Renewable Energy 272 (2026) 126015

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Integrating bio-hubs for resilience enhancement of wood pellet supply chains: A market analysis using system dynamics

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ARTICLE INFO

Keywords:
Bio-hubs
Wood pellet supply chains
Wood pellet market
Resiliency
System dynamics modeling
Bioenergy

ABSTRACT

Wood pellets have become a standardized commodity in the global energy market, with rapidly growing international trade. Canada, with its vast forest resources, has significant potential to expand its share of the global wood pellet market. However, the wood pellet industry faces multiple challenges on both the supply and demand sides of the supply chain. This study assesses the role of bio-hubs in enhancing the resilience and competitiveness of Canadian wood pellets in the global market. Bio-hubs are centralized facilities that aggregate, process, store, and redistribute bioenergy products, enabling improved logistics coordination, cost efficiency, and supply flexibility across the supply chain. Using a System Dynamics (SD) approach, the integration of bio-hubs into wood pellet supply chains (WPSCs) is modeled to evaluate their impacts on supply and demand dynamics under various scenarios. The model captures key complexities of WPSCs, including feedstock supply disruptions of 25% and 50%, macroeconomic demand-side changes in importing countries represented by GDP variations of ±20% and ±40%, and interactions with parallel energy markets through fossil fuel price changes of ±20% and ±40%. The results show that the inclusion of bio-hubs significantly strengthens supply chain resilience and enhances Canada's competitive position. The findings indicate that Canada has the potential to emerge as a leading global supplier, capturing approximately 50% of the global wood pellet market share. These results highlight bio-hubs as a critical strategic mechanism for supporting the long-term growth and stability of Canada's wood pellet industry despite market volatility and supply-side uncertainties.

1. Introduction and literature review

Wood pellets are a densified biomass fuel typically produced from woody residues generated through forest harvesting and industrial processing [1]. Their standardized cylindrical form, high energy density, mechanical durability, and compatibility with existing bulk-handling infrastructure have enabled wood pellets to emerge as a globally traded bioenergy commodity suitable for large-scale energy applications [2]. Global production increased from 28 Mt in 2015 to approximately 40 Mt in 2020, reflecting the growing role of bioenergy in decarbonization strategies [3]. This trend is expected to continue as countries adopt more ambitious renewable energy targets and expand biomass-related infrastructure [4]. In line with these developments, the International Energy Agency projects that bioenergy must supply nearly 146 Exajoules by 2050, almost three times its 2020 level, to support climate mitigation efforts [5].

From a market perspective, the global biomass pellet market was valued at USD 11.9 billion in 2024 and is projected to reach USD 17.9 billion by 2030 [6]. Fig. 1 shows North America, particularly Canada and the United States has emerged as a leading export region due to abundant forest resources, while Europe and East Asia have become major import hubs, resulting in extensive global trade flows [7]. Canada's wood pellet industry is underpinned by forest resources representing approximately 9% of global forest cover [8]. Feedstock supply is

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https://doi.org/10.1016/j.renene.2026.126015
Received 27 November 2024; Received in revised form 11 May 2026; Accepted 30 May 2026
Available online 1 June 2026

primarily derived from secondary processing residues, supplemented by primary harvest residues and salvaged biomass from natural disturbances such as wildfires and insect outbreaks [9]. As mill residues are already near full utilization and climate change is expected to increase the frequency and severity of disturbances, salvaged biomass is likely to play an increasingly important role in future feedstock supply [10]. These conditions position Canada to meet rising global demand and secure a substantial share of the expanding wood pellet market.

Despite this potential, the wood pellet industry faces significant challenges. Market risk, particularly price volatility and potential loss of global market share, represents the highest risk level within biomass supply chains (BSCs), exceeding financial and policy risks [11]. The global biomass market is evolving rapidly due to rising demand, technological advances, and changing policy frameworks such as carbon pricing and energy regulations, leading to increased competition and supply chain complexity [11]. Maintaining market share under demand fluctuations requires high production capacity and sufficient storage, conditions more readily achieved in mature, high-volume markets [12]. Disruptions in wood pellet supply chains (WPSCs) reduce resilience and can result in unmet demand, quality degradation, and revenue losses [13]. In addition, sustained product quality, including low ash content, remains essential for competitiveness and market expansion, necessitating continuous improvement in quality standards [14].

A wide range of modeling approaches has been applied to biomass-to-bioenergy supply chains. Mathematical programming and mixed-integer linear programming dominate studies on facility location, capacity planning, and logistics optimization [15], while techno-economic analysis and life cycle assessment have provided insights into economic feasibility and environmental impacts [16]. However, market-oriented analyses of BSCs remain limited. One study [17] examined global wood pellet trade dynamics from 2008 to 2016, identifying North America as the primary production region and Europe as the main consumer, but without explicitly addressing market resilience under uncertainty.

One strategy proposed to address these challenges is the implementation of bio-hubs. Originating from advanced uniform feedstock systems [18], bio-hubs, also referred to as depots or biomass logistics centers, can provide storage, preprocessing, and feedstock conditioning services depending on supply chain requirements [19]. Existing studies primarily focus on techno-economic optimization, facility location, and biomass flow modeling using mathematical programming and discrete event simulation [20,21]. While these studies demonstrate improvements in feedstock quality and logistics reliability, the role of bio-hubs in mitigating market volatility and strengthening supply chain resilience remains insufficiently explored [22].

System Dynamics (SD) offers a complementary approach for analyzing renewable energy systems characterized by feedback mechanisms, time delays, and long-term structural change [23]. SD has been applied to coordination strategies, policy evaluation, and investment risk assessment in BSCs [11,24], yet applications focusing on bio-hubs within WPSCs are scarce [25].

Based on the literature, there is a notable research gap in understanding the role of bio-hubs within wood pellet supply chains (WPSCs) and potentially other forest product supply chains, particularly concerning market analysis [25]. Furthermore, the biomass pellet market itself has received limited attention, with an extremely small body of research dedicated to this topic [22]. The novelty of this research lies in bridging a significant gap in the literature by providing an SD model to simulate the global wood pellet market while assessing the role of bio-hubs in integrating the supply and demand sides of WPSCs under various scenarios. This research seeks to answer the critical question: can bio-hubs enhance the resilience and competitiveness of the Canadian wood pellet supply chain in the global market, particularly in the face of fluctuating supply and demand conditions? To address this, we develop an SD model that simulates the integration of bio-hubs into WPSCs. The model evaluates how bio-hubs can mitigate risks from supply disruptions, price fluctuations, and changes in global demand, offering insights into long-term impacts on supply chain resilience.

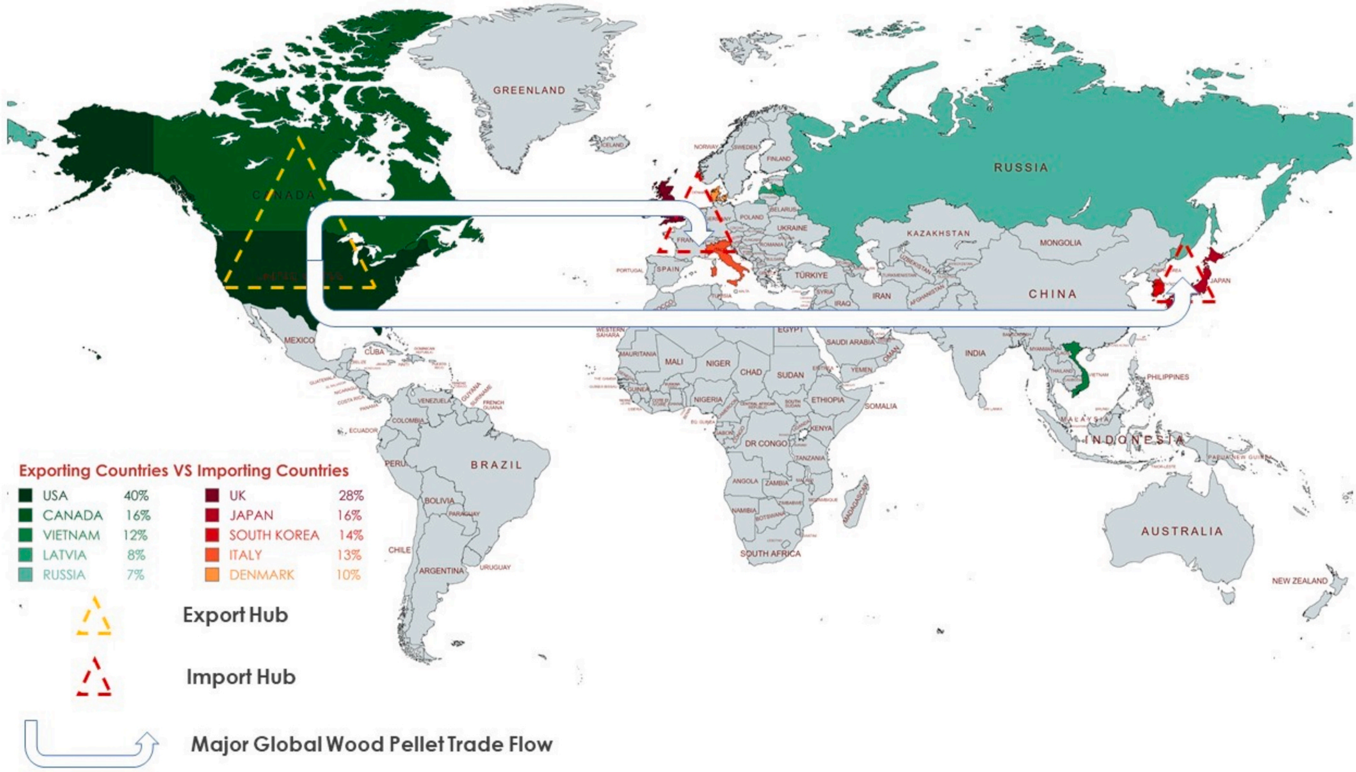


Fig. 1. Major global wood pellet trade flows and market shares of top players.

The abbreviations and symbols used throughout the text are listed in Table A.1, while the historical data utilized for model calibration, including production capacity and price information, are presented in Table A.2 (Appendix).

2. Methodology

This study employs an SD modeling approach to assess the role of bio-hubs in enhancing the resilience and competitiveness of Canadian wood pellets in the global market. The proposed SD model is implemented in the VENSIM software [26].

2.1. Model description

The proposed SD model consists of three interconnected sub-models: (1) Supply Side of WPSCs, (2) Bio-Hub, and (3) Demand Side of WPSCs. Fig. 2 presents a schematic of the wood pellet supply chain. The supply-side sub-model captures feedstock procurement and utilization for pellet production, while the bio-hub sub-model serves as an intermediary integrating supply and demand. The bio-hub's maximum production capacity is assumed at 40 Mt/year, leveraging modular pellet mills for scalable production [27] and benefiting from economies of scale [28]. A 2 Mt safety stock in an enclosed structure provides a buffer to maintain pellet quality. The bio-hub also functions as a research hub to enhance pellet specifications. The demand-side sub-model represents the global market, accounting for price, quality competitiveness, supply volumes, market capacity, and saturation. By combining scalable production, advanced storage, and research functions, the bio-hub enables adaptive supply–demand management, risk mitigation, and quality improvement, enhancing competitiveness. Price elasticity of demand, GDP of importing countries, and parallel markets (e.g., fossil fuels) are incorporated to capture market dynamics.

The primary assumptions of the model are as follows.

1. The model considers expenditure elasticity for the impact of GDP and Marshallian price elasticity for the impact of fossil fuel prices. These elasticity measures are assumed to be constant within the simulation period [29].
2. Throughout the simulation period, the inflation rate remains constant at 2%.
3. The model uses the CIF (Cost, Insurance, and Freight) price for wood pellets.
4. Based on market conditions, such as in a saturated market scenario, the price offered by the bio-hub can be lower than the unit cost of production.
5. Depending on market conditions, shortages at the bio-hub are possible.

2.2. Causal relationships

A causal loop diagram visualizes system feedbacks by representing variable interactions through causal links, where positive signs (+) indicate reinforcing relationships and negative signs (−) denote balancing effects [26].

2.2.1. Demand sub-model

The demand side of WPSCs, representing the global market, is depicted by a CLD (Fig. 3), illustrating interactions among variables through balancing and reinforcing feedback loops. Export decisions at the bio-hub depend on potential exports—driven by price and quality competitiveness—and actual exports, which also account for market conditions. Balancing loops regulate market stability: B1 (Over Supply) reduces exports when high bio-hub supply causes market saturation and elevated storage costs; B2 (Market Saturation) lowers potential and actual exports in saturated markets; B3 (Price Adjustment) shifts demand toward fossil fuels when wood pellet prices rise, reducing market capacity. Reinforcing loops enhance performance: R1 (Total Supply) links increased exports to higher potential exports via price adjustments; R2 (Global Price) shows that higher exports lower global prices, stimulating demand; R3 (Export Competitiveness) indicates that increased exports further improve competitiveness; R4 (Quality Improvement) highlights bio-hub investments in research, which boost exports, while B4 (Quality Competitiveness) reflects competitors' improvements, partially offsetting gains.

2.2.2. Bio-hub sub-model

This section highlights that wood pellet production begins only when sufficient feedstock is available, which must be acquired in advance to maintain buffer stocks. The bio-hub strategically integrates supply and demand in WPSCs, decoupling fluctuations and enhancing overall system resilience. Loop R1 (Fig. 4) is a reinforcing loop where increased desired bio-hub production boosts actual production, wood pellet exports, and expected exports, further raising desired production. Loop R2 reinforces this effect by linking exports and expected exports to storage adjustments, which feed back into desired production. Loop R3 optimizes feedstock flow, adjusting storage and acquisition to support higher production. Two balancing loops (Fig. 4), B1 and B2, regulate operations: B2 monitors feedstock storage, preventing over-ordering, while B1 controls wood pellet inventory, reducing production when oversupply occurs. These loops prevent bottlenecks, avoid market saturation, reduce costs, and stabilize prices, ensuring efficient bio-hub operation within WPSCs.

2.2.3. Supply sub-model

The CLD's supply side (Fig. 5) depicts a forest ecosystem as the source

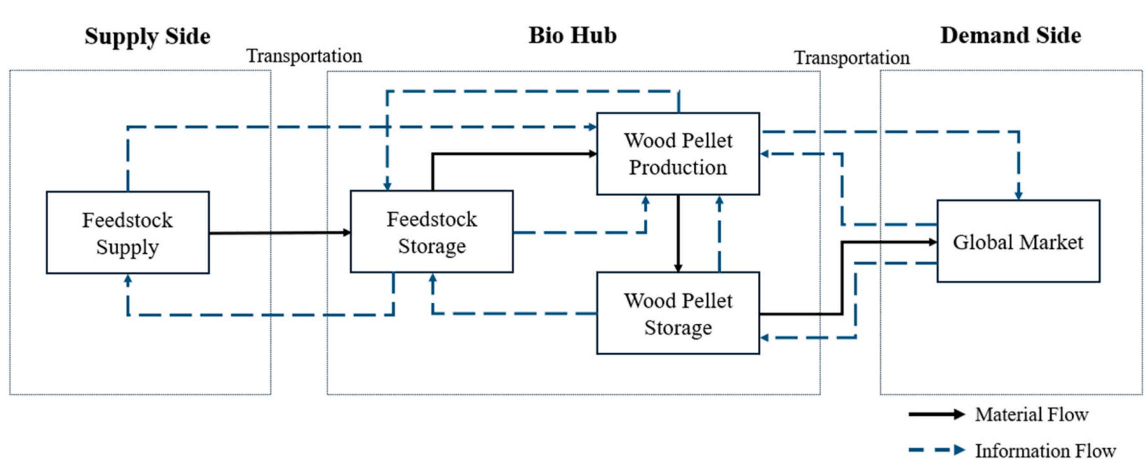


Fig. 2. Schematic design of the wood pellet supply chains.

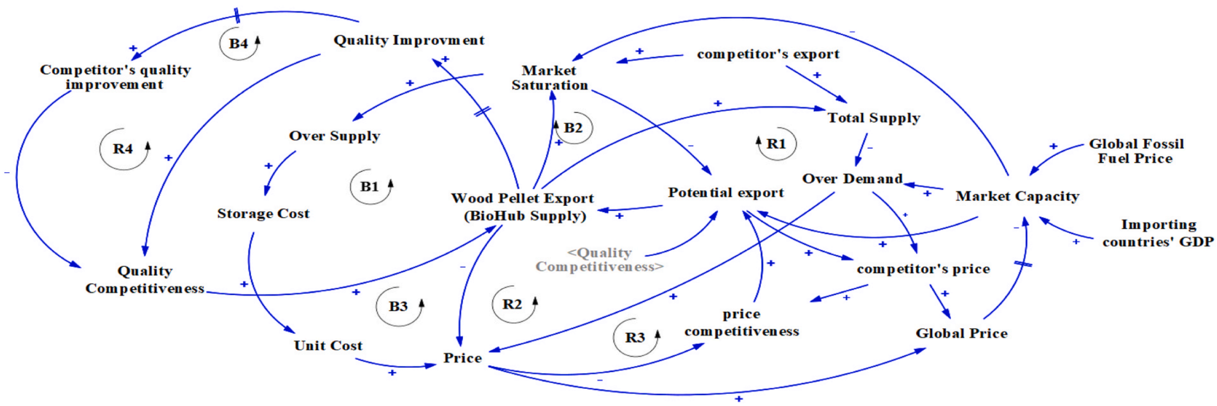


Fig. 3. Causal loop diagram of demand side of WPSCs.

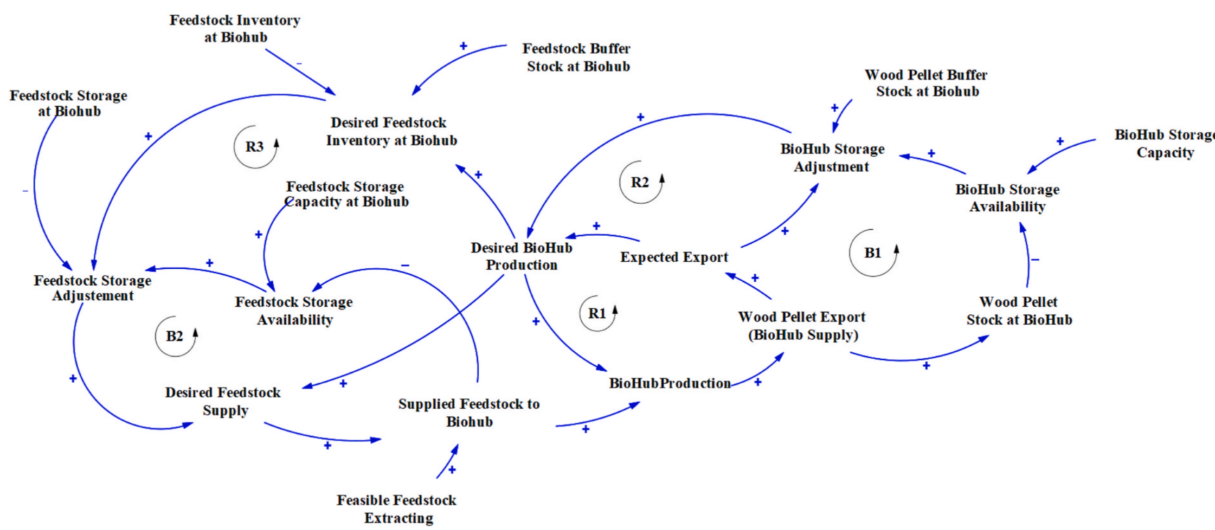


Fig. 4. Causal loop diagram of Bio-hub.

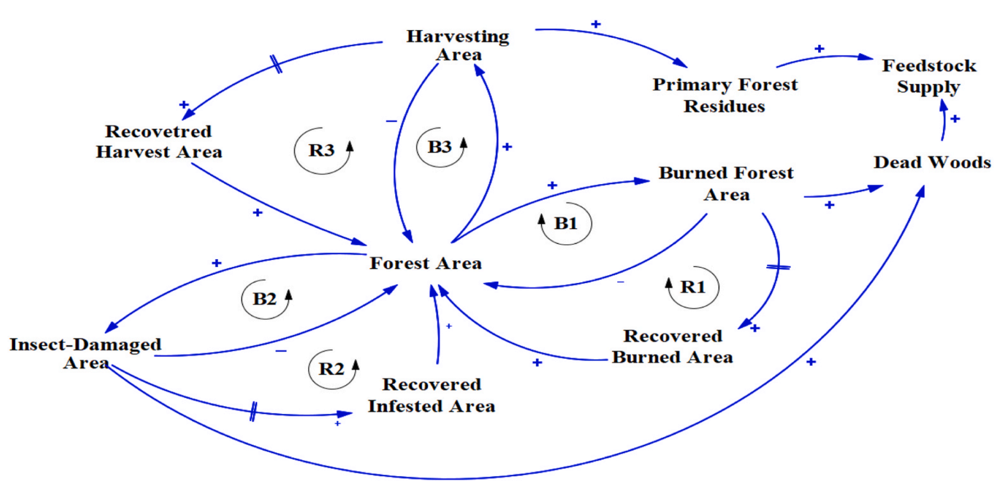


Fig. 5. Causal loop diagram of supply side of WPSCs.

of wood pellet production, acknowledging the intricate interplay between variables that can cause a forest's area to fluctuate in both directions over time. Natural disturbances like wildfires, insect infestations, and human activities such as harvesting all contribute to a decreasing trend in forest area (balancing loops B1, B2, B3). However, this model also takes into account the natural recovery of trees. After a few years, disturbed areas can naturally regenerate, which will cause the forest area to trend upward (reinforcing loops R1, R2, R3). Loop R3, for example, shows how a restored harvest area expands the total forest area, increasing the amount of feedstock available for subsequent harvests.

2.3. Stock – flow diagram

Stock-flow diagrams (SFDs) convert qualitative CLD relationships into quantitative equations, enabling dynamic behavior analysis and prediction [30]. SFDs represent system states through stocks (boxes in Fig. 6) and flows (double-lined arrows) that alter stock levels, while constants remain fixed and auxiliary variables are computed from stocks and constants [31]. A complete system representation requires defining key components as variables and expressing their interactions mathematically. This study incorporates scenario assessment and elasticity analysis: scenario assessment examines the influence of external factors (e.g., fossil fuel prices, GDP), while elasticity evaluates responses to internal factors. Understanding the interplay of external and internal drivers is crucial for analyzing the dynamics of the global wood pellet market.

Therefore, the global market capacity can be formulated using the following equation:

$$GWPM = C.(\Delta GDP)^{\varepsilon_{GDP}}.(\Delta FFP)^{\varepsilon_{FP}}.(\Delta GWPP)^{\varepsilon_{WP}} \tag{1}$$

Where GWPM is the Global Wood Pellet Market Capacity, ΔGDP, ΔFFP, and ΔGWPP represent the differences in GDP, fossil fuel price, and global wood pellet price respectively, and ε denotes the elasticity coefficients and C is an initial value.

Market saturation plays a crucial role in global trade dynamics. It is determined by the ratio of total wood pellet supply to market capacity (in %):

$$MS = \left(TS/_{GWPM} \right) \times 100 \tag{2}$$

Where MS is Market Saturation, TS is Total Supply. A value exceeding 100% indicates a saturated market with excess supply driving other variables, while a value below 100% suggests growth potential and opportunities for new market entrants.

The bio-hub's pricing strategy is directly linked to market saturation:

$$WPP = Max\left(UC/2, M \times UC \times \left(\frac{1}{MS} \right) \right) \tag{3}$$

Where WPP is Wood Pellet Price, UC is Unit Cost, and M is the profit margin. Market prices for wood pellets are generally set above production costs to account for marginal profit. Prices fluctuate based on supply capacity and energy demand, high demand with low supply results in higher prices, while low demand with ample supply leads to lower prices. This relationship is illustrated by incorporating market saturation into the formula. This equation incorporates a "max" function to prevent prices from falling below a minimum level which is assumed to be half of the unit cost during periods of extreme market saturation, ensuring a pricing safety net.

For the global wood pellet price, two alternative exporters are considered: Canada and the rest of the exporters as a single unit. Canada and the other exporters each follow pricing strategies based on supply-demand dynamics. Furthermore, establishing a global price for wood pellets is essential to assess its impact on global market capacity. This capacity is also influenced by the GDP of importing countries and the global fossil fuel price, with higher export volumes exerting a greater influence on the market price. The (average) global wood pellet price is then determined by a weighted average that considers both the bio-hub's export prices and competitors' prices:

$$GWPP = WPP \times \left(E/_{TS} \right) + CP \times \left(1 - \left(E/_{TS} \right) \right) \tag{4}$$

Where GWPP is Global Wood Pellet Price, E is Canadian Export Volume, TS is the total market supply and CP is Competitor's Price. Importing countries adjust their decisions based on fluctuations in the global wood pellet price. The global wood pellet price is determined by a weighted average that considers the export prices of both competitors and the bio-hub.

Canadian export volume represents the actual exports of the bio-hub and, therefore, Canada's share in the global wood pellet market. The export potential of the bio-hub is initially determined based on its price competitiveness relative to competitors and its quality superiority. As expressed in Eq. (4), the global wood pellet price influences the effective market capacity rather than directly determining export volumes, since market capacity is simultaneously affected by other external drivers

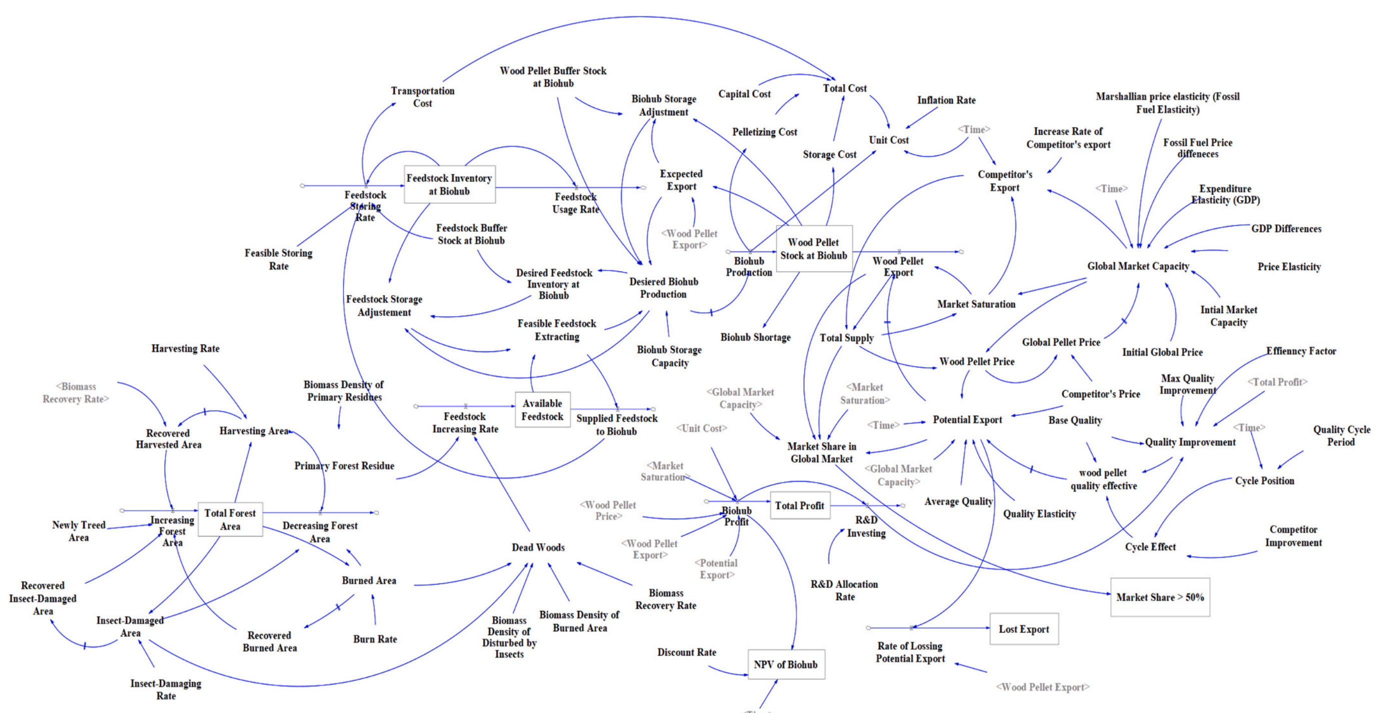


Fig. 6. Stock-Flow diagram of the WPSCs.

such as fossil fuel prices and broader energy market conditions. Considering these interacting factors, the global wood pellet price indirectly affects Canadian exports by shaping market capacity and saturation levels. In unsaturated markets with stable demand, the bio-hub can fully utilize its export potential, whereas increasing market saturation leads to proportional adjustments in export volumes to prevent oversupply. Expected export demand for the coming year is forecasted using past export fluctuations:

$$EE_{i+1} = Forecast\ (E_i, 10, 1) \tag{5}$$

Where EE_{i+1} is the Expected Export for year i+1 and the forecast function is a built-in feature in VENSIM. Therefore, the expected export for the following year is based on ten years of bio-hub exports. The model continuously adjusts the volume of stored feedstock to match target levels, ensuring sufficient feedstock to meet production demands without incurring excessive storage costs. The desired feedstock inventory level guides the supply of raw materials, adhering to feasible extraction constraints, thereby enhancing the resilience of the WPSCs.

The supply side of WPSCs is focused on the dynamics of forest areas as a proxy for the source for wood pellets. A key concept in this sub-model is the forest's ability to regrow after disturbances. The percentage of regrowth of a disturbed area over time depends on the type and extent of disturbance. This regrowth process is modeled using the DELAY1I function in VENSIM. The forest regrowth process after disturbances is modeled using a first-order delay function:

$$RA(i) = DELAY1I\ (DA_i, RT, IA) \tag{6}$$

Where RA(i) is Regenerated Area at year i, DA_i is Disturbed Area, RT is Regeneration Time, and IA is Initial Disturbed Area. This formulation captures the time-dependent nature of forest regeneration, a critical factor in the sustainability of wood pellet production.

2.4. Model validation

Model validation ensures alignment with real-world energy systems, enhancing credibility, predictive reliability, and policy relevance [32]. Prior to conducting simulations and analyses, it is essential to perform several tests. According to Qudrat-Ullah & Seong et al., [33] some of these tests include: 1. boundary and structure adequacy tests to ensure the model's appropriateness for its intended purpose; 2. dimensional consistency tests to verify that all significant variables are included and align with the research objectives; and 3. extreme conditions tests to examine the model's behavior under extreme scenarios, ensuring logical outcomes.

2.4.1. Comparisons between simulated values and historical data

Fig. 8 illustrates the comparison between the simulated values of price and market capacity and their actual historical values from 2020 to 2023, for assessing the accuracy of the developed model. Table 1 numerically demonstrates that the simulated errors are consistently within a 10% margin, which can confirm the validity of the model. However, there is a notable exception for the price of wood pellets in 2022, where the error reaches 44%. This large discrepancy can be attributed to the war between Ukraine and Russia, which has caused a significant surge in prices [34]. Fig. 7 illustrates the market capacity and wood pellet prices throughout the simulation period. All monetary values presented in the figures throughout this study are expressed in United States Dollars (USD).

Table 1
Simulated errors of Price and Market Capacity.

Year		2020	2021	2022	2023
Price	Error (%)	0.08	0.03	0.44	0.04
Market Capacity	Error (%)	0.002	0.10	0.02	0.07

2.4.2. Testing boundary adequacy, structural Verification, and dimensional consistency

The model was verified for completeness and dimensional consistency using unit-checking functions to ensure accurate equation formulation. The results of this unit check are illustrated in Fig. 9. The boundary and structural assessment were performed by reviewing literature and consulting with subject matter experts.

2.4.3. Extreme condition test

The extreme condition validation test examines how increased inflation rates impact the cost of wood pellet production, which subsequently result in increased unit costs. These higher unit costs translate into higher wood pellet prices, diminishing their price competitiveness in the market. This loss of competitiveness ultimately leads to a decrease in market share. In Fig. 10, graph business as usual (BAU) illustrates the baseline scenario featuring a 2% inflation rate. The other graphs illustrate various inflation rates considered after 2034, showing that higher inflation rates affect the market share of wood pellets over time. The results align with real-world situations.

3. Simulation results

3.1. Base line scenario

The model is simulated over a period of 34 years, from 2020 to 2054. The years 2020 to 2023 are used for model validation by comparing the output with historical data. The simulation runs with a time step of one year, and the unit of time is years. The baseline scenario initiates from a balanced state (equilibrium) and maintains stability without introducing sensitivity analysis or external disruptions (represented as BAU in graphs). This provides a reference point for comparing the impacts of future simulations that introduce more realistic complexities. Fig. 11 displays the simulated outcomes of the baseline scenario. Fig. 11-c illustrates market saturation trends across the planning horizon, values below 100% indicate unsaturated markets, while those above indicate greater saturation severity. This graph underscores that integrating a bio-hub into the WPSCs could potentially increase Canadian wood pellet market share by approximately 50%. Fig. 11-b illustrates the potential export capacity driven by wood pellet quality and price, alongside actual wood pellet exports influenced by market saturation. In unsaturated markets, the bio-hub leverages potential exports. However, in saturated markets, its leverage diminishes, leading to reduced exports proportional to saturation severity. Fig. 11-c, Fig. 11-d, and Fig. 11-es depict bio-hub production, export, and profit, as well as wood pellet storage and feedstock inventory, respectively.

3.2. Other scenarios and sensitivity analysis

This section presents simulations and sensitivity analyses designed to examine supply- and demand-side impacts within the supply chain. Using global market share as a benchmark for WPSC resilience, the analysis evaluates the bio-hub's role in enhancing system stability. In all figures, the BAU graph represents the baseline scenario.

3.2.1. Demand side scenarios

Sensitivity Analysis 1) The first scenario analyzes how fluctuations in the economies of importing countries between the years 2030 and 2040 in the simulation period might influence the demand for wood pellets and, consequently, the performance of the bio-hub in the global wood pellet market. The analysis explores four specific scenarios, a 40% and 20% increase, as well as a 40% and 20% decrease, in importing countries' GDP. These scenarios represent potential economic growth or decline due to factors such as economic expansions or recessions (Fig. 12).

Fig. 12-a illustrates that market capacity for wood pellets rises with higher GDP in importing countries, as increased demand drives prices

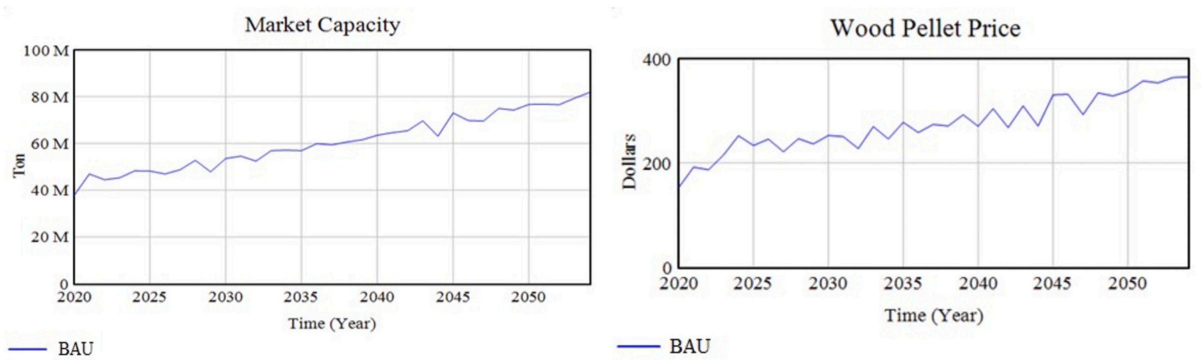


Fig. 7. Market capacity and wood pellet price in base line scenario.

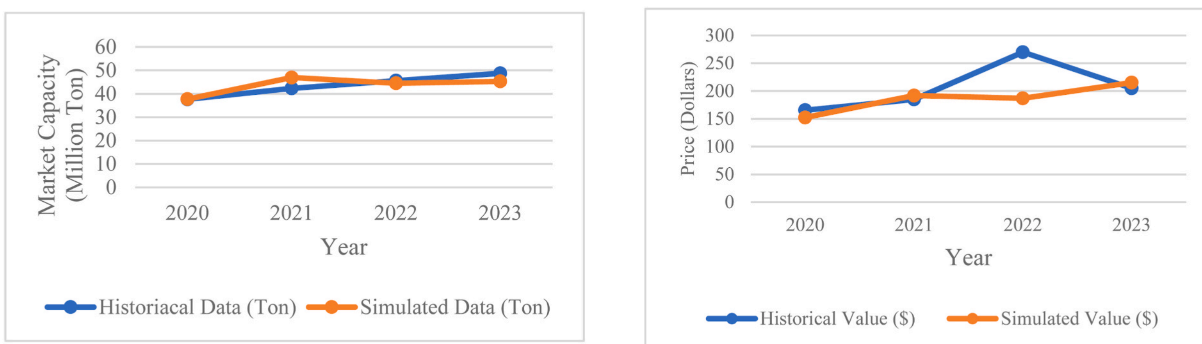


Fig. 8. Simulated and historical value of price and market capacity.

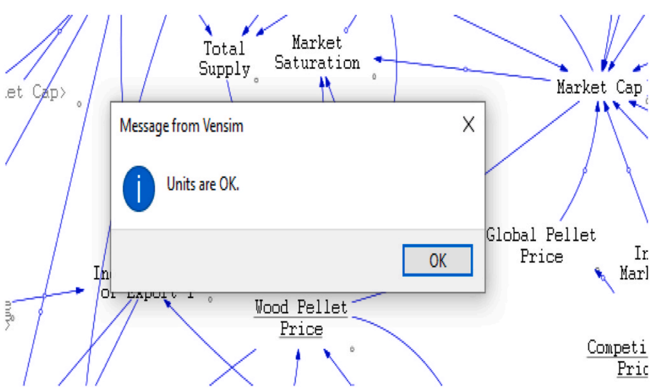


Fig. 9. Result of unit check.

up, allowing the bio-hub to capture a larger market share. Conversely, declining GDP reduces demand and market share. Fig. 12-d shows bio-hub inventory dynamics over the simulation period. The 2030 demand surge is initially met using stock reserves, but a temporary shortage occurs in 2033 (Fig. 12-e) due to the model's one-year feedstock supply delay, which depletes the safety stock. Once feedstock supply catches up, inventory stabilizes, enabling the bio-hub to recover quickly and maintain adequate stock for the remaining period.

Table 2 presents additional parameters from the GDP sensitivity analysis, highlighting the critical role of the bio-hub in supporting long-term profitability and market stability in Canadian WPSCs. In the baseline scenario, the supply chain sustains 14 saturated markets, 16 years with market share (MS) above 50%, an average MS of 51.89%, cumulative export losses of 22.5 million tons, and a net present value (NPV) of 16.65 billion USD. Even under a severe recession (−40% GDP over 10 years), the average MS remains 42.73% and NPV stays positive, indicating system profitability. In higher GDP scenarios (+20% and +40%), the bio-hub enhances performance by reducing market saturation, maintaining ~50% global market share, and extending years with MS above 50% to 20, despite 10 saturated markets. These results underscore the bio-hub's capacity to stabilize Canadian wood pellet exports under varying economic conditions.

Sensitivity Analysis 2) One of the most critical factors influencing the wood pellet market is the fluctuating price of fossil fuels. Fig. 13 shows the wood pellet market conditions and the bio-hub's performance under varying fossil fuel prices to assess its resilience and market effectiveness. The fossil fuel price sensitivity analysis figures also follow the same benchmarks as the GDP scenarios. However, in the fossil fuel scenario, there are no shortages, and bio-hub consistently meets the surge in demand driven by fluctuating fossil fuel prices, ensuring the resiliency of WPSCs.

Table 3 presents the sensitivity analysis of global fossil fuel price (FFP) fluctuations. Under a 40% decrease in FFP over 10 years, the number of saturated markets rises to 17, indicating lower market capacity and a greater tendency for fossil fuel usage. The bio-hub continues to hold its market share at an average of 48.79%, despite the growing competition in saturated markets. This percentage remains notably high. Conversely, when fossil fuel prices increase by 20% and 40%, importing countries are encouraged to adopt more renewables. The bio-hub prevents market shortages and fulfills the increasing demand, leading to a decrease in saturated markets to 10, a greater average market share of around 52.74%, and decreased cumulative export losses ranging from −10% to −1%, demonstrating its potential for maximum export. As a result, the number of years with a market share above 50% increases to 18 years, and the NPV improves significantly by up to 16%. This underscores the bio-hub's ability to capitalize on export opportunities and maintain a high market share, ensuring long-term profitability and stability in fluctuating global fossil fuel markets.

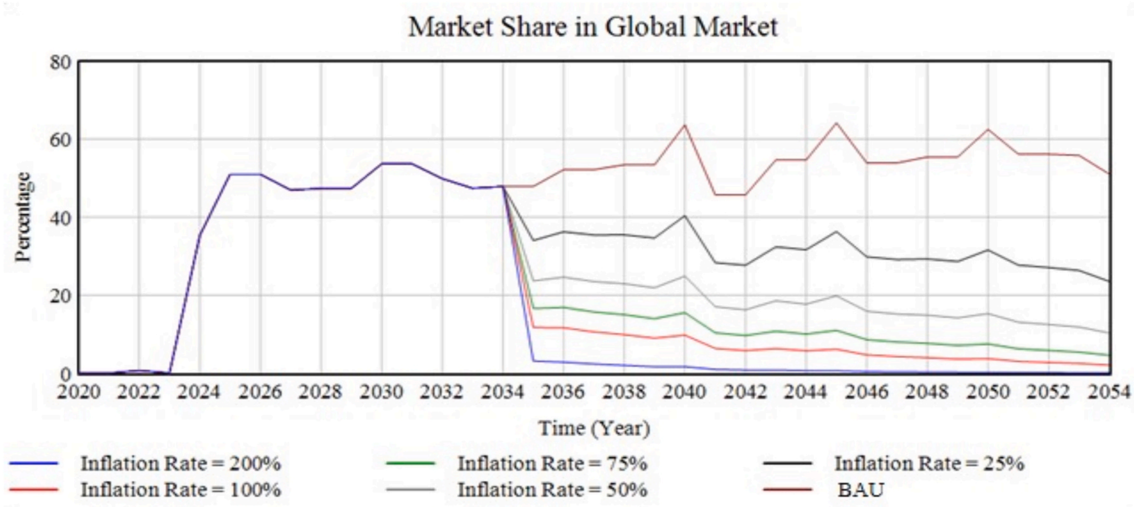


Fig. 10. Extreme condition test: inflation rate.

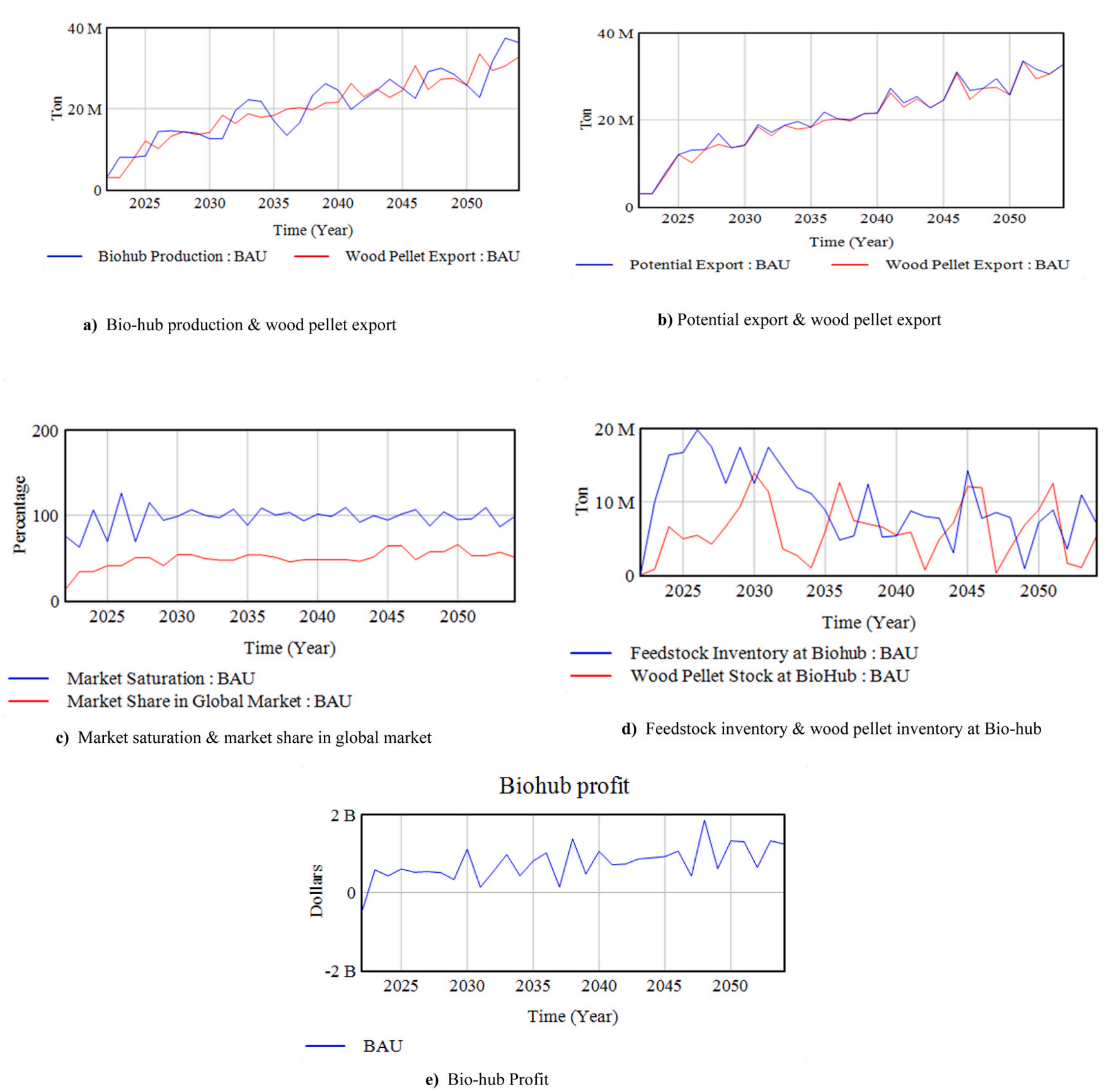
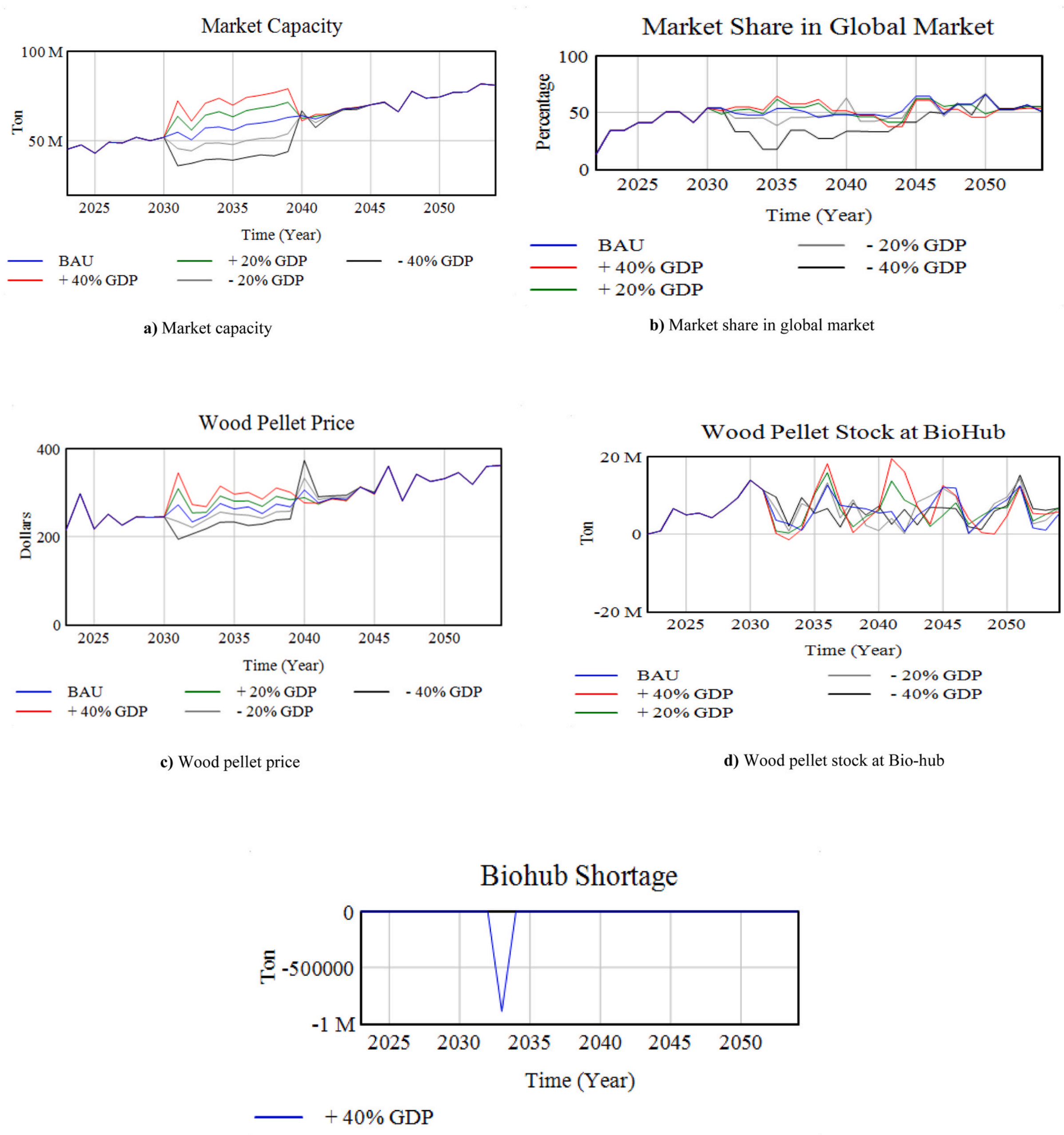


Fig. 11. Baseline scenario outcomes.



a) Market capacity

b) Market share in global market

c) Wood pellet price

d) Wood pellet stock at Bio-hub

e) Bio-hub Shortage

Fig. 12. GDP scenarios analysis.

3.2.2. *Supply side scenarios*

Wood pellet production is often affected by supply chain disruptions, impacting raw material availability. This section examines the role of bio-hubs in enhancing WPSC resilience under varying scenarios. Fig. 14-a illustrates bio-hub shortages, showing the gap between potential supply under uninterrupted conditions and actual supply affected by feedstock disruptions. Under a severe 50% feedstock reduction over a 10-year period starting in 2030, the bio-hub maintains supply for the first three years, with a notable shortfall in 2033 due to ongoing disruption. Subsequently, shortages gradually diminish as the bio-hub adapts. Less severe scenarios, a 25% reduction (green) and no reduction baseline (blue), experience milder and shorter-lived shortages. While larger inventories improve resilience to prolonged disruptions, they increase storage costs, raise prices, and reduce market competitiveness. Overall, the bio-hub demonstrates an ability to mitigate supply disruptions while balancing operational trade-offs. Fig. 14-b shows the bio-hub's global market share under different feedstock disruption scenarios over the simulation period. Even with severe supply reductions, the bio-hub maintains a relatively stable market position. In 2034, a notable decline of ~32% occurs under the 50% feedstock reduction scenario (blue line) due to a significant shortage, but market share gradually recovers in subsequent years. Table 4 presents a supply-side scenario analysis: a 25% feedstock reduction results in 4 years of shortage, lowering average market share to 48.95% and reducing NPV by 11% relative to the baseline. Under a 50% reduction, average market share falls to 46.86% and NPV by 19%, yet the bio-hub demonstrates resilience, maintaining profitability and market position despite significant disruptions.

Table 2
GDP scenario analysis.

Benchmarks Scenarios	Baseline Scenario	−40% GDP	−20% GDP	+20% GDP	+40% GDP
Saturated market years	14	16	15	11	11
Market share years >50%	16	10	13	17	20
Average Market Share (%)	51.89	42.73	50.42	51.96	52.80
Cumulative Export Loss (Ton)	22478200	+49%	+13%	−8%	−11%
NPV (Billion Dollars)	16.65	−24%	−13 %	+15%	+31%

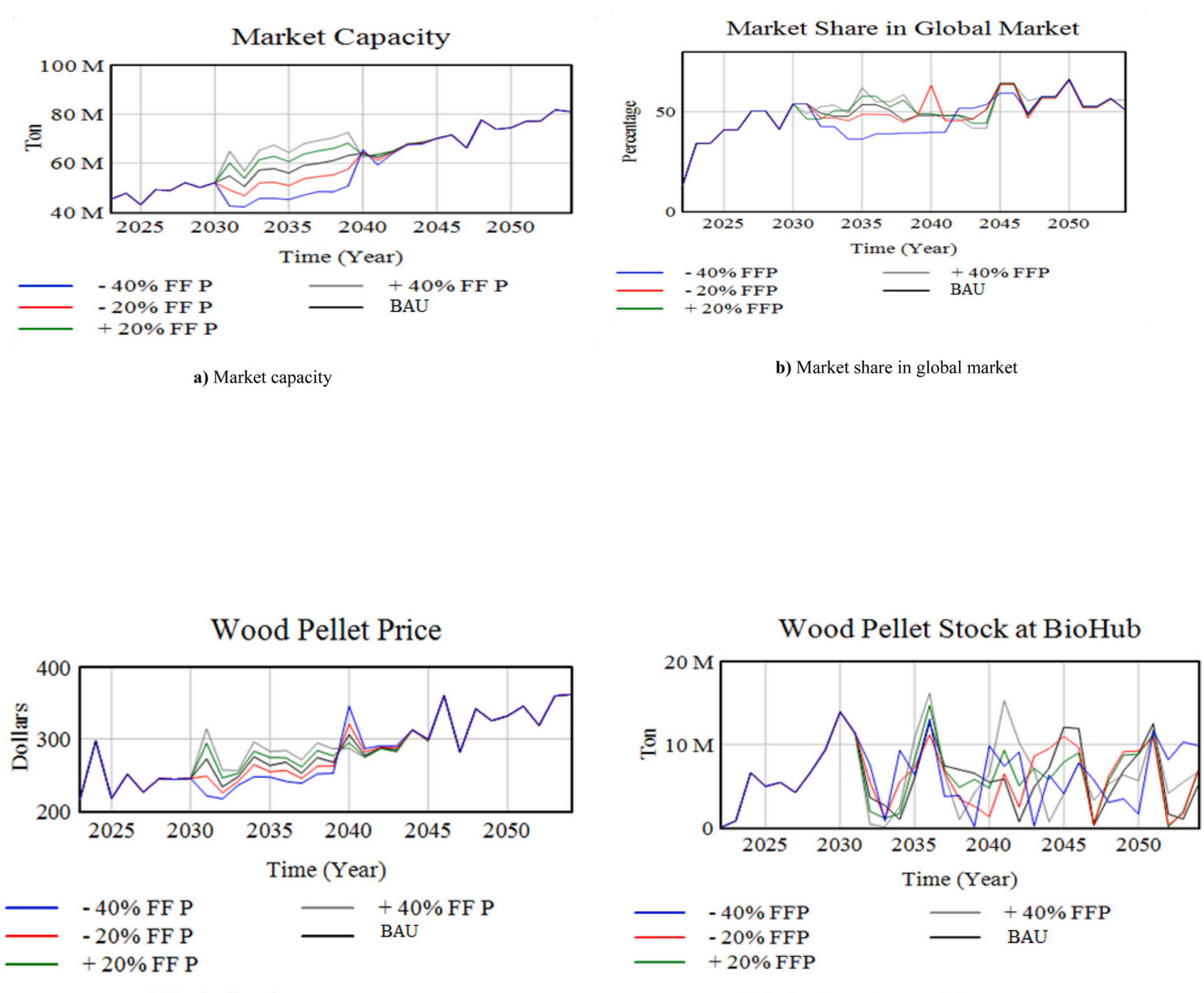
3.2.3. Product quality improvement scenarios

The potential for export hinges on price and quality competitiveness. Bio-hub, serving as a critical center, undertakes efforts to improve the quality of wood pellets. Here, we analyze the impact of bio-hub's quality enhancement measures on the market situation of Canadian wood pellet exports. To create a realistic model, we assume that increase in bio-hub's research and development (R&D) leads to improvements of the product (wood pellets) quality every five years and that the competitors are also motivated to update their products accordingly. Consequently, the effect of quality improvement is most pronounced in the year of introduction and gradually diminishes as competitors also enhance their product quality. Fig. 15 illustrates the market share of Canadian wood pellets in the global market and the NPV of bio-hub under various quality improvement scenarios over the years.

Table 5 demonstrates that in the baseline scenario, where 2% of each year's profit is allocated to R&D for quality improvement, the market share remains above 50% for 16 years, with an NPV of 16.65 billion dollars. Increasing the allocation rate to 5% extends the number of years

Table 3
Fossil fuel price analysis.

Benchmarks Scenarios	Baseline Scenario	−40% FFP	−20% FFP	+20% FFP	+40% FFP
Saturated market years	14	17	15	14	10
Market share years >50%	16	14	14	17	18
Average Market Share (%)	51.89	48.79	51.44	52.16	52.74
Cumulative Export Loss (Ton)	22478200	+45%	+33%	−1%	−10%
NPV (Billion Dollars)	16.65	−15%	−9 %	+7%	+16%



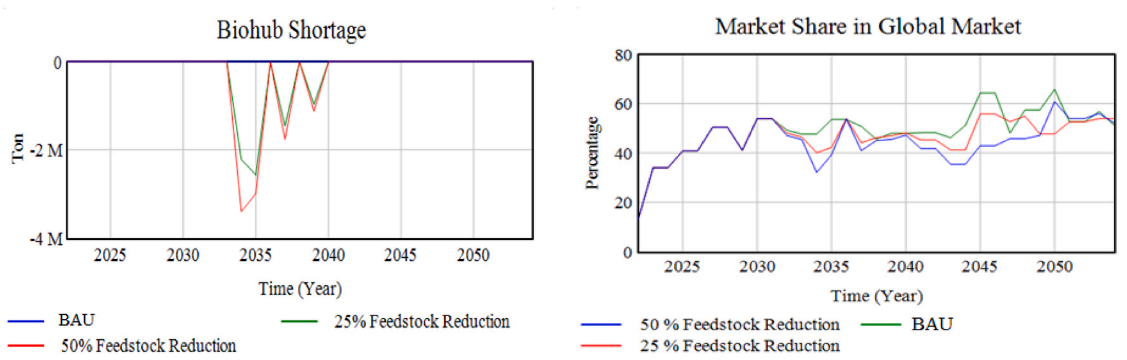
a) Market capacity

b) Market share in global market

c) Wood pellet price

d) Wood pellet stock at Bio-hub

Fig. 13. Demand side scenario analysis of fossil fuel Prices.



a) Bio-hub shortage

b) Market share in global market

Fig. 14. Supply side scenarios analysis.

Table 4
Supply side scenario analysis.

Benchmarks Scenarios	Baseline Scenario	−25% Feedstock Supply	−50% Feedstock Supply
The Number of Years with Bio-hub Shortage	0	4	4
Average Market Share (%)	51.89	48.95	46.86
NPV (Billion Dollars)	16.65	−11 %	−19 %

with a market share above 50% to 20 years and raises the NPV by 8%. Further increasing the allocation rate to 10% or 15% maintains the number of years above 50% market share at 21 years, with a 10% increase in NPV for both scenarios. These findings suggest that an allocation rate between 5% and 10% is optimal. This increased allocation leads to higher wood pellet exports, assuming market capacity remains constant, directly resulting in a higher market share. This analysis underscores the effectiveness of the bio-hub as a critical intermediary for enhancing the market share of Canadian wood pellets.

4. Discussions

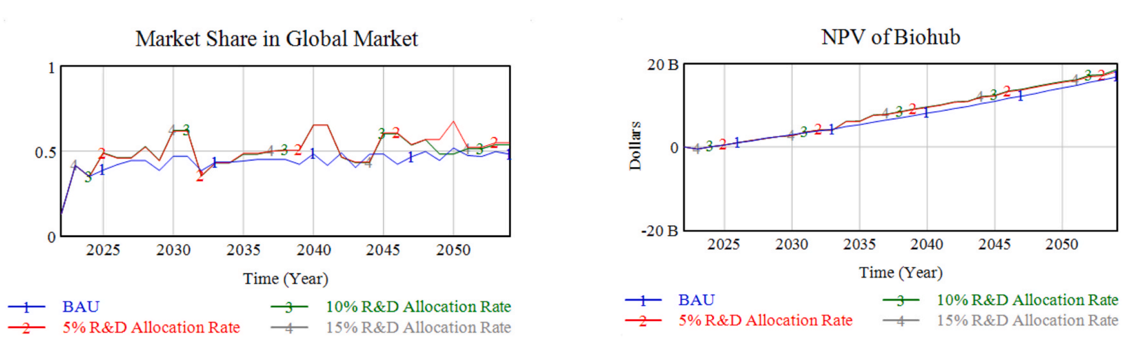
The simulation results provide several insights into the role of bio-hubs in enhancing the resilience and competitiveness of Canadian wood pellets in the global market. Previous studies, such as [35], suggest that terminal-based systems may increase costs due to storage and transportation inefficiencies. In contrast, bio-hubs benefit from economies of scale, making them well suited for large-scale production and international distribution. While direct supply chains may remain cost-effective for local markets, bio-hubs offer clear advantages over long distances and are therefore strategic assets in meeting rising global demand for renewable biomass energy. Although the global wood pellet market is policy-driven, particularly by the EU Renewable Energy Directive and UK renewable support mechanisms, these policy effects are implicitly reflected in market capacity, import demand, and price responsiveness in the model. The GDP and inflation scenarios are applied as proxy stressors to test the resilience of the supply chain under extreme demand-side conditions.

4.1. Demand-side factors

- **Economic fluctuations:** The model demonstrates that bio-hubs can effectively adapt to economic fluctuations in importing countries. Even under a 40% reduction in GDP, the market share declines by only 9% relative to the baseline, while the net present value (NPV) remains positive, indicating sustained profitability. Given that GDP levels strongly influence bioenergy demand in importing regions [36], this adaptive capacity is essential for maintaining market

Table 5
Quality improvement scenario analysis.

Benchmarks Scenarios	Baseline Scenario	5% allocation Rate	10% allocation Rate	15% allocation Rate
Market share years >50%	16	20	21	21
Average Market Share (%)	51.89	53.09	53.534	53.536
NPV (Billion Dollars)	16.65	+8 %	+10 %	+10%



a) Market share in global market

b) NPV of Bio-hub

Fig. 15. Quality improvement analysis.

stability under global economic uncertainty. This finding is consistent with [11], which demonstrated that system dynamics models of biomass supply chains can effectively capture the buffering capacity of centralized nodes against macroeconomic shocks, reinforcing the robustness of bio-hub integration as a strategic response to demand-side uncertainty.

- **Fossil fuel dynamics:** Sensitivity analysis of fossil fuel prices shows that bio-hubs can maintain market share despite fluctuations in competing energy markets that influence overall market capacity. This adaptability is critical for long-term viability. Based on a structural analysis of the Austrian wood pellet market [37], wood pellet demand is relatively price-inelastic with respect to competing energy sources, suggesting that demand tends to persist even when fossil fuel prices shift. Consistent with this finding, our results show that bio-hubs can exploit this inelasticity to maintain stable export volumes and market share even under significant fossil fuel price variations of ±40%. Moreover, the potential repurposing of existing fossil fuel refineries for biomass processing can significantly expand the market for biomass pellets [38], reducing reliance on fossil fuels and supporting the transition toward a bio-based economy. These findings collectively highlight the bio-hub's strategic role in ensuring a reliable and sustainable energy supply under volatile energy market conditions.
- **Wood pellet demand in importing countries:** Wood pellet demand in importing countries is relatively inelastic, making markets sensitive to price changes arising from supply shocks [37]. The bio-hub mitigates these effects by buffering supply fluctuations, preventing sharp price increases during periods of demand growth or supply disruption. Through inventory management and flexible production adjustments, bio-hubs enhance market resilience and provide importers with a stable and predictable supply, thereby strengthening confidence in the supply chain.

4.2. Supply-side factors

- **Feedstock supply disruptions:** Integrating bio-hubs into WPSCs significantly improves resilience to feedstock disruptions. Conventional systems often struggle in large markets due to high logistical costs associated with sourcing from remote or low-yield areas [39]. Simulation results show that bio-hubs can sustain operations for up to three years without shortages under severe conditions, such as a 50% reduction in feedstock availability. Centralized preprocessing and an expanded sourcing radius enable a steady biomass flow, reinforcing supply security and supporting sustainable energy production. These results extend the findings of [40], which demonstrated that centralized biomass depot strategies reduce supply interruptions, by showing that bio-hubs provide an additional layer of market-level resilience beyond operational continuity alone.

4.3. Quality improvement and market expansion

- **Quality improvement:** Scenario analysis indicates that allocating 5–10% of annual profits to R&D for quality improvement yields optimal outcomes. This investment prolongs periods in which market share exceeds 50% and increases NPV by up to 10%, highlighting the importance of continuous quality enhancement. Key quality attributes, such as ash and moisture content, are critical for meeting U.S. and European standards, with deviations potentially reducing production by 13.6% to 48.3% [41]. By investing in R&D, bio-hubs can better manage quality-related uncertainties, comply with stringent standards, and maintain competitiveness in a policy-driven global market.
- **Market expansion:** The model indicates that bio-hubs can increase the market share of Canadian wood pellets by up to 50%, revealing substantial opportunities for market expansion. This capacity supports Canada's ability to meet growing global demand for renewable energy. Expanding applications in power generation, steelmaking, and district heating further strengthen this potential [42], underscoring the strategic importance of bio-hubs in positioning Canada as a major supplier. This aligns with [17], which identified North America as the primary wood pellet production region with significant untapped export potential. It is also consistent with [42], which projected growing global demand, particularly in power generation and industrial heat applications, in which Canadian bio-hubs are well positioned to compete.

4.4. Supply chain resilience

- Findings by one study [40] emphasize the role of advanced supply chain strategies, such as biomass depots, in mitigating disruptions and sustaining operational performance. Consistent with these findings, bio-hubs function as centralized nodes that store and preprocess biomass, reducing supply interruptions and enhancing operational efficiency. The simulation results show that bio-hubs minimize shortages even under significant disruptions and recover rapidly from demand surges driven by economic growth in importing countries. Shortages occur only briefly under prolonged disruption scenarios, followed by rapid recovery. Through this buffering function, bio-hubs reduce market volatility, stabilize supply flows, and strengthen the resilience and competitiveness of Canadian WPSCs in the global wood pellet market.

5. Conclusions

Wood pellets have become an important global commodity in the renewable energy sector, with demand expected to grow as countries adopt stricter bioenergy targets. Canada's abundant forest resources position it well to benefit from this expansion. However, WPSCs face challenges such as feedstock disruptions and demand uncertainty. Managing these issues is essential for long-term stability and sustainability. Bio-hubs offer a potential solution, yet their effectiveness within WPSCs has not been systematically studied. To address this gap, this study develops an SD model to evaluate the role of bio-hubs in enhancing the resilience and competitiveness of Canadian wood pellets in the global market.

The model captures supply chain complexity, market dynamics, and interactions with related markets. Results indicate that Canada could capture nearly 52% of the global wood pellet market, with bio-hubs mitigating supply disruptions, adapting to market fluctuations, and maintaining competitiveness. Under a severe 50% feedstock reduction, market share temporarily drops ~32% but recovers, while less severe reductions cause smaller, shorter shortages. Fossil fuel price increases raise average market share to 52.7%, whereas decreases reduce it to 48.8%. Even under a −40% GDP shock, average market share remains 42.7%, while higher GDP (+20–40%) sustains ~50% market share and extends years above 50% to 20 years. These results highlight the bio-hub's ability to stabilize exports, buffer inventories, and sustain Canada's position in the global market under diverse adverse conditions.

The main contribution of this study is its integrated modeling approach, which links forest ecosystem dynamics, global market demand, and the strategic role of bio-hubs. This holistic perspective highlights how bio-hubs improve resilience, cost efficiency, and market positioning compared to traditional supply chains. By enabling economies of scale, flexible production, dual storage for feedstock and finished pellets, and continuous quality control, bio-hubs support stable supply, competitive pricing, and consistent product quality.

Overall, bio-hubs represent a promising strategy for strengthening Canada's role in the global wood pellet market and advancing sustainable WPSCs. Future research should focus on social impacts such as community engagement and job creation, as well as the role of government policies and incentives in supporting bioenergy development. Given strict international quality standards, further studies should also examine how bio-hubs can adapt to evolving regulations and ensure long-term competitiveness in the global market. Additionally, future research should incorporate residues generated during pellet production, such as sawdust and wood fines, which were considered outside the system boundary of the current model.

CRediT authorship contribution statement

Omid Mohagheghi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fereshteh Mafakheri:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing. **Fuzhan Nasiri:** Conceptualization, Formal analysis, Resources, Software, Supervision, Writing – review & editing. **Bruno Gagnon:** Conceptualization, Resources, Validation, Writing – review & editing. **Robert Prinz:** Conceptualization, Formal analysis, Validation, Writing – review & editing. **Dan Bergström:** Conceptualization, Formal analysis, Resources, Validation, Writing – review & editing. **Mark Brown:** Conceptualization, Formal analysis, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge funding from Natural Sciences and Engineering Research Council of Canada (Grant no. RGPIN-2019-07086) and the International Energy Agency (IEA) Task 43.

Appendix

Table A.1
List of symbols and abbreviations

symbols/abbreviations	Description	Unit
SD	System Dynamics	-
WPSCs	Wood Pellet Supply Chains	-
BSCs	Biomass Supply Chains	-
CLD	Causal Loop Diagram	-
SFD	Stock – Flow Diagram	-
C	Initial Value	Tonnes
ΔGDP	Differences in GDP	-
ΔFFP	Differences in Fossil Fuel Price	-
ΔGWPP	Differences in Global Wood Pellet Price	-
ε_{GDP}	GDP Elasticity	-
ε_{FP}	Fossil Fuel Price Elasticity	-
ε_{WP}	Wood Pellet Price Elasticity	-
$GWPM$	Global Wood Pellet Market Capacity	Tonnes
MS	Market Saturation	-
TS	Total Supply	Tonnes
WPP	Wood Pellet Price	USD/ton
UC	Unit Cost	USD/ton
M	Profit Margin	-
E	Export Volume	Tonnes
CP	Competitor's Price	USD
EE	Expected Export	Tonnes
RA	Regenerated Area	Hectare
DA	Disturbed Area	Hectare
RT	Regeneration Time	Years
IA	Initial Disturbed Area	Hectare

Table A.2
Data sources used in the study

Data	Source
Burning Rate	White et al., 2017
Insect-Damaging Rate	White et al., 2017
Harvesting Rate	White et al., 2017
Regeneration Time	White et al., 2017
Biomass Recovery Rate	Mansuy et al., 2015
Biomass Density of Burned Area	Mansuy et al., 2018
Biomass Density of Primary Residues	Mansuy et al., 2018
Biomass Density of Disturbed by Insects	Mansuy et al., 2018
Unit Storage Cost (Considered within Storage Cost)	Sultana et al., 2010
Unit Pelletizing Cost (Considered within the Pelletizing Cost)	Sultana et al., 2010
Unit Transportation Cost (Considered within the Transportation Cost)	Sultana et al., 2010
Marshallian price elasticity (Fossil Fuel Elasticity)	Sun & Niquidet, 2017
Expenditure Elasticity (GDP)	Sun & Niquidet, 2017

(continued on next page)

Table A.2 (*continued*)

Data	Source
Price Elasticity	Sun & Niquidet, 2017
Newly Treed Area	Government of Canada, 2021
Historical Wood Pellet Price & Market Capacity	Statista Research Department, 2024

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