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Environmental externalities of wood pellets from fast-growing and para-rubber trees for sustainable energy production: A case in Thailand

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ABSTRACT

Wood pellets are one of biomass-based energy carriers considered important as renewable energy source. This study considers wood pellets for heat and power generation from fast-growing Leucaena and Acacia trees and para-rubber trees in a life cycle perspective. The objectives of this study are to estimate the actual cost (including environmental externalities) of heat and electricity production from wood pellets, and comparison with the external cost of fossil fuels, as well as forecasting the external cost arising from the increase in wood pellet demand. For both heat and electricity production, it was seen that when external costs are included, wood pellets are cheaper than lignite and fuel oil although the latter are cheaper when only internal costs are considered. Four recommendations for reducing the external costs of wood pellet production are: 1) to support sustainable agriculture for para-rubber trees and fast-growing trees, 2) to consider clean transportation in the supply chain, 3) wood pellet factory zoning, including good logistics, and 4) considering the external cost of wood pellets for polluter pays principle. These results and recommendations of the study can provide important information to consider towards adjusting the national energy plan and to have strict measures for avoiding problem shifting from the use of non-renewable resources (fossil fuels) to issues related to the use of biomass-based fuels (use of agro-chemicals, forest encroachment, and so on).

Introduction

Increasing of greenhouse gas (GHG) emissions from the use of fossil fuels in several activities such as transportation, electricity production, and industry is an important concern due to their contribution to global warming and climate change. Biomass is one of the renewable energy sources that can at least partially replace fossil fuels. Several countries have policies to encourage the use of biomass for energy, particularly those in the tropical region that have agriculture all year round. Wood, one of the biomass feedstocks, can decrease direct emissions from the heat and power sector [1]. Wood pellets are one of the biomass-based energy carriers popularly used for heat and electricity production. They are produced from waste wood (shavings, sawdust, chips, and slabs) which is compressed by high pressure. Wood pellets are not only produced from biomass waste, but also from round wood [2,3]. Their advantages are ease of handling, low moisture, and high energy density and durability when compared with the unprocessed forms such as wood chips [4]. Moreover, compared to fossil fuels, utilizing wood pellets presents many economic, social and environmental benefits such as net financial saving, job opportunities creation, and CO_2 and NOx emissions reduction [5].

Global wood pellet demand has had significant growth in the past decade, especially in Europe, the United States, Canada, Japan, and South Korea [6]. Global wood pellet demand is projected to increase to 67 million tonnes in 2027, Europe being the largest wood pellet consumer in the world [7]. Wood pellet production in Thailand was evaluated to be about 0.36 million tonnes in 2019 although there was a potential to produce about 5.32 million tonnes per year [8]. The wood pellet demand of Thailand is anticipated to increase to 0.6 million tonnes in 2025 [8]. The increasing of wood pellet demand is the result of both domestic use and export. The Thai government launched the Alternative Energy Development Plan (AEDP2015) to achieve 5,570 MW of power from biomass use by 2036. The Thai government has encouraged the increased use of wood pellets in industry by supporting

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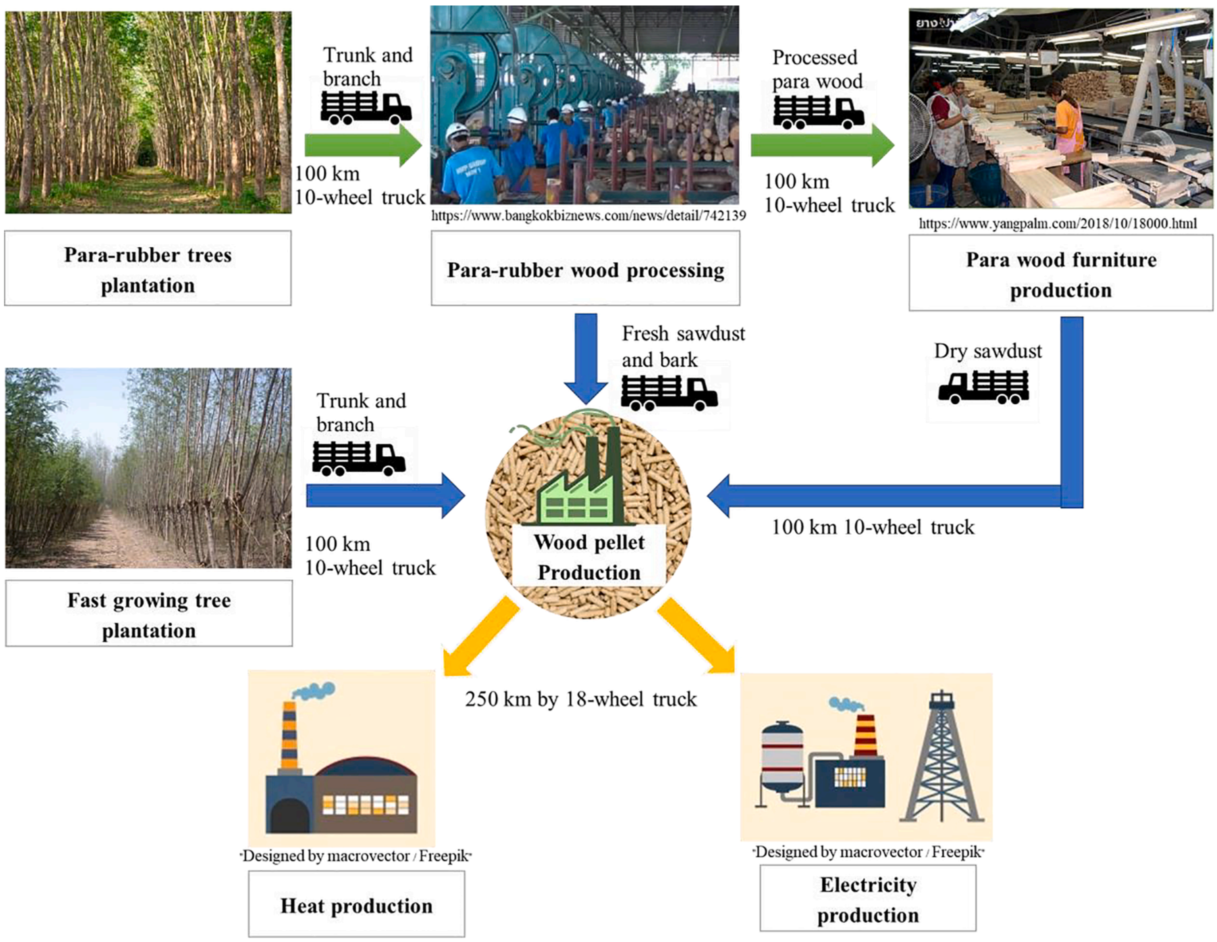

Fig. 1. System boundary for life cycle assessment of wood pellet production from fast-growing trees and para-rubber trees (cradle to grave).

funds to modify existing factory boilers to be able to utilize wood pellets [9]. The available feedstock supply of wood pellets in Thailand is 8.31 million tonnes per year (which can produce 5.32 million tonnes of wood pellets per year). Evaluating the wood pellet demand following the requirements of the main importers (Japan and South Korea) and increasing 10% of domestic use as in 2018 showed that the wood pellet demand of Thailand in 2025 would surge from the current production of 150,000–200,000 tonnes to 765,500 tonnes [8].

The increasing of wood pellet export follows the demand of Japan and South Korea who are the main importers. Energy management in Japan focuses on energy mix diversification, renewable energies, energy efficiency improvement, and carbon emissions reduction [10]. To this end, the Japanese government has a policy to substitute coal with industrial wood pellets which will lead to a surge in demand to 5.8 million tonnes in 2030 [11]. The South Korean government announced the Renewable Energy 2030 Implementation Plan in 2017 which focuses on increasing to 20% of renewable energy by 2030 (and to 30–35% by 2040), and relevant job creation, deployment of environmentally friendly and low-carbon energy cultivating new businesses and markets [12]. Although the supply capacity of wood pellets within South Korea is not enough, they imported three million tonnes of wood pellets from several countries, including Thailand in 2019 [13].

Although wood pellets are considered a renewable energy that can substitute fossil energy potentially reducing GHG emissions when compared with fossil fuels, the life cycle of wood pellet production releases pollution from feedstock plantation, wood pellet production and transportation, including removal of ash from combustion [14,15]. Thailand has been facing the problem of air pollution; particularly from particulate matter less than 2.5 μm (PM2.5) especially during November to February every year. Dry process of wood pellet production can release PM2.5 leading to photochemical smog. Moreover, Thailand still has a problem of water pollution and land use. If not managed properly, cultivation of plants for wood production can contribute to eutrophication and encroachment on forest land. Hence, the control of air pollution from agriculture, transportation, and industry should be seriously enforced.

Meanwhile, evaluation of wood pellet production cost considers only internal cost such as materials, energy, labor, plant, equipment, and overheads. However, wood pellet transportation uses diesel which contributes to air pollution. Moreover, waste wood (an important raw material of wood pellet production) is produced from plantations which utilize chemical fertilizers and herbicides; all these directly affect ecosystem and human health [15,16]. Therefore, environmental externalities of wood pellet life cycle should be evaluated to present the real cost. The environmental externalities or also known as external cost is a negative environmental impact to a third party from the production or consumption of a good; it is paid by medical expenses, accident compensation and taxes, including loss of the environmental quality and natural capital [17].

Studies of the environmental externalities from energy production both from fossil as well as renewable resources are important. Evaluation of environmental externalities for coal-fired power generation in China, indicated that the environmental cost is a significant factor for formulation of electric power development policies [18]. Silalertruksa et al. (2012) studied the environmental externalities of various palm oil biodiesel blends (B5, B10 and B100) and diesel in Thailand and found that total environmental costs contribute 3–76% of the total costs depending on the ratio of palm biodiesel blended with conventional diesel. Moreover, the external cost was also used for evaluating photovoltaic-oriented silicon production in China by calculating the cost of agricultural loss and health damage [19].

In the dimension of sustainable production and use of fuels, the external cost is a tool to support the reduction of the negative environmental impacts. For example, renewable energy can significantly reduce the external cost when compared with fossil fuels [20]. Olba-Ziety et al. (2020) used the estimation of external cost for sustainable production of poplar wood chips; they indicated that field emissions and harvest generate most of the external cost (related to particulate matter formation and terrestrial acidification).

The question this study will answer is "How much is the external cost of pollution from wood pellet production?". The objectives of this study are to (1) estimate the actual cost (including environmental externalities) of heat and electricity production from wood pellets (made from fast-growing trees (Leucaena and Acacia) and para-rubber trees), including comparison with the external cost of fossil fuels (lignite, fuel oil, and natural gas), and (2) forecast the external cost from increasing trend of wood pellet demand. The wood pellets under study are produced from para waste wood, para wood logs and fast-growing wood logs which are grown by farmers in Thailand. Key findings from this study provide supporting information for making policies on the control of pollution and the sustainability of the wood pellet industry in Thailand. Moreover, the findings and insights of this study will supply a new reference to future improvement of wood pellet life cycle in regions with similar climate, production, and use conditions.

Methods

Goal and scope

The goals of this study are to estimate environmental externalities of heat and electricity production from wood pellets (fast-growing trees and para-rubber trees). These are then compared to heat and electricity production from fossil fuels. The functional units are one GJ for heat production and one MWh for electricity production. The system boundary of heat and electricity production from wood pellets (fast-growing trees) consists of four main parts: plantation, wood pellet production, and heat or electricity production along with intermediate transportation (Fig. 1). The system boundary of para-rubber wood pellets has five main parts: plantation, wood processing, wood pellet production, and heat or electricity production and transportation.

The plantation process has four steps: sprout preparation, cultivation, fertilizing, and cutting. Leucaena and Acacia were chosen for this study because they can grow fast and are common in Thailand. Leucaena will be harvested every year and then will be replanted at the age of 10 years. Meanwhile, Acacia will be cut and replanted at the age of 5 years. Para-rubber tree will be cut at the age of 25 to 30 years, when latex production decreases. The wood from para-rubber tree is a byproduct; latex is main product. The wood (trunk and branches) from fast-growing trees will be sent directly to wood pellet factories. However, the para-rubber wood will normally be sent to para-rubber wood processing factories, only waste wood will be moved to the wood pellet factories.

The wood pellet production process comprises six processes: pretreatment, drying, comminution, pelletization, cooling, and storage. Firstly, soil, stones and metal are sorted in pretreatment process, including downsizing of raw material in case of trunk or branch. Secondly, the raw material is dried by a rotary drum dryer (the moisture content from about 30–40% to about 10%). Thirdly, the raw material is ground in a hammer mill and wood flour is separated in a cyclone. Fourthly, dry raw material is press through a die block in pelletizing process. Fifthly, cooling process uses a counter flow cooler to reduce the temperature from 70 to 80 °C to 30–40 °C after which the pellets are loaded in big bags.

The energy used in wood pellets factories is: 1) 0.4 L diesel per tonne of wood pellets for vehicles in a factory such as forklift trucks and tractors, 2) 0.06 tonnes firewood per tonne of wood pellets used in the furnaces for heat production in the drying process, and 3) 90 kWh electricity per tonne of wood pellets used in one chopper, one hammer mill, one screener, one rotary drum dryer, three pellet mills, one cyclone and one cooler.The inventory data can see in study "Life Cycle Assessment of Wood Pellet Production in Thailand" [15].

The wood of para-rubber tree is commonly used in the para wood furniture industry. There are two types of para-rubber wood pellets studied; 1) Para-rubber WP: made from fresh sawdust and bark generated in para-rubber wood processing factories, and 2) Para-rubber WP-D: made from only the dry sawdust generated in the para wood furniture industry. The wood pellets are sent to power plants (10 MW) for electricity production, and to factories for burning in steam boilers (3 tonne/hr). Transportation of wood from fast-growing trees is 100 km by 10-wheel truck, with 16 tonnes of wood log (100% loading) 0% loading on the return trip. Transportation condition of waste wood is the same except that only 80% loading is considered due to low bulk density of the waste wood. Transportation of wood pellets is 250 km by 18-wheel truck, with 16 tonnes of wood pellets (100% loading) one way and 0% loading on the return trip. The capital goods and infrastructure are not considered in this study because of their relatively long lifetime (25–30 years for buildings and 5–10 years for machines). Hence, their contribution to produce one tonne of wood pellets is very small. This has often been the case in previous studies. For example, in the study by Fantozzi and Buratti (2010) on the combustion of Short Rotation Coppice wood pellets for domestic heating purposes, the environmental impact of machinery and infrastructure contributed only to 2% of the overall impacts [21]. Klöpffer and Grahl (2014) showed that in case of cumulative energy demand relating to construction of power plants, factories, and roads are cut-off because they contribute less than 1% to the total energy [22].

Data analysis

External cost calculation

The external cost occurs from the (negative) impacts of producing or consuming a good or service. Hence, calculation of external cost is based on the environmental impacts from wood pellet and fossil fuel production and their monetary value. The environmental impacts of heat and electricity production from the wood pellets and the fossil fuels are shown in Appendix A and B [23]. For the environmental impacts of electricity production, the wood pellets are compared only to lignite and natural gas as diesel and fuel oil are not used for power production in Thailand. The environmental impacts from the cultivation of fast-growing trees and para-rubber trees, and wood pellet production were referred from a life cycle assessment study of wood pellet production in Thailand (Appendix C) [15].

In this study, the researchers, using the ReCiPe Midpoint (H) life cycle impact assessment method, selected nine environmental impact categories: climate change (kg CO_2 eq), particulate matter formation (kgPM10eq), terrestrial acidification (kgSO_2eq), freshwater eutrophication (kg P eq), terrestrial ecotoxicity (kg 1,4-DCB), freshwater ecotoxicity (kg 1,4-DCB), marine ecotoxicity (kg 1,4-DCB), human toxicity (kg 1,4-DCB), and fossil resource scarcity (kg oil eq). They are important categories which can reflect impacts from fuels life cycle towards ecosystems, human health, and resource scarcity. The environmental impacts of fossil fuel production (lignite, light fuel oil and natural gas) were referred from life cycle inventory databases (the European reference Life Cycle Database (ELCD) and the U.S. Life Cycle Inventory database (USLCI)). The ELCD and USLCI databases were adapted to Thai conditions and are presented in Tables A2 and B2

Monetary valuation is used to change goods which have no market and hence no price, such as better social and environmental impacts, into monetary units. It is a potential tool for application in the weighting

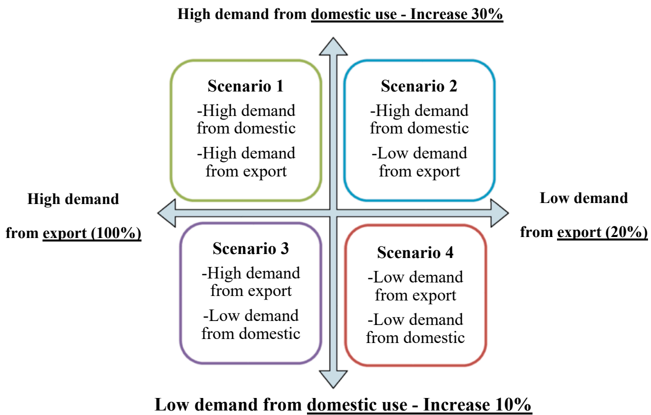

Fig. 2. A 2 × 2 scenario matrix of wood pellet demand.

phase of life cycle assessment. Moreover, monetary valuation is a tool for including external costs to consider the cost-effectiveness between recycling and production from new resources, including the social cost of CO_2 emission [24,25]. The best methods for monetary valuation in LCA are the choice experiment method and the budget constraint method [26]. Hence, in this study, evaluating the monetary value of impact categories selected the budget constraint method that referred from a study on the valuation of environmental impacts in Thailand [27]. The human health (a quality-adjusted life year: QALY) and ecosystem quality (a biodiversity-adjusted hectare year: BAHY) were chosen for the damage categories. The value of a BAHY measuring damage to ecosystems is calculated relatively to the value of a QALY. The result of a study of budget constraint and the valuation of environmental impacts in Thailand was conducted for the year 2011. Hence, to adjust the value of THB to 2021, the average inflation rate between the years 2011 and 2021 is used. The monetary values were updated by using this factor: $(1 + r)^{(t-2011)}$, where r is the average inflation rate between years 2011 and t; and t is the year for which we do the calculation (the average inflation rate between years 2011–2021 = 1.26%) [28].

Internal cost calculation

Internal cost of wood pellet production is the cost as per the normal accounting system including initial investment cost, operation cost, maintenance cost, salary and administration, fuel cost, and transportation cost which has been referred to Saosee et al. [23.29]. Internal cost of light fuel oil and natural gas production has been referred from the price structure of petroleum products in Thailand from the Energy Policy and Planning Office (EPPO), Ministry of Energy, Thailand [30]. Internal cost of lignite has been referred from the Electricity Generating Authority of Thailand. The discount rate (the rate used to discount future cash flows in discounted cash flow analysis) for internal cost was 6.6% (following interest on loan) [28].

Scenario analysis

Scenario analysis is evaluation of the impacts for possible future events. The expected value of a performance indicator is forecasted for different situations. The role of scenario analysis is to estimate the behavior of the system in response to an unexpected event and to explore the changes in system performance, in optimistic or pessimistic case [31]. Scenario analysis can be used for policymakers and decision-makers to identify problem issues and policymaking [32]. It is popular for design and management about biomass energy production [31]. It is important to predict the situation in the future to make a good policy for environmentally friendly fuels.

Hence, in this study, to evaluate the external cost of wood pellet production in 2021–2025, scenarios analysis was performed in terms of varying demand and supply of wood pellets. At present, wood pellets produced in Thailand are divided in two groups based on demand: domestic and export. Therefore, this study set scenarios by considering different proportions of wood pellet demand. The results of scenario analysis are presented based on changing the proportion of wood pellet demand, including changing of environmental and socioeconomic impacts. Moreover, the wasteland expected to support the cultivation of fast- growing trees for energy conversion is evaluated in terms of quantity of feedstock and potential of conversion to energy. In this study, the researchers applied the trend scenario and 2 × 2 scenarios matrix to present each scenario for different wood pellet demands related to environmental and socio-economic impacts, affecting the sustainability of the wood pellet situation in the future. The scenario analysis considers four scenarios related to the probability of wood pellet demand from export and domestic use as shown in Fig. 2. However, the results are presented for only 2 cases: high demand (Scenario 1) and low demand (Scenario 4) to present the range (maximum to minimum) in the future.

The Scenario 1 is the best case to increase the wood pellet production which results in the maximum income and employment increase. The wood pellet production of Scenario 3 is more than Scenario 2 because the wood pellet demand from export has more potential than that from domestic use. Scenario 4 is the worst case which can occur if there is disaster or other factors related to the main importers or even in the case of low fossil fuel price or strategies of competitors.

The high demand of wood pellet export is determined as 100% from main importers (Japan and South Korea) and low demand of wood pellet export is only 20% of wood pellet export. Japan set a plan to expand the number of power plants to increase about 2,000 MW of electricity production in 2065 for which it must import around 4.9 million tonne wood pellets [33]. South Korea increases the use rate of renewable energy from 2.0% in 2012 to 10% by 2023. For this reason, South Korea will import more than three million tonne of wood pellets in future [34]. Market share of Thailand for Japan and South Korea are 4.75% and 4% of all exporters to both, respectively. Hence, the high demand of wood pellet export (100% from two importers) is calculated by the total of wood pellet import of Japan (following the energy plan of Japan)

Table 1
Monetary values of environmental impact categories [27]

Impact category	Unit	Monetary value(USD/ kg characterized unit)
Climate change	kg CO_2 eq	0.036
Particulate matter formation	kg PM10 eq	0.003
Terrestrial acidification	kgSO_2 eq	0.011
Freshwater eutrophication	kg P eq	0.080
Terrestrial ecotoxicity	kg 1,4-DCB	0.272
Freshwater ecotoxicity	kg 1,4-DCB	0.002
Marine ecotoxicity	kg 1,4-DCB	0.003
Human toxicity	kg 1,4-DCB	0.011
Fossil resource scarcity	kg oil eq	0.161

Note: the average inflation rate = 1.26% (2011–2021) [28]

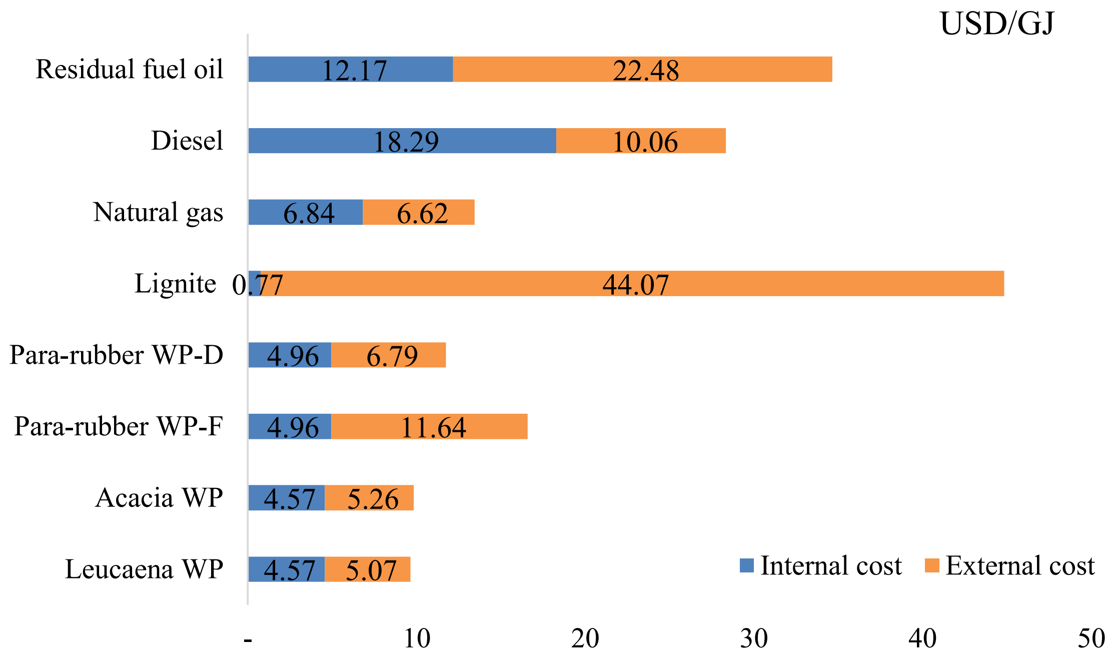

Fig. 3. External and internal costs of heat production from wood pellet and fossil fuels (Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood).

multiplied with market share of Thailand, combined with the same calculation results of South Korea.

The wood pellet demand of domestic use in Thailand is anticipated to increase only gradually because of low interest from entrepreneurs (participation of the consumers/entrepreneurs in the project to change the burner to use the wood pellets is very less). Hence, the low demand of wood pellets for domestic use is determined to increase only 10% compared to the demand in 2018, whereas the high demand of wood pellets from domestic use is set to increase 30% in the event that the government actively encourages the use of wood pellets and receives cooperation from many entrepreneurs.

Results and discussion

Monetary values of environmental impact categories

The monetary value of the impact categories in this study were referred from a study of budget constraint and the valuation of environmental impacts in Thailand [27]. However, the monetary values in 2011 were updated to 2021 by considering the average inflation rate and summing all the impacts shown in Table 1. The range of monetary values of environmental impact categories is 0.003–0.272 USD/characterized unit at midpoint. Terrestrial ecotoxicity is maximum at 0.272 USD/kg 1,4-DCB.

Comparison of external cost with internal cost for energy production from wood pellets and fossil fuels

Environmental impacts of one GJ of heat production (Appendix A) or one MWh of electricity production (Appendix B) (from wood pellets and other fuels) were multiplied with the unit monetary values of the respective environmental impact categories (Table 1) to obtain the external cost of wood pellets and other fuels. Internal cost of fuels came from production such as including initial investment cost, operation cost, maintenance cost, salary and administration, fuel cost, and transportation cost. The external cost of energy production from wood pellets reflects the costs the government pays for medical expenses, accident compensation and taxes, including loss of the environmental quality and natural capital. If the government is aware of these hidden costs that come from the environmental impacts, the government can create regulations, collect taxes or use some other instruments to account for the hidden costs in the future.

Heat production

The external cost of heat production from wood pellets (5–12 USD/GJ) is less than lignite (44 USD/GJ) and residual fuel oil (23 USD/GJ), but para-rubber wood pellets (about 12 USD/GJ) is over than external cost of natural gas which are about 7 USD/GJ (Fig. 3). The external cost of lignite is the highest of all fuels because of the high of environmental impacts (climate change, particulate matter formation, terrestrial acidification, terrestrial ecotoxicity and human toxicity), especially terrestrial ecotoxicity and human toxicity as shown in Table A2. The terrestrial ecotoxicity of lignite (147 kg 1,4-DCB) is higher than all fuels; the terrestrial ecotoxicity of wood pellets is only 13–35 kg 1,4-DCB. Meanwhile the monetary value of terrestrial ecotoxicity is 0.27 USD per kg 1,4-DCB which is the highest value of all the impacts considered (c.f. Table 1).

The external cost of lignite is the highest of all fuels as it is a low quality coal with high sulfur content. The greenhouse gas emissions from one GJ of heat production by wood pellets combustion are about 10–19 kg CO_2 eq which are less than from lignite combustion (90 kg CO_2 eq). This result corresponds to the study to Wang et al. (2017) which showed that greenhouse gas emissions from coal is approximately 94% higher than the wood pellets for heat production.

Although the Electricity Generating Authority of Thailand (EGAT) revealed that the biggest of lignite mines at Lampang province will be closed in the next 30 years due to insufficient supply of lignite, import of subituminous coal from Indonesia will affect the energy security of Thailand because of relying on energy sources from outside the country. Residual fuel oil is a product from petroleum oil known for its high environmental impacts, especially related climate change, ecotoxicity, and air pollution. Moreover, it is from a nonrenewable resource that will be depleted in the future. The external cost of natural gas production is lower than other fuels, but natural gas in Thailand will run out within the next 8 years. Hence, the impacts from use and reduced domestic reserves should be considered as they will affect the energy security in

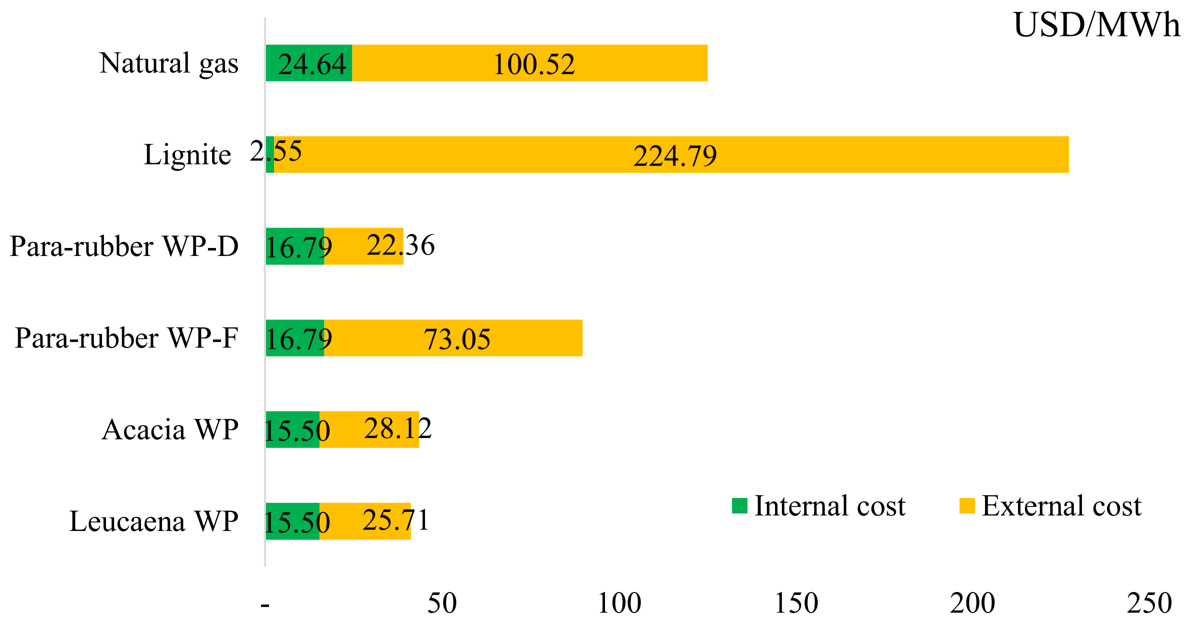

Fig. 4. External and internal costs of electricity production from wood pellets and fossil fuels (Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood).

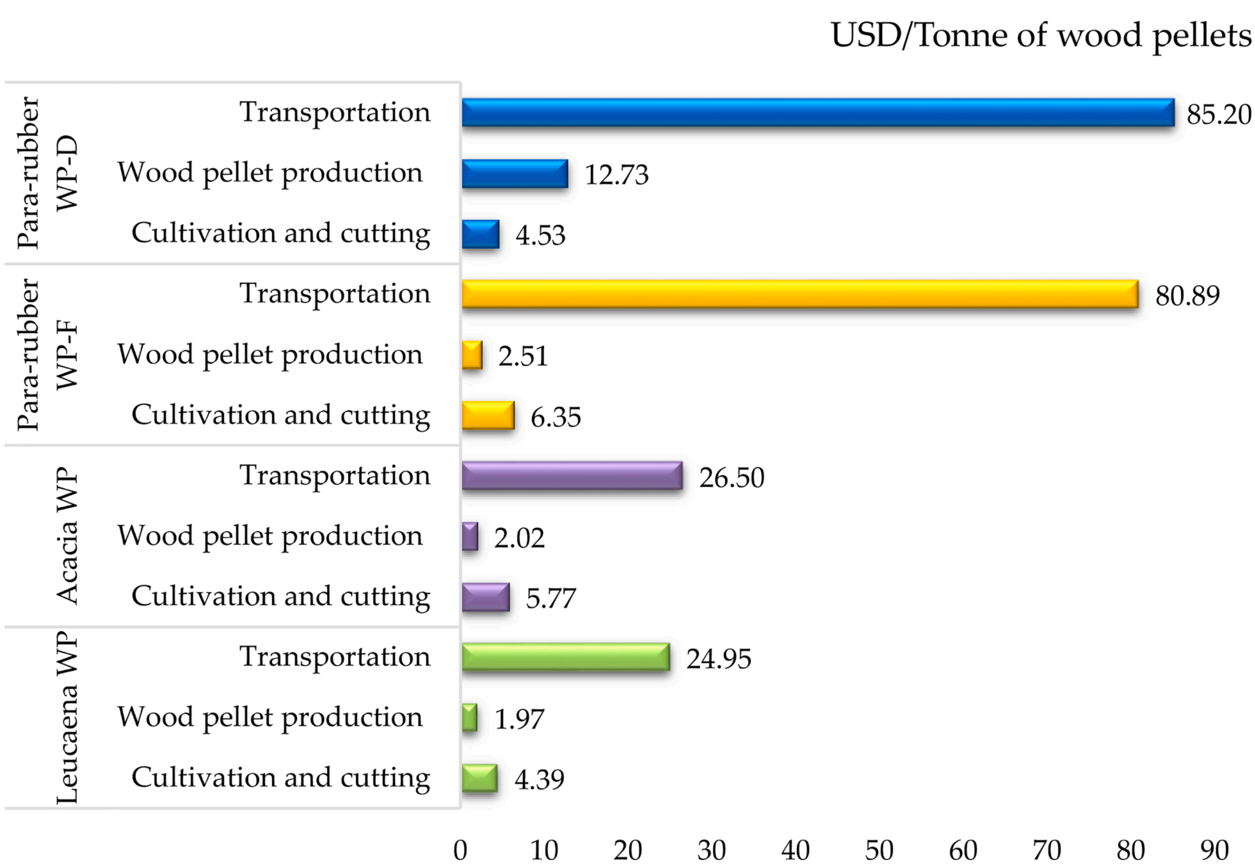

Fig. 5. External cost for wood pellets production depending on procedures (Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood).

Thailand. Therefore, these results indicate that if the lignite and residual fuel oil are replaced by wood pellets for heat production, the external cost of heat production will decrease. Morever, the use of wood pellets produced within Thailand will also help to increase the energy security in the country as crude oil is mainly imported and the domestic reserves of lignite and natural gas are also dwindling. In terms of the total cost (internal cost and external cost) of heat production, it can be seen that lignite (45 USD per GJ) and residual fuel oil (35 USD per GJ) are much higher than wood pellets, but natural gas (14 USD per GJ) is lower than para-rubber wood pellet (fresh wood) (17 USD per GJ). This result shows

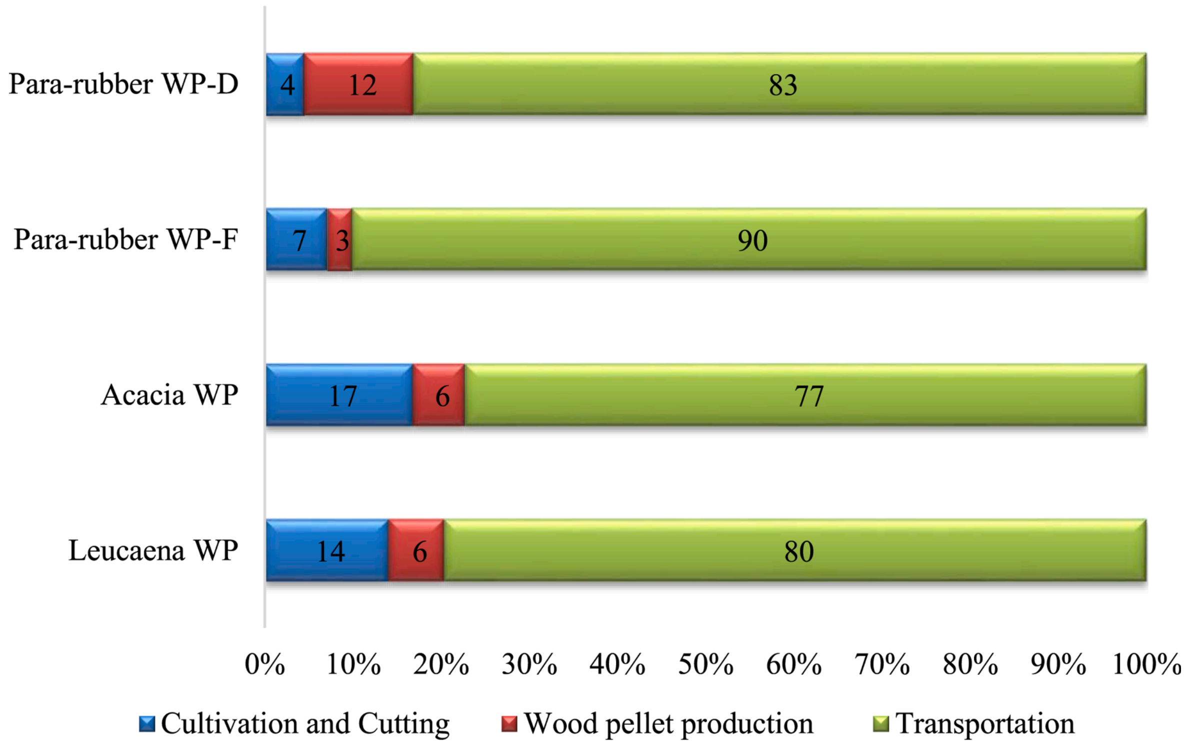

Fig. 6. Contribution to the sum of external cost of wood pellets production depending on procedures (Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood).

that the real cost (including the external cost) of lignite is higher than wood pellets, although the internal cost of lignite is much cheaper at only 0.8 USD per GJ.

Although the external cost of wood pellets is lower than lignite and residual fuel oil, the external cost of para-rubber wood pellets (contribution 58–70% of total cost) is higher than internal cost. The contribution of external cost of heat production from fast-growing wood pellets from terrestrial ecotoxicity is 3.6 USD per GJ of heat production (70% of all external cost) followed by human toxicity at 0.7 USD per GJ (14% of all external cost). The contribution of external cost of heat production from para-rubber wood pellets using dry sawdust and fresh trunk for terrestrial ecotoxicity is 5 and 9 USD per GJ of heat production (80% of all external cost), respectively. On the other hand, the human toxicity of para-rubber wood pellets using dry sawdust and fresh trunk is about 0.2 (3% of all external cost) and 0.7 (13% of all external cost) USD per GJ, respectively. This is because the para-rubber wood pellets use chemical fertilizers and herbicides in the plantation process, as also diesel for transportation. The contribution of external cost of fast-growing tree wood pellets is 53% of the total cost. The plantation process should decrease the use of chemical fertilizers and herbicides, including use of fossil fuels from production and transportation which can lead to a decrease in the external cost. The Ministry of Agriculture and Cooperatives can encourage organic farming without the use of synthetic chemical fertilizers, pesticides, herbicides, and antibiotics for raw material cultivation. Furthermore research on organic farming, should be supported to find suitable organic fertilizers, natural pesticides, and herbicides which are safe and environmentally friendly. However, as the external cost of para-rubber wood pellets (dry sawdust) is less than that of para-rubber wood pellets (fresh trunk), wood pellet production made from waste of para-rubber wood should be prioritized. The whole trunk of para-rubber wood can be processed into other products that give more value added, like furniture.

Electricity production

In 2021, the main fuels for the electricity production of Thailand are natural gas (60% of total electricity production) and coal (20%) [35]. Therefore this study selected to compare the wood pellets with natural gas and lignite. The renewable energy for electricity production of Thailand is only 17% of total electricity production (75 MW from biogas and 75 MW from biomass). Thailand has a lot of biomass power plants located in all areas of the country. These power plants use agricultural by-products as fuel to generate electricity. Bagasse and rice husk are main fuels for biomass power plants at 61 and 12% of total biomass. The others biomass (27%) are woodchip and empty fruit bunch.Disadvantage of these biomass is fluctuations of agricultural products due to season and annual rainfall. Moreover, the rice husk is used for other uses as well, such as the use of flooring for livestock and ingredient in soil preparation for growing plant, etc. Woodchip has high moisture content leading to high cost because of energy use to decrease moisture. Therefore wood pellets are biomass which anticipate to solve the problem of the shortage of other types of biomass. Hence, to encourage electricity production from wood pellets power plants or mixed-fuel biomass power plants, the external cost of electricity production from wood pellets is as important as the internal cost.

The results present that the external cost of electricity production from wood pellets (23–73 USD/MWh) is less than lignite (225 USD/ MWh) and natural gas (100 USD/ MWh), as shown in Fig. 4. In terms of the total cost (internal cost and external cost) of electricity production, it can be seen that lignite (228 USD per MWh) and natural gas (126 USD per MWh) are much higher than wood pellets. As for the case of heat production, the external cost of lignite is the highest of all fuels in electricity production as well because of the high environmental impacts (climate change, particulate matter formation, terrestrial acidification, freshwater eutrophication and terrestrial ecotoxicity) as shown in Table B2. Again, the terrestrial ecotoxicity of lignite (437 kg 1,4-DCB) is

Table 2
The External cost evaluated from the forecast of wood pellet production in 2020–2025 (Scenario 1- maximum demand and Scenario 4 - minimum demand).

	2020	2021	2022	2023	2024	2025
Scenario 1						
Demand from main importers (tonne): 100%	2.18E + 05	2.30E + 05	3.87E + 05	4.03E + 05	4.29E + 05	4.41E + 05
Demand from domestic use (tonne): +30%	8.75E + 04	1.14E + 05	1.48E + 05	1.92E + 05	2.50E + 05	3.25E + 05
Total (tonne)	3.06E + 05	3.43E + 05	5.35E + 05	5.95E + 05	6.79E + 05	7.65E + 05
External cost of para-rubber tree wood pellets [1](Million USD)	**30**	**33**	**52**	**58**	**66**	**75**
External cost of Acacia/Leucaena wood pellets[2](Million USD)	**10**	**11**	**18**	**20**	**23**	**26**
Scenario 4						
Demand from main importers (tonne):20%	4.36E + 04	4.59E + 04	7.75E + 04	8.05E + 04	8.58E + 04	8.81E + 04
Demand from domestic use (tonne): +10%	8.75E + 04	9.63E + 04	1.06E + 05	1.16E + 05	1.28E + 05	1.41E + 05
Total (tonne)	1.31E + 05	1.42E + 05	1.83E + 05	1.97E + 05	2.14E + 05	2.29E + 05
External cost of para-rubber tree wood pellets [1](Million USD)	**13**	**14**	**18**	**19**	**21**	**22**
External cost of Acacia/Leucaena wood pellets[2](Million USD)	**4.34**	**4.79**	**5.99**	**6.59**	**7.19**	**7.5**

[1] External cost of para-rubber tree wood pellets are about 97.36 USD/tonne of wood pellets.
[2] External cost of Acacia/Leucaena wood pellets are about 33.25 USD/tonne of wood pellets.

higher than all other fuels; the terrestrial ecotoxicity of wood pellets is only 68–230 kg 1,4-DCB. Meanwhile the monetary value of terrestrial ecotoxicity at 0.27 USD per kg 1,4-DCB is the highest of all impacts (c.f. Table 1). Moreover, the climate change impact for lignite is also the highest of all fuels at 1,360 kg CO_2 eq. These resulted in the very high contribution of external cost to the total cost of lignite.

The total cost of electricity production from para-rubber wood pellets (fresh wood) is the highest among all the wood pellet options at about 90 USD per MWh due to use of energy for drying to reduce moisture content. Hence, in term of total cost which includes the external cost, that wood pellets can replace natural gas and lignite. However, the government should plan systematically to ensure that there is enough raw materials for electricity production throughout the year.

The external cost of electricity production from lignite is the highest, contributing for 99% of the total cost. The contribution of internal cost is only 1% (2.5 USD per MWh). This result shows that lignite is not suitable for fuel of electricity production even though its internal cost is low. The contribution of lignite external cost interm midpoint catergories are terrestrial ecotoxicity 57% of external cost, climate change 22% of external cost and Fossil resource scarcity 21%. The contribution of natural gas external cost are fossil resource scarcity 40%, terrestrial ecotoxicity 33% of external cost and climate change 25% of external cost.

The contribution of wood pellet external cost is about 60–80% of total cost. The contribution of external cost of electricity production from wood pellets cause in term of terrestrial ecotoxicity about 20 USD per MWh (80% of all external cost) except the external cost of para-rubber wood pellets (fresh wood) at 63 USD per MWh (85% of all external cost). The external cost of wood pellets in term of human toxicity at 0.6 USD per MWh (7% of all external cost). It is found that the external cost of wood pellets in term of human toxicity (0.6–0.8 USD per MWh) is higher than lignite and natural gas (0.21–0.24 USD per MWh) except para-rubber wood pellets (dry sawdust) (0.12 USD per MWh).

From these results found that substitution of lignite or natural gas for electricity production by wood pellets reduce climate change, particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and fossil resource scarcity, but increase human toxicity. Therefore, use of wood pellets for electricity production can decrease the external cost. However, producers can reduce the external cost of wood pellets by focusing good agricultural practice for raw material plantation.

Comparison of the external cost of wood pellets by process

This topic shows the external cost from one tonne wood pellet production in order to know that which processes of wood pellet production should be improved to compete with fossil fuels. Processes of wood pellet production have three parts: 1) cultivation and cutting, 2) wood pellet production and 3) transportation. In wood pellet productions (Fig. 5), it is indicated clearly that the external cost from transportation of all are higher than other processes. Transportation from diesel affects the higher external cost about 77–90% of all processes (Fig. 6). Hence, logistic planning should be considered, wood pellet factories should be set near raw material sources and users. Furthermore, they should use more environmentally friendly energy sources such as biodiesel.

Trend of wood pellet production in Thailand

Although electricity is one of the main energy carriers in world, the impact of the Covid-19 crisis on electricity production decreased significantly due to implemented lockdown measures in 2020 [36]. This shows that disasters can influence the trend of electricity consumption. Therefore, forecasting the demand of wood pellets should be studied several cases at least; a best case and worst case.

Meanwhile, Thailand has the Power Development Plan (PDP) 2018 and AEDP 2015 which aim to use more electricity, especially due to the change of diesel engine to electric vehicle. It aims to establish 3,376 biomass power plants by 2037. Using wood pellets as one of the biomass fuels in the electricity generation can support energy security of Thailand in the future. Therefore, it is necessary to know the external costs of wood pellet production in order to use it as information to support the policy.

The results of scenario analysis present only the best case (scenario 1: high demand of wood pellets from export and domestic use) and worst case (scenario 4: low demand of wood pellets from export and domestic use) as shown in Table 2. The results indicate that Scenario 1 can increase the wood pellet production about to 765,500 tonnes in 2025 as there is still enough the feedstock. The Scenario 1 can make a profit of over 7.5 million USD and increases 1,100 persons-year of employment [23]. However, the 765,500 tonnes of wood pellet production in 2025 add about 75 million USD as the external cost of para-rubber wood pellets and about 26 million USD for Acacia/Leucaena wood pellets.

The wood pellet production of Scenario 4 (+10% of wood pellet for domestic use, 20% of wood pellets for export) is only 230,000 tonnes in 2025 which makes a profit of over 2.2 million USD and increases only 327 persons-year of employment [23,37]. The external cost of para-rubber wood pellets for Scenario 4 is about 22 million USD and about 7.5 million USD for Acacia/Leucaena wood pellets. The external cost from wood pellet production is the hidden costs required by the Thai government to manage the overall environmental quality of the country, including better human health.

In case, use of wood pellets for domestic use (increase + 30%) in 2025 is 325,000 tonnes which can reduce GHG emissions by 4.08×10^5 tonnes CO_2 eq for heat production (2.5% of GHG mission from energy consumption from power generation and industry). The GHG reduction of wood pellet domestic use helps the national greenhouse gas reduction plan for the year 2021–2030 achieve success (The national greenhouse gas reduction plan with the goal of reducing greenhouse gas by 7–20 % in the energy and transportation sectors by 2020).

Policy recommendations

Recommendations to reduce the external costs for sustainable wood pellet production comprise of two issues: 1) campaign to reduce environmental impact and 2) Polluter Pays Principle: PPP. To reduce environmental impact from wood pellet production and promote the sustainable wood pellet for energy, the results have the following policy implications.

First, to support sustainable agriculture for para-rubber and fast-growing trees which are important raw materials in Thailand. Although the Thai government (Ministry of Agriculture and Co-operatives) launched a policy "To develop and transfer agricultural technology focusing on effective, sustainable and environmental-friendly use of agricultural resources", there are still problems in implementing this policy. Farmers are still using pesticides and insecticides, including chemical fertilizers widely. Para-rubber wood pellet importers call for sustainable rubber tree planting certification. Although the entrepreneurs have organized groups to certify sustainable rubber plantation, but it not very widespread when compared to the area of para-rubber plantations in Thailand. This study can provide information for executing and accelerating the implementation of these important policies into real practice.

Second, clean transportation should be considered in the supply chain of wood pellets production and use. The dirty technology and use of fossil fuels in the past should be changed to electric vehicles, fuel efficiency, cleaner fuel, and new mobility models. However, the Ministry of Energy has a plan to reduce the proportion of natural gas in electricity production from 64% of total fuels for electricity production in 2014 to 37% in 2036, including proportion of using renewable energy produced in the country (for electricity, heat and biofuels production) at 26–30% of final power and efficiency energy increased by 5.98 thousand tonnes of crude oil equivalent / billion baht. Therefore, to implement sustainable energy development planning in Thailand, the results of this study can be used as important information to consider adjustment of the plan and to have strict measures for ameliorating pollution problems.

Third, to plan and organize to have wood pellet factory zone close to the source of raw materials to reduce transportation issues, including good logistics for domestic use and export. Moreover, the Thai government can consider the external cost of wood pellets for polluter pays principle by taking into account the hidden costs. Although the Enhancement and Conservation of Environmental Quality 1992 of Thailand had already considered the polluter pays principle, it never actually been applied in practice.

Conclusions and policy implications

Although the wood pellets are considered an important product from biomass for moving towards sustainable development, external cost of heat and electricity production from wood pellets has not been well studied and is usually ignored. Hence, this study evaluated the external cost of heat and electricity production from wood pellets as an information for environmental policymakers on the pollution problem of wood pellet production and use.

The external cost of heat and electricity production from wood pellets is lesser than the conventional fuels used in Thailand, except for para-rubber wood pellets for heat production whose external cost is higher than that of natural gas. In terms of the total cost, the results are in the same direction as the external cost. These results show that the real cost (including external cost) shows quite a different picture as compared to the conventionally considered internal cost. These findings indicate that in terms of total cost, the lignite, residual fuel oil and natural gas can and should be replaced by the wood pellets for both heat or electricity production. Morever, as the wood pellets are produced within Thailand, this will also help to increase energy security in the country. Additionally, the external cost of wood pellet production can be further decreased with the judicious use of chemical fertilizer and herbicide, and decreasing the use of fossil fuels during production and transportation.

From the scenario of wood pellet demand for both domestic use and exports in 2025, it is possible to produce 150,000–765,500 tonnes (worst case to best case) of wood pellets in 2025 with the external cost of approximately 4–75 million USD. Our results are helpful for policy makers in guiding to reduce the external costs for sustainable wood pellet production, comprising of four issues: 1) to support sustainable agriculture for para-rubber and fast-growing trees which are important raw materials of Thailand, 2) to consider clean transportation in supply chain of wood pellet production and use, 3) to plan and organize to have wood pellet factory zone close to the source of raw materials to reduce transportation costs, including studies on good logistics for domestic use and export, and 4) considering the external cost of wood pellets for polluter pays principle. These results and recommendations of the study can provide important information to consider for adjusting the plan and to have strict measures for avoiding problem shifting.

CRediT authorship contribution statement

Piyarath Saosee: Methodology, Formal analysis, Data curation, Visualization, Investigation, Software, Validation, Writing – original draft. **Boonrod Sajjakulnukit:** Investigation, Formal analysis. **Shabbir H. Gheewala:** Supervision, Conceptualization, Investigation, Writing – review & editing, Data curation, Validation.

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.

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Appendix

Tables A1-C1.

Table A1
Environmental impacts of production one GJ of heat from wood pellets.

Impact category	Unit	Wood pellets Leucaena	Acacia	Para-rubber tree-F	Para-rubber tree-D
Climate change	kg CO_2 eq	9.97E + 00	1.03E + 01	1.85E + 01	1.31E + 01
Particulate matter formation	kg PM10 eq	6.64E-02	6.71E-02	7.69E-02	1.45E-02
Terrestrial acidification	kgSO_2 eq	1.20E-01	1.21E-01	1.55E-01	4.39E-02
Freshwater eutrophication	kg P eq	1.08E-03	1.08E-03	1.04E-03	3.87E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.33E + 01	1.38E + 01	3.47E + 01	2.01E + 01
Freshwater ecotoxicity	kg 1,4-DCB	1.23E-02	1.27E-02	2.27E-02	1.17E-02
Marine ecotoxicity	kg 1,4-DCB	2.43E-02	2.51E-02	5.39E-02	3.05E-02
Human toxicity	kg 1,4-DCB	6.47E + 01	6.55E + 01	6.47E + 01	2.01E + 01
Fossil resource scarcity	kg oil eq	2.46E + 00	2.62E + 00	5.22E + 00	3.92E + 00

Note: Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood

Table A2
Environmental impacts of producing one GJ of heat from fossil fuels (lignite, light fuel oil and natural gas).

Impact category	Unit	Fossil fuels Lignite [1]	Light fuel oil[2]	Natural gas[3]
Climate change	kg CO_2 eq	9.04E + 01	9.88E + 01	6.70E + 01
Particulate matter formation	kg PM10 eq	1.68E-01	1.21E-01	1.54E-01
Terrestrial acidification	kgSO_2 eq	5.75E-01	4.09E-01	5.32E-01
Freshwater eutrophication	kg P eq	0	0	0
Terrestrial ecotoxicity	kg 1,4-DCB	1.47E + 02	5.26E + 01	5.77E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.28E-02	4.79E-01	1.84E-01
Marine ecotoxicity	kg 1,4-DCB	3.26E-02	6.74E-01	2.31E-01
Human toxicity	kg 1,4-DCB	8.07E + 01	23.90673609	5.57E + 00
Fossil resource scarcity	kg oil eq	5.05E-02	2.88E + 01	2.48E + 01

Note: [1-2] referred from the European reference Life Cycle Database (ELCD)
[3] referred from the U.S. Life Cycle Inventory database (USLCI)

Table B1
Environmental impacts of production one MWh of electricity from wood pellets.

Impact category	Unit	Wood pellets Leucaena	Acacia	Para-rubber tree-F	Para-rubber tree-D
Climate change	kg CO_2 eq	5.71E + 01	6.15E + 01	1.15E + 02	4.44E + 01
Particulate matter formation	kg PM10 eq	1.07E-01	1.16E-01	1.79E-01	4.91E-02
Terrestrial acidification	kgSO_2 eq	2.60E-01	2.81E-01	5.04E-01	1.49E-01
Freshwater eutrophication	kg P eq	1.99E-03	2.01E-03	1.52E-03	1.31E-03
Terrestrial ecotoxicity	kg 1,4-DCB	7.43E + 01	8.10E + 01	2.30E + 02	6.81E + 01
Freshwater ecotoxicity	kg 1,4-DCB	5.89E-02	6.29E-02	1.35E-01	3.95E-02
Marine ecotoxicity	kg 1,4-DCB	1.35E-01	1.45E-01	3.49E-01	1.03E-01
Human toxicity	kg 1,4-DCB	5.67E + 01	6.63E + 01	5.22E + 01	9.68E + 00
Fossil resource scarcity	kg oil eq	1.76E + 01	1.97E + 01	3.70E + 01	1.33E + 01

Note: Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood.

Table B2
Environmental impacts of producing one MWh of electricity from fossil fuels (lignite, and natural gas).

Impact category	Unit	Fossil fuels Lignite[1]	Natural gas[2]
Climate change	kg CO_2 eq	1.36E + 03	6.94E + 02
Particulate matter formation	kg PM10 eq	2.36E + 00	1.68E-01
Terrestrial acidification	kgSO_2 eq	5.67E + 00	4.95E-01
Freshwater eutrophication	kg P eq	3.11E-01	2.26E-03
Terrestrial ecotoxicity	kg 1,4-DCB	4.73E + 02	1.24E + 02
Freshwater ecotoxicity	kg 1,4-DCB	2.58E-01	5.36E-01
Marine ecotoxicity	kg 1,4-DCB	5.65E-01	9.18E-01
Human toxicity	kg 1,4-DCB	2.10E + 01	1.89E + 01
Fossil resource scarcity	kg oil eq	2.91E + 02	2.59E + 02

Note: [1]referred from the European reference Life Cycle Database (ELCD)
[2] referred from the U.S. Life Cycle Inventory database (USLCI)

Table C1
Environmental impacts of production one tonne wood pellets [15]

Impact category	Unit	Wood pellets Leucaena	Acacia	Para-rubber tree-F	Para-rubber tree-D
Climate change	kg CO_2 eq	6.79E + 01	7.34E + 01	1.40E + 02	2.06E + 02
Particulate matter formation	kg PM10 eq	1.25E-01	1.37E-01	2.15E-01	2.28E-01
Terrestrial acidification	kgSO_2 eq	3.06E-01	3.32E-01	6.12E-01	6.89E-01
Freshwater eutrophication	kg P eq	2.45E-03	2.48E-03	1.87E-03	6.08E-03
Terrestrial ecotoxicity	kg 1,4-DCB	9.25E + 01	1.01E + 02	2.87E + 02	3.16E + 02
Freshwater ecotoxicity	kg 1,4-DCB	5.74E-02	6.24E-02	1.52E-01	1.83E-01
Marine ecotoxicity	kg 1,4-DCB	1.47E-01	1.60E-01	4.14E-01	4.80E-01
Human toxicity	kg 1,4-DCB	7.00E + 01	8.20E + 01	6.44E + 01	4.49E + 01
Fossil resource scarcity	kg oil eq	2.09E + 01	2.35E + 01	4.51E + 01	6.17E + 01

Note: Para-rubber WP-F: made from fresh para-rubber wood, Para-rubber WP-D: made from dry sawdust of para-rubber wood.

References

[1] Jåstad EO, Bolkesjø TF, Trømborg E, Rørstad PK. The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector. Appl Energy 2020;274:115360. https://doi.org/10.1016/j.apenergy.2020.115360.

[2] Ruiz D, Miguel GS, Corona B, López-Serrano FR. LCA of a multifunctional bioenergy chain based on pellet production. Fuel 2018;215:601–11. Doi: 10.1016/j.fuel.2017.11.050.

[3] Quinteiro P, Greco F, da Cruz Tarelho LA, Righi S, Arroja L, Dias AC. A comparative life cycle assessment of centralised and decentralised wood pellets production for residential heating. Sci Total Environ 2020;730:139162. https://doi.org/10.1016/j.scitotenv.2020.139162.

[4] Thomson H, Liddell C. The suitability of wood pellet heating for domestic households: A review of literature. Renew Sustain Energy Rev 2015;42:1362–9. https://doi.org/10.1016/j.rser.2014.11.009.

[5] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;15(5):2262–89. https://doi.org/10.1016/j.rser.2011.02.015.

[6] Strauss W. 2020 Global pellet markets outlook. Can Biomass Mag 2020. https://www.canadianbiomassmagazine.ca/2020-global-pellet-markets-outlook/ (accessed May 25, 2020).

[7] European Pellet Council. World Pellet Map. Eur Pellet Counc 2020. https://epc.bioenergyeurope.org/about-pellets/pellets-statistics/world-pellet-map/ (accessed January 20, 2020).

[8] Saosee P, Sajjakulnukit B, Gheewala SH. Feedstock Security Analysis for Wood Pellet Production in Thailand. Energies 2020;13:5126. https://doi.org/10.3390/en13195126.

[9] Department of Alternative Energy Development and Efficiency. Using wood pellets for small boilers in industry, Bangkok: Department of Alternative Energy Department and Efficiency. Bangkok: Department of Alternative Energy Development and Efficiency, Ministry of Energy (Thailand); 2016.

[10] Zhu D, Mortazavi SM, Maleki A, Aslani A, Yousefi H. Analysis of the robustness of energy supply in Japan: Role of renewable energy. Energy Rep 2020;6:378–91. https://doi.org/10.1016/j.egyr.2020.01.011.

[11] Bossler A. Sailing into Japan: Wood Pellet Demand in a Changing Energy Market. Biomass Mag 2020. http://biomassmagazine.com/articles/16733/sailing-into-japan-wood-pellet-demand-in-a-changing-energy-market (accessed January 25, 2020).

[12] The International Energy Agency and The International Renewable Energy Agency. Korea Renewable Energy 3020 Plan: IEA/IRENA Renewables Policies Database 2020. https://www.iea.org/policies/6569-korea-renewable-energy-3020-plan (accessed October 19, 2020).

[13] FutureMetrics. This interactive Sankey map by FutureMetrics shows global wood pellet trade in 2019. 2019. https://www.futuremetrics.info/global-trade-sankey-map/ (accessed October 19, 2020).

[14] Wang C, Chang Y, Zhang L, Pang M, Hao Y. A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China. Energy 2017;120:374–84. https://doi.org/10.1016/j.energy.2016.11.085.

[15] Saosee P, Sajjakulnukit B, Gheewala SH. Life Cycle Assessment of Wood Pellet Production in Thailand. Sustainability 2020;12:1–22.

[16] Dias GM, Ayer NW, Kariyapperuma K, Thevathasan N, Gordon A, Sidders D, et al. Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario. Canada. Appl Energy 2017;204:343–52. https://doi.org/10.1016/j.apenergy.2017.07.051.

[17] European Commission. Handbook on the external costs of transport. Luxembourg: Publications Office of the European Union; 2019.

[18] Zhao X, Cai Q, Ma C, Hu Y, Luo K, Li W. Economic evaluation of environmental externalities in China's coal-fired power generation. Energy Policy 2017;102:307–17. https://doi.org/10.1016/j.enpol.2016.12.030.

[19] Wang Z, Wei W. External cost of photovoltaic oriented silicon production: A case in China. Energy Policy 2017;107:437–47. https://doi.org/10.1016/j.enpol.2017.05.019.

[20] International Renewable Energy Agency. Renewable Energy Outlook. Thailand. 2017. https://doi.org/10.1016/b978-0-08-092401-4.50007-4.

[21] Fantozzi F, Buratti C. Life cycle assessment of biomass chains : Wood pellet from short rotation coppice using data measured on a real plant. Biomass Bioenergy 2010;34:1796–804. https://doi.org/10.1016/j.biombioe.2010.07.011.

[22] Klöpffer W, Grahl B. Life Cycle Assessment (LCA). Weinheim, Germany: Strauss Gmbh, Mörlenbac; 2014.

[23] Saosee P. Environmental and Socio-economic Sustainability Assessment of Wood Pellet Industry in Thailand. King Mongkut's University of Technology Thonburi; 2020.

[24] Huber F, Fellner J. Integration of life cycle assessment with monetary valuation for resource classification: The case of municipal solid waste incineration fly ash. Resour Conserv Recycl 2018;139:17–26. https://doi.org/10.1016/j.resconrec.2018.08.003.

[25] van den Bergh JCJM, Botzen WJW. Monetary valuation of the social cost of CO2 emissions: A critical survey. Ecol Econ 2015;114:33–46. https://doi.org/10.1016/j.ecolecon.2015.03.015.

[26] Pizzol M, Weidema B, Brandão M, Osset P. Monetary valuation in Life Cycle Assessment: A review. J Clean Prod 2015;86:170–9. https://doi.org/10.1016/j.jclepro.2014.08.007.

[27] Kaenchan P, Gheewala SH. Budget constraint and the valuation of environmental impacts in Thailand. Int J Life Cycle Assess 2017;22(11):1678–91. https://doi.org/10.1007/s11367-016-1210-x.

[28] Bank of Thailand. Summary of economic and inflation projections in the Monetary Policy ReportNo Title 2021. https://www.bot.or.th/Thai/MonetaryPolicy/MonetPolicyComittee/MPR/Pages/default.aspx (accessed December 15, 2021).

[29] Saosee P, Sajjakulnukit B, Gheewala SH. Environmental and Socio-economic Assessment of Wood pellet Production from Fast growing trees in Thailand. Int Conf Sustain Energy Green Technol 2020;463(1):012049. https://doi.org/10.1088/1755-1315/463/1/012049.

[30] Energy Policy and Planning office. price structure of petroleum product in Bangkok 2021. http://www.eppo.go.th/index.php/th/petroleum/price/structure-oil-price.

[31] Balaman ŞY. Decision-Making for Biomass-Based Production Chains: The Basic Concepts and Medothologies. İzmir, Turkey: Academic Press; 2019.

[32] Wright D, Stahl B, Hatzakis T. Policy scenarios as an instrument for policymakers. Technol Forecast Soc Change 2020;154:119972. https://doi.org/10.1016/j.techfore.2020.119972.

[33] Jonsson R, Rinaldi F. The impact on global wood-product markets of increasing consumption of wood pellets within the European Union. Energy 2017;133:864–78. Doi: 10.1016/J.ENERGY.2017.05.178.

[34] Asia Biomass Office. The Demand for Wood Pellets in South Korea. Asia Biomass Off; 2019. https://www.asiabiomass.jp/english/topics/1211_03.html.

[35] Electricity Generating Authority of Thailand. Proportion of fuel use for generating electricity in the Electricity Generating Authority of Thailand (EGAT) system in 2021 2021. https://www.egat.co.th/index.php?option=com_content&view=article&id=2455&Itemid=116 (accessed September 17, 2021).

[36] International Energy Agency. Key electricity trends 2020 2021. https://www.iea.org/articles/key-electricity-trends-2020 (accessed April 9, 2021).

[37] Saosee P, Sajjakulnukit B, Gheewala SH. Life cycle assessment of wood pellet from para-rubber tree residues. In: RIFFAT S, SU Y, ISMAIL N, AHMAD MI, editors. Proc. 18th Int. Conf. Sustain. Energy Technol. (SET 2019), Kuala Lumpur, Malaysia: 2019, p. 552.