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Greenhouse Gas Emission Estimation Using Extended Input–Output Tables for Thailand's Biomass Pellet Industry

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Abstract: Greenhouse gas (GHG) emissions from Thailand's biomass pellet production were comprehensively assessed, with a specific focus on wood and corn pellets. Employing the extended input and output tables, the anticipated economic and environmental effects of the rising demand for biomass pellets within the Asia–Pacific Economic Cooperation region, which is projected to see an increase exceeding 33% by the year 2050, were investigated. The estimations of CO_2, CH_4, and N_2O emissions, which were conducted utilizing an open Leontief model based on the 2015 National Input–Output Tables, covered each stage of the production process. The results show that emissions from the production of corn pellets are expected to rise steadily, from 52.91 $MtCO_2e$ in 2022 to 75.77 $MtCO_2e$ by 2030, whereas emissions from wood pellet production are set to increase more substantially, from 210.30 to 301.18 $MtCO_2e$ within the same timeframe. Data derived from surveys and interviews with corn farmers and wood pellet manufacturers informed the lifecycle data for the biomass pellet supply chain from cradle to gate. The findings suggest that Thailand's power sector could benefit significantly from the biomass potential in the northern part of Thailand, which boasts an estimated energy content of corncob at 39 ktoe (0.0016 TJ). Market demand scenarios were explored in two forms: one where it was assumed that all biomass pellets are to be exported to Japan and South Korea, expecting a combined demand of approximately 560,262 tons by 2030, and another positing that 10% of production will be reserved for the domestic market, with a forecasted annual increase of 10% from 2020 to 2050. This paper highlights the need to prioritize low-emission renewable energy sources, expand technologies with lower lifecycle emissions, optimize the biomass supply chain to enhance efficiency, and introduce sustainable energy practices. The detailed GHG emissions analysis provides critical insights for policy formulation, underscoring the importance of sustainable transitions in the context of increasing biomass demand.

Keywords: biomass pellets; greenhouse gas emissions; life cycle; input–output analysis

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1. Introduction

In the late 20th and early 21st centuries, the demand for renewable energy (RE) has consistently increased worldwide, following an upward trajectory with an average annual growth rate of 4% [1]. The Asia–Pacific Economic Cooperation (APEC) region observed a notable 6% increase in RE demand in 2022 over the previous year, with predictions suggesting a continued 4% rise in 2023 [2]. In this context, the power generation sector, particularly within APEC nations utilizing solid fuels like coal and biomass pellets, leads in RE demand. The demand for renewable energy (RE), as reported by the Asia-Pacific Economic Cooperation (APEC), is expected to rise by over 33% among APEC members by 2050 compared to 2000 [3,4]. This significant growth in RE demand is propelled by the global push towards mitigating climate change, as outlined in the Paris Agreement's

objectives, such as achieving net zero emissions by 2050 and implementing carbon border taxes [5]. These initiatives have urged countries listed under both Annex I and Non-Annex I of the United Nations Framework Convention on Climate Change (UNFCCC) to implement robust GHG reduction strategies to meet their GHG reduction targets. The shift towards RE, particularly the adoption of biomass pellets for electricity generation by major importers like Japan and South Korea within APEC, underscores the critical role of GHG emissions in shaping energy policies [6,7]. Thailand was ranked in the top 5 APEC countries that significantly exported biomass pellets to Japan and South Korea [8]. According to the analysis of the Kasikorn Bank Research Center, in 2022, Thailand had an export volume of approximately 20,000 tons, accounting for about 2.0% of the market share. The cost per ton of product was around THB 4462.73. The Kasikorn Bank Research Center also forecasted total revenue from exporting this type of commodity in 2025, predicting that Japan will import approximately 209,000 tons of biomass pellets from Thailand due to the growth of biomass pellet power plants in Japan [9,10].

An analysis of the biomass pellet market in South Korea, published by the Department of International Trade Promotion in Seoul, reveals that the Renewable Portfolio Standard (RPS) increased the country's demand for biomass pellets as a substitute for solid fossil fuels in both conventional and biomass power plants. The country has continuously imported biomass pellets from Thailand since 2012. In 2022, South Korea imported approximately 409,233 tons of biomass pellets from Thailand at a cost per ton of around THB 3731.86 [11,12]. The analysis from the Kasikorn Bank also provides a forecast of the biomass pellets demanded by South Korea in 2025, predicting that the country may import around 232,000 tons of biomass pellets from Thailand.

As a significant exporter, it contributed to this dynamic by generating substantial revenue through biomass pellet exports, underscoring the economic impact of transitioning to RE. The anticipated increase in RE demand in Japan and South Korea's power sectors not only highlights a shift in energy consumption patterns but also points towards a strategic move to lower GHG emissions by reducing the reliance on fossil fuels. Moreover, the expected decline in biomass consumption in South Korea's power sector due to an expansion in solar PV capacity reveals a nuanced approach to achieving a sustainable energy mix, further aligning with GHG emission reduction goals. Thailand's energy strategy revisions, aiming for increased biomass fuel usage, reflect a broader commitment to both economic growth and environmental sustainability [13,14].

Most existing research has not adequately incorporated the biomass pellet industry into detailed economic models like input–output tables (IOTs). For example, Pruitichaiwiboon et al. [15] applied IOTs to construct energy IOTs to evaluate energy structural decomposition affected by the choice of energy from either side of energy demand and supply in South Korea. This study primarily examined energy consumption and GHG emissions from the demand side. The analysis considered 96.25% of major energy sources, including coal, crude petroleum, natural gas, and nuclear energy, while only 3.8% was considered from renewable resources such as wind and solar. Le Quyen Luu et al. [16] applied a hybrid multi-regional input–output approach for quantifying and assessing the life cycle GHG and other air emissions in Italy and its electricity sector. This study focused only on the power sector, and more than 90% of the considered electricity generation was from oil, natural gas, and solar energy.

This omission leaves a gap in understanding how shifts in the biomass pellet market specifically affect the broader economy and environmental outcomes. This study extends the existing input and output tables to incorporate the biomass pellet industry, offering a unique lens through which the economic and environmental implications of RE demand shifts can be analyzed. By integrating the open Leontief model, this research not only explores the economic impacts within the biomass pellet sector but also highlights the pivotal role of GHG emissions in driving policy decisions and market trends. The extended analysis of GHG emissions in response to shifts in RE demand provides invaluable insights

for policymakers and industry stakeholders, emphasizing the importance of sustainable energy transitions in mitigating climate change impacts.

2. Methods

As mentioned in the previous section, the primary objective of this research was to examine the GHG emissions of Thailand's biomass pellet industry in response to fluctuations in market demand, focusing on both wood pellets and corn pellets. The study estimated three types of GHG emissions—CO_2, CH_4, and N_2O—associated with the consumption of input materials at each stage of the production process. The 2015 National Input–Output Tables, published by the Office of the National Economic and Social Development Council (NESDC), were applied to enhance the input–output framework of Thailand's biomass sector [17]. An overview of the research methodology is shown in Figure 1. Data on inputs and outputs across the supply chain were collected through surveys and interviews. The details of input and output data will be presented in Section 3.

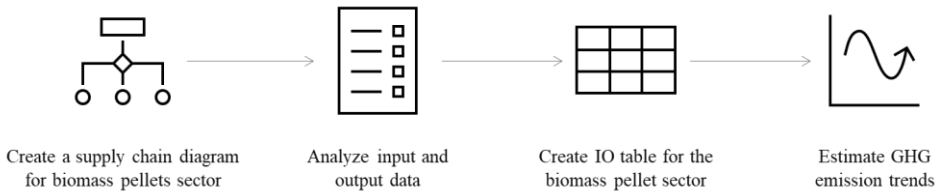


Figure 1. Process flow for the study.

For the production of corn pellets, Nan province was chosen as a demonstration province for developing the corn pellet supply chain diagram due to three major biomass pellet exporters being located in the province, enabling the study to cover the entire production process. The concept of developing a biomass supply chain diagram was considered to create a comprehensive process [18–25]. A template for data collection was distributed among groups of corn farmers to gather details regarding corn planting and sorting techniques. Moreover, four interview sessions were held to interact with both commercial and non-commercial corn pellet producers, with the objective of understanding their operational processes. For the production of wood pellets, this research incorporated findings from a survey conducted by Saosee et al. [26] aimed at obtaining insights into the wood pellet supply chain in Thailand. All collected input data served as the foundation for creating a diagram illustrating the biomass pellet supply chain. The operational boundary of corn pellet production focused on in this research covered four processes: corn growing, sorting, transportation of the product, and pellet production. Inputs and outputs of export products to other areas and import products from other areas were not considered in this research. The data collected during the data collection process were used as raw data for analyzing the input and output quantities of each process. Operational data from each process was organized into three main categories: raw material usage, energy consumption, and water supply. Financial data was categorized into four distinct groups: energy expenses, raw material costs, labor expenses, and transportation expenditures. An illustration of the entire process and inventory list of corn pellet production is shown in Figure 2.

This research considered wood pellets from both fast-growing and Para rubber trees. Wood logs harvested from fast-growing trees are directly sent to pellet manufacturing facilities as raw material. Conversely, wood logs from Para rubber tree plantations are transported to the Para rubber wood industry for plywood production. Only wood waste generated by the process (e.g., wood chips and sawdust) is sent to the pellet manufacturer. This research did not consider the input and output items of the Para rubber wood industry, as they were outside the operational boundary. The flow process for the production of wood pellets is depicted in Figure 3.

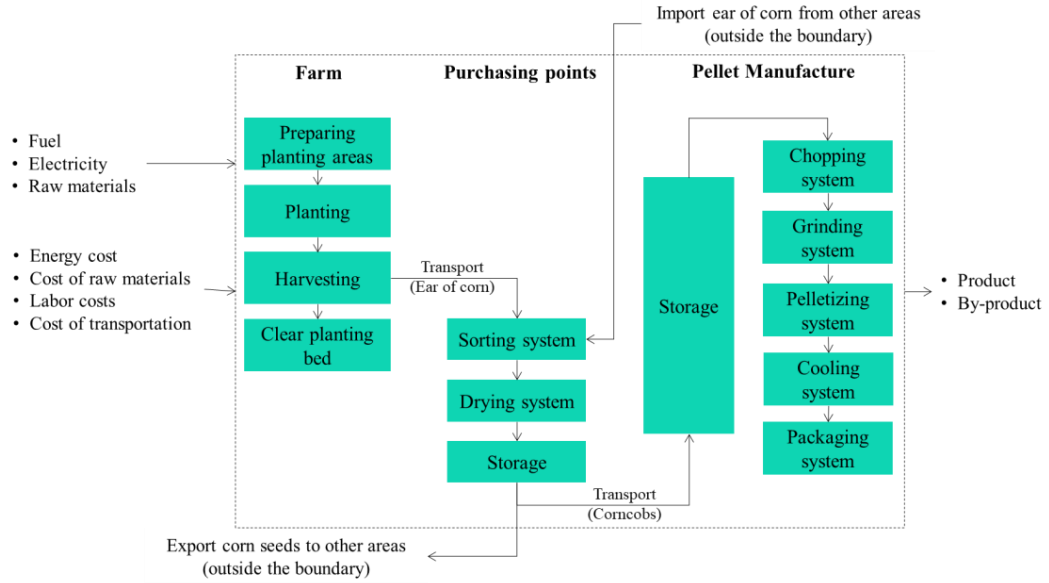


Figure 2. Process flow of production of corn pellets.

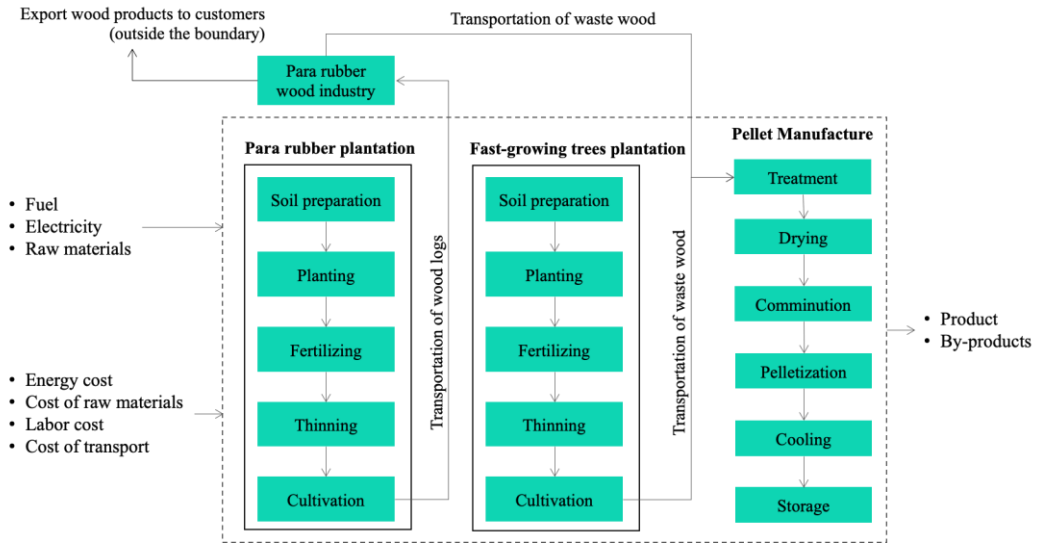


Figure 3. Process flow of production of wood pellets.

The data obtained from the preceding tasks were sorted into two categories: input and output. Inputs encompass raw materials, energy, and labor, whereas outputs consist of biomass products, generated energy, and its by-products. Employing a material balance approach, alternatively known as a mass balance approach, facilitated the calculation of input quantities per production unit. The raw data collected from the research conducted by Saosee et al. [26] were incorporated to develop a supply chain diagram for wood pellets. The research team developed a survey form and distributed it among eight targeted wood pellet manufacturers to gather operational data. The calculation of GHG emissions from fuel and electricity consumption utilized the IPCC Tier 2 approach [27]. Country-specific emission factors were sourced from the emission factors published by the Thailand Greenhouse Gas Management Organization [28]. The emission factors, measured in $kgCO_2e$ per unit of input, were applied to the activity data to derive the total GHG emissions in tCO_2e for each stage of the production process. Developing biomass input–output tables for Thailand's biomass pellet sector entailed gathering data on the various inputs and outputs associated with biomass production and utilization in the country. This undertaking typically involved a blend of data collection, analysis, and structuring. Data organization

was achieved using a matrix format. Guidance for this process was drawn from the Eurostat Manual of Supply, Use, and Input–Output Tables issued by the Statistical Office of the European Communities [29]. Monetary data obtained from the data collection stages were categorized based on input–output identification codes published by the Office of the National Economic and Social Development Council of Thailand. Sources of data for biomass pellet IOTs are shown in Table 1.

Table 1. Data sources for the development of biomass pellet IOTs.

Category	Data Sources	Details
Biomass pellets sector	Eurostat Manual of Supply, Use, and Input–Output Tables	- Core principle for constructing use and supply tables - Process of IOT development
	Office of the National Economic and Social Development Council (NESDC)	- Thailand Input–Output Tables (version 2010)—180 × 180 economic sectors - Input–output classification - Input–output identifier

The IO model's framework comprised four sections: (1) industries selling their products to other industries, (2) the primary input factors of the selling sector (e.g., labor cost, capital cost, and import cost), (3) the intermediate user sectors/industries purchasing products from the selling sector, and (4) sectors representing final demand. The structure of the IO model is shown in Table 2.

Table 2. A simplified structure of the IO model.

Selling Sector	Purchasing Sector					Final Demand (F)				Total Output (X)
	1	2	3	...	n	H	G	I	E	
1	z_{11}	z_{12}	z_{13}	...	z_{1n}	h_1	g_1	i_1	e_1	X_1
2	z_{21}	z_{22}	z_{23}	...	z_{2n}	h_2	g_2	i_2	e_2	X_2
3	z_{31}	z_{32}	z_{33}	...	z_{3n}	h_3	g_3	i_3	e_3	X_3
...	...	...	...	...	...	...	...	...	...	...
N	z_{n1}	z_{n2}	z_{n3}	...	z_{nn}	h_n	g_n	i_n	e_n	X_n
Labor	l_1	l_2	l_3	...	l_n					L
Capital	k_1	k_2	k_3	...	k_n					K
Government	O_1	O_2	O_3	...	O_n					O
Import	m_1	m_2	m_3	...	m_n					M
Total supply (Z)	Z_1	Z_2	Z_3	...	Z_n	H	G	I	E	

In general, let X_1, X_2, ..., X_n represent the total output of industries that produce products and supply them to the biomass pellet industry. z_{ij} is the value in monetary units of the delivery from industry I to industry j in a certain period for a certain economic system. Z_j is the total value of all inputs needed by the industry j. For the primary input factors, l_j represents labor costs of industry j. k_j is the capital cost of industry j. O_j is payments to the government by industry j, and m_j is import costs of industry j. For the section of final demand, h_i stands for the value of consumption by households of goods from industry i. g_i is purchased by the government of goods from industry i. i_i is purchased as an investment from industry I, and e_i is the export by industry i. In the IO model, the matrix equation depicts the net output of goods and services needed to satisfy industrial demand. Central to this method are the inter-sectoral direct requirements. Subsequently, matrix computation is employed to delineate a commodity system. Following the framework developed by Leontief and detailed by Miller and Blair [30–32], element z_{ij} of commodity sector A indicates the input value necessary in commodity sector I to produce sector J. To streamline the process, the matrix can be expressed as Equation (1), where A represents the

input and output matrix of an economic system, F denotes the external demand vector, and X signifies the production level vector.

$$A = \begin{bmatrix} z_{11} & \cdots & z_{13} \\ \vdots & \ddots & \vdots \\ z_{31} & \cdots & z_{33} \end{bmatrix}, \; X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \; F = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}, \tag{1}$$

The matrixes in Equation (1) are related according to Equation (2):

$$X = AX + F \tag{2}$$

The total output value of a commodity sector is the sum of final demand F and intermediate demand AX, which can be written by Equation (3):

$$X - AX = F$$

$$(I - A)X = F \tag{3}$$

where I is $n \times n$ identity matrix represented by

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The Leontief model serves as a comprehensive economic framework for analyzing entire countries or regions. Within this model, n industries generate n distinct products, ensuring that input equals output, implying that consumption matches production. In the case of the open Leontief model, some production is consumed internally by industries, while the remainder is consumed by external industries. This model yields production levels based on given external demand. Denoting the industries, the exchange of products is delineated through input and output data. The sectoral output in exogenous demand X is obtained by multiplying Equation (3) with $[I - A]^{-1}$:

$$X = [I - A]^{-1}F \tag{5}$$

Four datasets necessary for calculation according to the aforementioned formula were compiled. The first dataset, the intermediate transaction (matrix A), was derived from the preceding activity. Secondly, a 45×45 matrix (matrix I) was generated. Thirdly, the Leontief inverse matrix, also known as $(I - A)^{-1}$, was computed. Lastly, a demand matrix (matrix F) was constructed. The demand matrix was formulated to account for two scenarios: in the first scenario, there was an escalation in biomass pellet demand in the South Korean and Japanese markets, while the second scenario was shaped by national forecasts of biomass pellet demand. The quantity of biomass pellet demand in Japan and South Korea projected by the Kasikorn Research Center and the Office of Foreign Trade Promotion in Seoul was used as demand in the international market. Scenario 1 presupposed that all biomass pellets manufactured in Thailand will be exported to Japan and South Korea, as projected by the Kasikorn Research Center and the Office of Foreign Trade Promotion in Seoul. Conversely, the second scenario posited that 10% of total production will be allocated to the domestic market, with the remaining 90% destined for international markets. This scenario was derived from an assessment of wood pellet demand informed by importer policies and the Thai government's indication that biomass pellet demand in Thailand will increase by 10% annually from 2020 to 2030.

3. Results and Discussions

3.1. Create a Biomass Pellet Supply Chain Diagram

As mentioned in the methodology section, Nan province was selected as the demonstration province for the development of the corn pellet supply chain diagram due to three commercial biomass pellet manufacturers that export to the international market being located in the province. This made it convenient to gather data and ensure the research covers the entire process. A data collection survey form was developed and disseminated among the Na Noi Agriculture Cooperative members in Nan province of Thailand to obtain insights into their corn farming practices. Of these, fifty-five corn farmers returned the completed surveys and agreed to partake in a follow-up interview session. This session was split into two separate occasions. Detailed interviews were conducted with fifty-five corn farmers and two officials from the Office of Agricultural Economics in Nan province to delve into their corn cultivation methods, operational practices, and data. Based on input information from the interview, the process of corn cultivation begins with the preparation of the planting areas, where corn farmers enlist agricultural services for groundwork. Once the land is ready, corn seeds are sown. Early growth is enhanced, and the application of fertilizers and pesticides controls weeds. About four months are typically required for corn to mature. The harvesting of the crop is usually completed over a span of four to five days, with the collection of the corn ears from each field requiring at least three individuals. Once harvested, the corn ears are then transported to a sorting facility while others clear the farm area and prepare it for the next planting cycle. In the sorting facility, the corn is separated into two main products: corn seeds (88%) and corncobs (12%). These products are subsequently transported to a drying system to reduce their moisture content before storage. When the in-house raw materials are found to be insufficient to maintain production capacity, plant owners import additional corn ears from other regions.

The canning and preserving industry is usually where corn seed is consumed. The manufacture of biomass pellets is typically where most corncobs are utilized, with the remainder being consumed by the animal food industry. The allocation of corncobs between pellet plants and the animal feed industry is not fixed and depends on the purchase prices offered by buyers. Therefore, this research assumed that all corncobs are used as raw materials for the palletization of corn. The corncob is subjected to chopping and grinding systems at the pellet manufacturing stage to reduce its size. The fine particulate is then conveyed to the pelletizing system. The temperature of the product in this process varies from 100 to 120 °C. The product is introduced into a cooling system to reduce its temperature before being transferred to the packaging system.

For the wood pellet production process, fast-growing trees (Leucaena and Acacia) are used as raw materials by the first four plants for producing wood pellets, while the remaining four plants utilize waste wood from the Para rubber wood industry as raw materials. Wood pellet production is interconnected with three main aspects: tree plantation, the wood industry, and pelletizing. The tree plantation process comprises five steps, starting with soil preparation and monitoring of the initial step in wood plantation. Sprouts are needed as raw materials for tree planting, alongside fertilizers and pesticides for tree growth and weed removal. Diesel is consumed in transportation and operating agricultural machinery. Electricity is consumed in self-storage and small warehouses. A seven-year-old Para rubber tree can produce Para rubber latex, and these trees are typically felled when they reach twenty-five to thirty years of age. Para rubber logs are usually sent to Para rubber wood factories to be transformed into plywood. In comparison, fast-growing trees (FGTs) have a shorter life cycle, ranging from five to fifteen years. The production of wood pellets comprises six stages: treatment of raw materials, drying system, comminution system, pelletization, cooling, and packaging and storage. The demand for workers is determined by the scale of the plant. For example, the operation of a plant with an annual production capacity of 7840 tons requires five workers to manage.

3.2. Analysis of Input and Output Data

The annual production of the three pellet manufacturers is 55,125 tons. To achieve this production capacity, approximately 73,500 tons of corncobs are required annually. Consequently, the supply of corncobs necessitates approximately 612,500 tons of ears of corn. When considering the potential of Nan province to supply ears of corn to the manufacturers, according to the latest statistics published by the Office of Agricultural Economics, it was 388,937 tons in 2021. This implies that the biomass potential in the province is only 93,345 tons per year (using a residue-to-product ratio of 0.24 tons of residue per ton of corn to calculate the residual biomass from the total amount of corn). Therefore, 519,155 tons of ears of corn are needed from the nearest provinces to meet the production demand. Biomass potential in the northern part of Thailand in 2021 is depicted in Figure 4.

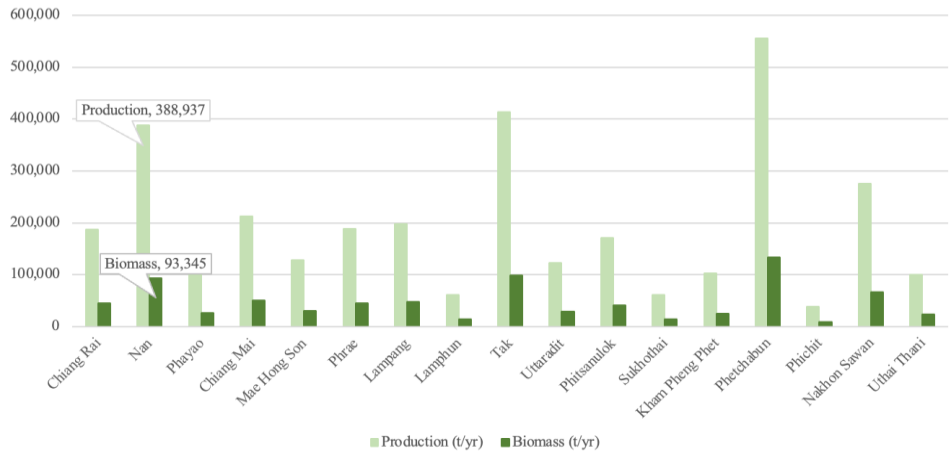


Figure 4. Biomass potential of the northern part of Thailand in 2021.

The same proportions of material consumption, energy usage in corn plantation and cultivation processes, and operating conditions observed in Nan province were applied to other provinces in the northern part of Thailand to achieve the total demand of 612,500 tons of ears of corn. The Thailand Alternative Power Development Plan 2015 [33] forecasted biomass demand for heat generation in 2036 to be 22,100 ktoe. Considering the biomass potential of the northern part of Thailand, the average growth rate from 2018 to 2021 was −1.34%. If the biomass production potential in this region continues to decline at this rate from 2021 to 2036, the accumulated biomass generation will be approximately 5286 ktoe. These figures indicate that the provinces located in the northern part of Thailand could be a significant supplier of biomass from agricultural residue for Thailand's energy needs. Thus, the input and output quantities discussed in the following sections are related to the production of 55,125 tons of corn pellets.

To generate an annual output of 55,125 tons of corn pellets, the corn cultivation process needs to produce approximately 612,500 tons of ears of corn annually. This requires 3810 tons of corn seed as input material for growing corn, followed by 24,500 tons of fertilizer and 4.49 L of diesel per ton of corn for agricultural machinery. All ears of corn produced from the corn cultivation process are transported to the sorting plant. The sorting process requires 12,000 MWh of electricity to operate the sorting system. The 73,500 tons of corncobs sorted by the system are then conveyed to the pellet manufacturing plant. Table 3 provides a resource breakdown per ton of corn pellets produced. Within the corn cultivation process, it is necessary to use 0.01 tons of corn seed, 0.04 tons of fertilizer, and 7.33 L of diesel to produce one ton of ears of corn. The corn sorting process then takes these ears and, through the use of 0.02 MWh of electricity, sorts them into 0.88 tons of corn seed and 0.12 tons of corncob. Moving to the pelletizing phase, 1.33 tons of corncob are transformed into one ton of corn pellets, utilizing an additional 0.22 MWh of electricity, with

no significant by-products. This systematic enumeration of inputs and outputs illustrates the resource efficiency across each stage of production.

Table 3. Input materials required for producing one ton of corn pellets.

Input Item	Quantity	Unit	Output Item	Quantity	Unit
Corn cultivation process					
Corn seed	0.01	Tons	Ear of corn	1	Tons
Fertilizer	0.04	Tons			
Diesel	7.33	Liters			
Corn sorting process					
Ear of corn	1.00	Tons	Corn seed	0.88	Tons
Electricity	0.02	MWh	Corncob	0.12	Tons
Pelletizing					
Corncob	1.33	Tons	Corn pellets	1	Tons
Electricity	0.22	MWh	By-products	0	Tons

Referring to input data derived from the sorting plant, the price of an ear of corn is THB 10 per kg (average annual exchange rate for 2023 was USD/THB 34.77) of product (THB 10,000 per ton of ear of corn). Therefore, the total value of the ear of corn in this research is 6125 mTHB. The average price of corncob sold to the pellet plant is THB 3 per kg of product (THB 3000 per ton of corncob), while the average price of corn seed sold to the animal feed industry is THB 11.50 per kg of product (THB 11,500 per ton of corn seed). The total economic value is calculated at THB 10,480. Of this amount, the economic value attributed to corn seeds is THB 10,120, comprising 96.6% of the total, while the economic value derived from corncobs amounts to THB 360, accounting for 3.4% of the total value. The cost of producing one ton of product is shown in Table 4, which presents a cost analysis for the production of corn-related products, segmented into the corn cultivation, corn sorting, and pelletizing stages. The costs of the corn cultivation process are broken down as follows: corn seed at THB 1026, fertilizer at THB 448, diesel at THB 256, and labor at THB 634, with the output, a ton of ears of corn, being valued at THB 10,000. The corn sorting process is characterized by the ear of corn, valued at THB 10,000, being processed with additional electricity and labor costs at THB 81.21 and 3, respectively, which yields corn seed and corncob valued at THB 11,500 and 3000, respectively.

Table 4. Cost analysis for producing corn pellets in THB per unit.

Input Item	Cost	Output Item	Value
Corn cultivation process			
Corn seed	1026	Ear of corn	10,000
Fertilizer	448		
Diesel	256		
Labor	634		
Corn sorting process			
Ear of corn	10,000	Corn seed	11,500
Electricity	81.21	Corncob	3000
Labor	3		
Pelletizing			
Corncob	3000	Corn pellets	4200
Electricity	71		
Labor	79		

For the pelletizing phase, corncob valued at THB 3000 is utilized, and when combined with the costs of electricity (THB 71) and labor (THB 79), corn pellets valued at THB 4200 are produced. The value addition at each phase of production is elucidated by this delineation of costs, tracing the financial transformation from initial inputs to the final product in a passive structure.

From an environmental perspective, the production of corn pellets emits 95.38 $MtCO_2e$ of GHG emissions. Table 5 presents the GHG emissions from the production of 55,125 tons of corn pellets. In the corn plantation process, GHG emissions are calculated based on activity data for consumption of fertilizer, diesel, and corn seed with their respective emission factors, resulting in 39.01 $MtCO_2e$ for fertilizer, 0.76 $MtCO_2e$ for diesel, and the lowest emissions of 1.08 $MtCO_2e$ for corn seed.

Table 5. Amount of GHG emitted in the corn pellet production process.

Items	Activity Data	Unit	Emission Factor ($kgCO_2e$/unit)	GHG Emissions ($MtCO_2e$)
Corn cultivation process				
Fertilizer	24,500	Tons	1.5922	39.01
Diesel	4,491,667	Liters	0.3522	0.76
Corn seed	3810	Tons	0.2827	1.08
Corn sorting process				
Electricity	12,000	MWh	0.4999	6.00
Ear of corn	612,500	Tons	66.6862	40.85
Pelletizing				
Electricity	12,128	MWh	0.4999	6.06
Corncobs	73,500	Tons	0.0221	1.63

Note: emission factors refer to the values published by TGO [20].

During the corn sorting process, the use of electricity is responsible for 6.00 $MtCO_2e$ of GHG emissions, and consumption of an ear of corn emits 40.85 $MtCO_2e$ of GHG emissions. At this stage, 3.4% is used as a factor for allocating GHG emissions from the cultivation process to corncobs. Lastly, in the pelletizing stage, electricity usage accounts for slightly higher emissions of 6.06 $MtCO_2e$, and consumption of corncobs is responsible for 1.63 $MtCO_2e$ of GHG emissions. The total emissions calculated using the economic allocation method are 4.08% lower compared to those calculated using the mass allocation method, i.e., when distributing GHG emissions among different products or processes, the economic allocation method (which allocates emissions based on the economic value or revenue of products) results in 4.08% less GHG emissions than when using the mass allocation method (which allocates emissions based on the physical mass of products). Essentially, the way emissions are divided between products based on economic value shows a lower total emissions figure than when divided based on their mass. Table 6 details the input materials needed for the production of one ton of wood pellets, with the data divided into three categories: cultivation of Para rubber trees, cultivation of fast-growing trees, and production of wood pellets. In the cultivation of Para rubber trees, 2.258 tons of sprout, a minimal amount of fertilizer (0.001 tons), diesel (0.002 L), and electricity (0.013 MWh) are required to produce 0.89 tons of Para rubber logs and 0.11 tons of latex. For fast-growing trees, 6 tons of raw materials, 147 cubic meters of water, 0.21 tons of organic fertilizer, a substantial amount of chemical fertilizer (1837 tons), and significant electricity usage (13 MWh) along with 588 L of diesel are used to yield 0.66 tons of Leucaena logs and 0.34 tons of Acacia logs. The production ratio of fast-growing trees was calculated based on data obtained from the study of Saosee et al. When it comes to the actual production of wood pellets, the input of 1.01 tons of raw materials, 0.75 L of diesel, 0.06 tons of firewood, and 0.02 MWh of electricity results in the creation of one ton of wood pellets, with no dust as a by-product.

This table systematically captures the resource inputs against their respective outputs for each step of the wood pellet production process.

Table 6. Input materials required for producing one ton of wood pellets.

Input Item	Quantity	Unit	Output Item	Quantity	Unit
Cultivation of Para Rubber Trees					
Sprout	2.258	Tons	Para rubber logs	0.89	Tons
Fertilizer	0.001	Tons	Latex	0.11	Tons
Diesel	0.002	Liters			
Electricity	0.013	MWh			
Cultivation of Fast-Growing Trees					
Raw materials	6	Tons	Leucaena logs	0.66	Tons
Water	147	m^3	Acacia logs	0.34	Tons
Organic fertilizer	0.21	Tons			
Chemical fertilizer	1837	Tons			
Electricity	13	MWh			
Diesel	588	Liters			
Production of Wood Pellets					
Raw materials	1.01	Tons	Wood pellets	1.00	Tons
Diesel	0.75	Liters	Dust	0	Tons
Firewood	0.06	Tons			
Electricity	0.02	MWh			

Table 7 presents the quantification of a cost analysis for the production of wood pellets. Within the cultivation of Para rubber trees, expenses are incurred for raw materials (THB 794), labor (THB 3021), and electricity (THB 54), leading to outputs of Para rubber logs and latex valued at THB 2500 and 2075, respectively. The cultivation of fast-growing trees incurs costs for raw materials (THB 530.26), electricity (THB 24.35), diesel (THB 8.25), and fertilizer (THB 27.02), which result in outputs of Leucaena and Acacia logs, each valued at THB 800.

Table 7. Cost analysis for producing wood pellets in THB.

Input Item	Quantity	Output Item	Quantity
Cultivation of para rubber trees			
Raw materials	794	Para rubber logs	2500
Labor	3021	Latex	2075
Electricity	54		
Cultivation of fast-growing trees			
Raw materials	530.26	Leucaena	800
Electricity	24.35	Acacia	800
Diesel	8.25		
Fertilizer	27.02		
Production of wood pellets			
Raw materials	1197.69	Wood pellets	2136
Diesel	26.30		
Firewood	78.13		
Electricity	36.99		
Labor	69.20		
O&M	120.05		

For the actual production of wood pellets, costs include raw materials (THB 1197.69), diesel (THB 26.30), firewood (THB 78.13), electricity (THB 36.99), labor (THB 69.20), and operations and maintenance (O&M; THB 120.05). These inputs contribute to the production of wood pellets valued at THB 2136. The table provides an itemized view of costs against the financial value of the outputs in each stage of the wood pellet production process.

Table 8 provides a comprehensive account of GHG emissions from the wood pellet production process, totaling 157.39 $MtCO_2e$. For the cultivation of Para rubber trees, GHG emissions are calculated from the use of fertilizer (5.74 $MtCO_2e$), diesel (26.39 $MtCO_2e$), and electricity (17.28 $MtCO_2e$), with each emission value derived by applying the respective emission factors to the activity data. In the cultivation of fast-growing trees, electricity, water, diesel, and chemical fertilizer contribute to emissions of 0.42, 3.03, 101.42, and 0.0002 $MtCO_2e$, respectively.

Table 8. Amount of GHG emitted in the wood pellet production process.

Items	Activity Data	Unit	Emission Factor ($kgCO_2e$/unit)	GHG Emissions ($MtCO_2e$)
Cultivation of Para rubber trees				
Fertilizer	3603	Tons	1.5922	5.74
Diesel	6382	Liters	2.7080	26.39
Electricity	52,794	MWh	0.4999	17.28
Cultivation of fast-growing trees				
Electricity	842,680	MWh	0.4999	0.42
Water	9,362,867	m^3	0.3238	3.03
Manure	13,108	Tons	0.0000	0.00
Diesel	37,451,469	Liters	2.7080	101.42
Chemical fertilizer	117	Tons	1.5922	0.0002
Production of wood pellets				
Diesel	174,840	Liters	2.7080	0.47
Firewood	14,640	Tons	0.0304	0.45
Electricity	4375	MWh	0.4999	2.19

Note: The emission factor refers to the value published by TGO [23].

The production of wood pellets sees further emissions from the use of diesel (0.47 $MtCO_2e$), firewood (0.45 $MtCO_2e$), and electricity (2.19 $MtCO_2e$). The emissions for each input are derived by applying the respective emission factors to the activity data. This comprehensive calculation of total emissions demonstrates the environmental impact of the wood pellet production process, as captured in the table. Considering the total GHG emissions from biomass pellet production (including corn and wood pellets), the overall emissions throughout the process amount to 219.96 $MtCO_2e$. Each ton of biomass pellets emits 0.7602 tCO_2e.

3.3. Develop an Input–Output Table for Thailand's Biomass Pellet Sector

The summary table presents monetary data of the items related to the production of biomass pellets as shown in Table 9.

The biomass pellet sector's total value amounts to 731.78 mTHB, with its annual operating surplus reaching 13,063 mTHB. Unit cost of biomass pellet is THB 2529 per ton. Monetary data from the preceding activity were classified according to Thailand's input–output identifier code to align new items obtained from the previous section with an existing sector. A list of economic sectors associated with the production of biomass pellets is shown in Table 10.

Table 9. Cost summary of Thailand's biomass pellet sector.

Activity	Items	Operation Cost (THB 1000)	Value of Product (THB 1000)
Corn pellets			
Plantation	Fertilizer and pesticides	274,400	0
	Diesel	156,939	0
	Labor	88,368	0
	Corn seed	318	0
	Ear of corn	0	6,125,000
Sorting	Ear of corn	6,125,000	0
	Electricity	4920	0
	Labor	1800	0
	Corn seed	0	6,198,500
	Corncob	0	220,500
Pelletizing	Corncob	220,500	0
	Electricity	3890	0
	Labor	2712	0
	Corn pellets	0	231,525
Wood pellets			
Plantation (FGT)	Raw materials	33,769	0
	Diesel	5110	0
	Fertilizer	2809	0
	Electricity	1550	0
	Leucaena	0	33,769
	Acacia	0	17,178
Plantation (Para rubber trees)	Raw materials	3,165,917	0
	Labor	1,489,843	0
	Electricity	216,587	0
	Latex	0	22,017,590
	Para rubber wood log	0	8,911,583
Pelletizing	Raw materials	280,538	0
	MA	28,121	0
	Firewood	18,300	0
	Labor	16,210	0
	Electricity	8663	0
	Diesel	6161	0
	Wood pellets	0	500,253

The assumption for selecting the demand industry was based on the payment for energy purchases and the list of industrial sectors that have the potential to use biomass pellets as fuel. It was assumed in this research that biomass pellets could partially replace the consumption of coal, electricity, petroleum, and natural gas. The expenditure on energy consumption by the demand sector was taken into account to calculate the sector's percentage of energy demand. Consequently, the maximum percentage of the sectors that can consume biomass pellets was applied to estimate the cost of biomass pellets by sector. The breakdown of biomass pellet demand by sector, expressed as percentages, is shown in Table 11.

Table 11 displays the sectors with high expenditure on energy, including electricity (54.00%), plastic wares (7.59%), cement (7.30%), petroleum and natural gas (5.92%), and spinning (3.97%). The value of the biomass pellets sector was allocated to each industry based on the maximum percentage of biomass pellets that each sector can utilize as an alternative energy source in their processes. The price of biomass pellets by sector is presented in Table 12.

Symmetric input–output tables for the biomass pellet sector in Thailand were created in accordance with the IOT development principle initiated by EUstat. The sector was structured within the same economic framework as Thailand's IOTs to ensure that integration of the biomass pellet sector into the existing IOTs is accurate and feasible. The biomass pellet sector comprises 45 × 45 inter-sectoral linkages. Intermediary transactions encompass sectors 002 to 190, representing the flow of goods and services in monetary terms. The value-added sector encompasses sectors 201 to 209, with Sector 210 indicating the total cost of the product inclusive of value-added. Final demand sectors, such as private consumption expenditure, government consumption expenditure, and gross fixed capital formation, are covered from sectors 301 to 309, with sector 310 representing the summation of final demand.

Table 10. Economic sector associated with the production of biomass pellet.

Category	Sector
Supply	002 Maize
	016 Rubber
	017 Other Agricultural Products
	024 Agricultural Services
	025 Logging
	026 Charcoal and Firewood
	085 Fertilizer and Pesticides
	093 Petroleum Refineries
	094 Other Petroleum Products
	113 Agricultural Machinery
	137 Water Supply System
	145 Wholesale Trade
	151 Road Freight Transport
	152 Land Transport Supporting Services
	153 Ocean Transport
	154 Coastal & Inland Water Transport
	155 Water Transport Services
	157 Other Services
	Biomass Pellets
	180 Unclassified
	190 Total Intermediate Transaction
Demand industry	031 Petroleum and Natural Gas
	043 Canning Preserving of Meat
	045 Canning of Fruits and Vegetables
	046 Canning Preserving of Fish
	059 Coffee and Tea Processing
	060 Other Food Products
	061 Animal Feed
	067 Spinning
	069 Textile Bleaching and Finishing
	081 Pulp Paper and Paperboard
	082 Paper Products
	086 Synthetic Resins and Plastics
	095 Rubber Sheets and Block Rubber
	096 Tires and Tubes
	097 Other Rubber Products
	098 Plastic Wares
	102 Cement
	103 Concrete and Cement Products
	104 Other Non-Metallic Products
	105 Iron and Steel
	108 Cutlery and Hand Tools
	110 Structural Metal Products
	132 Other Manufacturing Goods

Table 11. Demand for biomass pellets by sector.

Sector Name	Expenditure (THB 1000)			Total Expenditure (THB 1000)	% Expenditure
	Coal	Electricity	Petroleum and Natural Gas		
135 Electricity	29,277,094	29,277,094	115,693,142	174,247,330	54.00%
098 Plastic Wares	0	24,480,683	0	24,480,683	7.59%
102 Cement	9,018,138	14,545,637	0	23,563,775	7.30%
031 Petroleum and Natural Gas	0	3,078,083	16,013,170	19,091,253	5.92%
067 Spinning	0	12,798,704	0	12,798,704	3.97%
086 Synthetic Resins and Plastics	0	10,541,781	88,687	10,630,468	3.29%
084 Basic Industrial Chemicals	1,636,518	6,667,198	0	8,303,716	2.57%
105 Iron and Steel	0	8,094,361	0	8,094,361	2.51%
107 Non-ferrous Metal	5,658,946	2,403,556	0	8,062,502	2.50%
106 Secondary Steel Products	124,948	5,164,892	0	5,289,840	1.64%
096 Tires and Tubes	0	4,059,257	0	4,059,257	1.26%
081 Pulp Paper and Paperboard	0	3,057,984	0	3,057,984	0.95%
045 Canning of Fruits and Vegetables	0	3,030,187	0	3,030,187	0.94%
046 Canning Preserving of Fish	0	2,880,866	0	2,880,866	0.89%
095 Rubber Sheets and Block Rubber	0	2,243,528	0	2,243,528	0.70%
108 Cutlery and Hand Tools	0	2,166,207	0	2,166,207	0.67%
134 Other Manufacturing Goods	6897	2,125,375	0	2,132,272	0.66%
060 Other Food Products	0	1,707,257	0	1,707,257	0.53%
110 Structural Metal Products	0	1,677,512	0	1,677,512	0.52%
043 Canning Preserving of Meat	0	1,579,668	0	1,579,668	0.49%
103 Concrete and Cement Products	0	1,343,113	0	1,343,113	0.42%
061 Animal Feed	0	1,332,828	0	1,332,828	0.41%
059 Coffee and Tea Processing	0	453,652	0	453,652	0.14%
069 Textile Bleaching and Finishing	0	446,736	0	446,736	0.14%

Table 12. Price of biomass pellet by sector.

Demand Sector	Total Expenditure (THB 1000)	Maximum % of Biomass Pellets	Price Allocation (THB 1000)
135 Electricity	174,247,330	50%	11,761
098 Plastic Wares	24,480,683	10%	2919
102 Cement	23,563,775	50%	5600
031 Petroleum and Natural Gas	19,091,253	10%	5324
067 Spinning	12,798,704	10%	838
086 Synthetic Resins and Plastics	10,630,468	10%	3155
084 Basic Industrial Chemicals	8,303,716	10%	9419
105 Iron and Steel	8,094,361	30%	5115
107 Non-ferrous Metal	8,062,502	10%	6549
106 Secondary Steel Products	5,289,840	30%	1382
096 Tires and Tubes	4,059,257	10%	2501
081 Pulp Paper and Paperboard	3,057,984	50%	15,081
045 Canning of Fruits and Vegetables	3,030,187	30%	5600
046 Canning Preserving of Fish	2,880,866	30%	5324
095 Rubber Sheets and Block Rubber	2,243,528	10%	838
108 Cutlery and Hand Tools	2,166,207	10%	3155
134 Other Manufacturing Goods	2,132,272	30%	2463
060 Other Food Products	1,707,257	30%	2919
110 Structural Metal Products	1,677,512	30%	5600
043 Canning Preserving of Meat	1,579,668	30%	5324
103 Concrete and Cement Products	1,343,113	50%	838
061 Animal Feed	1,332,828	30%	838
059 Coffee and Tea Processing	453,652	30%	3155
069 Textile Bleaching and Finishing	446,736	10%	2463

3.4. Verification of the Extended IOTs

Two approaches were employed to validate the model of extending the national IOTs by incorporating a new sector. Firstly, the difference between the original IOTs and the table with the integrated biomass pellet sector was examined. The last approach involved checking the gross domestic product (GDP) value. The result of the first approach is presented in Table 13.

Table 13. Difference between original IOTs and the extended IOTs.

Sector	Original IOTs (mTHB)	Extended IOTs (mTHB)	Differentiate (%)
190 Total Intermediate Transaction	19,044,013	19,048,985	0.03%
210 Control Total	32,964,783	32,967,757	0.01%
310 Total Demand	41,618,641	41,618,641	0.00%

The value of total intermediate transactions, representing the financial transaction of a product from one firm to another, experienced a 0.03% increase compared to conventional IOTs in Thailand. Additionally, the value of the control total, which signifies the total amount of financial transactions between industries when considering value-added, also saw a slight increase of 0.01%. No difference was observed in the value of total demand. These results imply that the input data collected from the survey, as well as the assumptions used for data allocation in this research, are aligned and applicable to the current economic system. The value of the biomass pellet sector is not substantial when compared with sectors of higher value, such as office and household machinery, petroleum refineries, electricity, and motor vehicles. Therefore, the GDP is not expected to be significantly affected by adding the biomass pellet sector. This approach also involves comparing the GDP value between two cases: the total GDP of the original IOTs and the total GDP of the extended IOTs. The result of the validation of the GDP value is shown in Table 14.

Table 14. Comparison of GDP value of original IOTs and extended IOTs.

Case	301 Household & Private	302 Government Spending	303 Gross Fixed Capital Formation	304 Increase in Stock	305 Export (FOB)	306 Export (Special)	409 Total Import	GDP
Original IOTs (mTHB)	8,174,710	2,353,042	3,371,070	−537,193	7,225,723	1,987,276	−8,653,858	13,915,990
Extended IOTs (mTHB)	8,174,710	2,353,042	3,371,070	−537,193	7,225,723	1,987,276	−8,653,858	13,915,990

3.5. Biomass Pellet Demand

The year 2030, which is the target year for Thailand's NDC (nationally determined contribution) targets, was chosen to estimate biomass pellet demand in alignment with the national goal of increasing the use of renewable energy and reducing GHG emissions. Forecasted data on biomass pellet demand for heat applications in Thailand, along with data on international market demand, indicates that national revenue from selling biomass will be generated from both domestic and international markets. Therefore, two scenarios were defined as matrix F to analyze the impact of changing demand on biomass pellet consumption. Biomass pellet demand in the international market was denoted as Scenario 1. This scenario assumed that all biomass pellets produced in Thailand will be exported to the international market. The international market in this study focused on biomass pellet demand in Japan and South Korea, which have high pellet demand when compared with other importer countries. Forecasted data by the Kasikorn Research Center (2020) and the Office of Foreign Trade Promotion in Seoul (2020) revealed that both markets will require biomass pellets from Thailand at approximately 430,000 tons in 2024 and 441,000 tons in 2025. The growth rate of biomass pellet demand for each country was used as a driving

factor in forecasting the trend of biomass pellet demand from 2026 to 2030. The forecasted results of the scenario 1 were presented in Table 15.

Table 15. Supply all products to the international market (Scenario 1).

Country	Unit	2023	2024	2025	2026	2027	2028	2029	2030
Japan	Tons	171,000	198,000	209,000	228,750	250,366	274,025	299,920	328,262
South Korea	Tons	232,000	232,000	232,000	232,000	232,000	232,000	232,000	232,000
Total	Tons	403,000	430,000	441,000	460,750	482,366	506,025	531,920	560,262

The second scenario assumed that 10% of total production will be distributed to the domestic market, and 90% of total production will be exported to international markets. This scenario was defined based on the evaluation of wood pellet demand from the policy of importers and the fact that the Thai government mentioned that biomass pellet demand in Thailand will increase by 10% each year from 2020 to 2025. The growth rate of biomass pellet demand in the country was used as a key factor in forecasting the trend of biomass pellet demand in Thailand from 2026 to 2030. Table 16 illustrates the projected biomass demand for heat applications in Thailand.

Table 16. Biomass pellet demand for heat application in Thailand (Scenario 2).

Country	Unit	2023	2024	2025	2026	2027	2028	2029	2030
Thailand	Tons	116,000	128,000	141,000	154,000	168,199	183,706	200,644	219,143

The amount of biomass pellet demand presented in Tables 15 and 16 was converted into a monetary unit by multiplying the unit cost of biomass pellets (THB 2529 per ton of product). The price of biomass pellets is shown in Table 17.

Table 17. Price of biomass pellets according to forecasted demand from 2023 to 2030.

Country	Unit	2023	2024	2025	2026	2027	2028	2029	2030
Scenario 1									
Japan	mTHB	432	501	529	579	633	693	758	830
South Korea	mTHB	587	587	587	587	587	587	587	587
Scenario 2									
Thailand	mTHB	293	324	357	389	425	465	507	554

3.6. Forecasting of GHG Emissions According to Market Demand

The annual increase in market demand was applied to forecast the amount of GHG emissions from biomass pellet production under the assumption that production methods, efficiency, and input sources are held constant and the rise in demand is directly proportional to an increase in production. It was presumed that the emission intensity per ton of biomass pellets will not vary, allowing for a straightforward application of the growth rate to the current emissions to estimate future emissions. For multi-year forecasts, the growth rate was compounded annually.

3.6.1. GHG Emissions According to International Demand (Scenario 1)

An average growth rate of biomass pellet demand in the international market (4.59%) was applied to forecast GHG emissions from the production of corn and wood pellets from 2023 to 2030. The production of wood pellets is the larger contributor, starting at 164.62 $MtCO_2e$ in 2023 and rising to 255.40 $MtCO_2e$ by 2030. Corn pellet production

emissions also increase but remain significantly lower, starting at 104.00 $MtCO_2e$ in 2023 and reaching 142.40 $MtCO_2e$ by 2030.

As shown in Table 18, The total emissions from both categories show a consistent year-on-year increase. This trend suggests an upward trajectory in cradle-to-gate GHG emissions driven by international demand for these biomass sources, indicating a need for strategies to mitigate emissions as production scales up.

Table 18. Cradle-to-gate GHG emission trends based on international demand.

Country	Unit	2023	2024	2025	2026	2027	2028	2029	2030
Corn pellets	$MtCO_2e$	104.00	108.77	113.77	118.99	124.45	130.17	136.15	142.40
Wood pellets	$MtCO_2e$	164.62	172.18	180.08	188.35	197.00	206.05	215.51	225.40
Total	$MtCO_2e$	268.61	280.95	293.85	307.34	321.45	336.22	351.65	367.80

3.6.2. GHG Emissions According to Domestic Demand (Scenario 2)

An average growth rate of biomass pellet demand in the domestic market (5.64%) was applied to forecast the GHG emissions from 2023 to 2030. The results of forecasted GHG emissions are shown in Table 19. The forecasted data suggests a rising trend in national demand for corn and wood pellet production, with a consequent increase in GHG emissions from 2023 to 2030. For corn pellets, the emissions start at 105.04 $MtCO_2e$ and show a steady increase each year, reaching 154.22 $MtCO_2e$ by 2030. Wood pellet production starts at a significantly higher emission level of 166.27 $MtCO_2e$ in 2023, escalating to 244.12 $MtCO_2e$ by 2030, which indicates a more pronounced impact on the total GHG emissions.

Table 19. Cradle-to-gate GHG emission trends based on domestic demand.

Country	Unit	2023	2024	2025	2026	2027	2028	2029	2030
Corn pellets	$MtCO_2e$	105.04	110.96	117.22	123.83	130.82	138.19	145.99	154.22
Wood pellets	$MtCO_2e$	166.27	175.64	185.55	196.02	207.07	218.75	231.09	244.12
Total	$MtCO_2e$	271.30	286.61	302.77	319.85	337.89	356.95	377.08	398.35

The aggregate GHG emissions from both categories are reflected by the growing trend, with a movement from 267.03 $MtCO_2e$ in 2023 to 392.06 $MtCO_2e$ by 2030. A significant rise in national demand for biomass is implied by this progression, resulting in increased emissions. The data highlight the importance of environmental impact consideration as biomass production expands and the potential necessity for more sustainable practices or emission-offsetting measures to manage the environmental footprint.

In Figure 5, GHG emission trends are presented for the period 2023 to 2030, segmented by national and international demand.

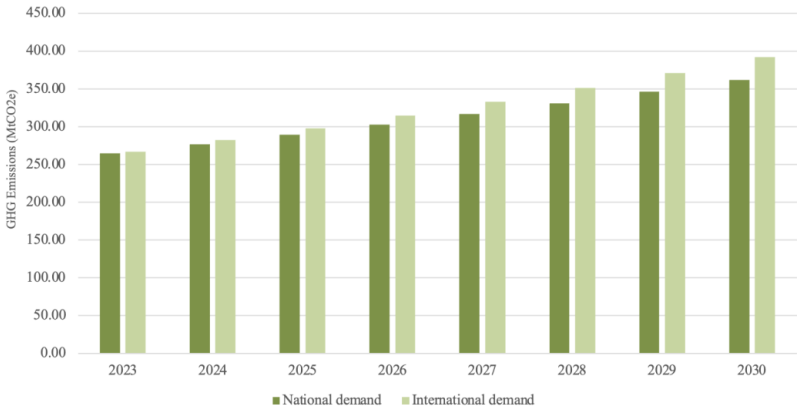


Figure 5. Comparative analysis of projected national and international GHG emission trends.

3.7. Recommendations

Based on comprehensive research into Thailand's biomass pellet production and its associated greenhouse gas (GHG) emissions, it is clear that biomass power plants using biomass pellets as fuel emit higher lifecycle emissions compared to other renewable energy technologies. This is primarily due to emissions from the cultivation, harvesting, processing, transportation, and combustion of biomass pellets. Although biomass is a renewable resource, its lifecycle emissions are still considerable. To integrate biomass as a solution for reducing GHG emissions and align with Thailand's nationally determined contribution (NDC) targets, the following recommendations are proposed. Each recommendation is tied to specific numerical insights from the study to reflect their real contribution to GHG reduction efforts.

3.7.1. Policy Recommendations

Prioritizing Low-Emission Renewable Energy Sources:

- The study found that emissions from wood pellet production are projected to rise from 210.30 $MtCO_2e$ in 2022 to 301.18 $MtCO_2e$ by 2030. In contrast, technologies such as solar PV and wind energy have far lower lifecycle emissions. By prioritizing these lower-emission technologies, Thailand could offset at least 20% of the forecasted GHG emissions from biomass by shifting focus to cleaner energy sources [34]. This would lead to a potential reduction of around 60 $MtCO_2e$ by 2030.

Monitoring and Improving Biomass Efficiency:

- Current emissions from biomass pellet production, including both wood and corn pellets, are projected to reach 367.80 $MtCO_2e$ by 2030 under international demand scenarios. Improving biomass efficiency by adopting stringent environmental standards and best practices in biomass pellet production could reduce emissions by at least 10%. This would equate to a real reduction of approximately 36.78 $MtCO_2e$ by 2030. By increasing the quality and combustion efficiency of biomass pellets, the sector could lower its emission intensity from 0.7602 tCO_2e per ton of biomass to around 0.6842 tCO_2e per ton.

Promoting Sustainable Agricultural Practices:

- Fertilizer use in corn pellet production alone accounts for 39.01 $MtCO_2e$ in GHG emissions. Implementing precision farming techniques, such as GPS-enabled fertilizer management, could improve fertilizer efficiency and reduce emissions from fertilizer application by 20–30% [35]. This would result in a real contribution of reducing emissions by approximately 7.80 to 11.70 $MtCO_2e$ by 2030. Substituting synthetic fertilizers with organic alternatives could further reduce emissions by 2–5 $MtCO_2e$, contributing significantly to Thailand's NDC targets.

3.7.2. Environmental Recommendations

Adoption of Lifecycle Emission Management:

- The total emissions from biomass pellet production in Thailand are expected to rise significantly, with wood pellet production alone reaching 225.40 $MtCO_2e$ by 2030. Encouraging lifecycle emission management could help reduce emissions at every stage—from cultivation to end use. A full lifecycle approach could cut emissions by approximately 15%, resulting in a real reduction of around 33.81 $MtCO_2e$ by 2030 [36–39]. This is particularly crucial for Thailand as it seeks to maintain its role in the international biomass market while reducing its overall carbon footprint.

GHG Offsetting Initiatives:

- Thailand could implement GHG offsetting initiatives such as reforestation or soil carbon sequestration to neutralize emissions from biomass production. For instance, the 154.22 $MtCO_2e$ projected from corn pellet production by 2030 could be offset

by expanding reforestation efforts, potentially sequestering around 10–15% of these emissions [40,41], equating to roughly 15–23 $MtCO_2e$.

Energy Efficiency Programs:

- The study shows that energy consumption in pelletizing processes contributes significantly to emissions, with electricity use accounting for 6.06 $MtCO_2e$ in corn pellet production and 2.19 $MtCO_2e$ in wood pellet production. Introducing energy efficiency programs in biomass pellet manufacturing could reduce electricity consumption and lower emissions by up to 10% [42,43]. This would result in a reduction of about 0.82 $MtCO_2e$ for corn pellets and 0.22 $MtCO_2e$ for wood pellets, contributing directly to lowering Thailand's biomass energy emissions.

3.7.3. Financial Recommendations

Financial Mechanisms for SMEs:

- Small- and medium-sized enterprises (SMEs) play a key role in Thailand's biomass sector, but transitioning to greener technologies requires substantial investment. Offering low-interest loans or grants to SMEs could facilitate the adoption of cleaner technologies, which would reduce emissions from processing and transport. For instance, transport-related emissions from corn pellet production are currently 5.68 $MtCO_2e$. If SMEs are able to invest in greener logistics and transportation technologies, this could lead to a 10–15% reduction in transport-related emissions [44], saving about 0.57–0.85 $MtCO_2e$ by 2030.

Economic Diversification within the Biomass Industry:

- The biomass sector is projected to produce 560,262 tons of pellets by 2030 for the international market. Diversifying this industry to include other renewable energy technologies could help stabilize the sector against market fluctuations while reducing emissions. For instance, by integrating solar and wind power into the biomass production process, Thailand could reduce overall energy-related emissions by up to 5%, according to information published by the Asia-Pacific Economic Cooperation, contributing to a reduction of approximately 18–20 $MtCO_2e$ by 2030.

4. Conclusions

This study quantitatively assessed greenhouse gas (GHG) emissions from Thailand's biomass pellet industry, focusing on the production of corn and wood pellets. Using the extended input–output tables (IOTs) model, the analysis projected that emissions from corn pellet production will increase from 52.91 $MtCO_2e$ in 2022 to 75.77 $MtCO_2e$ by 2030, while emissions from wood pellet production will rise more sharply, from 210.30 $MtCO_2e$ to 301.18 $MtCO_2e$ during the same period. These trends reflect the growing demand for biomass energy, particularly in international markets such as Japan and South Korea, where total biomass pellet demand is expected to reach 560,262 tons by 2030.

The study highlights that while biomass pellets contribute to renewable energy targets, their lifecycle greenhouse emissions remain significant, with the total emissions for wood and corn pellet production estimated to reach 367.80 $MtCO_2e$ under international demand scenarios and 398.35 $MtCO_2e$ under domestic demand scenarios by 2030. These figures underscore the need for emission reduction measures within the biomass supply chain to align with Thailand's nationally determined contribution (NDC) targets.

Policy recommendations include prioritizing low-emission renewable energy sources, such as solar and wind, over biomass and improving the efficiency of biomass production processes. For instance, the study estimated that improving combustion efficiency and reducing supply chain emissions could substantially reduce the 0.7602 tCO_2e emitted per ton of biomass pellets. As Thailand aims to scale up biomass production to meet domestic and international demand, these findings stress the importance of optimizing the supply chain and adopting more sustainable production practices. Without such measures,

the increasing GHG emissions from biomass production could undermine the country's renewable energy and climate goals.

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