S. Goyal, 2014) (C. Jaggi, M. Gupta, A. Kausar, S. Tiwari, 2019) (J. Ang, M. Fukushima, F. Meng, T. Noda, J. Sun, 2013).

In certain real-world scenarios, the existence of multiple equilibria leads to the outcome of the game being influenced by the player who takes the initial move. This equilibrium, prevalent in such situations with an asymmetric game, is known as the Stackelberg equilibrium (V. Stackelberg, D Bazin D, R. Hill R, L. Urch, 2010). The Stackelberg game is a prominent concept in game theory that models a sequential decision-making process in which one player, known as the leader, takes actions before the other players, referred to as followers, make their decisions. The leader's actions are observed by the followers, who then strategically respond to them. Unlike traditional simultaneous games, the Stackelberg game captures the concept of leadership and the ability of the leader to influence the behavior of the followers through their early moves. The leader aims to maximize their own payoff while considering the reactions of the followers. The followers, on the other hand, anticipate the leader's actions and strategically choose their strategies accordingly. The Stackelberg game has found applications in various domains, such as pricing decisions, supply chain management, and market competition, providing insights into strategic interactions and optimal decision-making in hierarchical settings. In the field of the biomass supply chain, Y. Bai et al (Y. Bai , Y. Ouyang , J. Pang, 2012) and D. Yue et al (D. Yue, F. You, 2017) aimed for adapting the concept of the standard Stackelberg game, with one leader and one follower to find the equilibrium point (quantity and price of biomass) in their model.

## 2.2 Cooperative Games

Cooperative game approaches within the biomass and bioenergy supply chain can also benefit from game theory. Cooperative game theory, for example, focuses on the analysis of joint decision-making and collaboration among multiple players. Cooperative games can provide insights into the formation of coalitions or alliances among stakeholders to achieve mutual benefits and optimize the overall performance of the supply chain (Q. Wu, H Ren, W. Gao, J. Ren, 2017). By considering issues such as cost sharing, revenue allocation, and risk management, cooperative game models can help identify stable cooperation structures and coordination mechanisms that enhance efficiency and sustainability. Gao et.al (E. Gao, T.

Sowlati, S. Akhtari, 2019) suggested a horizontal collaboration (coalition formation) among bioconversion facilities. In this research, various profit-sharing/ allocation approaches have been evaluated to find the most stable and satisfactory scheme.

Furthermore, game theory offers insights into incentive mechanisms and policy interventions within the biomass and bioenergy supply chain (Vazifeh Z, Mafakheri F, An C., 2023). By analyzing the strategic behavior of stakeholders, researchers can design appropriate incentive schemes to encourage cooperation, investment, and innovation. Game-theoretic models can be used to evaluate the effectiveness of policy instruments, such as subsidies, taxes, and regulations, in promoting sustainable practices, reducing environmental impacts, and ensuring the long-term viability of the biomass and bioenergy sector (G. Allameh, M. Saidi- Mehrabad, 2019).

## 2.3 Coordination Mechanism

Biomass supply chain coordination, influenced significantly by game theory (Z. Vazifeh, F. Mafakheri, C. An, 2021), involves strategically managing and integrating various activities and stakeholders throughout the production, processing, and distribution of biomass-based products, such as bioenergy and biofuels. The primary objective of coordination is to optimize the overall performance of the supply chain by minimizing costs, maximizing efficiency, and ensuring long-term sustainability. Game theory allows practitioners to devise strategies and mechanisms that foster collaboration, align interests, and improve decision-making across the biomass supply chain. In the literature, contracts are commonly used as a means of achieving coordination chain (Wang, 2002). Contractual arrangements, such as revenue sharing, quantity flexibility, quantity discount, buyback, and rebate contracts (Cachon G. P., 2003), are employed either individually or in combination to facilitate coordination. For instance, Fan et al. (K. Fan, X. Li, L. Wang, M. Wang, 2019) proposed a combination of protection price and subsidy contracts between farmers and manufacturers, along with a combination of buyback and revenue sharing contracts between middlemen and manufacturers, to effectively coordinate the biomass supply chain. Their work demonstrated that in a coordinated supply chain, the risk of price escalation by middlemen is minimized. However, the choice of contracts in practice depends on specific criteria and objectives. Cachon and Lariviere (Gerard. P. Cachon, 2000), for example, compared revenue sharing to buyback and quantity-flexibility contracts in order to enhance channel coordination. They found that revenue sharing is effective in coordinating systems with price-dependent demand

and multiple competing retailers but should be avoided when demand is significantly influenced by retail effort. Additionally, Yang et al. (Xi Yang, 2012) showed that suppliers' preferences for biomass contract design vary based on their level of risk aversion, with more risk-averse suppliers favoring fixed lease designs to mitigate exposure to yield and price risk.

Overall, the literature on game theory in the biomass and bioenergy supply chain covers a wide range of topics, including modeling strategic interactions, analyzing coordination mechanisms, and designing effective policies. These investigations enhance the profound comprehension of the intricacies and dynamics inherent in the biomass and bioenergy domain. They furnish valuable perceptions for professionals, policymakers, and researchers striving to enhance the effectiveness, sustainability, and financial viability of the supply chain. The reviewed papers in the area of supply chain coordination are summarized in the Table 2.1.

**Table 2.1 Summary of reviewed papers in the area of application of game theory in biomass supply chain coordination (C=Cooperative, NC=non-Cooperative)**

| Ref. | Article Title | Year | C | NC |
|---|---|---|---|---|
| (D. Yue, F. You, 2014) | Game-theoretic modeling and optimization of multi-echelon supply | 2014 | | *` |
| (D. Yue, F. You, 2017) | Stackelberg-game-based modeling and optimization for supply chain | 2017 | | * |
| (Y. Bai , Y. Ouyang , J. Pang, 2012) | Biofuel supply chain design under competitive agricultural land use and feedstock | 2012 | | * |
| (L. Wang, T. Watanabe, 2016) | A Stackelberg game theoretic analysis of incentive effects under perceived risk for China's straw-based power plant supply chain | 2016 | | * |
| (Xi Yang, 2012) | Optimal contracts to induce biomass production under risk | 2012 | | * |
| (RA. Ortiz-Gutierrez, S. Giarola, N. Shah, F. Bezzo, 2015) | An approach to optimize multi-enterprise biofuel supply chains including Nash equilibrium models | 2015 | | * |
| (E. Gao, T. Sowlati, S. Akhtari, 2019) | Profit allocation in collaborative bioenergy and biofuel supply chains | 2019 | * | * |
| (D. Yue, F. You, 2014 (2)) | Fair profit allocation in supply chain optimization with transfer price and revenue sharing | 2014 | * | |
| (F. Nasiri, G. Zaccour, 2009) | An exploratory game-theoretic analysis of biomass electricity generation | 2009 | | * |
| (F. Ye, Y. Li, Q. Yang , 2018) | Designing coordination contract for biofuel supply chain in China | 2018 | | * |

| | | | | |
|---|---|---|---|---|
| (K. Wamisho Hossiso, A. De Laporte, D. Ripplinger, 2017) | The effects of contract mechanism design and risk preferences on biomass supply for ethanol production | 2017 | | * |
| (R. Golecha, J. Gan, 2016) | Optimal contracting structure between cellulosic biorefineries and farmers to reduce the impact of biomass supply variation | 2016 | | * |
| (K. Fan, X. Li, L. Wang, M. Wang, 2019) | Two-stage supply chain contract coordination of solid biomass fuel involving multiple suppliers | 2019 | | * |
| (H. Gong, Y. Zhang, J. Li, 2010) | Coordination mechanism by option contract in the biomass supply chain | 2010 | | * |
| (F. Mafakheri, D. Adebanjo, A. Genus, 2020) | Coordinating biomass supply chains for remote communities | 2020 | * | |
| (E. Iakovou, A. Karagiannidis, D. Vlachos, A. Toka, A. Malamakis, 2010) | Waste biomass-to-energy supply chain management | 2010 | | * |
| (Z. Vazifeh, F. Mafakheri, C. An, 2021) | Biomass Supply Chain Coordination for Remote Communities: A Game-theoretic Modeling and Analysis Approach | 2021 | | * |
| (Vazifeh Z, Mafakheri F, An C., 2023) | Coordination of bioenergy supply chains under government incentive policies: a game-theoretic analysis | 2023 | | * |
| (C. Jaggi, M. Gupta, A. Kausar, S. Tiwari, 2019) | Inventory and credit decisions for deteriorating items with displayed stock dependent demand in two-echelon supply chain using Stackelberg and Nash equilibrium solution | 2019 | | * |
| (H. Rajabzadeh, R. Babazadeh, 2022) | A game-theoretic approach for power pricing in a resilient supply chain considering a dual channel biorefining structure and the hybrid power plant | 2022 | | * |

# Chapter 3

# Biomass Supply Chain Coordination for Remote Communities: A Game-theoretic Modeling and Analysis Approach[1]

**Zahra Vazifeh**[a], **Fereshteh Mafakheri**[b2], **Chunjiang An**[c]

*a Concordia Institute for Information Systems Engineering, Concordia University, Montreal, H3G 1M8, Canada*

*b École nationale d'administration publique (ENAP), Université du Québec*

*c Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, H3G 1M8, Canada*

## Abstract

Bioenergy, as one of the cheapest and most available renewable energies, not only reduces the dependency on fossil fuels, but also moderates the consequent environmental impacts. There is a need for biomass supply chain management, which is managing bioenergy production from harvesting feedstock to energy conversion facilities. In case of remote communities, bioenergy adoption requires dealing with dispersed geographies of suppliers and places of consumption with small scales of energy demand. As such, coordination plays a key role in increasing the efficiency of the biomass supply chain network through bundling of demand and thus improving the economy of scale. This paper employs a game-theoretic approach to formulate a coordinated biomass supply chain with three echelons including suppliers, hubs, and energy convertors. To investigate the strategic interactions of participants, three decision making structure scenarios have been considered under Stackelberg game providing insights into the impact of power distribution, the role of side payments in enforcing the flow of decisions, and the resulting efficiency and performance improvements. In doing so, a case study bioenergy supply chain for three northern Canadian communities is explored to demonstrate the application of the proposed formulation, solution methods, and the practicality and significance of the adopted approach and outcomes for remote communities.

***Keywords*** - Bioenergy, Supply Chains, Coordination, Remote Communities, Game Theory, Bi-level Optimization, Mathematical Program with Equilibrium Constraints (MPEC)

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[2] Corresponding author: fereshteh.mafakheri@enap.ca

## 3.1 Introduction

The use of renewable energy sources as a solution to decrease the world dependency on fossil fuel and to alleviate climate change has been increasingly studied in past decades. Among all types of renewable energies, biomass is one of the highly used sources, which includes plant and animal materials, forestry and agricultural residues, crops, seaweed, and some organic substances originating from living organisms (Mafakheri & Nasiri, 2014). Biomass has been the main source of energy in rural areas for centuries. However, there are several issues impacting the efficiency of bioenergy sector including low energy density of biomass materials, their seasonal availability, and as such, high variability of the investment and operational costs (Mafakheri & Nasiri, 2014). Beside these barriers, uncertainties involved in the biomass sourcing, transportation, logistics, production, operation, demand and price have further hindered the performance of biomass supply chains (Awudu & Zhang, 2012).

To overcome these barriers and challenges, coordination of biomass supply chain could play a key role (Awudu & Zhang, 2012). Supply chain coordination (or channel coordination) aims at improving supply chain performance by aligning the plans and the objectives of individual enterprises (Chan & Chan, 2010). It is a means of optimizing the entire benefit of supply chain by facilitating the information flow and/or providing incentives for key players to cooperate in the network. Although many articles have studied coordination among the players of traditional supply chains, studies that focus on channel coordination in biomass supply chains and its benefits to participating parties are very limited (Mafakheri et al., 2020).

A typical biomass supply chain is comprised of a three-echelon channel representing one or multiple biomass suppliers (and the first level) that collect and wholesale biomass to hubs (that coordinate the supply and demand sides). The hubs sell biomass to energy conversion facilities (at the third echelon of the chain) where biomass is converted to heat and energy for end users. This hierarchical structure of decisions resembles a (non-cooperative) Stackelberg leader-follower game (Zhang & Liu, 2013). The situation at which any individual member of the supply chain tries to maximize its own profit can be described as a non-cooperative game. Stackelberg games are a category of non-cooperative games in which the member with a dominant power (as a leader in the game) governs the other members who will follow the leader’s actions. This creates a strategic advantage (power) for the leader in anticipating and controlling the actions of the follower members, which is critical in elaborating the interactions among different supply chain members (Zhang & Liu, 2013).

Literature indicates that three main types of (leader-follower) Stackelberg games have been mainly adapted; first, single-leader-single-follower games (Yue & You, 2017) (namely referred to as standard Stackelberg games), in which the leader takes actions first and then the follower reacts to the leader's decisions in a rational manner. The second category includes the single-leader-multiple-follower games (Bai et al., 2013; Yue & You, 2014; Yue & You, 2017). In this case, the leader takes actions first and then the followers react to the leader's decisions simultaneously and might compete for a common resource/incentive. The third group accounts for multiple-leader-multiple-follower games (DeMiguel & Xu, 2009; Sinhaa et al., 2013; Hori & Fukushima, 2019) in which a group of channel members act primarily, and the followers optimize their objectives in reflection of decisions made by the leading members.

In leader-follower games, leadership management and the resulting assumption of the players' roles is a challenge. Although, traditionally, in manufacturing-oriented supply chains, a manufacturer acts as the leader, in recent years, the cases of the leading power being assumed by other players have been investigated (Shi et al., 2013) In this sense, many authors have studied the impact of power structure scenarios in manufacturer–retailer coordination problems (SeyedEsfahani et al., 2011; Sadigh et al., 2012; Shi et al., 2013; Zhi et al., 2018). Sadigh et al. (2012) investigated non-cooperative games for a multi-product manufacturer and retailer under two different power structures including the manufacturer as Stackelberg leader and retailer as Stackelberg leader. They demonstrated that each channel member gains more benefits when playing the Stackelberg leader at the expense of the follower. Shi et al. (2013) examined the impact of power structure and demand uncertainty on performance of supply chain members. Their work showed that the benefit gained from a leadership position in the game is influenced by the expected demand. Liu et al. (2015) explored the impacts of control power on the profits of the manufacturer, retailer, and the overall supply chain under four modes of decision-making, including a decentralized decision-making dominated by the manufacturer, a decentralized decision-making dominated by the retailer, a centralized decision-making, and a Nash equilibrium (negotiation) decision-making. They concluded that the profit of the whole supply chain with a centralized decision-making is higher than those of the other three modes. They also showed that the order quantity will increase and the wholesale price will decrease when control power is transferred from manufacturer to retailer.

For model formulation, most of the researches in the literature have focused on the maximization of net revenues of individual members. In this setting, the net revenue of the supply chain's leader is maximized according to the other members' optimal decisions (Bai et al., 2012; Yu, 2014). Early works on modelling the interactions of supply chain's members as Stackelberg games focused on bi-level Linear programming (LP) and Quadratic Programming (QP) problems (Ortiz-Gutiérrez et al., 2015). Later, more complex problems, considering continuous or categorized quantity discounts, were formulated through Non-Linear Programming (NLP) and Mixed Integer Non-Linear Programming (MINLP), respectively (Wang et al., 2007; Bai et al., 2012; Ortiz-Gutiérrez et al., 2015).

In the light of the above literature review, this paper investigates the performance of biomass supply chain coordination, for remote communities, under three power structure (leader-follower combination) scenarios as listed in Table 3.1. The aim is to investigate the effects of each power structure scenario on coordinating the decisions of biomass channel members and on overall efficiency and performance of the biomass supply chains. This is of particular importance as the economy of scale is the main barrier to implement biomass supply chains for remote communities (Mafakheri et al., 2020). This comparison provides the basis to analyze the effect of several supply chain coordination strategies (incentives), including quantity discounts and side payments, in directing a dominant equilibrium solution across these alternative power structures. The results reveal the importance of having communities to strategically assume a leading role in biomass supply chains in order to ensure an equilibrium solution with highest cost-efficiency, in contrary to conventional supply chains where suppliers lead the game (Mafakheri & Nasiri, 2013).

Discount quantities in supply chains (Shin & Benton, 2007) are adopted by supplying entities (suppliers or hubs) to encourage larger purchases which in turn serve as a motivation for bundling of orders. Side payments are provided by the leading entity to follower parties in a Stackelberg game to guarantee stability of an equilibrium solution and prevent follower parties to deviate and seek a leadership role in the game (Jackson & Wilkie, 2005; Zeng et al., 2019). Assuming and maintaining a leadership role provides the leader with the strategic advantage in driving the other players' choices. Obviously, the party that is better leveraged to provide side payments will be better positioned to assume and maintain the leadership role.

**Table 3.1** Summary of possible/potential leadership scenarios

| | **Suppliers** | **Hubs** | **Energy convertors** |
|---|---|---|---|
| **Scenario 1** | Leader | Follower | Follower |
| **Scenario 2** | Follower | Leader | Follower |
| **Scenario 3** | Follower | Follower | Leader |

In this paper, the quantity discount policy is formulated such that to adopt both purchasing (discount from suppliers) and ordering (discount from hubs) prices as functions of biomass quantity. This double-discount is to guarantee an increase in bundling of purchases as well as order quantities, such that the associated prices decrease with increase of the scale, presenting an improved economy of scale. The net revenues of suppliers and hubs are maximized and the cost for energy convertors is minimized following the order of the leadership. In addition, the problem is formulated as a multi-period problem, reflecting the realities of biomass supply chains in terms of the need to continuity and reliability over time (Sinha et al., 2013). This results in a multi-period model where the optimization problem of a follower serving as constraints for the preceding leader creating a joint decision space for players. The solution approach to such a complex (multi-level) decision making problem will be further discussed in the subsequent sections.

While the coordination of biomass supply chain players has been investigated at the city (for district heating systems) (Akgül & Seçkiner, 2019) or building scales (Nasiri et al., 2016), a focus on coordination of small and dispersed communities is emerging in the literature (Mafakheri et al., 2020). This study presents a first attempt at examining the impact of alternative power structures in coordination of biomass supply chains in case of remote communities (with dispersed small scales of demand). The coordination of biomass supply chain through means of demand bundling (encouraged by quantity discounts) and side payments is examined to seek the best strategy for improving the economy of scale and making the biomass a viable choice. A schedule of decisions including wholesale price, purchasing quantity, ordering quantity, and amount of produced bioenergy are examined in relation to the resulting performance of supply chain members.

A rational player can dominate the flow of information and assume a first mover advantage by offering a side payment to other (rational) players persuading them to remain a follower. This argument assumes that the players are rational and that the decisions are made according to players' objective functions with no involvement of negotiations/politics. In this regard, this study investigates the various leaders-follower scenarios in biomass supply chains, in case of remote communities, in order to identify the power structure that requires a lower side payment giving the leader a strategic first mover advantage to dictating the direction of information flow.

The remaining of the paper is organized as follows. Section 2 describes the background, assumptions, objectives, decision variables, constraints, and parameters of the biomass supply chain channel problem. In section 3, formulation of the proposed models is presented under the three power structure scenarios. Section 4 investigates the solution procedure as well as its implementation in the context of biomass supply for three remote communities in northern Canada. Section 5 is devoted to discussing the results of the case study, and finally, section 6 presents concluding remarks and a summary of avenues for future research.

## 3.2 Methodology

### 3.2.1 Problem Description

A three-echelon biomass supply chain includes suppliers, for collecting and harvesting the biomass, hubs, for coordinating the ordering and transport of biomass, and energy conversion facilities as users of biomass (Fig. 3.1). Each party, as a rational player, is a profit maximizer. The suppliers intend to maximize their profit by deciding on the selling price of biomass. In the second echelon, hubs are coordinating (and matching) the supply and demand sides of the supply chain. Since the existence of hubs must be economically feasible, they strive to maximize their own profit. The decision variables of hubs are the quantities to order from suppliers as well as the selling price of biomass to the energy conversion facilities. In the third echelon, biomass is converted to energy and transmitted to the consumers. The energy conversion facilities aim at minimizing the cost of energy production (their revenue is assumed independent of the source of energy) by deciding on the quantity of biomass to purchase and the amount of energy to generate from biomass. The interaction across this hierarchy of players resembles a leader–follower Stackelberg game (Yue & You, 2017). In this setting, the leader is the party that uses a first-mover advantage in deciding such that to align the other parties as a follower.

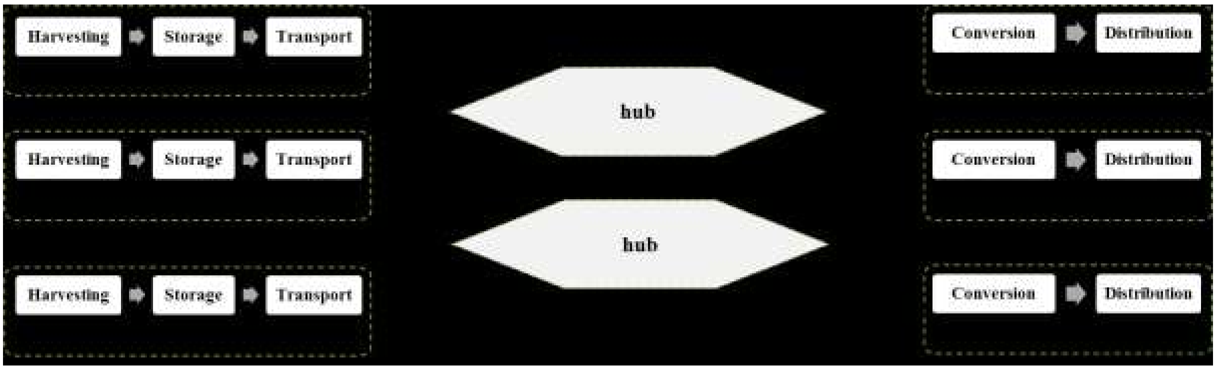



**Fig. 3.1** The three-echelon biomass supply chain network.

Stackelberg games are closely associated with bi-level optimization problems (Colson et al., 2007; Sinha et al., 2013), which are characterized by two levels of optimization problems where the constraint region of the upper-level problem is implicitly determined by the lower-level optimization problem. In this paper, the interactions between the supply chain members are formulated through a bi-level programming. The model will serve as a basis to investigate the various scenarios of the leadership (power structures) among the players in a biomass supply chain. These alternative scenarios are Suppliers-Stackelberg (suppliers act as the leader), Hubs-Stackelberg (hubs act as the leader), and Energy convertors-Stackelberg (Energy convertors act as the leader).

#### 3.2.2 Model Assumptions

The main modeling assumptions are itemized as follows:

- The cost of biomass transportation from a supplier to a hub is covered by the supplier.
- The cost of biomass transportation from a hub to an energy conversion facility is covered by the hub.
- In case of biomass supply to remote communities with small scale of supply and demand, it is to the best interest of members in each echelon, as rational parties, to form collations and act collectively to benefit from improving the economy of scale (through higher quantity discounts resulting in higher orders). Under this rational assumption, we consider a collective objective function of them in each echelon. Further to the improvement of the economy of scale, such collations provide the opportunity for using collective capacities in harvesting, storage, transportation, and conversion, considering the geographical distribution of the biomass, which further contributes to improving the efficiency of the supply chains.
- Supply chain members, as rational players, optimize their own objective function but will not share information with members in other echelons, due to anticipated conflicting interests (objectives).
- The initial (capital) costs (to create the generation capacities) are assumed to be compensated through the investments from the government and thus are not included in the proposed supply chain model.

## 3.3 Model Formulation

Below, the optimization problems of players in the biomass supply chain game are first formulated (i.e. suppliers' problem, hubs' problem, and the energy convertor's problem). Then, in each power structure scenario, one of the players assumes the leadership role forming the upper level problem, and the two other players form the lower level (follower) problems. Thus, this joint (hierarchical) decision process is formulated as a bi-level non-linear program (BNLP) problem (Colson et al., 2007; Nasiri & Zaccour, 2009). The non-linearity originates from the incorporation of quantity discount policies (to encourage bundling of biomass quantities across communities), which promotes a decrease in prices when quantities increase. This will be followed by exploring the solution approach for each of the power structure scenarios. The descriptions of acronyms, parameters and variables used in the model formulations are provided in Appendix 3.1.

### 3.3.1 Formulation of the Suppliers' Problem

The objective function of suppliers' problem ($Obj_{sup}$) reflects maximization of the total (annual) payoff, presented by Equation (3.1). The first term in this equation represents the revenue obtained from the sale of biomass to hubs, which is calculated as the product of the biomass price at time 't' ($P_{ik}^{t}$) and the total quantity sold to hubs ($\sum_k X_{ik}^{t}$). Other components of the suppliers' objective function incorporate harvesting/processing, holding, and transportation costs.

$$Max\ Obj_{sup} = \sum_i \{ \sum_t [(\sum_k X_{ik}^{t}\ P_{ik}^{t}) - hs_i\, S_i^{t} - H_i\, IS_i^{t} - \sum_k X_{ik}^{t}\ T_{ik} ] \} \quad (3.1)$$

where biomass price at time 't' ($\mathrm{P}_{\mathrm{ik}}^{\mathrm{t}}$) is considered as a function of sale quantity and capacity of the supplier (reflecting a quantity discount policy). This relationship is given by Equation (3.2)

$$P_{ik}^{t} = P_i^{u} - \left(P_i^{u} - P_i^{l}\right) \frac{X_{ik}^{t}}{S_i^{t}} \quad (3.2)$$

Inventory level for supplier 'i' at time 't' is calculated considering the inventory level at time '$\mathrm{t}-1$', available (harvested/processed) biomass (i.e. supplier's capacity) at time 't', and the amount of biomass deliveries to hubs at time 't':

$$IS_i^{t} = IS_i^{t-1} + S_i^{t} - \sum_k X_{ik}^{t} \quad , \ IS_i^{0} = 0 \quad (3.3)$$

There are also a number of technical constraints. First, the amount of biomass dispatched for delivery to hubs from each supplier shall not exceed its capacity:

$$\sum_k X_{ik}^t \leq S_i^t \tag{3.4}$$

In addition, each supplier's inventory cannot exceed its capacity:

$$0 \leq IS_i^t \leq S_i^t \tag{3.5}$$

With the nonnegative decision variables of:

$$X_{ik}^t \geq 0 \tag{3.6}$$

### 3.3.2 Formulation of the Hubs' Problem

The optimization problem of hubs is formulated as Equation (3.7). The first term denotes the revenue of hubs, which is calculated as the product of total quantity sold to energy convertor facilities ($\sum_j y_{kj}^t$) and hubs' biomass price at time 't' ($B_{kj}^t$). The costs include biomass purchasing (from suppliers) and holding cost.

$$Max\ obj_{hub} = \sum_k \{ \sum_t [(\sum_j y_{kj}^t\ B_{kj}^t) - \sum_i X_{ik}^t\ P_{ik}^t - Hc_k\ h_k^t ] \} \tag{3.7}$$

Hubs' biomass price offered to energy convertors at time 't' ($B_{kj}^t$) is considered as a function of selling quantity and capacity of the hub (reflecting hubs' discount policy):

$$B_{kj}^t = B_{kj}^u - \left(B_{kj}^u - B_{kj}^l\right) \frac{y_{kj}^{t-rp}}{h_k} \tag{3.8}$$

Inventory level at hub '$k$' at time 't' is presented as:

$$h_k^t = h_k^{t-1} + \sum_i X_{ik}^{t-rs} - \sum_j y_{kj}^t \quad , \quad h_k^0 = 0 \tag{3.9}$$

This inventory cannot exceed the hub's capacity:

$$h_k^t \leq hk(k) \tag{3.10}$$

With the nonnegative decision variables of:

$$y_{kj}^t \geq 0 \tag{3.11}$$

### 3.3.3 Formulation of the Energy Convertors' Problem

The optimization problem of energy convertors is formulated as Equation (3.12). The costs include biomass acquisition cost paid to hubs, biomass holding cost, biomass to electricity conversion cost, and electricity generation cost from an alternative (competing or backup) source:

$$Min\ Obj_{cf} = \sum_j \{\sum_t [(\sum_j y_{kj}^t\ B_{kj}^t) + (I_j^t\ a_j) + (LB_j\, z_j^t) + (LD_j\ (D_j^t - z_j^t))\} \quad (3.12)$$

The consideration of an alternative source is a reflection of the need to have a reliable production of energy in case of biomass supply fluctuations from the perspectives of quantity and/or price. Also, in many remote (off-grid) communities, diesel is used as the main source for generation of electricity (NEB, 2016). In this sense, the energy convertor facility decides about the least cost mix of energy sources between the conventional/existing source (such as diesel) and biomass. In doing so, minimization objective function presented in Equation 3.12 could result in having biomass as part of the energy mix only if biomass is a viable option in comparison with the alternative source(s) as the last component of the equation (capturing the cost associated with alternative source) is in trade-off with the remaining components of the equation (representing the costs associated with biomass). Inventory levels of each conversion facility 'j' at time 't' is presented as:

$$I_j^t = I_j^{t-1} + \sum_k y_{kj}^{t-rp} - \frac{z_j^t}{fc_j} \quad , \quad I_j^0 = 0 \quad (3.13)$$

There are a number of technical constraints. First, bioenergy production at each conversion facility is bounded by (the minimum of) associated energy demand and energy production capacity of the facility. This relationship could be represented by Equation (3.14) for any given month (720 hours):

$$z_j^t \leq \min\ (D_j^t, Lf_j * Z_j * 720) \quad (3.14)$$

Also, inventory levels of biomass conversion facility 'j' at time 't' cannot exceed its storage capacity:

$$I_j^t \leq Ib_j \quad (3.15)$$

With nonnegative decision variables of:

$$z_j^t \geq 0 \quad (3.16)$$

### 3.3.4 Formulation of BNLP Problem

In the scenario 1, the suppliers' Stackelberg problem includes the objective function (3.1) and constraints (3.2) – (3.16). In the scenario 2, the hubs' Stackelberg problem includes the objective function (3.7) and constraints (3.1) – (3.6) and (3.8) - (3.16). In the scenario 3, the energy convertors' Stackelberg problem includes the objective function (12) and constraints (3.1) – (3.11) and (3.13) - (3.16).

## 3.4 Solution Approach

This section presents the solution strategy for the Stackelberg single-leader-multi-follower game formulated as a multi-period BNLP problem. In BNLP problems, the outcome of any solution or decision taken by the upper-level authority (leader) to optimize their goals is affected by the response of lower-level entities (follower), which also tend to optimize their own outcomes (Nasiri & Zaccour, 2009). When the lower-level problem is convex, the conventional solving approach to the BNLP problems is to transform the original two-level problems into a single level one by replacing the lower-level optimization problem with the set of equations that define its Karush–Kuhn–Tucker (KKT) conditions (Jiang et al, 2019). Using the KKT conditions, Kim and Ferris (2019) introduced an extended mathematical programming (EMP) to reformulate the bi-level problem to its equivalent Mathematical Program with Equilibrium Constraints (MPEC) framework solved with an MPEC solver in General Algebraic Modelling System (GAMS) (GAMS, 2020). They showed that their approach resulting less error compared to the traditional complementarity-based models that require the derivative computation of the Lagrangian by hand. In this study, EMP tool in GAMS is adopted to transform the hierarchical problem into its MPEC equivalent problem. The transformed problem is then solved by using the non-linear program with equilibrium constraints (NLPEC) solver in GAMS.

## 3.5 Case Study

A case study of northern Quebec communities is considered for adoption of biomass as an alternative source for electricity generation. This is in recognition of the energy security (and resilience) concerns for this region as these isolated communities are entirely dependent on diesel fuel for electricity generation (NEB, 2016). This single-source situation could result in high operating costs, low efficiency, high environmental risks and total dependence on a fossil fuel with elevated carbon dioxide emissions. The case study considers three Quebec northern communities of Kangigsujuaq (KA), Salluit (SA), and Ivujivik (IV). Despite the fact that Canada has access to a great amount of biomass resources from various sources, there is strictly no possibility of relying upon a local biomass supply in this region, because of the unsuitable vegetation texture of the region not supporting any reliable sources of biomass. Therefore, biomass must be imported from other places. In this situation, pellets are considered as the preferred type of biomass due to their higher level of standardization and higher energy density, making them a suitable candidate for delivery and storage. In this study, six suppliers from both Canada and US have been considered to provide biomass for energy production in these communities. A schematic superstructure of the investigated biomass supply chain is presented in Fig. 3.2.

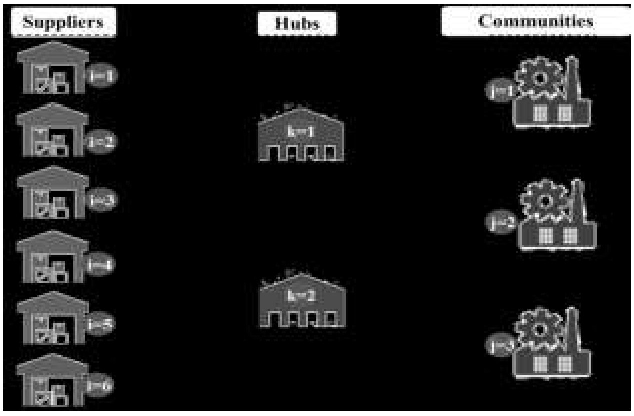



**Fig. 3.2** Superstructure of the case study supply chain

Hubs contribute to increasing the economy of scale and coordination of supply and demand in biomass supply chains. Two hubs are considered in the biomass supply chain. This is the minimum number of hubs needed to ensure a diversification of supply-demand matching channels. One hub is located in the west of Quebec (QC) province and the other one in the northeast of New Brunswick (NB) province, in line with the main alternative transportation pathways to northern Quebec via Hudson Bay or Labrador Sea, respectively. The parameters of the models associated with the case study are described and presented in Table 3.2 (Mafakheri et al., 2020).

**Table 3.2** Parameters of the model and their values used in the case study.

| Definitions | Symbols and Units | Value |
|---|---|---|
| Transportation cost from supplier 'i' to hub 'k' | $T_{ik}$(\$/kg) | Shown in Appendix 3.2 |
| Capacity (biomass availability) of supplier 'i' at time t | $S_i^t$ (kg) | Shown in Appendix 3.3 |
| Biomass price of supplier 'i' without discount | $P_i^u$(\$/kg) | Shown in Appendix 3.3 |
| Biomass price of supplier 'i' with discount | $P_i^l$(\$/kg) | Shown in appendix 3.3 |
| Biomass harvesting cost for supplier 'i' | $\text{hs}_i$ (\$/kg) | 0.04 |
| Holding cost for supplier 'i' | $\text{Hi}_i$(\$/kg) | Shown in Appendix 3.3 |
| Capacity of hub 'k' | $h_{k\text{k}}$ (kg) | 350,000, 400,000 |
| Holding cost at hub 'k' | $Hc_k$(\$/kg) | 0.0020, 0.0015 |
| Biomass ordering cost from hub 'k' without discount | $B_{kj}^u$(\$/kg) | Shown in Appendix 3.4 |
| Biomass ordering cost from hub 'k' 'j' with discount | $B_{kj}^l$(\$/kg) | Shown in Appendix 3.4 |
| Capacity of biomass inventory at energy convertor 'j' | $Ib_j$(kg) | 200,000, 200,000, 1,500,000 |
| Holding cost at energy convertor 'j' | $a_j$(\$/kg) | 0.004, 0.003, 0.003 |
| Conversion rate of biomass to electricity at convertor 'j' | $fc_j$(kWh/kg) | 4.7, 4.8, 4.6 |
| Loading factor of energy convertor 'j' | $Lf_j$ (%) | 80, 85, 80 |
| Electricity generation cost from biomass | $LB_j$(\$/kWh) | 0.046, 0.044, 0.048 |
| Electricity generation cost from diesel | $LD_j$(\$/kWh) | 0.208, 0.215, 0.207 |
| Demand in energy convertor 'j' at time t | $D_j^t$ (kWh) | Shown in Appendix 3.5 |
| Capacity of electricity generation | $Z_j$ (kW) | 500, 500, 500 |
| Delivery time between supplier 'i' and hub 'k' | $rs$ (Month) | 1 |
| Delivery time between hub 'k' and convertor 'j' | $rp$ (Month) | 1 |

The solution of the BNLP model associated with the case study was obtained using an Intel (R) Core (TM) i5-4210U CPU 1.70GHz computer equipped with General Algebraic Modelling System (GAMS) software. The bi-level problem is reformulated as a Mathematical Program with Equilibrium Constraints (MPEC) and is passed to a NLPEC solver. The computational time to solve the above BNLP models was 5.7 seconds. The solutions obtained are presented in the Tables 3-3 to 3-6.

## 3.6 Results and Discussions

In this section, the results obtained based on three power structure scenarios will be discussed and compared. The values of the objective functions obtained for players in each scenario are presented in Table 3.3. The results show that the suppliers generate $393,600 revenues when they act as the leader, which is approximately 20% higher compared to their gains in other scenarios. If scenario 2 is employed, hubs assume the leadership with higher benefits achieved in comparison with the other scenarios. By choosing scenario 3, the communities would gain the most savings while the hubs would lose at the highest level of $60,773.

**Table 3.3** Players' objective function values based on alternative leadership scenarios.

| Players | Objective | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| **Suppliers** | Max (Revenue) | **$393,600** | $323,000 | $322,900 |
| **Hubs** | Max (Revenue) | $265,000 | **$563,090** | $-60,773 |
| **Communities** | Min (Cost) | $-1,577,400 | $-1,889,956 | **$-1,008,500** |

As the price of biomass and ordering costs offered by each supplier to each hub changes over time, to establish a pricing indicator for each scenario, the weighted average prices, for suppliers (i.e. biomass price) and hubs (i.e. ordering cost), are calculated according to Equations (3.17) and (3.18) and reported as presented in Fig. 3.3:

$$\bar{P} = \frac{\sum_{i,k,t} X_{ik}^{t} \ P_{ik}^{t}}{\sum_{i,k,t} X_{ik}^{t}} \tag{3.17}$$

$$\bar{B} = \frac{\sum_{k,j,t} y_{kj}^{t} \ B_{kj}^{t}}{\sum_{k,j,t} y_{kj}^{t}} \tag{3.18}$$

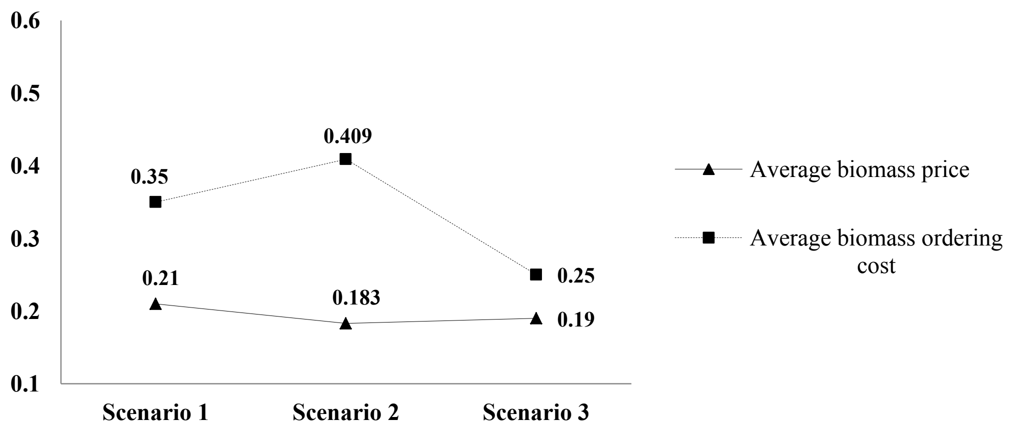



**Fig. 3.3** Average biomass purchasing price and ordering cost in various scenarios.

In scenario 1, an average biomass price of \$0.21 per kg is achieved, the highest unit price compared among the scenarios. In scenario 2, however, biomass is at its lowest average price; while the ordering cost paid by the communities is at its highest average rate of \$0.409 per kg. In scenario 3, biomass ordering cost is of \$0.25 per kg is the lowest one among the three scenarios.

The cost breakdown for supply chain members in each scenario is shown in Table 3.2. Reviewing the results shows that the harvesting cost is a major cost for suppliers, forming around three quarters of their total costs. The proportion of various costs of suppliers as well as the cost associated with hubs appears to remain the same in all scenarios. However, in the case of the communities, the ordering cost appears to be changing amongst scenarios leading to the highest in scenario 2.

**Table 3.2** Cost breakdown of biomass supply chain participants

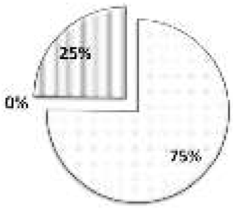
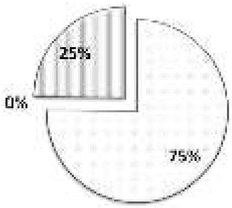
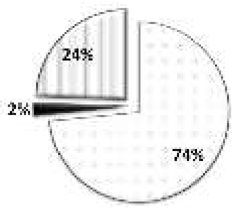
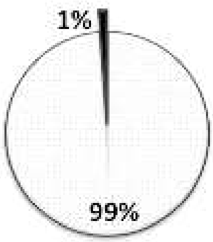
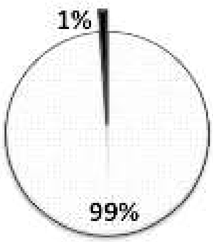
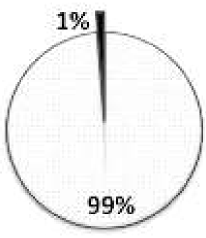
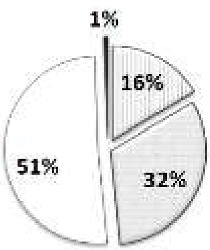
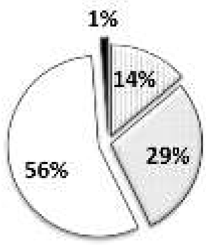
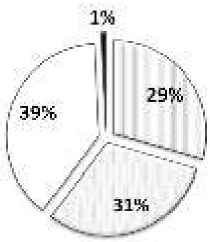
| Participants | Cost's labels | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| Suppliers | Harvesting cost<br>Holding cost<br>Transportation cost |  |  |  |
| Hubs | Ordering cost<br>Holding cost |  |  |  |
| Communities | Biomass to electricity conversion cost<br>Diesel to electricity generation cost<br>Ordering cost<br>Holding cost |  |  |  |

Table 3.3 presents the amount of electricity generated through scenarios in each community and as a fraction of demand. These results indicate that the demand is highly satisfied through scenario 3 to the extent of 92%, 74% and 92 % for communities 1, 2, and 3,

respectively. The next effective scenario in terms of the biomass electricity power generation would be scenario 1, where the demand is satisfied to the extent of 87%, 73% and 86% for communities 1, 2, and 3, respectively. Amongst all, scenario 2 yields the lowest share. There are some key findings from the case study:

- The best value of objective function in each echelon is obtained when that echelon acts as a leader. This is due to the strategic (first mover) advantage given to the leader, to decide while anticipating the response of the follower players. This further confirms the observations made by Shi et al. (2013) reporting on the impact of power structure in the manufacturer–retailer coordination problems.
- If the leadership switches from the suppliers to the hubs, the average biomass price (offered by suppliers to hubs) decreases while the average biomass ordering price (offered by hubs to communities) increases. This power allocation thus has a similar impact, with the hubs acting as leaders, and imposing the purchase of biomass at relatively cheaper prices (from suppliers) and the sale of biomass (to the communities) at remarkably higher prices.
- If the leadership switches from the hubs to communities, the average biomass price (offered by suppliers to hubs) increases while the average biomass ordering price (offered by hubs to communities) decreases remarkably. In this case, the communities could use this strategic advantage to acquire biomass at the cheapest possible price to minimize their cost and thus increasing the share of biomass in their energy mix. In this sense, biomass-based electricity generation will be at its highest level when communities assume the leading role. In this scenario, biomass will be at its highest competitive advantage compared to the alternative fuel (diesel).

The findings indicate that the most desired scenario varies across the players meaning that no scenario can be dominating and agreed among all the parties. Each player prefers the scenario that ensures its leadership role. In such circumstances, the player that has the highest leverage to enforce its preferred scenario (leadership) can motivate the other players to remain a follower creating a dominant (stable) scenario that no player will deviate form it. Revisiting objective function values reported in Table 3.3 could provide insights on the amount of loss each player will incur when accepting a follower role in either of its non-preferred scenarios. These losses provide a basis for calculation of side payments that shall be offered from a leader player to the followers to ensure the dominance of their preferred (leadership) scenario. In doing so, the leader should be able to “match the best outcome of the follower parties” to have them committed to the leader’s strategic advantage (Zeng et al., 2019). Otherwise, the other players will deviate from their follower roles in the supply chain.

As the objective function of communities includes both biomass and diesel related costs, the minimization of the objective function automatically generates the best trade-off between biomass and diesel. If the economies of the supply chain result in a competitive cost of biomass for communities, the biomass share increases, otherwise the diesel becomes the dominant one. Table 3.5 presents the share of biomass in the energy mix ranging from 0% to 100% for communities over time.

On that basis, the required side payments to (to ensure dominance of a leader over the followers) are calculated as the difference between the actual outcome of each follower player and its best performance (as a leader). This would be the amount of payment required to motivate a player to remain a follower and accept to have the payment-offering player as the leader. In this sense, Tables 3.6, 3.7 and 3.8 present the required side payments that communities, suppliers, and hubs have to offer to others in order to maintain a leadership role.

The comparison of the required side payments to guarantee the dominance of each leadership scenarios shows that the scenario with the communities assuming the leadership role (scenario 3 with side payments from communities to suppliers and hubs) is achieved with the least total amount of required side payments ($694,563). Considering the ratio of required side payments to leader’s best payoff, the community leadership will be the only scenario that still yields a positive payoff for the leader despite side payments. Moreover, in this scenario the expected (average) amount of electricity generated from biomass accounts for 86% of the electricity mix (14% share for diesel), which is the highest biomass share compared to other scenarios. As such, this scenario provides enough motivation for the leadership role of communities in the supply chain from both economic and environmental perspectives.

**Table 3.3** Electricity generation, $\boldsymbol{z_j^t}$ (kWh), and share of satisfied demand, $\mathbf{\acute{D}_j}$(%), for communities.

| | First Scenario | | | | | | Second scenario | | | | | | Third Scenario | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | j=1 | | j=2 | | j=3 | | j=1 | | j=2 | | j=3 | | j=1 | | j=2 | | j=3 | |
| **t** | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ | $z_j^t$ | $\acute{D}_j$ |
| **1** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **2** | 132,028 | 77% | 173,693 | 54% | 82,647 | 89% | 0 | 0% | 3,582 | 1% | 92,398 | 100% | 171,900 | 100% | 190,168 | 59% | 92,800 | 100% |
| **3** | 162,688 | 95% | 290,923 | 90% | 90,965 | 99% | 171,000 | 100% | 48,236 | 15% | 91,905 | 100% | 171,000 | 100% | 306,000 | 95% | 92,300 | 100% |
| **4** | 179,695 | 99% | 305,245 | 89% | 96,393 | 99% | 155,540 | 86% | 1,192 | 0% | 97,213 | 100% | 180,900 | 100% | 306,000 | 90% | 97,600 | 100% |
| **5** | 178,503 | 99% | 305,256 | 90% | 95,808 | 99% | 179,700 | 100% | 272,987 | 81% | 96,535 | 100% | 179,700 | 100% | 306,000 | 90% | 97,000 | 100% |
| **6** | 167,484 | 99% | 305,248 | 96% | 89,907 | 99% | 168,700 | 100% | 288,696 | 91% | 90,490 | 99% | 168,700 | 100% | 306,000 | 96% | 91,100 | 100% |
| **7** | 176,913 | 99% | 304,962 | 90% | 95,191 | 99% | 178,700 | 100% | 305,668 | 91% | 92,175 | 96% | 178,700 | 100% | 306,000 | 91% | 96,400 | 100% |
| **8** | 189,845 | 97% | 305,193 | 83% | 102,656 | 98% | 194,800 | 100% | 2,411 | 1% | 102,797 | 98% | 194,800 | 100% | 306,000 | 83% | 105,100 | 100% |
| **9** | 211,286 | 97% | 305,170 | 75% | 111,650 | 95% | 216,800 | 100% | 241,403 | 59% | 116,643 | 100% | 216,800 | 100% | 306,000 | 75% | 117,000 | 100% |
| **10** | 238,384 | 97% | 305,141 | 65% | 123,123 | 92% | 246,663 | 100% | 305,819 | 66% | 132,983 | 100% | 246,900 | 100% | 306,000 | 66% | 133,300 | 100% |
| **11** | 216,779 | 96% | 305,085 | 71% | 112,572 | 92% | 226,243 | 100% | 305,866 | 72% | 122,008 | 100% | 226,500 | 100% | 306,000 | 72% | 122,300 | 100% |
| **12** | 186,538 | 85% | 291,999 | 70% | 91,268 | 77% | 213,177 | 97% | 305,023 | 74% | 118,187 | 100% | 219,900 | 100% | 306,000 | 74% | 118,700 | 100% |
| **Average** | **170,012** | **0.87** | **266,493** | **0.73** | **91,015** | **0.86** | **162,610** | **0.82** | **173,407** | **0.46** | **96,111** | **0.91** | **179,650** | **0.92** | **270,847** | **0.74** | **96,967** | **0.92** |

**Table 3.6** Required side payments for communities' leadership (scenario 3)

| Player | Objective | Best Payoffs ($) | Leader Scenario ($) | Side Payment ($) * | Revised lead scenario ($) |
|---|---|---|---|---|---|
| **Suppliers** | Max (Revenue) | 393,600 | 322,900 | 70,700 | 393,600 |
| **Hubs** | Max (Revenue) | 563,090 | -60,773 | 623,863 | 563,090 |
| **Communities** | Min (Cost) | -1,008,500 | -1,008,500 | 0 | -1,703,063 |

*Total required side payment: $694,563 (as a percentage of leader's best payoff: 68.9%)

**Table 3.7** Required side payments for hubs' leadership (scenario 2)

| Player | Objective | Best Payoffs ($) | Leader Scenario ($) | Side Payment ($) * | Revised lead scenario ($) |
|---|---|---|---|---|---|
| **Suppliers** | Max (Revenue) | 393,600 | 323,000 | 70,600 | 393,600 |
| **Hubs** | Max (Revenue) | 563,090 | 563,090 | 0 | -388,966 |
| **Communities** | Min (Cost) | -1,008,500 | -1,889,956 | 881,456 | -1,008,500 |

*Total required side payment: $952,056 (as a percentage of leader's best payoff: 169.1%)

**Table 3.8** Required side payments for suppliers' leadership (scenario 1)

| Player | Objective | Best Payoffs ($) | Leader Scenario ($) | Side Payment ($)* | Revised lead scenario ($) |
|---|---|---|---|---|---|
| **Suppliers** | Max (Revenue) | 393,600 | 393,600 | 0 | -473,390 |
| **Hubs** | Max (Revenue) | 563,090 | 265,000 | 298,090 | 563,090 |
| **Communities** | Min (Cost) | -1,008,500 | -1,577,400 | 568,900 | -1,008,500 |

*Total required side payment: $866,990 (as a percentage of leader's best payoff: 220.2%)

## 3.7 Conclusions

This study was a first attempt in examining the impact of alternative power structures in coordination of biomass supply chains in case of remote communities (with dispersed and small scales of demand). In doing so, the interaction of players in a biomass supply chains were formulated as a Stackelberg game. This formulation was used to evaluate the impact of three leadership scenarios of suppliers as leader, hubs as leaders, and communities (energy convertors) as leaders. Each player of the supply chain can assume a leadership role by offering a side payment to other players to persuade them to remain a follower. The key question is to know which player is better leveraged in offering of side payments. In a simple sense, the player who requires a lower side payment has the strategic first mover advantage, by dictating the direction of information flow, and will assume the leadership role.

The problem was uniquely formulated as a multi-period BNLP model with quantity discounts influencing the decisions at each echelon of the biomass supply chain. A case study of a biomass supply chain of three northern Canadian (remote) communities was explored. Although the results indicated that each supply chain member achieves the best payoff when assuming the leadership role, the leverages of leaders to persuade other players to assume follower roles differed remarkably across the scenarios. The concept of side payments, as a coordination incentive, is employed to identify the dominating supply chain coordination (leadership) strategy, with stable leader-follower interactions. The results showed that scenario 3 with communities assuming a leadership position dominated the other scenarios. The communities were better leveraged to provide the required side payments (to suppliers and hubs) preventing their deviation from a follower role. Moreover, it was shown that the share of biomass in electricity generation mix reached its highest under this scenario.

This study could be extended in a number of directions. First, the multi-echelon supply chain formulation can be represented by a network game considering competition among the players at each level. However, for remote communities with small and dispersed scale of demand, such a non-cooperative (competitive) arrangement at each echelon is expected to yield inferior solutions compared to the ones achieved in this study with assumption of cooperation at each echelon. This is due to the fact that the economy of scale for biomass ordering from hubs, and consequently from suppliers, is improved with bundling of orders through cooperation of communities. In addition, since the short durability is one of the main disadvantages of biomass fuel, the models can be extended by considering a biomass decay rate (BDR) in each echelon. Also, carbon emission inventories can be incorporated into this supply chain game either as an overall supply chain objective pursued by a social planner (ex. Government) or as a joint target (in form of a constraint) for the communities (Nasiri & Zaccour, 2009). A supplier selection component can also be added as a prerequisite step in order to direct the choice of suppliers based on a select set of criteria before formulating the suppliers' problem (Mafakheri et al., 2011). Moreover, ordering restrictions can be incorporated into the optimization models of players at each level, including restrictions on schedule or quantity of deliveries as a consequence of the availability or capacity of the means and pathways of transportation. Finally, the BNLP model can be coupled with a simulation model (Nasiri et al., 2016) to incorporate future scenarios for biomass availability and energy demand into problems of suppliers and communities.

**Appendix 3.1** symbols and nomenclatures

| Type | Symbol | Description | Units |
|---|---|---|---|
| Sets | $i$ | Set of suppliers | - |
| | $k$ | Set of hubs | - |
| | $j$ | Set of energy convertor facilities | - |
| | $t$ | Time periods | - |
| Parameters | $T_{ik}$ | Transportation cost from supplier 'i' to hub 'k' | \$/kg |
| | $S_i$ | Capacity of supplier 'i' | kg |
| | $P_i^u$ | Biomass price of supplier 'i' without discount | \$/kg |
| | $P_i^l$ | Biomass price of supplier 'i' with discount | \$/kg |
| | $\bar{P}$ | Weighted average of biomass price | \$/kg |
| | $\mathrm{hs}_i$ | Biomass harvesting cost at supplier 'i' | \$/kg |
| | $\mathrm{H}_i$ | Holding cost for supplier 'i' | \$/kg |
| | $h_{k\mathrm{k}}$ | Capacity of hub 'k' | kg |
| | $Hc_k$ | Holding cost at hub 'k' | \$/kg |
| | $B_{kj}^u$ | Biomass ordering cost from hub 'k' to energy convertor 'j' without discount | \$/kg |
| | $B_{kj}^l$ | Biomass ordering cost from hub 'k' to energy convertor 'j' with discount | \$/kg |
| | $\bar{B}$ | Weighted average of biomass ordering cost | \$/kg |
| | $Ib_j$ | Capacity of biomass inventory at energy convertor 'j' | kg |
| | $a_j$ | Holding cost at energy convertor 'j' | \$/kg |

| | | | |
|---|---|---|---|
| | $fc_j$ | Conversion rate of biomass to electricity at energy convertor 'j' | kWh/kg |
| | $Lf_j$ | Loading factor of energy convertor 'j' | % |
| | $LB_j$ | Electricity generation cost from biomass | $/kWh |
| | $LD_j$ | Electricity generation cost from diesel | $/kWh |
| | $D_j^t$ | Demand in energy convertor 'j' at time t | kWh |
| | $\acute{D}_j$ | Share of satisfied demand in community 'j' | % |
| | $Z_j$ | Capacity of electricity generation | kW |
| | $rs$ | Delivery time between supplier 'i' and hub 'k' | Month |
| | $rp$ | Delivery time between hub 'k' and energy convertor 'j' | Month |
| Decision variables | $X_{ik}^t$ | Quantity of biomass delivered from supplier 'i' to hub 'k' at time 't' | Kg |
| | $y_{kj}^t$ | Quantity of biomass delivered from hub 'k' to energy convertor 'j' at time 't' | kg |
| | $z_j^t$ | Electricity generation from biomass in community 'j' at time 't' | kWh |
| Other variables | $IS_i^t$ | Biomass inventory level at supplier 'i' at time 't' | kg |
| | $h_k^t$ | Biomass inventory level at hub 'k' at time 't' | kg |
| | $I_j^t$ | Biomass inventory level at energy convertor 'j' at time 't' | kg |
| | $P_{ik}^t$ | Biomass price offered by supplier 'i' to hub 'k' at time 't' | $/kg |
| | $B_{kj}^t$ | Biomass ordering price offered by hub 'k' to energy convertor 'j' at time 't' | $/kg |

**Appendix 3.2** Cost of biomass transportation from supplier 'i' to hub 'k'

| | | Hubs | |
|---|---|---|---|
| | | 1 | 2 |
| Suppliers | 1 | 0.012 | 0.015 |
| | 2 | 0.011 | 0.016 |
| | 3 | 0.012 | 0.015 |
| | 4 | 0.014 | 0.012 |
| | 5 | 0.015 | 0.011 |
| | 6 | 0.016 | 0.010 |

**Appendix 3. 3** Holding cost ($H_i$), Capacity ($S_i$), and biomass price ranges ($P_i^l, P_i^u$) of suppliers

| Supplier | $\boldsymbol{H_i}$ | $S_i$ | $\boldsymbol{P_i^l}$ | $\boldsymbol{P_i^u}$ |
|---|---|---|---|---|
| **1** | 0.002 | 33,300 | 0.168 | 0.205 |
| **2** | 0.0015 | 34,000 | 0.170 | 0.210 |
| **3** | 0.002 | 34,700 | 0.175 | 0.200 |
| **4** | 0.002 | 37,000 | 0.190 | 0.215 |
| **5** | 0.0015 | 35,000 | 0.190 | 0.220 |
| **6** | 0.002 | 34,000 | 0.185 | 0.220 |

**Appendix 3.4** Ordering cost of biomass from hub 'k' for delivery to energy convertor 'j' ($B_{kj}^l, B_{kj}^u$)

| | | **Communities** | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| **Hubs** | 1 | (0.235, 0.362) | (0.235, 0.362) | (0.235, 0.362) |
| | 2 | (0.266, 0.409) | (0.266, 0.409) | (0.266, 0.409) |

**Appendix 3.5** Electricity demand in community 'j' at time 't'

| | Community | | |
|---|---|---|---|
| Year | 1 | 2 | 3 |
| 1 | 186,300.000 | 351,500.000 | 100,500.000 |
| 2 | 171,900.000 | 324,400.000 | 92,800.000 |
| 3 | 171,000.000 | 322,600.000 | 92,300.000 |
| 4 | 180,900.000 | 341,200.000 | 97,600.000 |
| 5 | 179,700.000 | 339,100.000 | 97,000.000 |
| 6 | 168,700.000 | 318,300.000 | 91,100.000 |
| 7 | 178,700.000 | 337,100.000 | 96,400.000 |
| 8 | 194,800.000 | 367,500.000 | 105,100.000 |
| 9 | 216,800.000 | 409,000.000 | 117,000.000 |
| 10 | 246,900.000 | 465,900.000 | 133,300.000 |
| 11 | 226,500.000 | 427,400.000 | 122,300.000 |
| 12 | 219,900.000 | 414,900.000 | 118,700.000 |

# Chapter 4

# Coordination of Bioenergy Supply Chains under Government Incentive Policies: A Game-theoretic Analysis[3]

**Zahra Vazifeh[a], Fereshteh Mafakheri[b], Chunjiang An[c]**

*a Concordia Institute for Information Systems Engineering, Concordia University, Montreal, H3G 1M8, Canada*

*b École nationale d'administration publique (ENAP), Université du Québec*

*c Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, H3G 1M8, Canada*

## Abstract

Biomass as an abundant renewable energy source can play a vital role in controlling the Greenhouse Gas (GHG) emissions. The distributed nature of biomass and its low energy density have complicated the utilization of this cheap and available source of energy. Governments can stimulate the bioenergy industry and remove barriers for adoption of bioenergy by implementing supporting regulations and incentives. In this paper, two types of government incentives, representing direct and indirect incentives, are analyzed and their efficiencies in fostering bioenergy generation are compared. A Stackelberg (leader-follower) game is proposed to formulate the integration of incentives as a bi-level problem in coordination of biomass supply chains. We further illustrate the applicability of the proposed approach through an empirical case study of three Canadian remote communities. The case study demonstrates the effects of incentives on coordination of biomass suppliers and end-user communities and promoting bioenergy share in electricity generation mix of communities. The findings of this study highlight the importance of government's support, in form of indirect incentives, for provisioning of infrastructure needed for biomass supply and conversion, with a significant impact on increasing the share of bioenergy generation.

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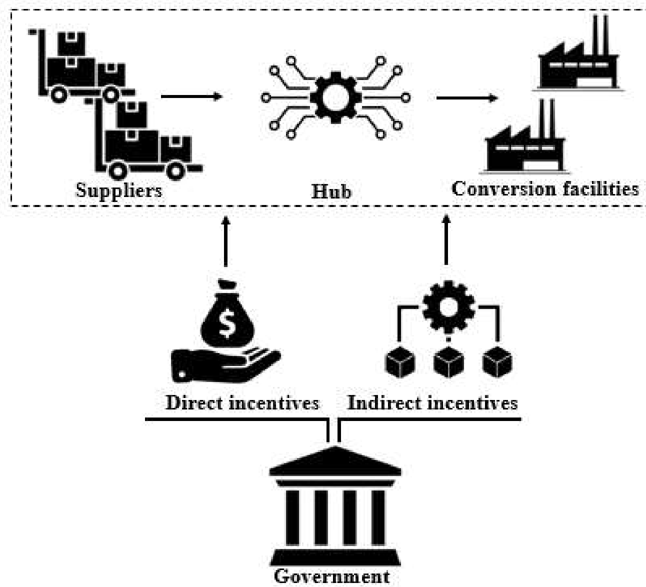
**Graphical abstract**




***Keywords*** — Biomass, Supply Chain Coordination, Governance, Energy Policy, Game Theory, Incentives, Remote Communities

## 4.1 Introduction

Generating electricity from renewable energy sources is a key strategy to reduce both air pollutions and Greenhouse Gas (GHG) emissions compared to fossil fuel electricity generation. In addition, the role of renewable energy in increasing energy security, reducing dependency on fossil fuels, and developing local employment, provides motivations to support renewable sources of energy (Philibert, 2011). Bioenergy is a type of renewable energy sourced from organic materials. Biomass resources are comprised of a variety of distinct materials including wood, crop residues, sawdust, straw, paper waste, household wastes and wastewater (Antar et al. 2021). Due to the high potential capacity of biomass in contribution of global energy supply, the utilization of bioenergy is growing gradually (Masud et al. 2019). Forestry and agricultural residues are major biomass sources in bioenergy production for electricity and heating (Igliński et al. 2015). In 2017, electricity generated from biomass sources was the third largest renewable electricity source after hydropower and wind with 596 terrawatt hour (TWh) of biopower generation (9% of world energy production) (Global Bioenergy Statistics, 2019). According to a forecast, by 2050, 3000 TWh of bio-based electricity could be generated, and consequently, 1.3 Bt equivalent $CO_2$ emission could be saved per year (Energy Strategy Reviews 2019). The bioenergy generation potential in each jurisdiction depends on various factors such as geography, technology, economy, and presence of agriculture and forest industries. The state of the art of bioenergy has made significant progress in recent years. New approaches, such as biorefineries, and advanced waste-to-energy systems, have the potential to escalate the efficiency and sustainability of bioenergy production (Seo et al. 2022). The future of bioenergy is expected to play a significant role in meeting the world's energy needs while reducing greenhouse gas emissions and dependence on fossil fuels.

Canada with 347 M ha forest land, has a great potential for biomass and bio-based products (Mupondwa et al. 2017). In Canada, biomass has the second largest share of renewable energy production with 23% (after hydro with 68%) (NRCan 2020). However, bioenergy is still a developing industry with several barriers and challenges due to seasonality of biomass, low energy density of biomass materials, and more important, the need to coordinated logistics (due to dispersion of biomass resources across a vast geography) (Mafakheri and Nasiri 2014). In this sense, it is essential to enhance the efficiency of biomass supply chains to improve profitability and thus adoption of bioenergy. In doing so, it is very crucial to manage conflicts among various parties across biomass supply chains and keep their objective aligned/coordinated with each other.

The concept of coordination in supply chain was developed by Cachon (Cachon G. P., 2003) as a means of optimizing the entire benefit of supply chain. Among various mechanisms suggested in the literature for supply chain coordination, game theory has become a common method to study the supply chains with multiple players, often with conflicting objectives (Wang and Watanabe 2016). Game theory provides a modeling approach for supply chain coordination in both cooperative (Gao et al. 2019) and non-cooperative (Mafakheri and Nasiri 2013) assumptions for players' objectives. In this situation, there are several mechanisms to formulate coordination and reach a profit sharing among the players. Hence, selection of an appropriate coordination mechanism by comparing various types of coordination schemes has been the focus of many studies (Cachon and Lariviere 2000).

Cooperative games mainly focus on achieving collaboration among players through cooperation (Wu et al. 2017). The focus in a cooperative game is to determine how the benefits should be shared among supply chain participants in order to enhance coordination and satisfy all parties (Gao et al. 2019). In a non-cooperative game, on the other hand, participants of a supply chain try to maximize their own profit on an individual basis. In a biomass supply chain, players could link their resources and join forces in order to generate and sell bioenergy.

A non-cooperative approach is a more common approach in directing a supply chain and creating a trade-off (equilibrium) among participants' benefits (Bai et al. 2013). In case the non-cooperative participants make decisions following the flow of information, an asymmetric game called Stackelberg is initiated (Stackelberg et al. 2010). In a Stackelberg game, the member assuming a leading power (with precedence in access to information and decision making) initiates the game with its own strategy and rules the other participants who will follow by responding to the leader's strategy. In this sense, to model a Stackelberg game, the common approach is to formulate a bi-level decision-making problem optimizing the leader's objective function (payoff) while considering the followers' anticipated responses (Yue and You 2014 and 2017).

In the sense of the non-cooperative alignment of supply chain participants, there is a need to incentivize coordination among players through adoption of supporting mechanisms in order to promote the economy of scale in bioenergy supply chains. In this process, governments as major players in energy sector can design and implement policies and measures to facilitate development of more efficient bioenergy supply and conversion (Giri et al. 2019). A common example of an intervention strategy, to promote uptake of bioenergy as an emerging technology, is a direct subsidy such as the one provided to electronic car manufacturers to compensate their R&D investments (Nielsen et al. 2019). Policies for promoting renewable energy are mainly in form of economic or regulatory incentives. Economic policies could be in form of incentives given for generating renewable energy or penalties imposed on using/generating fossil fuel-based energies. In this regard, Ghani et al. 2018 proposed a decision support system to formulate the trade-off between bioenergy incentives and emission penalties in ensuring attractive profits for participants in biomass supply chains (suppliers, logistics firms, and energy generation facilities) aiming at decreasing GHG emissions. Simsek and Simsek 2013, pointed that essential criteria to assess effectiveness of incentive mechanisms in increasing the share of bioenergy in energy mix, ensuring low-cost bioenergy generation, reducing consumer energy prices, improving the supply-demand balance in energy sector, and being compatible with other regulatory mechanisms. Examples of incentive mechanisms related to renewable energy include feed-in-tariffs, obligatory quotas and green certificates, tax exemptions and tax deductions, tender incentives, and investment incentives. A summary of the common governmental policies and incentives for promotion of bioenergy are presented in Several researchers investigated the influence of government incentives on reducing the adverse environmental impacts of energy generation and improving more sustainable practices (Nielsen et al. 2019; Simsek and Simsek 2013; Azevedo et al. 2019). Azevedo et al. 2019, reviewed the literature about the role of biomass, as a renewable source of energy, to elevate the sustainable energy agenda. They emphasized the impact of government incentives, in comparison with other solutions, to stimulate bioenergy conversion. In addition, several researchers investigated various renewable energy policies, including those of bioenergy, and compared their outcomes. Abolhosseini and Heshmati provided a comparison between feed-in-tariffs and tax incentives as two common ways, in which governments finance renewable energy development programs. In another study, concessional government lending and non-repayable subsidies were compared with the case of no governmental support (Chebotareva et al. 2020). Hafezalkotob 2018 provided a comparative analysis of direct and indirect schemas of governmental interventions. It was concluded that the bioenergy stimulation is a multidimensional problem involving different stakeholders including the government, consumers, suppliers, and the environment, with conflicting preferences.

Several articles investigated the renewable energy policies of different countries to benchmark the best governments' approaches and strategies. For instance, Pablo-Romero et al. 2013, indicated in their research that despite providing many supportive measures for generating and use of solar energy in Spain (such as tax incentives, non-refundable grants and favorable lines of finance), the supports are still insufficient, and alternative motivations are needed to improve efficiency and economy of scale.

While most researchers investigated the incentive policies for renewable energy generation and analyzed their impact, there are also studies that particularly focused on the government policies for promotion of bioenergy development. Ohimain 2013, reviewed the Nigerian government's biofuel policies and pointed out that technology transfer incentives and opportunities had been widely ignored by policy makers in this area. Ericsson et al. 2004, investigated bioenergy supporting policies in Finland and Sweden. Government's measures to support bioenergy in Finland and Sweden included R&D support, investment grants, tax reduction, and subsidies. Reviewing the literature revealed that one of the most common governments' incentives are tax relieves in which governments offer a flat-rate tax reimbursement per each unit of bioenergy generated (Sameeroddin et al. 2021). Flexible tax incentive schemes were also proposed proportional to bioenergy plant capacity, whereas higher rates of incentives are provided to smaller plants to compensate their lower economies of scale (Karimi et al. 2018).

One of the main challenges faced in bioenergy policy design and implementation is the prioritization of stakeholders eligible to receive governments' incentives. Wang and Watanabe 2016 evaluated various incentive structures provided for farmers, distributors, and biomass power plants. They revealed that although all incentive structures create some levels of stimulation in biomass supply and stakeholders' profit, incentivizing farmers could remarkably enhance social welfare and uptake of bioenergy.

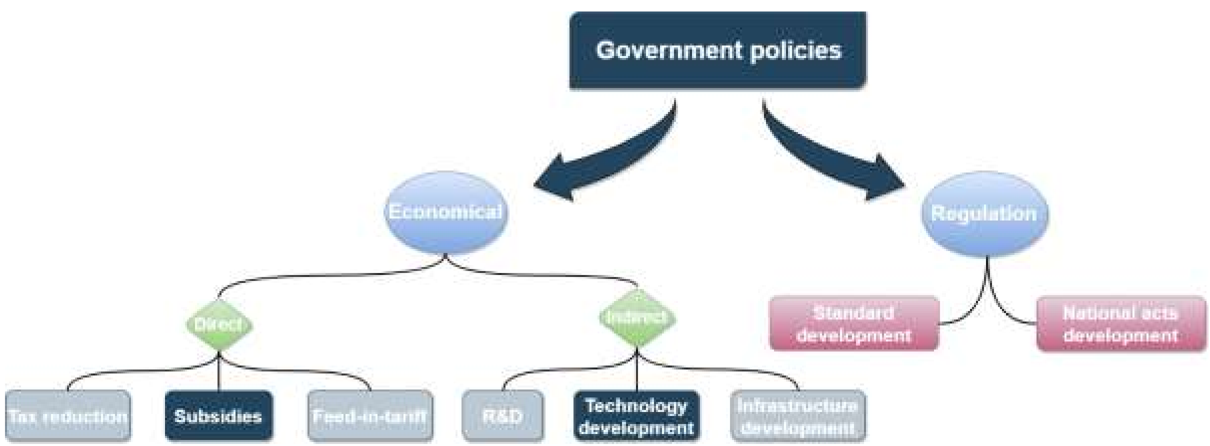



**Figure 4.1** A taxonomy of governmental policies in bioenergy development

In the light of the above review, several types of government intervention were identified for promotion of bioenergy (as presented in Figure 4.1). Therefore, it is necessary to establish a systematic approach for comparison of the outcomes of such government intervention policies. Such a comparison shall be carried out across the supply chain of bioenergy to investigate the impact on involved stakeholders.

In doing so, this study aims at investigating two of the widely practiced government's incentive policies in promoting the adoption of bioenergy, particularly in case of small and remote (off-grid) communities exhibiting low economies of scale. The paper analyzes the impact of direct and indirect incentives from the government on bioenergy development as well as coordination and profitability of biomass supply chain's stakeholders. We focus on subsidies (as an example of direct support) and technology development funds (as an example of indirect incentives) as mainstream bioenergy incentive polices in Canada. To the best of our knowledge, this study is a first attempt towards the formulation, comparison, and analysis of alternative government's incentive pathways focusing on enhancing the coordination of stakeholders in biomass supply chains for enhanced cost efficiency. The modeling and formulation of biomass supply chain is based on consideration of alternative power structures among the participating parties (Vazifeh et al. 2021). The communities, as energy convertors, initiate the demand for bioenergy and thus play a leadership role in the Stackelberg game, whereas the suppliers of biomass act as followers, responding to the above demand. The supply chain is coordinated through distribution channels, represented by hubs to facilitate the process of biomass ordering, collection and transportation to communities. The hubs will also act as followers in the supply chain, responding to communities' demand. For each player, a decision model is adopted integrating the government interventions as depicted in Figure 4.2. In this sense, the main novelties of this study can be summarized as 1) Integration of government's bioenergy incentives in coordination of biomass supply chains; 2) Formulating a Stackelberg (leader-follower) game to represent the coordination problem in biomass supply chain; 3) Adopting a bi-level (nonlinear) programming approach as a solution approach to the above hierarchical; and 4) Implementing the proposed approach in a real case study of remote (off-grid) communities in Canada.

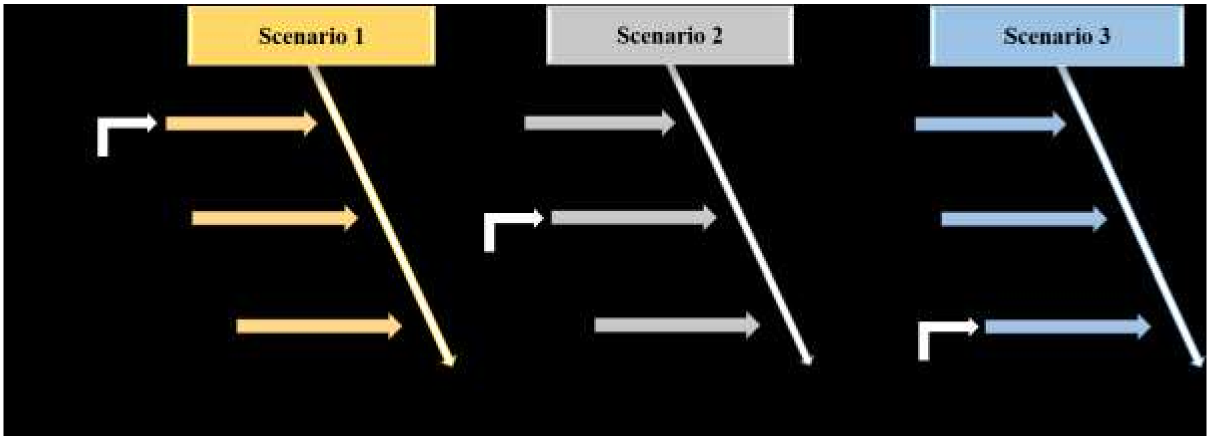


**Figure 4.2** Schematic representations of alternative incentive scenarios

The remaining of the paper is organized as follows. In the section 2, problem description and model formulation are provided. Section 3 presents the case study. Section 4 is devoted to analysis of the results. Finally, section 5 discusses concluding remarks and avenues for future research.

## 4.2 Methodology

In this study, two mainstream government intervention policies in biomass supply chains are investigated. First, a direct incentive approach, in which government offers a direct payment to supply chain's participants encouraging them to collaborate as a member of the supply chain. The government's subsidy support- which is one of the most common support mechanisms- is selected as a representative example of this approach. Second, an indirect incentive approach, in which government provides funds to elevate capacities of supply chain members. Technology development is chosen as a representative example of this approach, which indirectly assists in increasing bioenergy share in energy mix by boosting biomass harvesting and bioenergy generation capacities. As the aim of governments is to stimulate bioenergy development using these incentives, it is crucial to analyze efficiency and performance of such intervention policies.

In doing so, it is essential to formulate decision problems of participants across bioenergy supply chains, reflecting on their conflicting objectives, to investigate the impact of incentive policies on performance of each party as well as the whole supply chain. Game theory has been explored as a means of formulating biomass supply chains and their hierarchical decision problems (Cachon G. P., 2003). A bioenergy supply chain game structure follows the sequence of actions of participating members. Thus, a Stackelberg game, which is a non-cooperative leader-follower game, could well represent sequential decisions in biomass supply chains (Wang and Watanabe 2016). Such a formulation aims at identifying a set of equilibrium solutions reflecting the trade-off among objectives of the supply chain players. In a Stackelberg game, the leader has a first mover advantage, and thus, can anticipate the response of other parties (followers) in the game. In a biomass supply chain, conversion facilities are the ones that initiate the demand for bioenergy, and thus are assuming a leader role by announcing their intention and demand for bioenergy generation. The other players (such as suppliers of biomass) will respond to this potential demand and will adjust their supply quantities and prices of biomass (Vazifeh et al. 2021). Characteristics of leader-follower decisions in biomass supply chains and their corresponding equilibrium values have been reported in the literature under a single-period planning horizon (Yue and You 2017). However, in reality, interactions of supply chain members could create interdependent planning periods. For example, participants could end up keeping a reasonable amount of biomass inventory to reduce the risk of shortages in between two ordering periods (Mafakheri et al. 2020). In this sense, this paper proposes a multi-period Stackelberg game adopted to formulate biomass supply chains. In this formulation, biomass inventories are incorporated as the state variables representing the transition between consecutive periods.

In this paper, incentives are incorporated in form of coefficients (rates) into payoff (objective) functions of the players such that to reflect the type and target of the incentives. This study provides a novel bi-level programming approach for comparative analysis of the effectiveness of alternative incentive mechanisms in promoting bioenergy supply and utilization. In case of direct incentives, we have the following scenarios:

1. Suppliers' incentivization, in which government offers an incentive rate for each unit of biomass sold to the hubs.
2. Hubs' incentivization, in which government offers an incentive rate for each unit of biomass sold to the communities.
3. Communities' incentivization, in which government offers an incentive rate for each unit of generated energy from biomass.

In case of indirect incentives, the government supports biomass supply chain participants by investing in their required infrastructure and technology. This helps expand the capacity of biomass supply and bioenergy generation. In this category of incentives, we have the following scenarios:

1. Supply capacity improvement, in which the government provides facilities, and required tools to elevate the capacity of suppliers.
2. Bioenergy conversion capacity improvement, in which the government provides support for technologies and infrastructures that improve bioenergy generation capacity at the communities.

Considering the above scenarios, the formulation of biomass supply chains with integration of direct and indirect incentive policy schemas will be discussed in the following section.

## 4.3 Model Formulation

In this section, the optimization problems of players in a biomass supply chain are formulated. In all scenarios, communities, as the point of demand, play a leader role in the Stackelberg game representing biomass supply chains, while suppliers and hubs, responding to demand, will follow. Since the problem is not symmetric and the upper-level decision maker (leader) can anticipate the lower level (follower) decision maker's responses, we formulate the supply chain decision making process using a bi-level programming (Sinha et al. 2018). This approach is applicable for modelling decision making problems with hierarchical structures (Lv et al. 2008). In a bi-level Stackelberg problem, the goal is to reach to a trade-off among objective functions of all players. To encourage hubs and communities to elevate their order quantities, biomass purchasing and ordering prices will be discounted accordingly. Such a quantity discount (Mafakheri et al. 2020) transforms participants' decision problems into a Non-linear Bi-level problem (NLBP).

Ben-Ayed and Blair 1990 proved that bi-level problems are NP-hard. To address this issue a complex bi-level problem can be converted into a simpler single level optimization problem (Sinha et al. 2018). As later shown, in this study, the lower-level decision problem is a convex one (Vazifeh et al. 2021). Thus, we can replace the lower-level optimization problem with its equivalent set of Karush–Kuhn–Tucker (KKT) conditions and transform the bi-level optimization problem to a single level one.

In order to investigate the impact of government incentive policies on the performance of biomass supply chains, the incentive mechanisms will be incorporated into the objective functions of supply chain members (including direct and indirect schemas) (Vazifeh et al. 2021). This will be followed by exploring the analysis of the results obtained under each incentive scenario. The decision models and their details are provided in the following sections with the descriptions of parameters and decision variables provided in Appendix 4.1.

### 4.3.1 Direct Scheme

In order to evaluate the impact of direct incentive payments to biomass supply chain participants, three scenarios are considered: (i) Communities' incentive scenario, (ii) suppliers' incentive scenario, (iii) hubs' incentive scenario. The incentive provided at each echelon of the biomass supply chain is a function of (proportional to) quantities exchanged. Initial units receive higher levels of incentive to compensate lower economies of scale. Once the biomass exchange quantities increase, the higher economy of scale triggers a shrink in the level of support provided by incentives. The rationale behind such mechanisms is that incentives are designed to foster saturation of bioenergy in the energy mix. Once the bioenergy share increases, incentives shall start to diminish gradually, and removed at full saturation. The objective functions of players receiving the incentives are formulated accordingly in the following subsections:

- ***Communities' incentive scenario***

The objective function of communities reflects their aim at minimizing the cost of energy conversion. To incentivize communities, government pays a rate payment of $\lambda_j^t$ for each unit of bioenergy generated by community '$j$' at time '$t$', as presented in Equation (4.1). The incentive payment is considered as a negative value in communities' objective function (representing an income). The rate is incorporated from a range of values to assess the impact of varying incentive levels on the performance of biomass supply chains:

$$Min\ F_1 = \sum_j \sum_t \left( \sum_k y_{kj}^t\ B_{kj}^t \right) + I_j^t\ a_j + \left( LB_j - \lambda_j^t \right) * \ z_j^t + \ LD_j * (D_j^t - \ z_j^t) \quad (4.1)$$

Where, the value of $\lambda_j^t$ is a function of the quantities exchanged between hubs and communities (Eq. 4.2):

$$\lambda_j^t = \lambda\,(1 - \frac{z_j^t}{D_j^t}) \tag{4.2}$$

- ***Suppliers' incentive scenario***

The suppliers' objective function reflects their desire to maximize profit. Therefore, their objective function consists of the revenues from selling biomass to hubs minus costs. In the suppliers' incentives scenario, a supplier '$i$' receives an incentive rate payment of $\gamma_i^t$ for each unit of biomass they sell to the hubs at time '$t$', as presented in Equation (4.3). Descriptions of parameters and symbols used in equations related to this scenario are provided in Appendix 4.2. A range of incentive rates are incorporated to evaluate the influence of this support mechanism on performance of biomass supply chains:

$$Max\ F_2 = \sum_i \{ \sum_t [(\sum_k X_{ik}^t\ (P_{ik}^t + \gamma_i^t)) - hs_i\, S_i - H_i\, IS_i^t - \sum_k X_{ik}^t\ T_{ik} ] \} \tag{4.3}$$

Where, $\gamma_i^t$ is a function of quantities exchanged between suppliers and hubs:

$$\gamma_i^t = \gamma(1 - \frac{\sum_k X_{ik}^t}{S_i}) \tag{4.4}$$

- ***Hubs' incentive scenario***

The hubs also aim at maximizing their profit, which is calculated by subtracting their costs from their collected revenue. To incentivize hubs, the government pays an incentive rate payment of $\beta_k^t$ for each unit of biomass sold by a hub '$k$' to communities at time '$t$', as presented in Equation (4.5). Again, a range of incentive rates are considered to investigate their influence on performance of biomass supply chains:

$$Max\ F_3 = \sum_k \{ \sum_t [(\sum_j y_{kj}^t\ (B_{kj}^t + \beta_k^t)) - \sum_i X_{ik}^t\ P_{ik}^t - Hc_k\, h_k^t] \} \tag{4.5}$$

Where, $\beta_k^t$ is a function of quantities purchased from suppliers and sold to communities:

$$\beta_k^t = \beta\,(1 - \frac{\sum_j y_{kj}^{t-rp}}{h_k}) \tag{4.6}$$

#### 4.3.2 Indirect Scheme

In case of indirect incentives, government supports the development and operation of a biomass supply chain by providing funds for required infrastructure and technology to increase the capacity of biomass supply (at source) and bioenergy generation (at communities). Two schemes are considered under this category of incentives explained in the following sections:

- ***Suppliers' capacity increase policy***

The effect of government support in increasing suppliers' capacity, on biomass supply chain participants' objective functions and their performance are examined. Here the government's support is dedicated in providing required infrastructure to increase the capacity of suppliers' biomass harvesting. Various levels of support (ς) are examined to investigate the impacts of this policy:

$$Max\ F_2 = \sum_i \{ \sum_t [(\sum_k X_{ik}^t\ P_{ik}^t) - hs_i\, S_i * (1 + \varsigma) - H_i\, IS_i^t - \sum_k X_{ik}^t\ T_{ik} ] \} \quad (4.7)$$

- ***Bioenergy generation's capacity increase policy***

The effect of government support in increasing the capacity of biomass-based electricity generation on objective functions and performance of supply chain participants are also examined. Various levels of government's support to increase communities' bioenergy generation capacities indicated by ($\tau$) are examined to investigate the impacts this policy. Equation (4.8) presents the objective function of communities with integration of this indirect incentive:

$$Min\ F_1 = \sum_j \sum_t \left( \sum_k y_{kj}^t\ B_{kj}^t \right) + I_j^t\ a_j + LB_j * z_j^t * (1 + \tau) + LD_j * (D_j^t - z_j^t * (1 + \tau)) \quad (4.8)$$

In the light of the above incentive mechanisms, Figure 4.3 provides the modeling descriptions of alternative incentive scenarios.

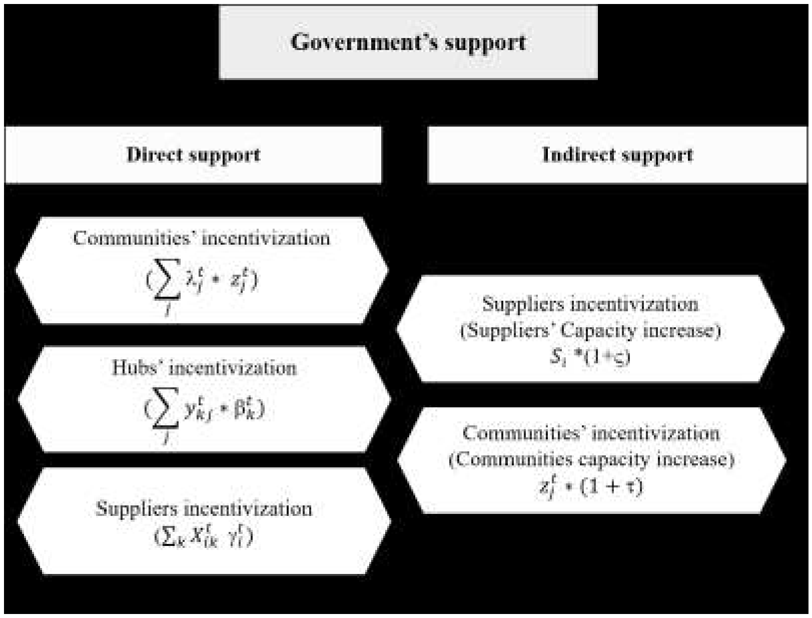



**Figure 4.3** Overall view of problem description and model formulation of all scenarios

## 4.4 Case Study

To demonstrate the applicability of the proposed game-theoretic policy analysis approach, the case study of a bioenergy supply chain for three northern Quebec communities of Kangiqsujuaq, Salluit, and Ivujivik in Nunavik region is explored. These communities are isolated, and off-grid located by the Hudson strait, as shown in Figure 4.4. Energy for residents of these communities is most often generated from diesel. These communities are among the coldest regions of Canada and highly rely upon diesel deliveries to ensure their needed heat and power, particularly during winter months (NRC 2017) when residents of these communities face high costs for space heating (Stephen et al. 2016). Therefore, utilizing biomass as a source of energy will benefit these communities to have access to an alternative type of energy, which is cheaper, cleaner, and more available.

The role of governments' policies in fostering biomass development projects in remote areas is crucial because of the small scale of demand (lack of economies of scale) as well as expected contribution of bioenergy to the bioeconomy adoption in these communities by creating local jobs opportunities and enhancing community resilience in the face of climate change. Consequently, by providing support to bioenergy projects, and subsequently, to stakeholders of bioenergy value-chains, the governments could contribute to reducing the need for fossil fuels use, increasing energy security of communities and enhancing environmental protection.


**Figure 4.4** Schematic map showing the locations of case study communities.

There are different sources of biomass including plants, animal manure, agricultural residues and forestry and wood processing residues. In this study, wood pellets are chosen as the preferred type of biomass as they are denser with higher energy contents, have lower moisture content, and are more convenient for storage and transport in comparison with other types of biomasses (Peksa-Blanchard et al. 2007). In this case study, six suppliers and two hubs have been considered to form biomass supply chain channels providing biomass for electricity generation in these communities. The superstructure of this supply chain is presented in Figure 4.5. It shall be mentioned that we have chosen three communities to provide a diverse geographical coverage, with representative communities from eastern, western, and northern part of the Nunavik region. Each community is provided with at least a minimum choice of two suppliers. Thus, we have considered six suppliers for these three communities. In addition, two hubs are considered corresponding to the existing alternative logistics pathways from Labrador Sea and from Hudson Bay.

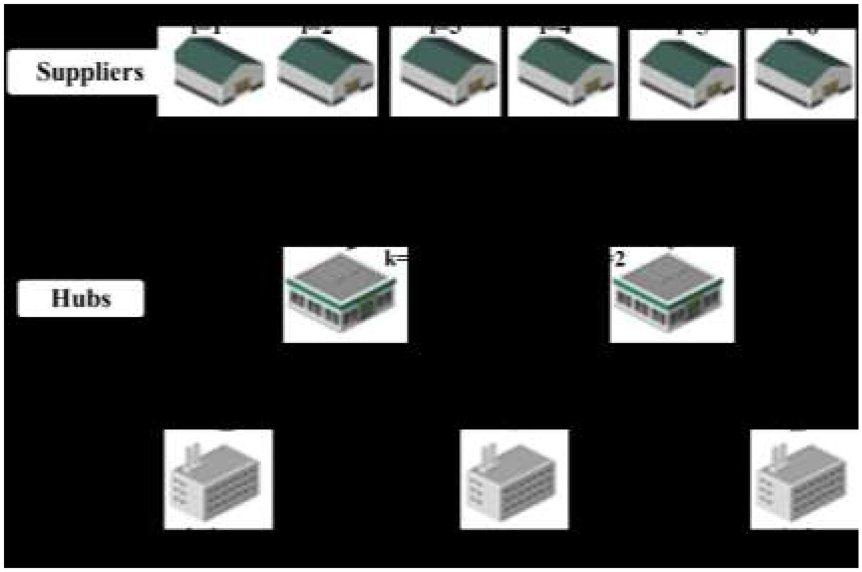



**Figure 4.5** Schematic representation of the case study biomass supply chain.

## 4.5 Results and Discussion

- **Results analysis for direct incentives**

The equilibrium results obtained from solving NLBP problem discussed in section 2 based on a flat (independent of the quantities) direct incentive rate are discussed and evaluated in this section, where $\lambda_j^t = \lambda$, $\beta_k^t = \beta$, and $\gamma_i^t = \gamma$. The equilibrium values of objective functions for players in different levels of communities', suppliers', and hubs' incentive rates are presented in Table 4.1 to 4.3. To conduct a sensitivity analysis, the communities' incentive rate (λ) was differed from 0 to 0.05 ($/kWh), the suppliers' incentive rate of (γ) was changed from 0 to 0.25 ($/kg), and the hubs' incentive rate (β) was varied between 0 to 0.25 ($/kg).

**Table 4.1** The equilibrium values of players' objective functions ($) with direct flat-rate incentivization of communities

| Participants | λ=0 | λ=0.01 | λ=0.02 | λ=0.03 | λ=0.04 | λ=0.05 |
|---|---|---|---|---|---|---|
| **Suppliers** | 322,900 | 319,600 | 322,700 | 318,900 | 322,300 | 322,900 |
| **Hubs** | -60,773 | -59,416 | -60,574 | -56,911 | -62,045 | -60,733 |
| **Communities** | -1,008,500 | -940,880 | -877,140 | -810,950 | -743,770 | -680,050 |

**Table 4.2** The equilibrium values of players' objective functions ($) with direct flat-rate incentivization of suppliers

| Participants | γ=0 | γ=0.05 | γ=0.1 | γ=0.15 | γ=0.20 | γ=0.25 |
|---|---|---|---|---|---|---|
| **Suppliers** | 322,900 | 437,700 | 549,100 | 665,600 | 778,800 | 897,300 |
| **Hubs** | -60,773 | -60,852 | -59,993 | -59,165 | -57,891 | -63,111 |
| **Communities** | -1,008,500 | -1,008,300 | -1,006,600 | -1,010,200 | -1,009,800 | -1,008,500 |

**Table 4.3** The equilibrium values of players' objective functions ($) with direct flat-rate incentivization of hubs

| Participants | β=0 | β=0.05 | β=0.1 | β=0.15 | β=0.20 | β=0.25 |
|---|---|---|---|---|---|---|
| **Suppliers** | 322,900 | 321,600 | 322,500 | 321,400 | 322,200 | 324,900 |
| **Hubs** | -60,773 | 15,630 | 91,390 | 169,600 | 247,800 | 322,500 |
| **Communities** | -1,008,500 | -1,006,600 | -1,006,200 | -1,006,600 | -1,009,200 | -1,008,900 |

The results indicate that the equilibrium values of objective function for the player receiving an incentive would improve with the incentives, while no changes would be observed in equilibrium values of other players' objective functions. The equilibrium values for the amount of bioenergy generated under each scenario are presented in Table 4.4.

**Table 4.4** The equilibrium values of bioenergy generation, $\boldsymbol{z_j^t}$ (kWh), and share of satisfied demand, $\frac{\boldsymbol{z_j^t}}{\boldsymbol{D_j^t}}$ (%) for communities under direct flat-rate incentive scenarios.

| Time period (t) | j= 1 | | j=2 | | j=3 | |
|---|---|---|---|---|---|---|
| | $z_j^t$ | $\frac{z_j^t}{D_j^t}$ | $z_j^t$ | $\frac{z_j^t}{D_j^t}$ | $z_j^t$ | $\frac{z_j^t}{D_j^t}$ |
| 1 | 0 | 0% | 0 | 0% | 0 | 0% |
| 2 | 171,900 | 100% | 190,168 | 59% | 92,800 | 100% |
| 3 | 171,000 | 100% | 306,000 | 95% | 92,300 | 100% |
| 4 | 180,900 | 100% | 306,000 | 90% | 97,600 | 100% |
| 5 | 179,700 | 100% | 306,000 | 90% | 97,000 | 100% |
| 6 | 168,700 | 100% | 306,000 | 96% | 91,100 | 100% |
| 7 | 178,700 | 100% | 306,000 | 91% | 96,400 | 100% |
| 8 | 194,800 | 100% | 306,000 | 83% | 105,100 | 100% |
| 9 | 216,800 | 100% | 306,000 | 75% | 117,000 | 100% |
| 10 | 246,900 | 100% | 306,000 | 66% | 133,300 | 100% |
| 11 | 226,500 | 100% | 306,000 | 72% | 122,300 | 100% |
| 12 | 219,900 | 100% | 306,000 | 74% | 118,700 | 100% |

The amount of generated bioenergy resulted from alternative incentive scenarios (from suppliers, hubs and communities) are identical across the range of incentives. The results indicate that the objective function of the incentive receiving party is expectedly increased. However, that increase does not reflect an increase in the amount of bioenergy generated. This is due to the fact that equilibrium solutions for biomass sourcing (from suppliers), distribution (through hubs), and conversion (in communities) are directed by the quantity discounts provided by suppliers and hubs, creating a trade-off between profit/cost and quantities at each echelon of biomass supply chain. Thus, a flat incentive, though contributes to a better payoff for the receiving members, has no influence on the share of biomass in energy mix of communities.

The result varied slightly in the case of quantity-dependent direct incentives. The equilibrium values of the players' objective functions with direct dynamic incentivization of communities are presented in Table 4.5. According to the results provided in this table, communities are the only players who have been impacted by government's supports (similar to the flat-rate scenario). Fig 4.6(a) indicates the relationship between the values of λ and the average value of $\lambda_j^t$ for each community over the course of one year. As it is shown, communities 1 and 3, receive the same average amount of support from government while the community 2 receives more incentives. This can be justified based on the mechanism behind the dynamic incentivization, which is designed to provide higher support to the entities with lower capabilities for bioenergy generation, and subsequently reducing the support when the production levels increase gradually. Similarly, the average value of $\beta_k^t$ and $\gamma_i^t$ are plotted in Fig 4.6(b) and 4.6(c). The full lists of the equilibrium values of these incentive categories are presented in Appendix 4.3.

**Table 4.5** The equilibrium values of players' objective functions ($) with direct dynamic incentivization of communities

| Participants | λ=0 | λ=0.01 | λ=0.02 | λ=0.03 | λ=0.04 | λ=0.05 |
|---|---|---|---|---|---|---|
| **Suppliers** | 322,900 | 322,400 | 320,100 | 322,600 | 320,700 | 323,000 |
| **Hubs** | -60,773 | -59,925 | -57,810 | -62,308 | -59,872 | -58,477 |
| **Communities** | -1,008,500 | -1,003,200 | -997,070 | -988,660 | -983,850 | -980,690 |

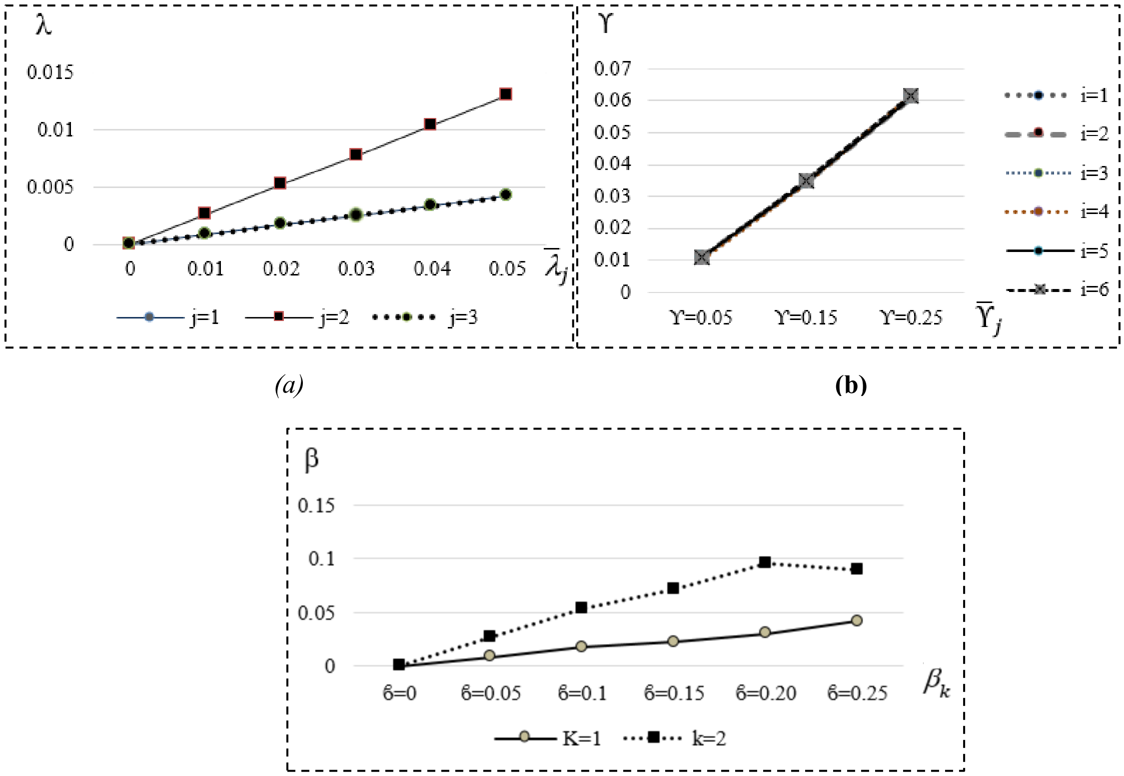



**Figure 4.6** Average rate of (a) received incentives for each community, (b) received incentives for each supplier, and (c) received incentives for each hub.

These results indicate the equilibrium values of players' objective functions with direct incentivization of communities in case of flat-rate and dynamic approach, respectively. The results revealed that despite stability of equilibrium values of players' objective functions in both approaches, the amount of incentive decreases in the dynamic incentivization approach. It means that with a dynamic incentive management, government would be able to spend less to impose motivation for bioenergy uptake in the energy mix.

**Table 4.6** The equilibrium values of players' objective functions ($) with direct dynamic incentivization of suppliers

| Participants | γ=0 | γ=0.05 | γ=0.1 | γ=0.15 | γ=0.20 | γ=0.25 |
|---|---|---|---|---|---|---|
| **Suppliers** | 322,900 | 366,600 | 467,400 | 559,400 | 621,300 | 732,700 |
| **Hubs** | -60,773 | 8,239 | 3,491 | 8,152 | 28,110 | 18,210 |
| **Communities** | -1,008,500 | -1,005,300 | -1,004,500 | -1,005,800 | -1,005,900 | -1,005,300 |

**Table 4.7** The equilibrium values of players' objective functions ($) with direct dynamic incentivization of hubs

| Participants | β=0 | β=0.05 | β=0.1 | β=0.15 | β=0.20 | β=0.25 |
|---|---|---|---|---|---|---|
| Suppliers | 322,900 | 336,400 | 336,100 | 335,900 | 335,800 | 339,300 |
| Hubs | -60,773 | -18,672 | -6,413 | -13,627 | -7,731 | -27,951 |
| Communities | -1,008,500 | -1,091,000 | -1,090,400 | -1,083,500 | -1,083,500 | -1,061,200 |

- **Results analysis for indirect incentives**

Considering a government (funding) support to increase suppliers' capacity, the equilibrium values of players' objective functions in each echelon of case study biomass supply chain are shown in the Fig 4.7. The results indicate that by increasing the suppliers' capacity to 50%, no significant change is observed in payoffs of hubs and communities. If further investment is authorized (beyond 50%), it further increases the capacity of suppliers, which leads to dramatic increases in hubs' profit and communities' cost. This result can be attributed to the trend of biomass ordering price (B). The average value of B has jumped from 0.25 ($/kg) to 0.35 ($/kg) with doubling of supply capacity, reducing the discounts given by hubs to communities. In case of equilibrium values of suppliers' objective functions, with a growing supply capacity, the profits of suppliers increase steadily. This is due to the fact that suppliers' discount (to hubs) will shrink with demand of communities being fulfilled.

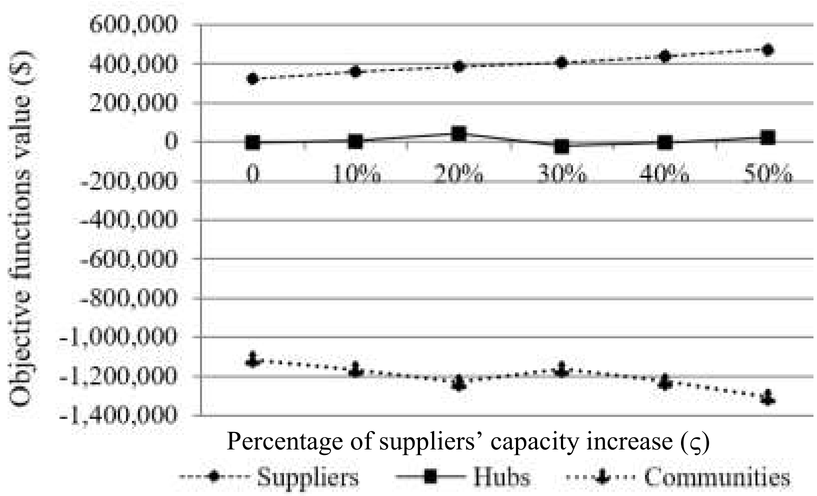



**Figure 4.7** Sensitivity analysis of players' equilibrium objective function values in case of indirect incentives to suppliers

In case of indirect incentives to suppliers, a modest increase in capacity investments will lead to an increase in annual bioenergy generation in communities. However, bioenergy generation remains steady beyond a 30% increase in capacities. As such, any investment targeting a capacity increase beyond 30% is considered an over investment (Figure 8).

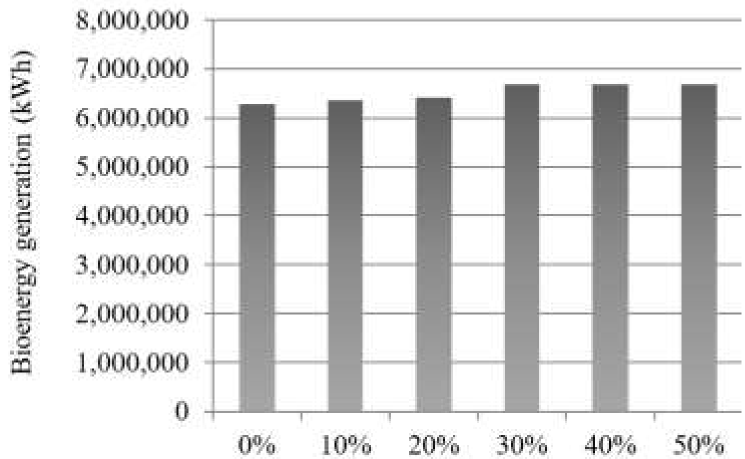



**Figure 4.8** Sensitivity analysis of bioenergy generation with respect to government's indirect incentives to suppliers (i.e., incentive at source)

A sensitivity analysis is also conducted to investigate the effect of government's indirect incentives (investments) for increasing the bioenergy generation capacities at communities. In doing so, the communities' electricity generation capacities are increased investigate the effects on equilibrium values of participants' payoffs at each level of supply chain.

The equilibrium values of objective functions for supply chain participants are recalculated assuming increasing government's investments represented by an increase in electricity generation capacities of communities. The results are shown in Figure 4.8.

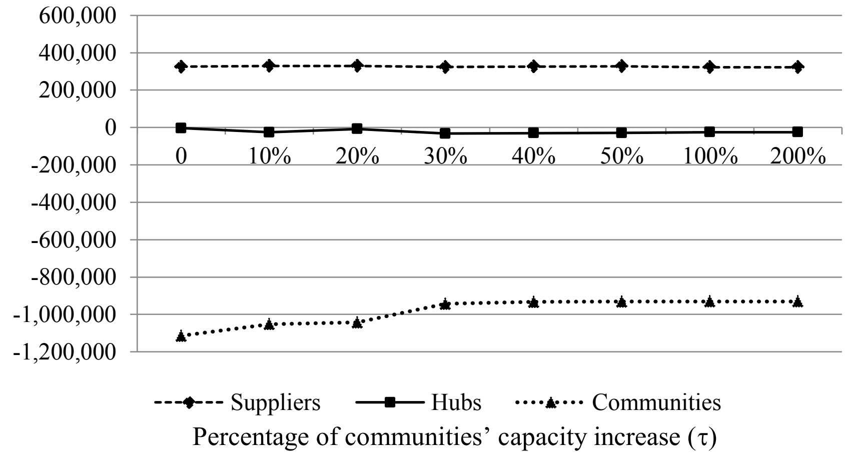



**Figure 4.9** Sensitivity analyses of players' equilibrium objective functions values to government's indirect incentive to communities

According to Figure 4.9, profits made by suppliers and hubs are not influenced by further investments in bioenergy generation capacities. However, by increasing the capacity of biomass-to-energy conversion, communities' costs decrease due to improvements in economy of scale. Although, an increase beyond 40% in generation capacities will have no further benefits (representing an over investment case).

In case of indirect incentives to communities, with a modest increase in capacity investments, the annual bioenergy generation will increase but remains steady with a capacity increase beyond 40%. Thus, scenarios beyond a 40% capacity increase present an over investment situation (Figure 4.10).

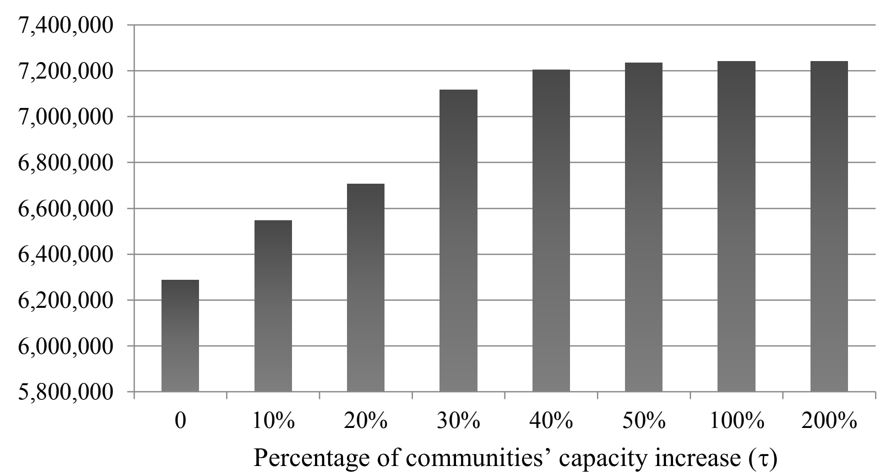



**Figure 4.10** Sensitivity analysis of bioenergy generation with respect to government's indirect incentive to communities (i.e., incentive at the end-user)

Comparing the results obtained for alternative incentivization approaches (direct and indirect), it is revealed that although providing direct incentives is a direct encouragement for the receiving participants, it is not guaranteed that these extra earnings will stimulate their production capacity. On the other side, indirect government investments towards increasing the production capacity of suppliers and conversion facilities not only improves the payoff of receiving participants but also stimulates bioenergy generation. Based on the above results, it is shown that increasing the capacity of bioenergy generation presents the highest impact on boosting the share of bioenergy in energy mix for these small communities.

## 4.6 Conclusions

In this study, government incentives, direct and indirect, to support bioenergy development were investigated. The aim was to compare the impact of direct and indirect incentives and identify the most effective and efficient ways of policy interventions in bioenergy development. Three direct incentive approaches and two indirect incentive approaches were formulated and analyzed through adopting a game-theoretic approach. We then considered a case study of remote communities in northern Quebec. To formulate the problem, we adopted a leader-follower game, Stackelberg game, where communities assumed a leadership role by presenting their willingness in switching to bioenergy to satisfy their demand for electricity (partially or fully) and thus triggering the formation of a biomass supply chain.

The results indicated that increasing direct incentives could improve the payoffs of the biomass supply chain participants receiving the incentives but have no further impact on the amount/share of bioenergy generation (beyond an established share). This can be considered as one of the main findings of this study which confirms the low efficiency of traditional incentive policies in form of subsidies.  On the other hand, indirect incentivization (up to 40%) presented a significant impact on increasing the share of bioenergy generation. Such indirect incentives could provide/ improve the necessary infrastructure for biomass supply and bioenergy conversion. Among the two indirect incentivization approaches, investment of government on bioenergy conversion facilities, as an indirect incentive, is shown to have a greater impact on increasing the share of bioenergy generation. This can be justified considering the fact that a key barrier in development of bioenergy is the capital intensity of conversion technologies requiring supporting policies at least at the initiation phase of the capacities.

This study was an attempt to provide a comparative analysis of government incentives, and their effect on coordination and performance of biomass supply chains. Although the proposed model focused on the case of northern communities of Canada, with small scale of demand and a need to coordinated supply chains, the proposed approach can be applicable for formulating the coordination of bioenergy supply chains in other jurisdictions. This requires consideration of location-specific characteristics such as type and cost of transportation, type of available biomass, and the extent of biomass supply as well as demand for bioenergy.

The result of this study not only can provide insights for the governments (in policy design) but also for all other players of biomass supply chain such as supplier and communities to plan accordingly and to ensure that decisions from all parties lead to the best overall supply chain-wide outcomes.

Future avenues of research include incorporation of biomass supply and demand uncertainties in the optimization problems of each player. Also, besides quantity discounts, other types of contract mechanisms among supply chain members can be considered such as guarantees, and revenue/cost sharing (Chakraborty et al. 2015; Mafakheri and Nasiri 2015). In addition, there are government policies targeting carbon emissions such as carbon credit or tax that can benefit bioenergy development as a replacement for diesel (Nasiri and Zaccour 2009). In this regard, the inventory of carbon emissions across the supply chain of bioenergy has to be counted including those related to logistics and transport (Nasiri et al. 2009). This is to calculate the net carbon savings that could result by switching from diesel to biomass in the target communities further justifying direct and indirect incentives. In addition, Techno-economic analysis (TEA) and life-cycle analysis (LCA) are the methods that can support such decisions (Vazifeh et al. 2023).

## Appendix 4.1

The supply chain model incorporating a direct incentive scheme for communities is presented by equations (4.9) - (4.24).

$$Min\ F_1 = \sum_j \{ \sum_t [\left( \sum_j y_{kj}^t\ B_{kj}^t \right) + (I_j^t\ a_j) + (LB_j\ z_j^t) + \ (LD_j\ (D_j^t - z_j^t))\} \quad (4.9)$$

Subject to:

$$I_j^t = I_j^{t-1} + \sum_k y_{kj}^{t-rp} - \frac{z_j^t}{fc_j} \quad , \quad I_j^0 = 0 \quad (4.10)$$

$$z_j^t \leq \min\ ( D_j^t,\ Lf_j * Z_j * 720) \quad (4.11)$$

$$I_j^t \leq Ib_j \quad (4.12)$$

$$y_{kj}^t, I_j^t, z_j^t \geq 0 \quad (4.13)$$

$$Max\ F_2 = \sum_i \{ \sum_t [(\sum_k X_{ik}^t\ (P_{ik}^t + \gamma)) - hs_i\ S_i - H_i\ IS_i^t - \sum_k X_{ik}^t\ T_{ik}\ ] \} \quad (4.14)$$

$$P_{ik}^t = P_i^u - \left(P_i^u - P_i^l\right) \frac{X_{ik}^t}{S_i} \quad (4.15)$$

$$IS_i^t = IS_i^{t-1} + S_i - \sum_k X_{ik}^t \quad , IS_i^0 = 0 \quad (4.16)$$

$$\sum_k X_{ik}^t \leq S_i \quad (4.17)$$

$$IS_i^t \leq S_i \quad (4.18)$$

$$P_{ik}^t\ , IS_i^t \geq 0 \quad (4.19)$$

$$Max\ F_3 = \sum_k \{ \sum_t [(\sum_j y_{kj}^t\ B_{kj}^t) - \sum_i X_{ik}^t\ P_{ik}^t - Hc_k\ h_k^t\ ] \} \quad (4.20)$$

$$B_{kj}^t = B_{kj}^u - \left(B_{kj}^u - B_{kj}^l\right) \frac{y_{kj}^{t-rp}}{h_k} \quad (4.21)$$

$$h_k^t = h_k^{t-1} + \sum_i X_{ik}^{t-rs} - \sum_j y_{kj}^t \quad , h_k^0 = 0 \quad (4.22)$$

$$h_k^t \leq hk(k) \quad (4.23)$$

$X_{ik}^t\ , y_{kj}^t, z_j^t \geq 0$ (Decision Variables) (4.24)

Equations (4.9) - (4.13) are representing the optimization problem of communities, which are the leader of the game. To formulate the problem as a bi-level problem, the optimization problem of the suppliers (equations 4.14 - 4.19) and hubs (equations 4.20 - 4.24) are considered as the constraints of the leaders' problem. To formulate hubs' direct incentive scenario, equation (4.20) is replaced by equation (4.5), and in case of suppliers' direct incentive scenario, equation (4.14) is replaced by equation (4.3).

**Appendix 4.2** symbols and nomenclatures

| Symbols | Definitions | Units |
|---|---|---|
| **Sets** | | |
| $\boldsymbol{I}$ | Set of suppliers | |
| $\boldsymbol{K}$ | Set of hubs | |
| $\boldsymbol{J}$ | Set of energy convertor facilities | |
| $\boldsymbol{t}$ | Time periods | |
| **Parameters** | | |
| $\boldsymbol{T_{ik}}$ | Transportation cost from supplier 'i' to hub 'k' | $/kg |
| $\boldsymbol{S_i}$ | Capacity of supplier 'i' | Kg |
| $\boldsymbol{P_i^u}$ | Biomass price of supplier 'i' without discount | $/kg |
| $\boldsymbol{P_i^l}$ | Biomass price of supplier 'i' with discount | $/kg |
| $\mathbf{hs}_{\boldsymbol{i}}$ | Biomass harvesting cost at supplier 'i' | $/kg |
| $\mathbf{H}_{\boldsymbol{i}}$ | Holding cost for supplier 'i' | $/kg |
| $\boldsymbol{h_k}$ | Capacity of hub 'k' | Kg |
| $\boldsymbol{Hc_k}$ | Holding cost at hub 'k' | $/kg |
| $\boldsymbol{B_{kj}^u}$ | Biomass ordering cost from hub 'k' to energy convertor 'j' without discount | $/kg |
| $\boldsymbol{B_{kj}^l}$ | Biomass ordering cost from hub 'k' to energy convertor 'j' with discount | $/kg |
| $\boldsymbol{Ib_j}$ | Capacity of biomass inventory at energy convertor 'j' | Kg |
| $\boldsymbol{a_j}$ | Holding cost at energy convertor 'j' | $/kg |
| $\boldsymbol{fc_j}$ | Conversion rate of biomass to electricity at energy convertor 'j' | kWh/kg |
| $\boldsymbol{Lf_j}$ | Loading factor of energy convertor 'j' | % |
| $\boldsymbol{LB_j}$ | Electricity generation cost from biomass | $/kWh |
| $\boldsymbol{LD_j}$ | Electricity generation cost from diesel | $/kWh |
| $\boldsymbol{D_j^t}$ | Demand in energy convertor 'j' at time t | kWh |
| $\boldsymbol{Z_j}$ | Capacity of electricity generation | kW |
| $\boldsymbol{rs}$ | Delivery time between supplier 'i' and hub 'k' | Month |
| $\boldsymbol{rp}$ | Delivery time between hub 'k' and energy convertor 'j' | Month |
| $\gamma$ | Government subsidy's rate to suppliers | $/kg |
| $\gamma_{\mathbf{i}}^{\mathbf{t}}$ | Government subsidy's rate to supplier 'i' at time 't' | $/kg |

| | | |
|---|---|---|
| $\bar{\gamma}_i$ | Average government subsidy's rate to supplier ‘i’ | \$/kg |
| $\beta$ | Government subsidy's rate to hubs | \$/kg |
| $\beta_k^t$ | Government subsidy's rate to hub ‘k’ at time ‘t’ | \$/kg |
| $\bar{\beta}_k$ | Average government subsidy's rate to hub ‘k’ | \$/kg |
| $\lambda$ | Government subsidy's rate to communities | \$/kWh |
| $\lambda_j^t$ | Government subsidy's rate to community ‘j’ at time ‘t’ | \$/kWh |
| $\bar{\lambda}_j$ | Average government subsidy's rate to community ‘j’ | \$/kWh |

**Decision variables**

| | | |
|---|---|---|
| $X_{ik}^t$ | Quantity of biomass delivered from supplier ‘i’ to hub ‘k’ at time ‘t’ | Kg |
| $y_{kj}^t$ | Quantity of biomass delivered from hub ‘k’ to energy convertor ‘j’ at time ‘t’ | Kg |
| $IS_i^t$ | Biomass inventory level at supplier ‘i’ at time ‘t’ | Kg |
| $h_k^t$ | Biomass inventory level at hub ‘k’ at time ‘t’ | Kg |
| $P_{ik}^t$ | Biomass price offered by supplier ‘i’ to hub ‘k’ at time ‘t’ | \$/kg |
| $B_{kj}^t$ | Biomass ordering price offered by hub ‘k’ to energy convertor ‘j’ at time ‘t’ | \$/kg |
| $I_j^t$ | Biomass inventory level at energy convertor ‘j’ at time ‘t’ | Kg |
| $z_j^t$ | Electricity generation from biomass in community ‘j’ at time ‘t’ | kWh |
| $\varsigma$ | Percentage of suppliers’ capacity increase | % |
| $\tau$ | Percentage of communities’ bioenergy generation capacity increase | % |

# Chapter 5

## A Game Theoretic Approach to Contract-based Enviro-Economic Coordination of Wood Pellet Supply Chains[4]

**Zahra Vazifeh[a], Fereshteh Mafakheri[b], Chunjiang An[c], Farid Bensebaa[d]**

*a Concordia Institute for Information Systems Engineering, Concordia University, Montreal, H3G 1M8, Canada*
*b École nationale d'administration publique (ENAP), Université du Québec*
*c Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, H3G 1M8, Canada*
*d National Research Council Canada,*
*Energy, Mining and Environment, 1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada*

## Abstract

Bioenergy has emerged as a viable alternative to fossil fuels to promote sustainable development while maintaining economic growth. Wood pellets have gained global attention due to their economic availability and increasing public demand for the different types of bioenergy. Efficient management of the wood pellet supply chain, from feedstock harvesting to bioenergy conversion, is critical to ensure competitiveness in the market and optimize the objectives of the supply chain. Supply chain coordination can play a strategic role in enhancing bioenergy generation by efficiently utilizing existing resources. This paper proposes a new contract-based coordination mechanism for pellet production supply chains and compares the results with centralized and decentralized decision-making structures. A bi-level nonlinear model with two objective economic and environmental functions is developed utilizing the concept of life cycle assessment in the Stackelberg leader-follower game to obtain the equilibrium solution. This study examines the wood pellet supply chains in three remote Canadian communities through a detailed case study. The aim is to showcase the practicality and significance of the proposed approach and its outcomes. By focusing on these communities, the study underscores the crucial role of supply chain coordination in fostering sustainable development, particularly in the context of bioenergy generation.

***Keywords–*** *Bioenergy, Wood pellet, GHG emission, Game theory, Coordination, Revenue sharing contract*

[4] This manuscript is published in the journal of Sustainable Energy Research.

## List of Symbols

| | |
|---|---|
| $I$ | Set of suppliers |
| $J$ | Set of pellet factories |
| $K$ | Set of energy convertor facilities (Communities) |
| $t$ | Time periods |
| $z_k^t$ | Electricity generation from biomass in conversion facility 'k' at the time 't' |
| $LD_k$ | Electricity generation cost from diesel |
| $f_c$ | The conversion rate of biomass |
| $P_{jk}^t$ | Wood pellet price of factory 'j' for convertor 'k' |
| $C_{con}$ | Conversion cost |
| $D_k^t$ | Demand in energy convertor 'k' at time t |
| $X_{ij}^t$ | Quantity of feedstock delivered from supplier 'i' to factory 'j' at the time 't' |
| $X_{jk}^t$ | Quantity of wood pellet delivered from factory 'j' to convertor 'k' at the time 't' |
| $P_{ij}^t$ | Feedstock price of supplier 'i' for factory 'j' |
| $CF_S$ | The carbon footprint of the upstream process |
| $CF_P$ | The carbon footprint of the midstream process |
| $CF_C$ | The carbon footprint of the downstream process |
| $C_{ha}$ | Harvesting cost |
| $CF_{de}$ | Debarking cost |
| $CF_{sa}$ | Head sawing cost |
| $CF_{tp(ij)}$ | Transportation cost of feedstock from supplier *i* to pellet factory *j* |
| $CF_{dr}$ | Drying cost |
| $CF_{mi}$ | Milling cost |

| | |
|---|---|
| $CF_{pe}$ | Pelletizing cost |
| $CF_{co}$ | Cooling cost |
| $CF_{tc}$ | Transportation cost to the location of communities |
| $CF_{con}$ | Conversion cost |
| $CF_{tf}$ | Transmission cost to the place of final customer |
| $S_i$ | The capacity of supplier 'i' |
| $S_j$ | The capacity of pellet factory 'j' |
| $NPV_C$ | Net present value of communities |
| $NPV_S$ | Net present value of suppliers |
| $NPV_P$ | Net present value of pellet factories |

## 5.1 Introduction

The rising demand for bioenergy, driven by the global transition to renewable and sustainable energy sources for mitigating climate change and reducing dependence on fossil fuels, has led to an increased interest in wood pellets as a prominent biofuel (Duarah et al., 2022). Wood pellets, being a common and widely used form of biofuel, offer a renewable energy solution that can be sustained through responsible forestry practices. Moreover, wood pellets are recognized as a cleaner substitute for conventional fossil fuels, including coal, further emphasizing their environmental advantages. They have lower emissions of greenhouse gases and other pollutants when burned, making them more environmentally friendly. Wood pellets are a type of biomass fuel produced from compressed sawdust, wood chips, or other wood residues. With a moisture content below 10% and a bulk density of approximately 650 kg m-3 (Lee et al., 2020), wood pellets offer distinct advantages in terms of storage, handling, and overall practicality compared to alternative biomass forms. Furthermore, their uniform cylindrical shape has established them as a standardized, internationally traded commodity, with an estimated global market projection of 54 million tons by 2025 (Wolf et al., 2006).

The wood pellet supply chain primarily relies on standing forest biomass as its main source of feedstock. This biomass is obtained through the harvesting of merchantable logs, which are then transported to sawmills for processing into lumber. Valuable co-products such as sawdust and wood chips are generated throughout this conversion process. Subsequently, these sawdust and wood chips are transported to pellet mills where they undergo pelletizing and classification procedures. The classification of wood pellets is determined by their properties and sources, adhering to the CAN/ISO-ISO 17225 solid biofuels standards (ISO 17225, 2021), with Grade A and Grade B representing the primary categories. Typically, Grade A wood pellets are utilized for residential or commercial heating purposes and are derived from mill residues and stem wood, whereas Grade B pellets are manufactured using a broader range of sources (ECCC, 2020). Wood pellets find application in various contexts and can be efficiently combusted in different devices depending on the intended use. The combustion of wood pellets can be effectively modeled for two broad applications: residential pellet stoves and large-scale electricity generation.

The significant challenge of high production costs in wood pellet commercialization is multi-faceted. One of the core issues involves the need to ensure cost-effective transportation of feedstock from diverse and geographically distant sources to production facilities. Simultaneously, it's essential to account for the resulting carbon emissions generated throughout the supply chain. Adding to this complexity, uncertainties surrounding critical supply chain parameters, such as the seasonality of vital primary resources for wood pellet feedstock (Mafakheri & Nasiri, 2014), introduce further intricacies.

Pricing and logistics costs of biomass are not immune to the influence of international fluctuations in fossil fuel prices (Hamelinck et al., 2005). Additionally, conflicts of interest among the diverse stakeholders involved in the supply chain introduce inconsistencies that hinder overall channel performance (Abusaq et al., 2022; Mafakheri et al., 2020). Consequently, to facilitate a swift transition towards a more environmentally sustainable fuel source, it is paramount to establish a well-coordinated and efficient wood pellet network design.

In pursuit of these objectives, a coordinated forestry-based wood pellet supply chain framework is introduced. This framework operates under a contract-based structure designed to encompass the hierarchical decision-making process. To address the intricacies of this challenge, a bi-level modeling approach is employed. Within this approach, two nested optimization problems interact, influencing each other's outcomes. The primary aim of our optimization model is dual-fold: to minimize greenhouse gas (GHG) emissions across the entire wood pellet production life cycle while simultaneously maximizing profits for all stakeholders involved. This model is instrumental in reducing the environmental footprint associated with wood pellet production and ensuring optimal benefits for participants throughout the supply chain. To achieve this, we employ a novel approach known as two-objective bi-level non-linear programming. It's important to note that even a multi-objective bi-level linear programming problem falls within the ambit of highly challenging and strongly nondeterministic polynomial-time hard (NP-hard) issues (Pakseresht et al., 2020; Zhang et al., 2023). Thus, specialized optimization tools are essential for resolution. To overcome this computational hurdle, we apply a transformation approach.

This work represents a pioneering effort, focusing on optimizing both economic and life cycle GHG emissions within the wood pellet supply chain, with a specific emphasis on non-cooperative stakeholders. Furthermore, the proposed optimization modeling framework amalgamates elements from the leader-follower game (Liu et al., 2021) and the life cycle optimization approach (García-Velásquez et al., 2023), offering a unique perspective. To validate the framework, we conduct a case study in three off-grid communities situated in northern Canada. The results are subjected to thorough analysis and are further compared against a centralized model, offering comprehensive insights.

The organization of this paper is as follows: Firstly, we provide essential background information and a concise overview of wood pellet supply chains, highlighting the challenges they entail. Next, in Section 3, we present the formulation of our mathematical model and describe the dedicated solution algorithm employed. Section 4 introduces the details of the case study conducted, outlining its methodology and key parameters. Moving on to Section 5, we present the results and analysis derived from the case study. Finally, we conclude the paper by summarizing the main findings and suggesting potential avenues for future research.

## 5.2 Background and Literature Review

Wood pellets have gained widespread popularity as an environmentally friendly energy source and have been extensively utilized in numerous countries (Nunes et al., 2016; Proskurina et al., 2019; Erlich, 2009). Consequently, scholars have directed their attention toward this sustainable energy solution, recognizing its significance and potential impact. In general, the existing literature can be classified into the following five sets, each addressing different aspects of wood pellets:

- Overview and challenges: Various studies have reviewed the benefits, challenges, and future research directions in the wood pellet supply chain (Proskurina et al., 2017; Mohammadi, 2021). These works provide a comprehensive understanding of the overall landscape, identifying key obstacles and suggesting potential avenues for improvement.
- Production: Researchers have examined the technological aspects and processes involved in the production and conversion of wood pellets (Di Marcello et al., 2017). These studies delve into the intricacies of the production methods, exploring the efficiency and effectiveness of different techniques.
- Market Analysis and Economics: Understanding the market dynamics, pricing mechanisms and economic viability of wood pellets is crucial for sustainable development. Several studies have focused on analyzing the market for wood pellets and evaluating their economic prospects (Peng et al., 2010). Such research aids in shaping effective strategies and policies to promote the growth of the wood pellet industry.
- Environmental impact analysis: Assessing and mitigating the environmental impacts associated with wood pellet supply chains is of utmost importance. Researchers have conducted studies to evaluate the environmental consequences of wood pellet production and distribution (Myllyviita et al., 2012) (Laschi et al., 2016). These works identify potential environmental risks and propose strategies for minimizing negative impacts.
- Policy and Regulation: Investigation of policy frameworks, regulations, and analysis of the impact of government policies on the development of wood pellet supply chains have been explored (Kittler, 2020). These studies shed light on the role of policy interventions in fostering the growth of the wood pellet industry while ensuring sustainable practices.

In the realm of academic literature, a limited number of studies have addressed the economic and environmental sustainability of pellet processing, as highlighted by Pergola et al. (2018), Wang et al. (2017), and Golonis et al. (2022). Despite the increasing significance of wood pellets as a renewable energy source, there remains a noticeable dearth of comprehensive studies delving into the intricate interplay between economic viability and environmental impact throughout the wood pellet supply chain. Similarly, only a few investigations have ventured into the multifaceted challenges associated with the coordination of wood pellets from the supply side to conversion or consumer regions. This evident gap in the literature underscores the necessity for a more profound and holistic understanding of the environmental and economic facets of wood pellet production and utilization.

Given the growing importance of wood pellets as a sustainable energy source, it is imperative to address these research gaps. This study seeks to bridge this void by exploring the synergies between environmental considerations and economic aspects within the context of wood pellet supply chain coordination. By doing so, we can achieve a more comprehensive understanding of the interplay between these two critical dimensions. This knowledge is not only vital for advancing the sustainability and efficiency of the wood pellet industry but also for shaping environmentally responsible energy policies and strategies that align with our overarching objectives of mitigating climate change and fostering economic development.

To evaluate the environmental performance of wood pellet production, main focus has been on life cycle GHG emissions (Gao & You, 2017). Roos and Ahlgren (2018) while considering the classification of life cycle assessment (LCA) into attributional and consequential approaches, conducted a comprehensive literature review on consequential LCA of bioenergy systems. The initial phase of the LCA process involves establishing the system boundaries, encompassing the upstream, midstream, and downstream aspects of the supply chain. Subsequent sections present a comprehensive overview of the wood pellet supply chain (Vazifeh et al., 2023), highlight existing gaps, and propose the implementation of game theoretic coordination tools as a viable solution.

### 5.2.1 Wood Pellet Supply Chains

The production process of wood pellets can be divided into three sections, namely upstream (feedstock supply), midstream (wood pellet production), and downstream (conversion), which are explained below to consider the life cycle of pellet production.

- ***Feedstock supply***

The wood pellet supply chain begins with the acquisition of raw materials, where the availability, quality, and cost of these materials play a crucial role in determining the feasibility and design of the supply chain (Lu & Rice, 2011). Generally, forestry products and by-products can be classified into five categories, including lumber, wood chips, shavings, sawdust, and barks, as shown in Fig. 5.1 (Mobini, 2015). Currently, the primary raw material used in pellet production is sawdust, which is a by-product of the sawmill industry (Obernberger & Thek, 2010). Shavings and sawdust are highly preferred as raw materials due to their small particle size, low ash content, and low moisture content. Apart from sawmill residue, wood chips also serve as a residue directly obtained from the forestry process.

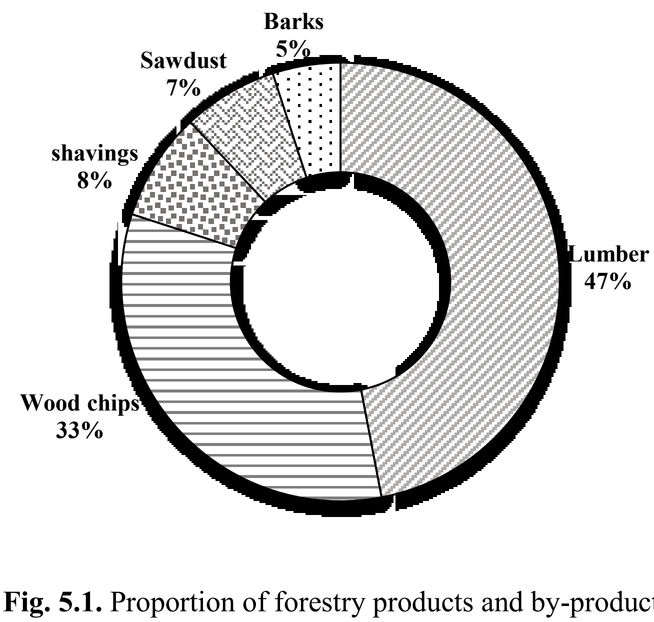



**Fig. 5.1.** Proportion of forestry products and by-products.

- ***Wood pellet production***

The wood pellet production process comprises several essential stages. Initially, raw materials such as sawdust, wood chips, or other wood residues are sourced from forestry operations, sawmill, or wood processing facilities. These raw materials undergo a meticulous processing phase to eliminate impurities like stones and metal particles. Subsequently, the processed wood material undergoes size reduction through grinding or chipping, ensuring the attainment of the desired particle size. This size reduction step is crucial for achieving uniformity and optimizing the combustion properties of the final pellets. To further enhance the quality of the pellets, the prepared wood particles are carefully dried to reduce moisture content. This drying process plays a pivotal role in improving energy efficiency and enhancing the combustion performance of the pellets. Once adequately dried, the wood particles are subjected to high-pressure compression, compacting them into dense and cylindrical pellets. This compression process often involves the utilization of a specialized pellet mill, where the wood particles are forcefully extruded through small holes in a die, resulting in the formation of pellets. In order to ensure the structural integrity of the pellets, heat may be applied during the compression process, activating the natural lignin present in the wood. This lignin acts as a binding agent, effectively holding the pellets together. Following the pelletization stage, the newly formed wood pellets are subjected to cooling and screening procedures to eliminate any fines or irregularly shaped pellets. Finally, the finished wood pellets are typically packaged in bags or bulk containers, ready for storage, transport, and distribution. It is important to note that the specific intricacies of the wood pellet production process can vary depending on factors such as the equipment used, desired pellet specifications, and the quality standards established by pellet manufacturers.

- ***Conversion***

The conversion process of wood pellets is a crucial step in the production of bioenergy. The selection of a conversion technology determines the efficiency of the process and the quality of the end product. Two common conversion technologies are used for wood pellet conversion: gasification and direct combustion. Gasification technology has a higher capital cost but provides a higher energy efficiency rate, making it an attractive option for large-scale industrial applications. Direct combustion, on the other hand, has a lower capital cost but a lower energy efficiency rate, making it suitable for smaller-scale and more localized operations. The selection of a conversion technology should take into consideration the cost-benefit analysis, the desired level of efficiency, and the scale of the operation.

### 5.2.2 Applications of Game Theory in the Coordination of Biomass Supply Chains

Applications of game theory have emerged as a valuable tool for analyzing and coordinating complex systems, including biomass supply chains. Game theory provides a mathematical framework for modeling strategic interactions among multiple stakeholders involved in the biomass supply chain, such as feedstock suppliers, biomass producers, processors, and end-users. By considering the behavior and decision-making of these stakeholders as strategic players, the game theory allows for a comprehensive analysis of their incentives, conflicts, and potential cooperation opportunities (Toktas-Palut, 2022). In the context of biomass supply chains, game theory can be applied to various aspects, including the following:

- Game-theoretic modeling of biomass supply chain coordination: Research by Vazifeh et al. (2021) proposed a game-theoretic model to analyze the coordination strategies among multiple biomass supply chain participants. The study considered factors such as pricing decisions, and quantity decisions aiming to optimize the overall supply chain performance and achieve coordination.
- Pricing and Contract Design: Gong et al. (2015) developed a game-theoretic framework to study contract design in a biomass supply chain. The research considered the interactions between the farmer (supplier) and the producer company and analyzed how contract designs affect supply chain coordination and efficiency.
- Cooperative Game Theory: Cooperative game theory has been employed to analyze cooperative behavior and coalition formations in biomass supply chains. Gao et al. (2019) proposed a cooperative game model and investigate various profit allocation methods among biomass supply chain agents. The study concludes by recommending the nucleolus and equal profit methods as the most stable profit allocation methods.
- Resource Allocation and Optimization: Research has focused on using game theory to optimize resource allocation decisions in biomass supply chains. Tang et al. (2017) proposed a non-cooperative game-theoretic model for analyzing and identifying the best resource allocation strategy for the biomass industry owner.

The literature on the applications of game theory in the coordination of biomass supply chains demonstrates the effectiveness of this approach in addressing coordination challenges, pricing mechanisms, contract design, risk management, and resource allocation. These studies highlight the importance of strategic decision-making, cooperation, and efficient coordination among stakeholders to improve the overall performance and sustainability of biomass supply chains. Existing research in the field of game theory applied to biomass supply chain coordination has predominantly focused on simpler models, neglecting the incorporation of additional crucial factors. These factors include environmental considerations and the diverse economic preferences of individuals within the supply chain. By disregarding these significant elements simultaneously, the understanding of the inherent nature of real-world biomass supply chains remains limited. To overcome this limitation, this research emphasizes the development of more comprehensive and complex game-theoretic models that effectively capture the interplay between environmental concerns and the diverse economic motivations of stakeholders. Such advancements would contribute to a deeper understanding of the dynamics and complexities involved in coordinating biomass supply chains, facilitating the formulation of more realistic and effective strategies for sustainable biomass utilization. Motivated by this knowledge gap, the objective of this research is to develop a contract mechanism that effectively coordinates the wood pellet supply chain. By managing the interactions among participating agents, the aim is to steer their actions toward the benefit of the entire supply chain (Nugroho et al., 2022). Additionally, a key focus of this research is to minimize GHG emissions throughout the life cycle of wood pellet production. By incorporating strategies to reduce GHG emissions, this study seeks to enhance the sustainability and environmental performance of the wood pellet supply chain. Through the design and implementation of this contract mechanism, the research aims to optimize both economic outcomes and environmental considerations, fostering a more sustainable and efficient biomass supply chain.

## 5.3 Methodology

In order to systematically assess the performance of the contract coordination mechanism from the emission trading point of view, its whole life cycle needs to be investigated. LCA is employed to evaluate the GHG emissions of the proposed system. A comparative LCA is adopted to evaluate the carbon intensity of wood pellet production from hardwood forestry residues. Table 5.1 summarizes the three scenarios with corresponding decision-making (DM) structures and schematic views. In the first scenario, which is a centralized channel, the environmental impact (GHG) of the wood pellet production life cycle is calculated to provide a baseline. In scenario 2, net present value (NPV) and GHGs in the case of a decentralized decision-making structure are investigated, and scenario 3 is designed to show the impact of revenue sharing and quantity discount contract coordination techniques.

**Table 5.1** Scenarios definition

<table>
<tr><th>Scenario</th><th>DM structure</th><th>Schematic view</th></tr>
<tr><td>1</td><td>Centralized</td><td>
</td></tr>
<tr><td>2</td><td>Decentralized</td><td>
</td></tr>
<tr><td>3</td><td>Coordinated</td><td>
</td></tr>
</table>

A case study of northern Canadian communities is considered to validate the proposed models. Due to the low economy of scale of bioenergy in these communities, direct combustion is selected as the conversion technology. The case study considers three Quebec northern communities in the Nunavik region. Although Canada has access to a great number of biomass resources from various sources, there is strictly no possibility of relying upon a local biomass supply in this region because the unsuitable vegetation texture of the region does not support any reliable sources of biomass. Therefore, wood pellets produced in three selected pellet mills must be imported to these communities. The mathematical modeling of the biomass supply chain problem is described in the following sections.

- ***Centralized scenario***

For a centralized scenario, the GHG of the wood pellet production life cycle is calculated to establish a baseline. Therefore, to estimate the GHG emissions for the production and conversion of 1 kg wood pellet, the open-source software, openLCA version 1.11 (openLCA, 2006) is used. This software is widely used for life cycle assessments and provides a comprehensive platform for data analysis and modeling. Data come from the Ecoinvent database (V3.6), which is a widely recognized and trusted source of life cycle inventory data. Furthermore, the consultation of peer-reviewed literature enhances the acquisition of additional data and valuable insights. To comprehensively assess the environmental impact, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methodology is utilized. TRACI considers a range of environmental factors, including energy consumption, greenhouse gas emissions, water usage, air pollution, and waste generation. By employing TRACI, a holistic evaluation of the environmental implications associated with the studied subject is achieved. For a specific reference, Table 5.2 provides an overview of the raw materials and energy requirements to produce 1 kg of dry wood pellets.

**Table 5.2** Raw materials used to produce 1kg wood pellet.

| Flow | Amount | Unit |
|---|---|---|
| electricity, medium voltage | 0.18 | kWh |
| heat, central or small-scale | 9 | MJ |
| maize starch | 0.005 | kg |
| packaging film (low-density polyethylene) | 0.002 | kg |
| sawdust | 0.57 | kg |
| hardwood shavings | 0.3 | kg |
| Water | 3.00E-05 | m3 |
| wood chips | 0.13 | kg |

- ***Decentralized scenario***

In the dynamic and fiercely competitive business environment of today, every participant within a supply chain functions as an autonomous entity, driven by the pursuit of maximizing their individual profits. Consequently, a decentralized decision-making system takes shape, where each member operates independently, often with conflicting interests. Recognizing this complex interplay of interests, the Stackelberg game emerges as a valuable and influential tool for modeling the behavior of supply chain participants. By employing the Stackelberg game, the intricate dynamics of the supply chain, characterized by varying power dynamics and conflicting objectives, can be effectively captured and analyzed. This game-theoretic approach enables a deeper understanding of the strategies and decision-making processes employed by different supply chain members, ultimately facilitating improved coordination and performance within the supply chain ecosystem. The Stackelberg game comprises two distinct decision-making levels:

the leader(s) and the follower(s). The leader, representing the upper-level problem, assumes the role of decision-maker and takes the initial action, while the follower(s) subsequently make their decisions based on the leader's choice.

In the context of this study, the upper-level problem encompasses two objective functions: economic and environmental considerations. The primary objective in the upper level involves maximizing the net present value (NPV) for the leader (as illustrated in Fig. 5.2). Adhering to the principles of the Stackelberg game, the leader possesses comprehensive information about the supply chain and holds the advantage of making decisions before others. A study by Vazifeh et al. (2021) examined power structures within the biomass supply chain of Canadian northern communities, and their findings revealed that if the conversion facilities assume the role of the leader in the supply chain, it leads to enhanced efficiency in terms of bioenergy generation and minimized side payments. Therefore, in this study, the upstream conversion facilities are designated as the leader. As the initiator and first mover in the pellet supply chain, the conversion facilities not only have the privilege of making decisions first to maximize their total NPV but also shoulder the responsibility of taking care of mitigating life cycle greenhouse gas (GHG) emissions throughout the entire supply chain. By adopting the Stackelberg game framework, this study recognizes the autonomous decision-making nature of supply chain members and employs it to examine the interplay between economic objectives, environmental considerations, and power dynamics within the biomass supply chain. Through the strategic positioning of the conversion facilities as the leader, this research aims to optimize both economic outcomes and environmental performance while effectively managing life cycle GHG emissions across the entire supply chain.

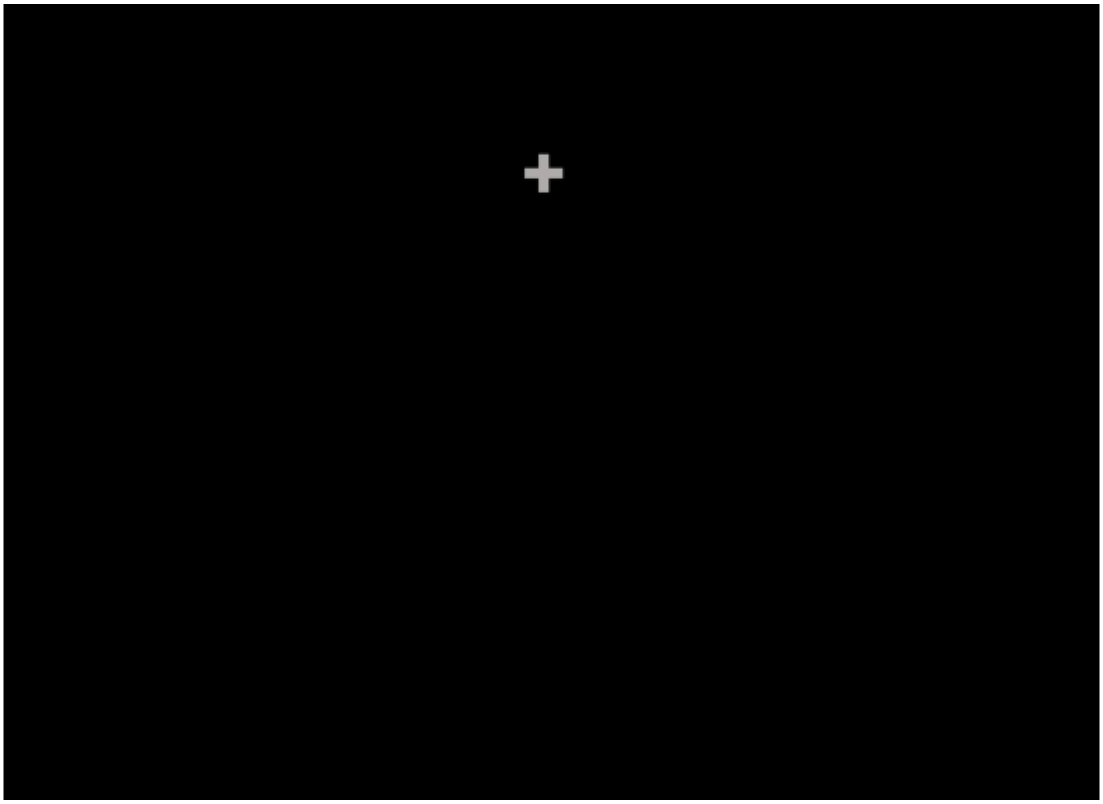


**Fig. 5.2** Structure of the proposed multi-objective bi-level model.

The leaders' objectives (upper-level) encompass maximizing the communities' NPV and minimizing the life cycle GHG emissions associated with wood pellets, as outlined in Equations 1 and 2, respectively. It is worth nothing that the communities' NPV is defined as the total profit that communities earn with replacing diesel with wood pellets as the main source of electricity generation. So, in Equation (1) is define as the cost of generating $z_k^t$ kwh from diesel (not wood pellet) minus the total cost of generation $z_k^t$ from wood pellet and subtracting the cost of generating the unsatisfied part of demand $(D_k^t - z_k^t)$ with diesel. The decision variable of the upper-level problem is $z_k^t$ , which is the kWh of electricity generation from biomass in conversion facility $k$ at time $t$. $z_k^t$ is a function of $X_{jk}^t$, the quantity of transported pellet to the location of conversion facility $k$.

$$Max\ NPV_C = \sum_k \sum_t [(z_k^t\ LD_k) - z_k^t . f_c^{-1} \left(P_{jk}^t + C_{con}\right) - LD_k\ (D_k^t - z_k^t)] \quad \text{(Eq. 5.1)}$$

$$Min\ F_{LC} = CF_S + CF_P + CF_C \quad \text{(Eq. 5.2)}$$

where $CF_S$ is the carbon footprint of the upstream (supply) process including, harvesting ($CF_{ha}$), transportation ($CF_{tr}$), debarking ($CF_{de}$), sawing ($CF_{sa}$), and transportation to the location of pellet factory ($CF_{tp}$) , Eq. (5.3). $CF_P$ is the carbon footprint of the midstream (pellet production) process including drying, milling, pelletizing, cooling, and transportation to the location of conversion facilities, which are represented by $CF_{dr}$ , $CF_{mi}$ , $CF_{pe}$, $CF_{co}$, and $CF_{tc}$, respectively in Eq. (5.4).

$$CF_S = \sum_i \sum_j X_{ij}^t \ (CF_{ha} + CF_{de} + CF_{sa} + CF_{tp\,(ij)}) \quad \text{(Eq. 5.3)}$$

$$CF_P = \sum_j \sum_k X_{jk}^t \ (CF_{dr} + CF_{mi} + CF_{pe} + CF_{co} + CF_{tc(jk)}) \quad \text{(Eq. 5.4)}$$

Meanwhile, due to limited information, the supplier and pellet factory take actions after the converter and only tend to care about their own profit. Thus, after the realization of the leader's decisions, the followers will react accordingly to optimize their own objective, which is maximizing followers' total NPV (Eq. 5.5 - 5.6). The NPV for the pellet factories is calculated by deducting the revenue generated from selling pellets to communities from the overall cost of pellet production. This cost comprises several components, namely $C_{dr}$(cost of drying), $C_{mi}$ (cost of milling), $C_{pe}$ (cost of pelletization), $C_{co}$ (cost of cooling), and $C_{tc}$ (cost of transportation to the communities' location). In a similar fashion, the NPV for the suppliers is determined by subtracting the revenue obtained from selling feedstock to pellet factories from the total cost of feedstock preparation. This cost encompasses several elements, including $C_{ha}$ (cost of harvesting), $C_{tr}$ (cost of raw material's transportation for preprocessing), $C_{de}$ (cost of debarking), $C_{sa}$ (cost of head sawing), and $C_{tp}$ (cost of transportation to the pellet factories' location).

The decision variables of the lower-level side are $P_{ij}^t$ (feedstock price from supplier *i* to pellet factory *j* at time *t*), $P_{jk}^t$ (wood pellet price transported from pellet factory *j* to community *k* at time *t*) pellet and $X_{ij}^t$ (the quantity of feedstock transported from supplier *i* to pellet factory *j* at time *t*). The price of wood pellets and the quantity of required biomass feedstock are determined by the pellet factory based on the quantity of wood pellets ordered by conversion facilities. Subsequently, suppliers make decisions regarding the price of feedstock.

$$Max\ NPV_P = \sum_j \{ \sum_t [(\sum_k X_{jk}^t \ P_{jk}^t) - X_{ij}^t \ (P_{ij}^t + C_{dr} + C_{mi} + C_{pe} + C_{co} + C_{tc})]\} \quad \text{(Eq. 5.5)}$$

$$Max\ NPV_S = \sum_i \{ \sum_t [(\sum_j X_{ij}^t\ P_{ij}^t) - \alpha_m X_{ij}^t\ (C_{ha} + C_{tr} + C_{de} + C_{sa} + C_{tp})]\} \quad \text{(Eq. 5.6)}$$

Constraints of the model are presented in Eq. 5.7 - 5.13. Eq. (5.7) demonstrates that at time 't' the quantity of ordered feedstock cannot exceed the capacity of the suppliers. Similarly, Eq. (5.8) considers the capacity of wood pellet plants. Eq. (5.9) indicates that the electricity generation in kWh from wood pellets cannot exceed the quantity of wood pellets purchased by the conversion facilities, multiplied by the conversion rate of wood pellets to electricity ($\mathrm{f_c}$). Eq. (5.10) considers the electricity demand of the communities and the capacity of electricity generation plants. It ensures that the electricity generation in kWh does not exceed the lower value between the communities' electricity demand and the capacity of the generation plants. Eq. (5.11) - (5.13), ensure that the variables cannot have negative values in the solution space.

$$\sum_j X_{ij}^t \leq S_i \quad \text{(Eq. 5.7)}$$

$$\sum_k X_{jk}^t \leq S_j \quad \text{(Eq. 5.8)}$$

$$\sum_k z_k^t \leq \sum_k X_{jk}^t\ \mathrm{f_c} \quad \text{(Eq. 5.9)}$$

$$z_k^t \leq \min\ (D_k^t,\ f_c^{-1} * Z_j * 720) \quad \text{(Eq. 5.10)}$$

$$X_{ij}^t \geq 0 \quad \text{(Eq. 11)}$$

$$X_{jk}^t \geq 0 \quad \text{(Eq. 12)}$$

$$z_k^t \geq 0 \quad \text{(Eq. 13)}$$

- ***Coordinated scenario***

In the coordinated scenario, a contract mechanism is designed using game theory to model the strategic interactions between different parties in the wood pellet supply chain. By considering the incentives and actions of all parties, contracts can help to align the interests of all parties and create a stable and efficient supply chain. In this study, revenue sharing (Cachon & Lariviere, 2005) and quantity discount (Weng & Wong, 1993) contracts coordination mechanism are used to encourage collaboration between suppliers, pellet factories and conversion facilities. Revenue sharing allows for profits to be shared between the two parties, creating an incentive for pellet producers to provide high-quality wood pellets and for conversion facilities to purchase it at a fair price. This helps to reduce transaction costs and promote long-term relationships between the parties involved. Quantity discount contracts, on the other hand incentivize customers to increase their order size or volume by providing cost savings as the quantity increases. By coordinating the volume and price of purchases, the parties involved can optimize their operations and improve their bottom line. Under these contracts, the conversion facility can obtain wood pellets from the pellet factory at a discounted price while as a compensation, the conversion facility must share his revenue with the pellet factory at a certain revenue-sharing rate, say r ($0 \leq r \leq 1$), where r represents the portion of the revenue to be shared with the pellet factory. The mathematical formulation of this model is presented below.

$$Max\ NPV_C = (1-r).\sum_{k,t} \left[ (z_k^t . LD_k) - Z_k^t . f_c^{-1} \left( P_{jk}^t + C_{con} \right) - LD_k . (D_j^t - z_k^t) \right] \quad \text{(Eq. 5.14)}$$

Where $P_{jk}^t$ a function of the quantity of wood pellets is shipped to the location of the conversion facility and is dependent on the portion of demand that is satisfied in the specific period.

$$P_{jk}^t = P_j^u - \left( P_j^u - P_j^l \right) \frac{X_{jk}^t}{D_j^t} \quad \text{(Eq. 5.15)}$$

If we define $R_k^t$ as the total revenue of the conversion facility $k$ in time $t$, the objective function of the pellet factory is presented in Eq. (5.16).

$$Max\ NPV_P = \sum_{j,t} \sum_k [(R_k^t . r).(X_{jk}^t . P_{jk}^t)] - X_{ij}^t . (P_{ij}^t + C_{dr} + C_{mi} + C_{pe} + C_{tc})\} \quad \text{(Eq. 5.16)}$$

We will examine another quantity discount contract between suppliers and pellet factory. Therefore $P_{ij}^t$ is defined as Eq. (5.17). To encourage the wood pellet factory to purchase more, the suppliers offer a quantity discount price on each order.

$$P_{ij}^t = P_i^u - \left( P_i^u - P_i^l \right) \frac{X_{ij}^t}{S_i^t} \quad \text{(Eq. 5.17)}$$

The objective function of suppliers and the constraints in this scenario remain unchanged (Eq. 5.6 - 5.13).

## 5.4 Case Study

To assess the viability of the designed model, a comprehensive case study in three remote Canadian communities: Kangigsujuaq (KA), Salluit (SA), and Ivujivik (IV) is considered. These communities present a distinctive geographical context from the standpoint of supply chain dynamics, as their access is solely through water routes. Specifically, they can be reached either via the Hudson Bay from the east or the Labrador Sea from the west (as depicted in Fig. 5.3).

The purpose of this case study was to evaluate the efficacy of our proposed models in the context of these remote Canadian communities. By examining the adoption and utilization of wood pellets within the communities, we sought to determine the extent to which wood pellets can serve as a viable alternative for meeting their electricity and heat requirements. This analysis took into consideration various factors, such as the availability and accessibility of wood pellets, transportation logistics, community-specific energy demands, and environmental considerations.

By focusing on these unique locations and their distinct supply chain characteristics, our case study aimed to provide valuable insights into the feasibility and effectiveness of wood pellets as a sustainable energy solution for remote communities that rely on water routes for access. The findings of this study contribute to the broader understanding of the practical applications and potential benefits of wood pellets as an alternative energy source in similar remote settings. The parameters pertaining to the case study and their references are presented in Table 5.3.

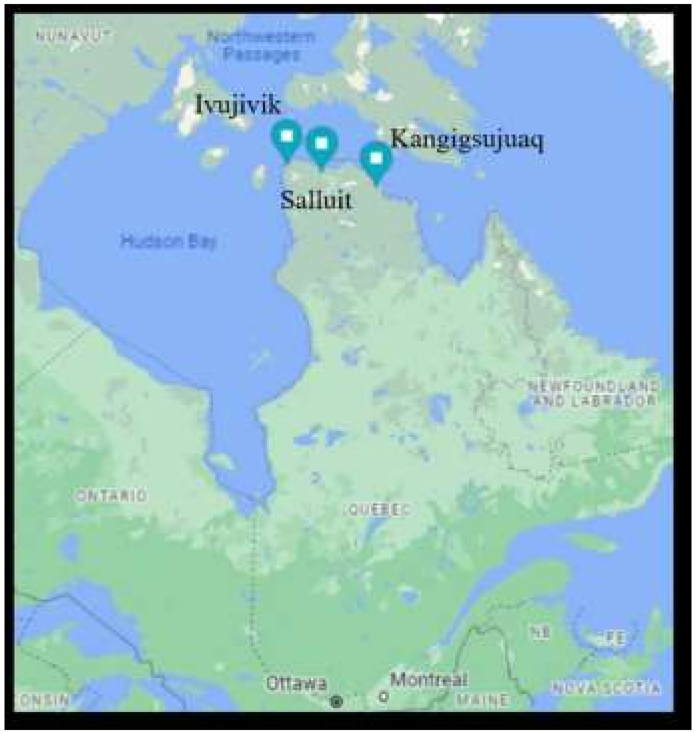



**Fig. 5.3** Location of the selected Communities.

**Table 5.3** Parameters of the model and references.

| Definitions | Symbols and units | Value | Reference |
|---|---|---|---|
| Transportation cost from supplier 'i' to pellet factory 'j' | $T_{ij}$($/kg) | Appendix 5.1 | (Vazifeh et al., 2021) |
| Capacity of supplier 'i' | $S_i$ (kg) | Appendix 5.2 | (Mafakheri et al., 2020) |
| Biomass price of supplier 'i' with and without discount | $P_i^{l,u}$($/kg) | Appendix 5.2 | (Mafakheri et al., 2020) |
| Biomass harvesting cost for supplier 'i' | $\text{hs}_i$ ($/kg) | 0.4 (for all suppliers) | (Vazifeh et al., 2021) |
| Wood pellet ordering cost from pellet factory 'j' with and without discount | $P_j^{l,u}$($/kg) | Appendix 5.3 | (Mobini, 2015) |
| Conversion rate of wood pellet to electricity | $fc$ (kWh/kg) | 4.7, 4.8, 4.6 | (Mobini, 2015) |
| Loading factor of energy convertor 'k' | $Lf_k$ (%) | 0.80, 0.85, 0.80 | (Vazifeh et al., 2023) |
| Electricity generation cost from biomass | $LB_k$($/kWh) | 0.046, 0.044, 0.048 | (Vazifeh et al., 2021) |
| Electricity generation cost from diesel | $LD_k$($/kWh) | 0.208, 0.25, 0.207 | (Mafakheri et al., 2020) |
| Demand in energy convertor 'k' at time t | $D_k^t$ (kWh) | Appendix 5.4 | (Mafakheri et al., 2020) |
| Capacity of electricity generation | $Z_k$ (kW) | 500 (for all communities) | (Mafakheri et al., 2020) |

## 5.5 Results and Discussions

The proposed modeling framework in this paper results in a MOBNLP programming problem, which cannot be solved directly using any off-the-shelf global optimizers (Zhang et al., 2023). Therefore, the solution approach involves transforming the original problem into a single-level using Karush-Kuhn-Tucker (KKT) conditions. Kim and Ferris (2019) introduced an extended mathematical programming (EMP) approach, utilizing the Karush-Kuhn-Tucker (KKT) conditions, to reformulate the bi-level problem into the Mathematical Program with Equilibrium Constraints (MPEC) framework. This reformulated problem was solved using an MPEC solver within the General Algebraic Modeling System (GAMS) (GAMS, 2020). Their method demonstrated superior performance in terms of accuracy compared to traditional complementarity-based models, which necessitate manual computation of the Lagrangian derivatives. In this current study, we leverage the EMP tool in GAMS to transform our hierarchical problem into an MPEC-equivalent problem. Subsequently, we solve the transformed problem by employing the non-linear program with equilibrium constraints (NLPEC) solver available in GAMS. This solution approach offers a robust and effective method for addressing multi-objective non-linear bi-level programming problems with equilibrium constraints, making it applicable to a wide range of challenges within the field. The proposed solution approach was applied to the wood pellet supply chain to investigate the economic and environmental impact of coordination. The results obtained showed that coordination has a positive impact on both economic and environmental performance.

#### 5.5.1 Comparison of economic and environmental impact under different scenarios

- ***Economic impact***

Based on the obtained results, it is evident that the coordinated approach has a positive impact on the Net Present Value (NPV) of suppliers and wood pellet factories, as shown in Table 5.4. This improvement reflects the benefits of cooperation and coordination within the supply chain. Conversely, the decrease in NPV for communities in the coordinated scenario indicates that they incur some costs associated with the coordination of the supply chain. However, it is important to note that part of this cost has been offset by the increase in bioenergy generation realized in the coordinated scenario.

It's noteworthy that the results for the coordinated scenario are based on the assumption of a revenue-sharing rate set at r=10%. To gain a deeper understanding of the sensitivity of the outcomes to changes in the revenue-sharing rate, a sensitivity analysis will be presented in section 5.2. This analysis will help assess how different revenue-sharing rates may impact the NPV of the involved parties and provide insights into the optimal rate for achieving a balance between coordination costs and benefits in the bioenergy supply chain.

**Table 5.4**
Players' NPV in decentralized and coordinated scenarios ($)

| Players | Decentralized | Coordinated |
|---|---|---|
| Suppliers | 322,900 | 418,480 |
| Wood pellet factories | 516,240 | 598,440 |
| Communities | 786,280 | 708,500 |

In terms of bioenergy generation, the findings presented in this study reveal a substantial disparity in the quantity of wood residues supplied and the corresponding bioenergy generation between a decentralized and a coordinated supply chain. The results clearly demonstrate the impact of coordination on these crucial factors within the supply chain. Table 5.5 shows that in a decentralized supply chain, the quantity of wood residues provided to the pellet factories ($X_{ij}^{t}$) is approximately 15% lower than in a coordinated supply chain. This suggests that there may be issues with coordination or communication between the various actors in the supply chain, resulting in a less efficient flow of resources.

Furthermore, the lower quantity of wood residues in the decentralized supply chain has an impact on the amount of bioenergy generated. The amount of bioenergy generated in the decentralized supply chain is reported as 6,779,300 kWh, which is lower than the coordinated scenario at 7,925,669 kWh (Fig. 5.4). This suggests that a coordinated supply chain is considerably more effective at maximizing the amount of bioenergy generated from the available resources. In a centralized supply chain, wood pellet can fully satisfy the energy demand in these communities.

**Table 5.5** Total feedstock ordered by pellet factories in various scenarios (kg).

| $\sum_t X_{ij}^t$ | Centralized | | Decentralized | | Coordinated | |
|---|---|---|---|---|---|---|
| | j=1 | j=2 | j=1 | j=2 | j=1 | j=2 |
| i=1 | 444,100 | 482,300 | 366,300 | 374,000 | 437,500 | 428,500 |
| i=2 | 472,500 | 524,000 | 381,700 | 407,000 | 448,300 | 511,000 |
| i=3 | 461,200 | 498,800 | 385,000 | 374,000 | 454,600 | 448,100 |
| Total | 2,882,900 | | 2,288,000 | | 2,728,000 | |

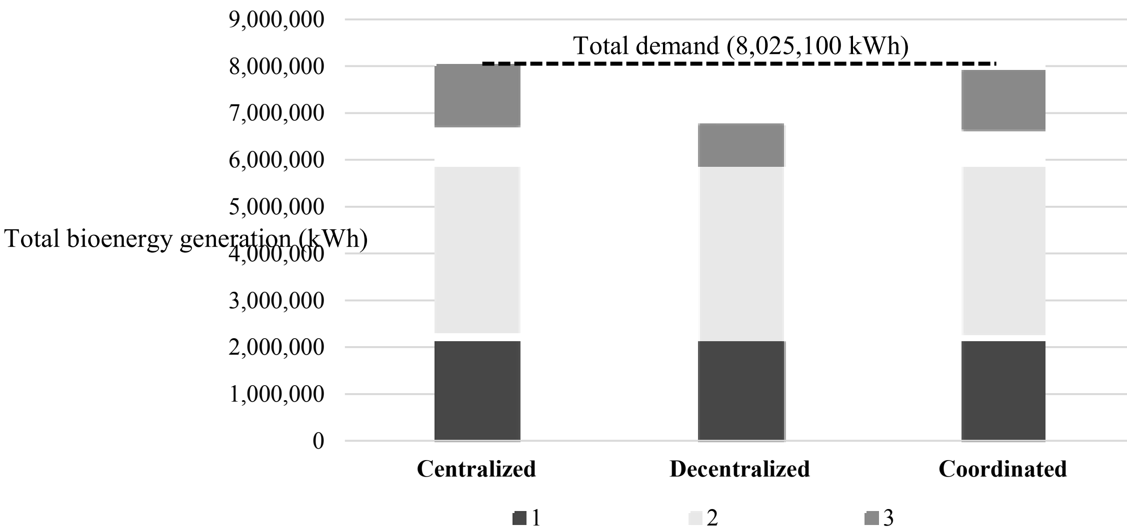



**Fig. 5.4.** Bioenergy generation in different scenarios.

- ***Environmental impact***

The environmental impact analysis of the wood pellet supply chain is crucial to assess the sustainability of bioenergy production. In this study, the $CO_2$ equivalent ($CO_2$-Eq) emissions of a wood pellet supply chain is assessed throughout its life cycle, including production, transportation, and conversion. The results show that in the centralized scenario, the total $CO_2$-Eq emissions from wood pellets were 622,334 kg, which is mainly attributed to the energy consumption for drying, pelletizing, and transportation of wood pellets. In contrast, the decentralized scenario emitted a lower amount of $CO_2$-Eq due to lower wood pellet production. However, to meet the remaining energy demand in the communities, diesel was used, which emitted 1,011,741 kg $CO_2$-Eq into the air, indicating that diesel combustion contributes significantly to GHG emissions. In the current situation in which diesel is the primary source of energy in Northern communities, the use of 2,431,848 L of diesel results in 6,514,354 kg $CO_2$-Eq emissions. This high level of emissions underscores the need for transitioning to sustainable bioenergy sources such as wood pellets to mitigate the negative environmental impact of fossil fuels. Fig. 5.5 demonstrates the proportion of $CO_2$ emissions attributed to pellets and diesel in three scenarios.

The coordinated scenario, which involved quantity discounts and revenue sharing, significantly reduced the environmental impact to 80,750 kg $CO_2$-Eq, which is comparable to the centralized scenario. This outcome indicates that coordination in the wood pellet supply chain can have positive environmental impacts by reducing GHG emissions and contributing to sustainable energy development. Overall, the results of the environmental impact analysis emphasize the need for a coordinated approach to the wood pellet supply chain to promote sustainable energy development and mitigate the negative environmental impact of fossil fuels.

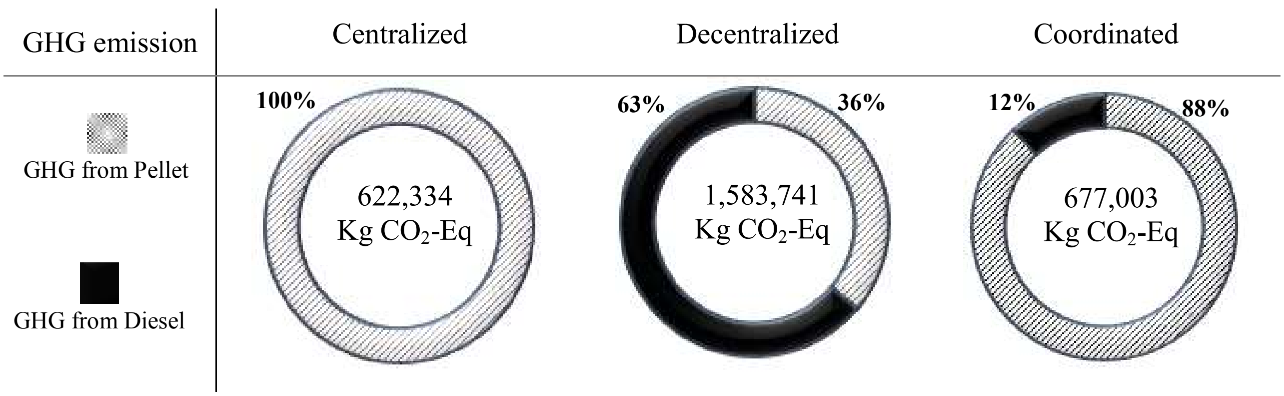



**Fig. 5.5.** GHG emissions from pellet and diesel through different scenarios to meet the demand.

It is worth mentioning that, in the case that we used diesel as the source of energy to satisfy the annual demand in the communities, the $CO_2$-Eq emissions were 1,902,069, 3,588,682, and 1,026,602 kg, respectively.

### 5.2 Sensitivity analysis

Sensitivity analysis is carried out to study the impact of the key coordination system parameter, revenue-sharing rate ($r$) on the coordinated supply chain performance (players' NPV and bioenergy generation). We have varied one parameter while keeping all other parameters constant to perform sensitivity analysis. This analysis help assess how different revenue-sharing rates may impact the NPV of the involved parties and provide insights into the optimal rate for achieving a balance between coordination costs and benefits in the bioenergy supply chain.

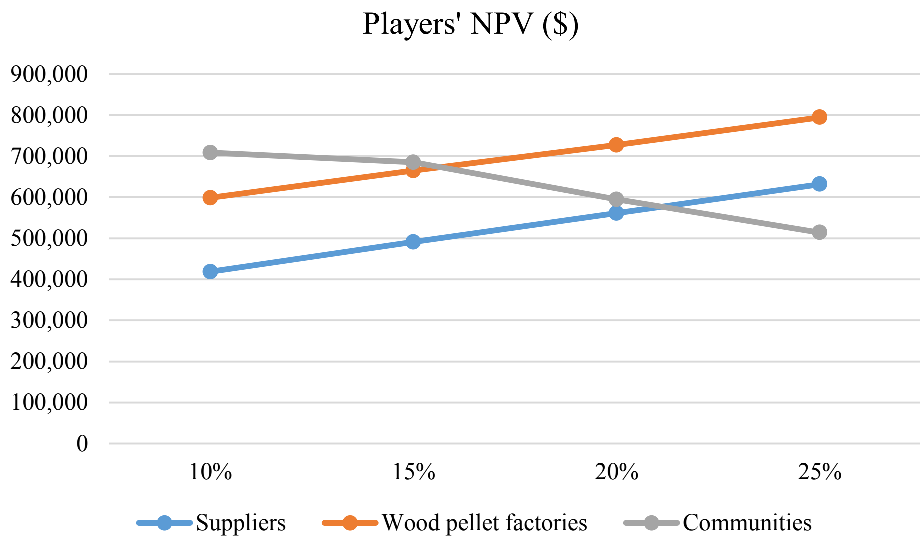



**Fig. 5.6.** Impact of revenue-sharing rate ($r$) in the supply chain players' NPV

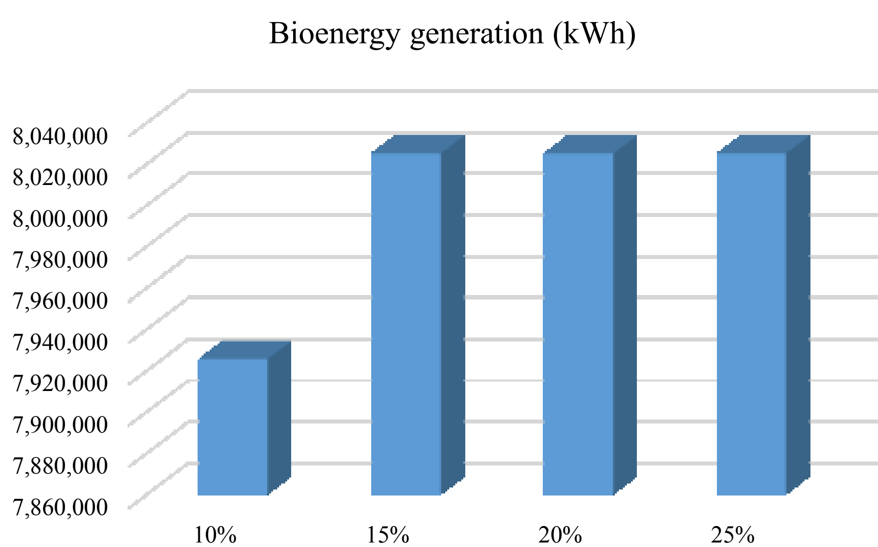



**Fig. 5.7.** Impact of revenue-sharing rate ($r$) in the bioenergy generation

Together, Figs. 5.6 and 5.7 show that first, the threshold value of the revenue-sharing rate approximately remains 15%. In other words, an excessively high revenue-sharing rate does not contribute to the coordination of the supply chain. This observation is crucial, as it highlights the critical point where increasing the rate further does not yield coordination benefits. The rationale behind this phenomenon is that when the revenue-sharing rate surpasses 15%, the communities' NPV experiences a significant decrease. This decline occurs even though the bioenergy generation remains constant at its maximum capacity, satisfying 100% of the communities' demand. Therefore, the reduction in communities' NPV outweighs the potential benefits of further coordination, emphasizing the importance of finding the right balance between revenue-sharing and the financial well-being of the communities within the supply chain.

This finding underscores the significance of not only identifying the optimal revenue-sharing rate but also considering the implications on different stakeholders, especially the communities in the off-grid area (In the context of limited demand and in the absence of efficient energy storage systems), when making decisions about coordination in the bioenergy supply chain. It highlights the need for a nuanced approach to revenue-sharing that maximizes the benefits of coordination while safeguarding the economic interests of all parties involved.

## 5.6 Conclusions

This study highlighted the importance of coordination in the wood pellet supply chain for both economic and environmental factors. It suggested a coordinated approach that includes quantity discounts and revenue sharing to address the issue of conflicting interests among different participants in the supply chain. By focusing on the adoption of biomass as an alternative source for electricity generation in Quebec northern communities, the study acknowledged the energy security concerns faced by isolated regions heavily reliant on diesel fuel (Canada's Energy Future, 2016). This approach not only demonstrated the potential for improved economic performance but also showcased a substantial reduction in environmental impact.

However, it is important to recognize that the findings of this study are specific to the case study conducted in three Quebec northern communities. Therefore, the generalizability of the results to other regions or contexts may be limited, influenced by transportation options and the availability of biomass residues. Furthermore, the assumptions and parameters used in the coordination model, such as quantity discounts and revenue sharing mechanisms, may not fully capture the complexities of real-world supply chain dynamics. Future research should include an in-depth analysis of potential risks and barriers associated with the adoption of biomass as an alternative energy source in isolated communities. Moreover, it is essential to consider potential unintended consequences or trade-offs that could arise from policies promoting bioenergy usage and reducing diesel dependence. Further investigations should explore the impact of various factors on the wood pellet supply chain, including government policies and regulations (Liu et al., 2022). This analysis should consider economic and environmental trade-offs, such as investment costs, job creation, and long-term sustainability.

To advance the field, future studies should delve into quantifying the economic performance improvements resulting from the proposed coordinated approach and measuring the achieved reduction in environmental impact. Additionally, the scalability of the model should be assessed, exploring its implications for large-scale implementation within the wood pellet industry. By addressing these research directions, we can enhance our understanding of the wood pellet supply chain and contribute to the development of sustainable energy systems.

**Appendix 5.1 Cost of biomass transportation from supplier 'i' to hub 'k' ($/kg)**

| | | Pellet factories | |
|---|---|---|---|
| | | 1 | 2 |
| Suppliers | 1 | 0.012 | 0.015 |
| | 2 | 0.011 | 0.016 |
| | 3 | 0.012 | 0.015 |
| | 4 | 0.014 | 0.012 |
| | 5 | 0.015 | 0.011 |
| | 6 | 0.016 | 0.010 |

**Appendix 5.2 Capacity of suppliers (Si) (kg), biomass price of suppliers with and without discount ($P_i^l, P_i^u$) ($/kg)**

| | $S_i$ | $P_i^l$ | $P_i^u$ |
|---|---|---|---|
| 1 | 33,300 | 0.168 | 0.205 |
| 2 | 34,000 | 0.170 | 0.210 |
| 3 | 34,700 | 0.175 | 0.200 |
| 4 | 37,000 | 0.190 | 0.215 |
| 5 | 35,000 | 0.190 | 0.220 |
| 6 | 34,000 | 0.185 | 0.220 |

**Appendix 5.3 Wood pellet ordering cost from pellet factory 'j' to community 'k' ($P_{jk}^l, P_{jk}^u$) ($/kg)**

| | | Communities | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Wood pellet factory | 1 | (0.235, 0.362) | (0.235, 0.362) | (0.235, 0.362) |
| | 2 | (0.266, 0.409) | (0.266, 0.409) | (0.266, 0.409) |

**Appendix 5.4 Demand in community 'k' at time 't'(12 months) (kWh)**

| | 1 | 2 | 3 |
|---|---|---|---|
| 1 | 186,300.000 | 351,500.000 | 100,500.000 |
| 2 | 171,900.000 | 324,400.000 | 92,800.000 |
| 3 | 171,000.000 | 322,600.000 | 92,300.000 |
| 4 | 180,900.000 | 341,200.000 | 97,600.000 |
| 5 | 179,700.000 | 339,100.000 | 97,000.000 |
| 6 | 168,700.000 | 318,300.000 | 91,100.000 |
| 7 | 178,700.000 | 337,100.000 | 96,400.000 |
| 8 | 194,800.000 | 367,500.000 | 105,100.000 |
| 9 | 216,800.000 | 409,000.000 | 117,000.000 |
| 10 | 246,900.000 | 465,900.000 | 133,300.000 |
| 11 | 226,500.000 | 427,400.000 | 122,300.000 |
| 12 | 219,900.000 | 414,900.000 | 118,700.000 |

# Chapter 6

# Conclusions and Future Research

In this section, we provide an overview of the bioeconomy, which serves as the overarching system encompassing the biomass supply chain—a primary focus of this PhD research. We then delve into the research findings and their implications within the broader context of the field. This chapter represents the culmination of the entire doctoral journey, presenting a holistic view of the study's significance and contributions. The central goal of this thesis was to address the challenges related to players' interactions and coordination within the biomass supply chain, with a specific focus on off-grid communities in Canada. Throughout this investigation, we aimed to shed light on novel decision-making structures and coordination mechanisms that enhance the efficiency and sustainability of the biomass supply chain.

Bioeconomy represents an economic system that hinges on the sustainable utilization of biological resources, encompassing living organisms like plants, animals, microorganisms, and renewable biological materials derived from them. This paradigm shift emphasizes moving away from a fossil fuel-dependent economy and towards one that relies on renewable biological resources to produce goods, energy, and services. Bioeconomy finds diverse applications, including bioenergy, where biofuels and biogas are produced from crops, agricultural residues, and organic waste. It also extends to biobased materials, involving the manufacturing of bioplastics, bio composites, and biomaterials from renewable feedstocks. Additionally, bioeconomy embraces biochemicals, where valuable chemicals, enzymes, and compounds are extracted from biomass for industrial use. Moreover, it encompasses sustainable practices in agriculture and aquaculture, leveraging biotechnology to enhance crop yields and improve food production, as well as pharmaceuticals that leverage biotechnology to develop medicines and drugs using biological compounds. Within the realm of bioeconomy, this PhD research represents a modest endeavor focused on enhancing the efficiency of the bioenergy supply chain. The core of this effort lies in developing bioenergy supply chain coordination models to remove desynchronization within the channel. By exploring the intricacies of the bioeconomy and adopting the concept of game theory, this study contributes to a broader understanding of biomass supply chain coordination approaches by proposing mathematical equilibrium modeling, incentivization framework, and finally coordination approaches. Moreover, the practical implications of our findings hold promise for off-grid communities, offering valuable insights into optimizing biomass utilization and promoting effective coordination among stakeholders.

## 6.1 Conclusions

In the initial stage of this dissertation, an extensive review and classification of the existing body of literature were conducted to identify gaps and research opportunities. This comprehensive analysis served as a foundation for contextualizing our research findings within the broader landscape of game theoretic applications, with a specific focus on bioenergy channel coordination. By positioning our study within this relevant context, we aimed to enhance the understanding of the intricate interplay between game theory and bioenergy supply chain coordination. Moreover, this research delves into exploring the untapped potential for advancing the current knowledge base in this field. We seek to contribute novel insights and innovative approaches that can propel the application of game theory to optimize the efficiency and sustainability of bioenergy channels. Through this dissertation, we endeavor to bridge the gap between theory and practice, propose models for stakeholders' interactions in the bioenergy sector to make informed and strategic decisions. By embracing the power of game theory, the concept of contracts, life cycle analysis, and coupling it with practical platforms such as GAMS and OpenLCA, we aspire to create a more efficient bioenergy ecosystem that aligns with the principles of sustainability and resource optimization. As we unravel the complexities of coordinating bioenergy channels through the lens of game theory, we envisage contributing to the advancement of both academic scholarship and real-world solutions in the rapidly evolving bioenergy landscape.

This thesis explored the modeling and coordination of biomass supply chains, focusing on the case of three Canadian northern communities. By addressing the energy security concerns of isolated regions heavily reliant on diesel fuel, the study emphasized the importance of coordination among supply chain members to improve overall performance. To contribute to the existing literature on biomass supply chain management and coordination, this thesis utilized game theory as a method to analyze decision-making in situations with interdependent parties.

In the first attempt, alternative power structures in the coordination of biomass supply chains for remote communities were examined using a Stackelberg game formulation. The research aimed to identify which player had the advantage in offering side payments, thus assuming the leadership role. The results demonstrated that communities assuming a leadership position were better leveraged to provide the required side payments, ensuring the participation of suppliers and hubs and maximizing the share of biomass in the electricity generation mix.

The second attempt shed light on the crucial role of government in driving and accelerating the development of bioenergy through a comprehensive evaluation of various incentivization strategies. By carefully examining different approaches to incentivize bioenergy projects and initiatives, our research endeavors to inform evidence-based policymaking in the bioenergy sector. Through this research, we proposed a contract-based coordination approach (quantity discount) and examine two common types of government support aiming to foster collaboration stakeholders and policymakers, paving the way for the establishment of well-informed and forward-thinking policies that align with the broader goals of sustainable energy development. The findings revealed that increasing direct incentives improved the payoffs of biomass supply chain participants but had no significant impact on the amount or share of bioenergy generation. Conversely, indirect incentivization, particularly through government investment in bioenergy conversion facilities, had a significant positive effect on increasing the share of bioenergy generation.

In the third attempt, we narrow our focus to the scope of wood pellet life cycle and show the impact of coordination through revenue sharing and quantity discount contracts in reducing GHG emission and stakeholders' profits. A coordinated approach that included quantity discounts and revenue sharing was proposed to address conflicting interests among participants. This approach demonstrated potential for improved economic performance and substantial reduction in environmental impact. The results highlighted the disparity in wood residue supply and bioenergy generation between decentralized and coordinated supply chains. The coordinated supply chain showed higher efficiency in resource utilization and generated more bioenergy. Furthermore, the centralized supply chain using wood pellets fully satisfied energy demand in the communities and resulted in lower $CO_2$-Eq emissions compared to the decentralized scenario that relied on diesel combustion.

In conclusion, this thesis contributed to the existing literature on biomass supply chain management and coordination by employing game theory to analyze decision-making dynamics. The research emphasized the importance of coordination among supply chain members, identified effective policy interventions, and showcased the economic and environmental benefits of a coordinated approach. By addressing these aspects, this thesis has advanced our understanding of biomass supply chains and provided valuable insights for the development of sustainable energy systems in isolated communities.

## 6.2 Potential Directions for Future Research

This study has provided insights into the biomass supply chain within Quebec's northern communities. However, to further enhance our understanding of biomass utilization and contribute to the development of sustainable energy systems, there are several directions for future research that should be considered. It is important to acknowledge that the findings of this study are specific to the case study conducted in Quebec, and their generalizability to other regions or contexts may be limited due to factors such as transportation options and biomass residue availability. Additionally, the assumptions and parameters used in the coordination model may not fully capture the complexities of real-world supply chain dynamics. Therefore, future research avenues are suggested as follows:

1. **Potential risks analysis:** It is crucial to investigate the risks and uncertainties associated with the adoption of biomass as an alternative energy source in isolated communities. This can be accomplished through the application of various approaches, such as stochastic modeling, to assess the potential challenges and vulnerabilities. By identifying and understanding these risks, policymakers and stakeholders can develop strategies to mitigate them effectively.

2. **Impact analysis of promoting policies:** Future investigations should explore the impact of different government policies and regulations on the biomass supply chain. This analysis should consider economic and environmental trade-offs, including investment costs, job creation, and long-term sustainability. For instance, evaluating the effectiveness of government policies targeting carbon emissions, such as carbon credits or taxes, can

provide insights into the potential benefits of bioenergy development as a viable alternative to diesel. Calculating the net carbon savings resulting from the transition from diesel to biomass in target communities will further justify direct and indirect incentives.

3. **Quantifying the economic performance:** Extending this work to quantify the economic improvements resulting from the proposed coordinated approach is recommended. This can involve assessing cost reductions, efficiency gains, and potential revenue streams within the biomass supply chain. Additionally, measuring the achieved reduction in environmental impact, such as greenhouse gas emissions, will provide a comprehensive evaluation of the proposed coordinated approach's overall benefits.

4. **Developing forecasting scenarios for biomass availability**: To account for changing dynamics in biomass availability and energy demand, it is advisable to couple suggested models with simulation approaches. Incorporating future scenarios into supply chain optimization problems allows for robust decision-making and strategic planning. By considering factors such as population growth, technological advancements, and changing energy policies, researchers can provide insights into the long-term viability and scalability of biomass utilization in different regions.

5. **Developing a Sustainable Analysis Framework for Biorefineries:** The biorefinery concept plays a pivotal role in the bioeconomy framework, encompassing diverse biomass resources, a variety of conversion technologies, and a broad product portfolio. To ensure its successful integration and sustainability, a comprehensive decision-making framework is essential. This framework must not only integrate existing optimization models but also evaluate the feasibility and sustainability of establishing biorefineries in different regions with unique geographical, environmental characteristics, and technological capabilities. A valuable starting point for developing this model is the research conducted by Ebadian et al. (2023), which reviewed recent trends in integrating decision-making models in biorefinery systems.

By addressing these research directions, we can further advance our knowledge of biomass supply chains and contribute to the development of sustainable energy systems.

### 6.3 Thesis modifications

Following the thesis defense, the author has made the subsequent modifications to the text:

- Modification 1- In chapter 3 (Equations 3-1 to 3-5), $S_i^t$ has been revised to $S_i$.
- Modification 2- in chapter 3 (Equation 3-10) *hk(k)* has been revised to $h_k$.
- Modification 3- $LB_j$ is defined as "Electricity generation cost from biomass at convertor j in chapter 3".
- Modification 4- In Equation 4.2, the value of $\lambda_j^t$ is contingent upon the quantities exchanged between hubs and communities. This design ensures that initial units receive higher incentives to compensate for lower economies of scale. As biomass exchange quantities increase, the higher economy of scale triggers a reduction in the level of support provided by incentives. A similar case exists in Equations 4-4 and 4-6.
- Modification 5- For Fig 5-2, variable $P_{ij,jk}^t$ represents both $P_{ij}^t$ and $P_{jk}^t$.

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