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Study on the Potential of Rice Straws as a Supplementary Fuel in Very Small Power Plants in Thailand

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Abstract: Agricultural residue is a major raw material for renewable energy production, particularly heat production, in Thailand. Meanwhile, the process-based residue, such as bagasse, rice husk, wood residue, palm fiber, palm shell, and saw dust, is used as a fuel for energy production in the agro-industry. Hence, this study is intended to assess the net potential and capacity of alternative agricultural residues, specifically rice straws, to serve as the supplementary fuel for very small power plants (VSPPs) in Thailand. According to the results obtained during the crop season of 2015/2016, approximately 26 Mt of rice straws were generated upon the harvesting process. The net potential of rice straws, including those that were burned and those that were left in the fields, was only about 15% or 3.85 Mt, which could be used for heat and electricity production at 1331 kilotons of oil equivalent (ktoe) or 457 MWe. As agro-residues vary by seasonality, the peak season of rice straws was in November, where approximately 1.64 Mt (43%) were generated, followed by December, at 1.32 Mt (34%). On the basis of the results, rice straw has the potential to serve as a fuel supply for VSPPs at 14.2%, 21.6%, 26.3%, and 29.0% for the radii of compilation at 24, 36, 48 km and 60 km, respectively.

Keywords: agricultural residues; biomass; renewable energy; biomass power plant

1. Introduction

Renewable energy has gained a lot of interest amongst many countries. In Thailand, renewable energy has been used continually in various forms such as electricity, heat, and biofuel. According to the Thailand Alternative Energy Situation Report of the Department of Alternative Energy Development and Efficiency (DEDE), the Ministry of Energy [1], in 2016, the total energy consumption in Thailand was 79,929 ktoe, of which 13.8% or 11,051 ktoe was renewable energy, which had increased by 9.7% from the previous year. On the basis of the data in 2016, renewable energy was mainly used in the form of heat (7183 ktoe), followed by electricity (2121 ktoe) and biofuel (1746 ktoe) at the percentage shares of 65.0%, 19.2%, and 15.8%, respectively. Regarding heat production, biomass was the greatest share at 90.6%, followed by biogas, municipal waste and solar energy, which shared 8.3%, 1.0% and 0.1%, respectively. The main biomass feedstock was agro-residue that generated over 15,701 ktoe, including agricultural waste at 8274 ktoe, bagasse at 6432 ktoe and rice husk at 995 ktoe. Indeed, the agro-industries, such as the sugar, rice, and palm oil industries, were the main manufacturers of renewable heat, as these manufacturers used their own residue generated in the production process for fuel supply in order to save costs. The agricultural waste was used for heat and power productions of about 2904 and 5370 ktoe respectively, whereas bagasse was used as a fuel for heat and power productions of about 3248 and 3184 ktoe respectively, and rice husk was used to produce heat and power productions of about 193 and 802 ktoe respectively.

Concerning the continuous rise in the demand for renewable energy, private and public sectors have begun to invest more in renewable energy projects, particularly in the biomass energy segment that accounts for 38.7% of alternative energy investment. Under the Alternative Energy Development Plan 2015 (AEDP 2015) [2], renewable energy is targeted to achieve 30% of the total energy consumption, which is equivalent to 39,388 ktoe, by 2036. This target is based on three perspectives: energy security, economy saving, and eco-friendliness. The primary objective of the plan is to promote the use of renewable energy by maximizing the full potential of the country's capacity. Under the renewable energy target, solid biomass is the main raw material for all energy production, particularly heat production, which is expected to generate 22,100 ktoe or 88.09% of the renewable heat production target. Upon the comparison between the true and targeted usage, it was found that the true usage was less than half of the target. Hence, there is still a large gap to meet the target (the true usage is 9283 ktoe, and the targeted usage is 22,100 ktoe for the renewable heat production from agro-residue). The strategy that can be implemented to facilitate the target's achievement is the preparation of raw materials and technology to support the target's feedstock demand. Finding an alternative feedstock and potential zoning area are also part of the strategic plan. Likewise, a suitable arrangement of feedstock at an appropriate area, particularly the remote area, also serves as a means to support the achievement of the target of AEDP 2015 [2].

In this regard, the government has to take into consideration the agricultural field-based residue as an alternative fuel for the production of heat and electricity in factories. In particular, rice straw residue should be contemplated, as it is the major field-based residue in Thailand. Accordingly, this study intends to assess the net potential of alternative agro-residues, specifically rice straws, for energy-related purposes. The obtained results can be used to provide information to support policy measures concerning the utilization of agro-residues as energy feedstock. In addition, this study also emphasizes assessing the efficiency of the rice straw supply as an additional fuel for very small power plants (VSPPs) in Thailand.

2. Materials and Methods

2.1. Site Study

Thailand is an agricultural country with rice as the main economic crop that is planted spatially across the country, as illustrated in Figure 1 [3]. The northeastern region is the main cultivation area and covers approximately 7.1 Mha. The second cultivation area is the northern region (3.1 Mha), particularly the lower northern area. Meanwhile, the central region has the highest frequency of rice plantations, as well as the highest yield as a result of the relatively high abundance of water resources and high nutrient levels in the soil as compared to other regions [4]. The frequency of rice plantations in the central region, including photosensitive or non-photosensitive varieties, is approximately 2–2.5 rounds per year, which is higher than the average plantation frequency of the country at 1.0 round per year [5]. The characteristics of rice cultivation are typical for the region, wherein broadcasting plantation and machinery harvesting are widely used in order to reduce the cultivation time. According to the Agricultural Statistics of Thailand 2015 of the Office of Agricultural Economics (OAE) [4], in 2015, the total harvesting area of rice in Thailand was about 9.49 Mha, comprising 8.46 Mha of major rice fields and 1.03 Mha of minor rice fields.

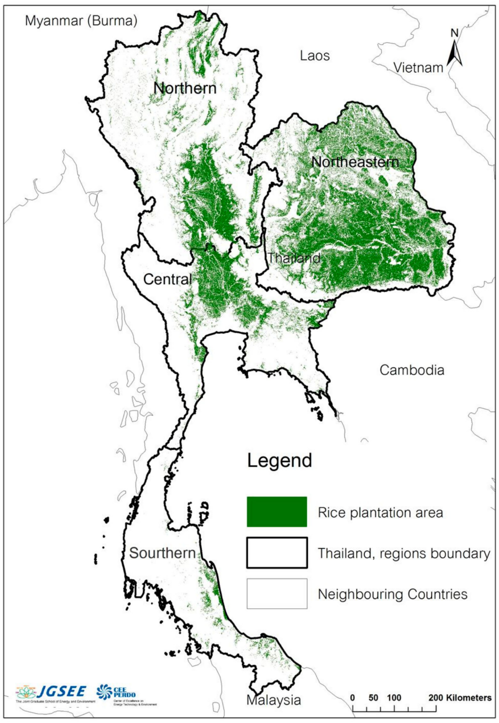


Figure 1. Spatial allocation of paddy field, modified from land use information (2014) of Land Development Department, Thailand [3].

According to the report published by the Rice Department (RD), the Ministry of Agriculture and Cooperatives [6], there are about 116 varieties of rice in Thailand, which can be classified into two groups on the basis of their sensitivity to light: (1) Photosensitive varieties, which will only form flowers in the months when the day length is less than 12 h. Farmers generally use this type of variety for in-season rice cultivation, specifically in November, as the day length is less than 11 h 40 min. (2) Non-photosensitive varieties, for which flowering does not depend on the day length. Once the rice reaches a certain age, it will form flowers immediately, regardless of the day length. Farmers generally use this type of variety for off-season rice cultivation. In addition, rice plantations can also be categorized into two groups on the basis of farming practices: (1) rain-fed fields in which rice is planted during the rainy season (plantation frequency is only once per year), which are associated with major rice cultivation; and (2) irrigated fields in which rice is planted all-year-round upon the availability of water resources, which is associated with minor rice cultivation. About 70% of rice in Thailand is planted in rain-fed areas, and the rest is planted in irrigated areas, mainly in the central region [6]. Concerning the varieties of rice species, the differences in rice plantations and harvesting patterns influence the amount of rice residue generated in each field.

2.2. Assessment of Rice Straw Potential

There is numerous information used as statistical information for the biomass (agricultural residue) potential assessment, such as field survey information, remotesensing information, and so forth. Statistical information, such as the annual crop production or annual harvested area, is multiplied with the coefficient of crop residue to product ratio (RPR) or biomass load respectively to obtain the potential [7]. The statistical value is obtained from various sources, either national reports (e.g., OAE, the Ministry of Agriculture and Cooperatives) or international reports (e.g., Food and Agriculture Organization—FAO). There are several studies reporting the values of the RPR and the biomass load. In the case of rice straw, the values are in the range of 0.31–1.69 t/ha [8] and 7.0–19.0 t/ha [5,9,10] for the RPR and biomass load respectively, depending upon the soil quality, the rice varieties, the fertilization level, the supply of water used in the plantation, and the harvesting method [11]. However, this method provides only the theoretical potential, which accounts for the maximum amount but ignores the spatial and temporal allocation and realistic potential.

Questionnaire survey information from a field survey method is another way to collect information on various issues related to biomass production and consumption [12]. The sampling might be biomass producers such as farmers, dealers, and so forth, or biomass consumers such as related farmers, industries, power plants, and so forth, which depend upon the objective of the survey. From the perspective of the rice residue supply, this method is an important tool to obtain common understanding of farmer behaviors regarding rice residue management. Moreover, remotesensing information, such as satellite images, is applied for assessing or monitoring the field-based biomass residues by image interpretation together with a geographic information system program (GIS) [12]. Medium-resolution images, such as Landsat 8 images, can be used to assess the spatial allocation of biomass resources [13]. The routine of satellite orbits can be used to monitor the crop growth and the temporal allocation of the biomass generated. This method is suited for the assessment on the large scale, particularly in remote areas.

This study combines these methods to assess the net potential of alternative agro-residues, specifically rice straws, for energy-related purposes. Satellite information from the Moderate Resolution Imaging Spectroradiometer (MODIS) is used to assessed the spatial and temporal allocation of the rice residue generation; a field survey experiment was used to develop the "rice physical determination model" for the gross potential assessment and validation with the statistical information; a questionnaire survey used to create the "rice straw flow diagram" for the net potential assessment.

Therefore, this study assesses the potential of rice straws to be used as energy feedstock by using Equations (1)–(5). The gross potential is defined as the amount of rice straws generated after the harvesting process. The net potential is defined as the amount of residue subjected to open-burning and the amount of unused rice residue that is left in the field and that farmers are willing to sell.

$$S_p = S_b + S_f \tag{1}$$

$$S_b = \sum_m \sum_r \sum_w (G_{mrw} \times F_{b_{rw}} \times FS_{b_{rw}} \times C_{rw}) \tag{2}$$

$$S_f = \sum_m \sum_r \sum_w \left(G_{mrw} \times F_{f_{rw}} \times FS_{f_{rw}} \times C_{rw}\right) \tag{3}$$

$$G_{mrw} = \sum_p (A_{mpw} \times BL_{pw}) \tag{4}$$

$$\left(F_{b_{rw}} + F_{f_{rw}} + F_{u_{rw}}\right) = 100\% \tag{5}$$

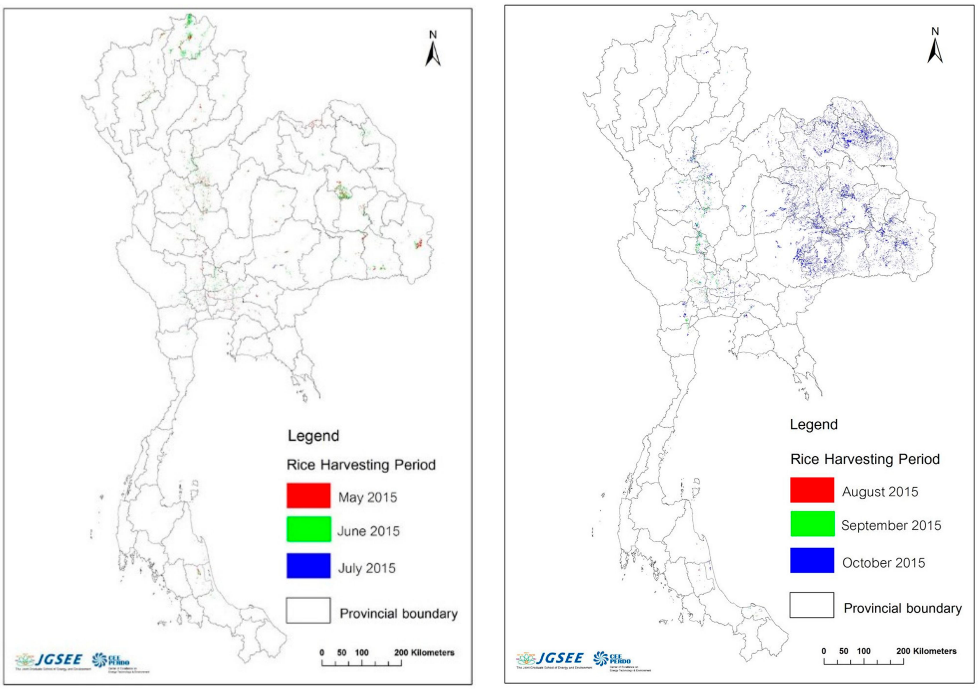
Here we have the following:
S_p is the net potential of rice residue (t).
S_b is the net potential of rice residue obtained from rice residue that is subject to open-burning (t);
S_f is the net potential of rice straws obtained from rice residue that is left in the field (t);
m, r, p, and w are the months, regions, provinces, and irrigation system;
G is the gross amount of rice straws generated in the field (t);
A is the paddy harvested area from May 2015 to April 2016 (ha);
BL is the average amount of rice residue per unit area (t/ha);
F_b is the fraction of rice residue that is subject to open-burning (%);
F_f is the fraction of unused rice residue that is left in the field (%);
F_u is the fraction of rice residue used for sale, animal feeding, agricultural purposes, and so forth (%);
FS_b is the fraction of rice residue subjected to open-burning that farmers are willing to sell (%);
FS_f is the fraction of rice residue left in the field that farmers are willing to sell (%);
C is the collection efficiency of baling rice straws (%).

There are four main information points concerning the assessment of the gross and net potential of rice residue, which comprise the paddy harvested area, the rice residue per unit area, the rice residue management after the harvesting season, and the collection efficiency of baling rice residue.

2.3. Assessment of Paddy Harvested Area

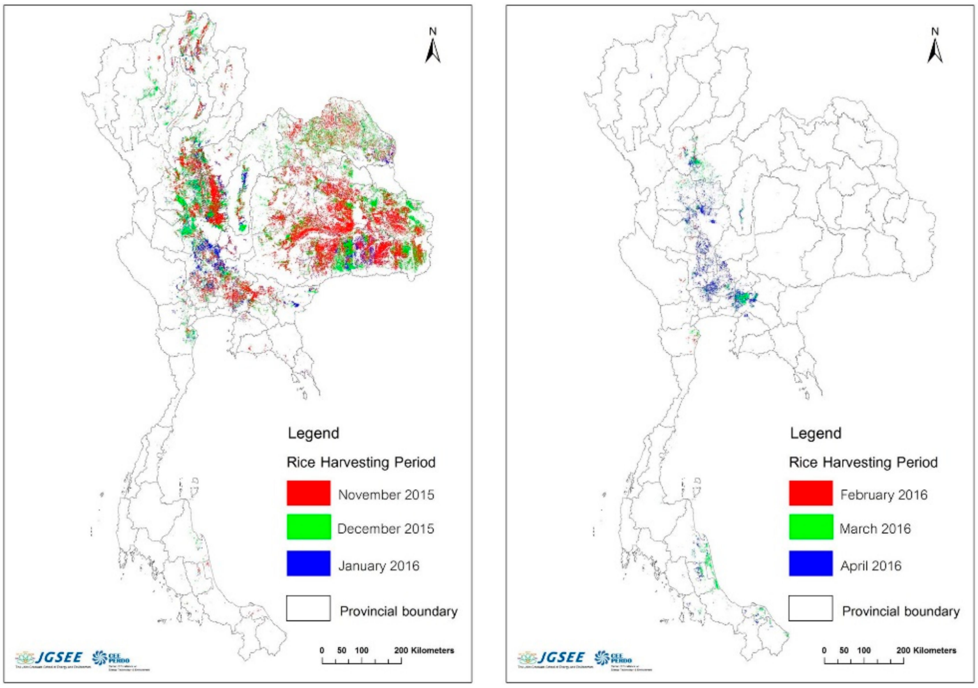
This study uses remotesensing information to assess the spatial and temporal distribution of paddy harvested areas. The information of the spatial allocation of the rice harvesting area was obtained from the satellite information of the MODIS from both the Terra and Aqua satellites developed by the Geo-Informatics and Space Technology Development Agency (GISTDA) [14]. The GISTDA has developed a system to monitor the plantation and cultivation of four main economic crops, rice, corn, cassava, and sugarcane, every 2 weeks, with the objective to provide information pertaining to agricultural production management. This study tracked such information, including the rice plantation area, from January to December 2015 and tracked the harvesting area from May 2015 to April 2016, which corresponded to the mature rice age of about 4 months after planting; it then analyzed the spatial and temporal allocation of the rice harvest area, as presented in Figure 2.

Paddy fields can be classified into two main types according to the water resources: (1) irrigated areas, which are cultivated all-year-round; and (2) rain-fed areas, which are cultivated only during the rainy season. According to the remotesensing information of the MODIS on the Terra and Aqua satellites, the total paddy field area, planted from January to December 2015 and harvested from May 2015 to April 2016, was expected to be about 7.90 Mha, comprising the irrigated area at 2.14 Mha or 27% of the total paddy harvested areas and the rain-fed area at 5.76 Mha or 73%. Such results corresponded to an abundance of water resources in the central region, which accounted for nearly one-fourth of the irrigated areas in Thailand [4].



(**a**) (**b**)

Figure 2. *Cont.*



(**c**) (**d**)

Figure 2. Spatial and temporal distribution of paddy harvested area in Thailand during the crop season of 2015/2016: (**a**) May–July 2015, (**b**) August–October 2015, (**c**) November 2015–January 2016, and (**d**) February–April 2016.

Considering the aspect of seasonality as demonstrated in Figure 3, the peak harvesting period was from October to December 2015, which encompassed the harvested areas of 0.66, 3.49, and 2.45 Mha. For the spatial and temporal allocation of the irrigated area, harvesting occurred between September 2015 and April 2016, which corresponded to the major rice season. Alternatively, for the rain-fed area, harvesting was mainly performed between October 2015 and December 2015, which corresponded to the minor rice season. Such results demonstrated the fact that the production of rice residue varied by season. The highest amount of rice residue produced was between October and December, which was the harvesting period of the irrigated field and the rain-fed field. Figure 4 illustrates the monthly distribution of the paddy harvested areas in Thailand during the 2015/2016 period, categorized by region.

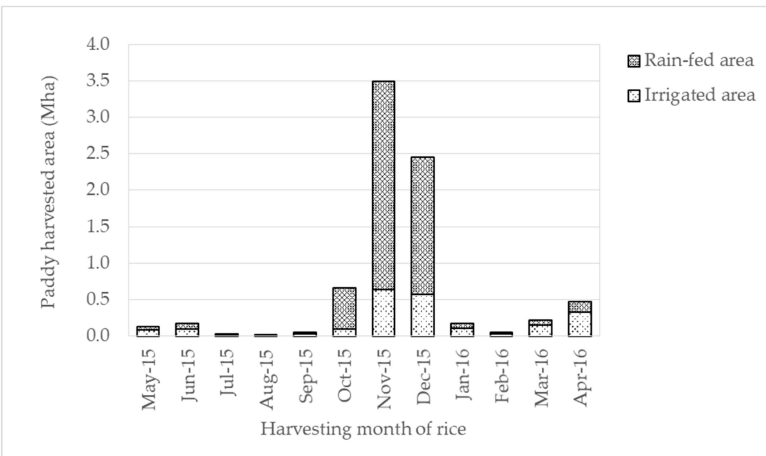


Figure 3. Monthly distribution of paddy harvested area in Thailand categorized by water resources during the crop season of 2015/2016.

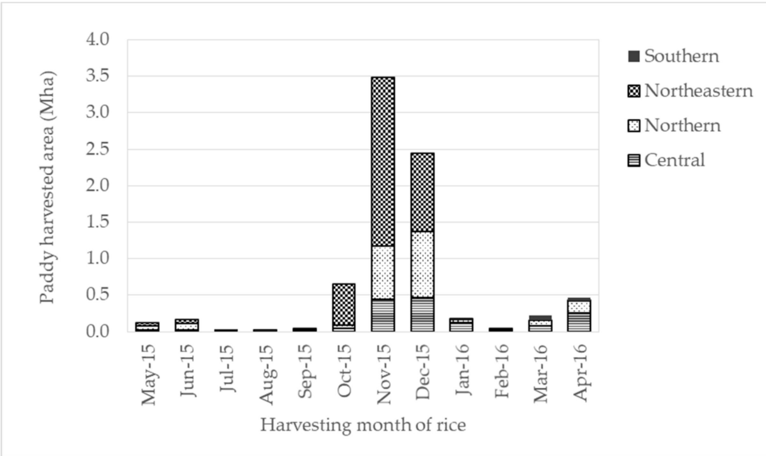


Figure 4. Monthly distribution of paddy harvested area in Thailand categorized by region during the crop season of 2015/2016.

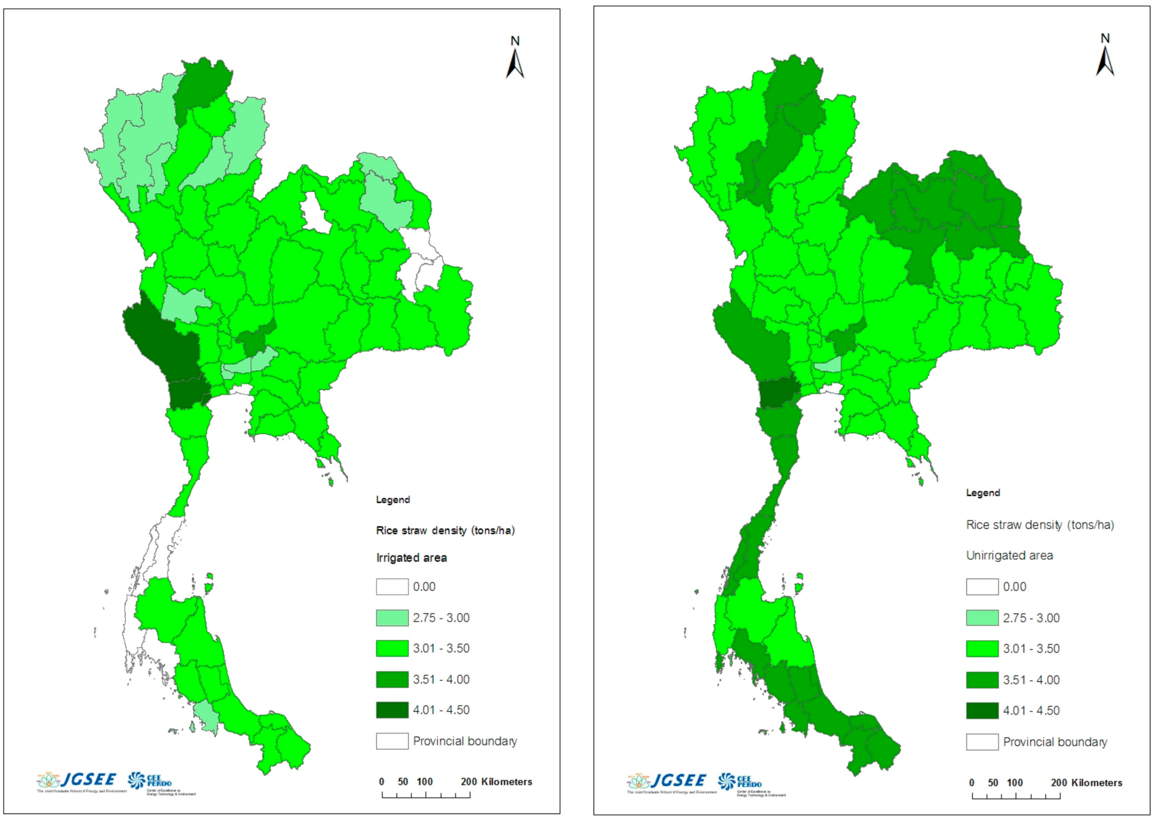
2.4. Assessment of Rice Residue per Unit Area

This study employed the "rice residue determination" model, which is a function of the mass and height of rice stalks and is used to quantify the average rice straw density of each province. This model was developed from the study of Summer, M.D. et al. (2003) [15] on the basis of the physical characteristics of rice, whereby the mass varies with height in each segment of rice stalks. The model was later extended by Cheewaphongphan, P. and Garivait, S. (2013) [5]. Regarding this study, 15 varieties of rice that are widely planted in Thailand, including photosensitive varieties (as a representative of major rice) and non-photosensitive varieties (as a representative of minor rice), were randomly collected and measured for density. Each variety was collected from three sites. Hence, a total of 45 sample plots was employed in this research. The measurement of density was performed using the following procedure:

1. Rice sample collection: The sample plot at a size of 2 m × 2 m was set in the paddy field, whereby all rice plants were reaped from the sample plot at the ground level.
2. Rice sample physical measurement: A cluster of rice was measured from grain to stem in order to determine the overall net weight and height. After that, each rice plant was divided into sections, with each section being 10 cm in length; each section was then measured for weight.
3. Rice sample moisture content analysis: The rice sample from step 2 was randomly selected to measure the moisture content on the basis of the American Society of Agricultural Engineers (ASAE) standard 358-1 (the samples were weighed before and after baking at 105 °C for 24 h). The moisture content of the rice stem was then calculated.
4. Rice residue determination model development: Information from step 3 was used to develop the rice residue determination model on the basis of regression, which represented the relationship between the mass and height of each rice plant. The best fit of the model was identified from the highest R^2 regression value, as illustrated in Table 1. On the basis of the results, the rice plants were approximately 0.9–1.8 m in height and 2–2.5 cm in width, which depended on the rice varieties, the fertility of the soil, and the water abundance [6]. The rice residue determination model demonstrates the relationship between the height and weight in each section of rice stalk; the relationship between each rice variety is summarized in Table 1.
5. Rice straw density assessment: Fifteen models, which were representative of each rice variety, were used to assess the density of the rice straw and rice stubble by using the height of the rice and the harvest method of each area. After applying this model to assess the residue density by using the height of the rice stalk of each variety (the height was between 0.90 and 1.50 m) and the harvesting method, which was mainly the machinery method (30 cm) [5], the results indicated

that the density of the rice residue lay in the range between 4.18 and 8.02 t/ha (dried weight), with an average value of 5.81 t/ha. There were four varieties that provided more than 6.25 t/ha of residue, which were Suphan buri 1, Gor kor 23, Pitch sa nu lok 60-2, and Chai nat 1 at 8.02, 7.78, 6.52, and 6.33 t/ha, respectively. Each of the four varieties are non-photosensitive and are short and thick in terms of physical characteristics [6]. When dividing the rice plant into stubble and straw at the cutting level of 30 cm above the ground level (which is the height for machinery harvesting), the results indicated that rice stubble was in the range between 1.72 and 3.41 t/ha, with an average of 2.31 t/ha. Meanwhile, rice straw was in the range between 3.09 and 4.63 t/ha, with an average of 3.37 t/ha. It can be inferred from these results that the quantity of rice straw was about 59% of the gross rice residue. Considering the density of rice residue from previous studies, which was found to be approximately 7–19 t/ha [5,9,10], this was higher than the values obtained in this study. The primary reason for this difference is due to the differences in the rice varieties (whereby this study mainly used non-photosensitive varieties in order to reduce the plantation time) and planting methods (which was mainly the broadcasting method).

6. Average rice residue by province determination: The obtained density of rice straw of each variety and the average rice straw density from each province were determined using the weighted average method. The percentage share of the planting area for each rice variety, which was obtained from the Agricultural Production Data 2015 from the OAE [4], was multiplied by the rice straw density of each variety in order to identify the average rice straw density of each province, as illustrated in Figure 5. The obtained value of each province was close to the range between 2.75 and 4.50 t/ha, which was due to the similarity of the rice varieties grown in each province. The results demonstrated the unique characteristics of rice cultivation in each area.



(a) (b)

Figure 5. Rice straw density in each province classified by water resource system: (**a**) irrigated area; (**b**) rain-fed area.

Table 1. Relationship between the mass and height of rice plant and rice residue density classified by rice variety.

Rice Varieties	Model	(R^2)	Rice Height, *h* (cm)	Rice Residue Density, *R* (t/ha)		
				Straw	Stubble	Total
RD 23	$R = -0.0819(h)^2 + 20.31(h)$	0.9972	110	4.43	3.35	7.78
Suphan buri 60	$R = -0.062(h)^2 + 15.32(h)$	0.9994	130	3.38	2.53	5.90
Pitch sa nu lok 60-2	$R = -0.064h2+ 16.40(h)$	0.9991	120	3.81	2.71	6.52
Suphan buri 90	$R = -0.046(h)^2 + 11.55(h)$	0.9969	120	2.57	1.91	4.47
Chai nat 1	$R = -0.074(h)^2 + 17.37(h)$	0.9981	110	3.49	2.84	6.33
Suphan buri 1	$R = -0.083(h)^2 + 20.69(h)$	0.9978	120	4.61	3.41	8.02
Suphan buri 2	$R = -0.055(h)^2 + 14.52(h)$	0.9954	120	3.53	2.41	5.94
Khlong Luang 1	$R = -0.048(h)^2 + 12.91(h)$	0.9976	110	3.08	2.15	5.23
Suphan buri	$R = -0.040(h)^2 + 10.38(h)$	0.9949	120	2.45	1.72	4.18
Pathum thani 1	$R = -0.060(h)^2 + 14.83(h)$	0.9953	110	3.19	2.44	5.63
Khao Dawk Mali 105	$R = -0.035(h)^2 + 10.45(h)$	0.9948	140	3.04	1.76	4.80
Pitch sa nu lok 1	$R = -0.041(h)^2 + 11.68(h)$	0.9984	150	3.12	1.96	5.08
Khao Tah Haeng 17	$R = -0.036(h)^2 + 10.63(h)$	0.9943	140	3.02	1.79	4.81
RD 27	$R = -0.036(h)^2 + 10.69(h)$	0.9958	150	3.16	1.81	4.96
Pathum thani 60	$R = -0.037(h)^2 + 11.14(h)$	0.9953	150	3.29	1.88	5.16

2.5. Assessment of Rice Residue Management

This study used a questionnaire as a tool to examine the farming behavior, the characteristics of rice straw management, and the farmers' willingness to supply rice straw. The survey was conducted with the objective to quantify the share of rice straw subjected to open-burning (F_b), the share of unused residue that was left in the field (F_f), and the share of rice residue used for other purposes (F_u). The questionnaire comprised four main sessions: paddy field tenure, planting characteristics, rice residue management, and farmers' perceptions on supplying rice residue. The population of this study comprised 1,277,400 farmers who planted rice during the crop season of 2014/2015 in Thailand [4]. The sample size was calculated on the basis of the stratified random sampling method, which is a method that divides the population into strata with the same characteristics. A stratum in this study was the provincial strata. According to the calculation, the sample size was about 3900 samples at a 2% proportional error and 95% confidence level; 3900 questionnaire surveys were conducted in 16 provinces and were distributed using a proportional allocation method on the basis of the number of rice farmers in each province.

The 3900 questionnaire surveys were classified into two field types: irrigated fields and rain-fed fields. The pattern of rice straw management in each field is presented in Table 2. For the irrigated paddy fields, nearly half of the rice residue (47.2%) was for off-field utilization, whether for personal use or for sales as compost, animal feeding, and mushroom planting. Moreover, approximately 29.7% of the rice residue was open-burned in the field, and about 23.2% was left in the field. The reason for open-burning was to eliminate rice residue in order to prepare the area for the next cultivation. In addition, it was evident that the field with rice residue burning had a lower tillage cost than the field without rice residue burning by about $19–57 USD/ha, which was primarily due to the difficulty and time consumption of tillage. Alternatively, for the rain-fed paddy field, the pattern of rice residue management was similar to that of the irrigated area but with a different share. Most of the rice residue in the rain-fed area was for off-field utilization, which accounted for 56.0% of the total rice residue. Meanwhile, 22.6% of the rice residue was left in the field, and 21.4% was open-burned in the field.

Table 2. Percentage share of rice straw management derived from the questionnaire survey.

Rice Straw Management	Percent Share of Rice Straw Management (%)									
	Northern		Northeastern		Central		Southern		Whole Country	
Fermentation	**21.6**	(20.1)	**6.9**	(11.9)	**13.9**	(5.4)	**31.0**	(13.0)	**16.5**	(12.9)
Animal feed	**25.3**	(21.3)	**38.3**	(31.1)	**6.2**	(13.2)	**31.5**	(30.2)	**12.1**	(22.1)
Mushroom plantation	**6.5**	(4.5)	**5.7**	(9.8)	**0.8**	(1.7)	**17.7**	(6.2)	**3.3**	(5.3)
Sold to baler operator	**14.1**	(5.5)	**0.0**	(1.7)	**15.9**	(32.9)	**1.0**	(3.2)	**14.1**	(12.5)
Baling and personal use	**0.8**	(0.9)	**0.2**	(6.8)	**1.5**	(2.2)	**0.0**	(0.0)	**1.2**	(3.1)
Open-burning	**20.3**	(26.2)	**1.1**	(21.2)	**35.9**	(18.3)	**0.0**	(2.1)	**29.7**	(21.4)
Left in the field	**11.3**	(21.5)	**47.7**	(17.6)	**25.8**	(26.4)	**18.8**	(45.4)	**23.2**	(22.6)

The numbers in bold represent irrigated fields and the numbers in brackets represent rain-fed fields.

2.6. *Assessment of Willingness of Farmers to Sell Rice Residue*

This study assessed the net potential of rice straw by taking into consideration the willingness of farmers to bale and sell rice bales. The willingness of farmers is one of the indicators for the sustainability of utilizing rice residue for energy-related purposes. The questionnaire asked farmers about their willingness to bale and sell rice bales to operators. The results indicated that the portion of rice straw available for use was a group of left and burned rice straw. According to the feedback of farmers, more than four-fifths of the farmers in the groups were willing to bale rice straws in the field. Meanwhile, the remaining farmers declined to sell rice straws to buyers because of the damage to the field caused by the wheels of the tractor as they rolled and pulled the straw bales. Moreover, when the roller baler was pulled by the tractor and ran across the field, it compacted the soil, which increased the difficulty of the tillage. Furthermore, the lack of machinery was also a reason for the farmers' unwillingness to sell rice straws. The feedback of farmers on the sales of rice bales, classified by rice straw management, is summarized in Table 3.

Table 3. Characteristics of rice bale from the baling experiment.

Regions	Willingness of Farmers to Bale and Sell Rice Bales (%)	
	Farmers Managing Rice Straws by Leaving Them in the Fields	Farmers Managing Rice Straws by Burning Them in the Fields
Northern	92.0	96.7
Northeastern	61.2	60.2
Central	79.4	86.4
Southern	86.5	60.0
Whole country	79.4	82.3

2.7. *Assessment of Baling Rice Straw Efficiency*

This study conducted the straw baling test (baler pulled by a tractor) on the paddy field in order to evaluate the baling efficiency. The baling experiment was performed for 2 days after the harvesting period and in two types of fields: irrigated and rain-fed fields at the central region. The number of straw bales with a size of 32 cm $\times$ 80 cm $\times$ 42 cm and a weight of 18 kg in a field plot size of 1.0 ha was counted. The experiment found that 125 bales and 93 bales were collected from the irrigated fields and rain-fed fields, respectively. According to the amount of rice straw generated and baled, the efficiencies of rice straw collection were 62% and 46% for the irrigated fields and rain-fed fields, respectively. On the basis of the information from baler operators who kindly supported the baling rice straw experiment in this study, it is noteworthy that weather had an influence on the collection efficiency. During the rainy season, it is inappropriate to collect rice straws, as rain increases the moisture content of rice straw and causes muddy soil—both of these are unsuitable for rice baler machines. According to the experiment, the characteristics of rice bales in the irrigated and rain-fed fields are summarized in Table 4.

Table 4. Characteristics of rice bales from the baling experiment.

Characteristic	Paddy Field	
	Irrigated Field	Rain-Fed Field
No. of rice bales collected (bale/ha)	125	93
Straw collection efficiency (%)	62	46
Straw bale size (cm^3)	32 × 80 × 42	32 × 80 × 42
Straw bale weight (kg/bale)	18	18
Moisture content (%)	9.0	9.0

2.8. Assessment of Spatial and Temporal Distribution of Rice Straw Potential

The rice cultivation area had spatial heterogeneous characteristics according to the land use in each area, regarding irrigation systems, rice varieties, soil types, and so forth. The distributions of the rice cultivation areas had an influence on the amount, availability, and potential of rice straws. This study employed a gridded map of the rice cultivation area at a resolution of 12 km × 12 km in order to study the characteristics of the spatial distribution of the rice straw potential in Thailand. The gridded map was created from the information pertaining to the rice cultivation area derived from the GISTDA [14], together with the rice straw density and the diffuse attenuation coefficients. The details of the rice straw density are presented in Section 2.4. The coefficient was assessed from three parameters, the share of the rice straw management, the baling rice straw efficiency, and the willingness of farmers to sell rice straws.

2.9. Assessment of Efficiency of Supply Materials for Very Small Power Plants in Thailand

The supply of rice straw for VSPPs was estimated from the following equation:

$$E_{ij} = \left(\frac{\sum_i \sum_j S_{p_{ij}}}{\sum_i \sum_j (P_{ij} \times D)} \right) \times 100\% \quad (6)$$

Here we have the following:

E_{ij} is the efficiency of supply materials for VSPPs within the radius distance (*i*) in the region (*j*) (%).

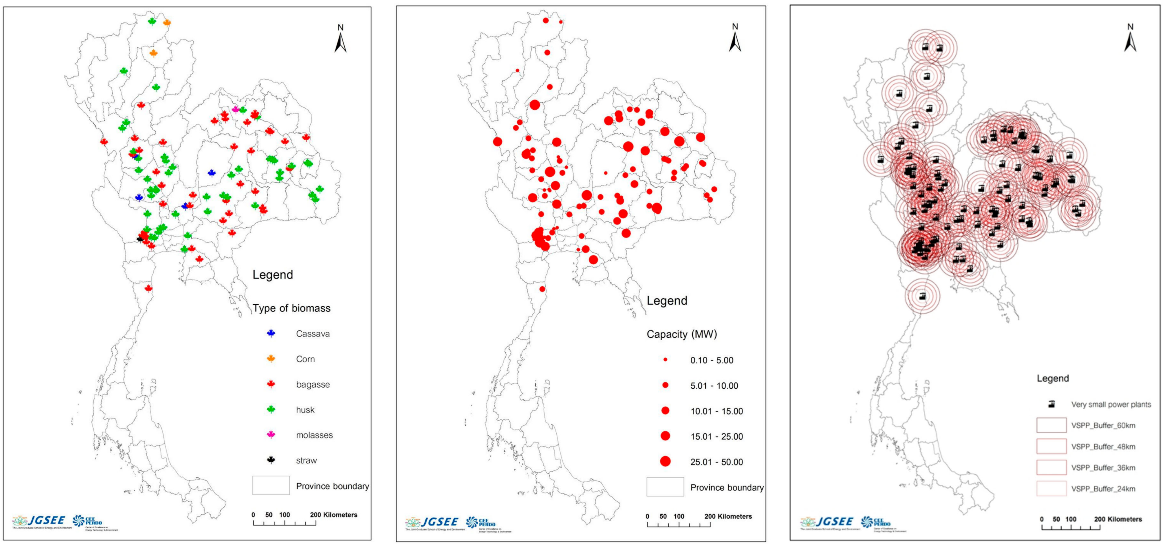
$S_{p_{ij}}$ is the amount of rice straw collected for VSPPs within the radius distance (*i*) in the region (*j*) (Mt).

P_{ij} is the capacity of VSPPs in the region (*j*) (MW of electricity—MWe).

D is the coefficient of rice straw demand to generate 1 MWe of electricity (Mt/MWe).

This study devised the map of VSPPs on the basis of the information from the Department of Alternative Energy Development and Efficiency, the Ministry of Energy [16] by using a GIS program to show the location, capacity, and fuel consumption of VSPPs. Figure 6a,b demonstrates the allocation of 110 VSPPs in Thailand that were examined in this study (excluding a biomass VSPP located in the southern region because of the low potential of rice straw production).

Next, the map of the net potential of the rice straw residue was created at a resolution of 12 km × 12 km. After that, this map was overlaid with the VSPP map in order to assess the net potential of the rice straw residue available for each power plant at various radii: 24, 36, 48, and 60 km. The fraction of the rice straw supply to demand was then quantified for each power plant. The radii of the collected rice straw residues are presented in Figure 6c.



(**a**) (**b**) (**c**)

Figure 6. Very small biomass power plants categorized by (**a**) type of biomass fuel, and (**b**) capacity of very small power plants (VSPPs); (**c**) the radii of collected rice straw residue.

3. Results and Discussion

3.1. Gross Potential of Rice Straws

From Equation (4), the gross potential of rice straws in Thailand for the crop season of 2015 was about 26.0 Mt, which comprised 6.8 Mt or 26.2% of the total rice straws generated from the irrigated areas and 19.2 Mt or 73.8% generated from the rain-fed areas. The highest volume of rice straws was generated in November, which accounted for 44% of the total rice straws or 11.5 Mt, most of which were found in the northeastern region. The second highest volume of rice straws was generated in December at about 31% or 8.1 Mt, which was mainly in the northeastern and northern regions. The third highest volume was generated in October at approximately 2.2 Mt or 8%, which was found in the northeastern region. The period from July to September was the low season of rice straws; this is the rainy season and the starting point of the rice planting season. The regional and temporal distributions of the rice straws generated are summarized in Figure 7.

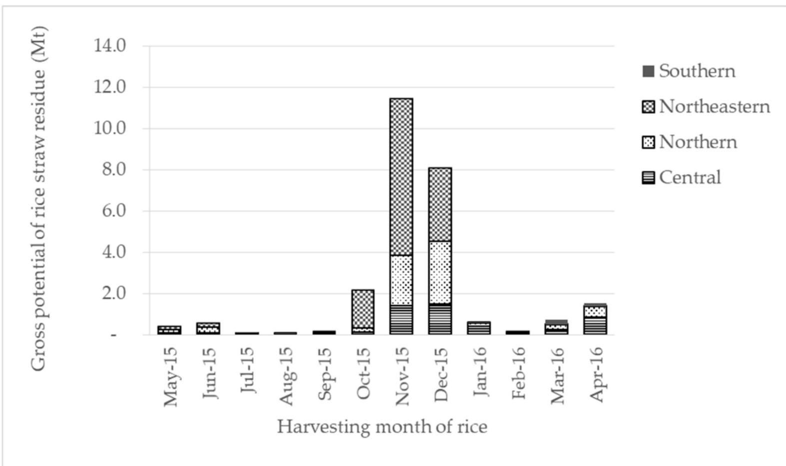


Figure 7. Regional and monthly temporal distribution of gross potential of rice straws.

The rice harvesting season starts in October in the central, lower-northern, and northeastern regions of Thailand, as demonstrated by the blue grids of Figure 8. During this period, the rice straw density was about 1.0–20.0 kt/grid, which later increased to 20.0–80.0 kt/grid from November to December. For the remaining period, the straw density was only about 1.0–5.0 kt/grid, which was mainly from minor rice in the irrigated area of the central region, where rice was planted all-year-round. The map of the monthly temporal allocation of generated rice straws provides useful information for biomass entrepreneurs, as it enables entrepreneurs to determine the balance between the demand and supply of biomass fuel used in biomass power plants. Moreover, the analysis of such information together with the information of road networks can be used to decrease the cost of fuel transportation. In addition, such results serve as fundamental information for the government in locating the zoning of straw power plants in the future.

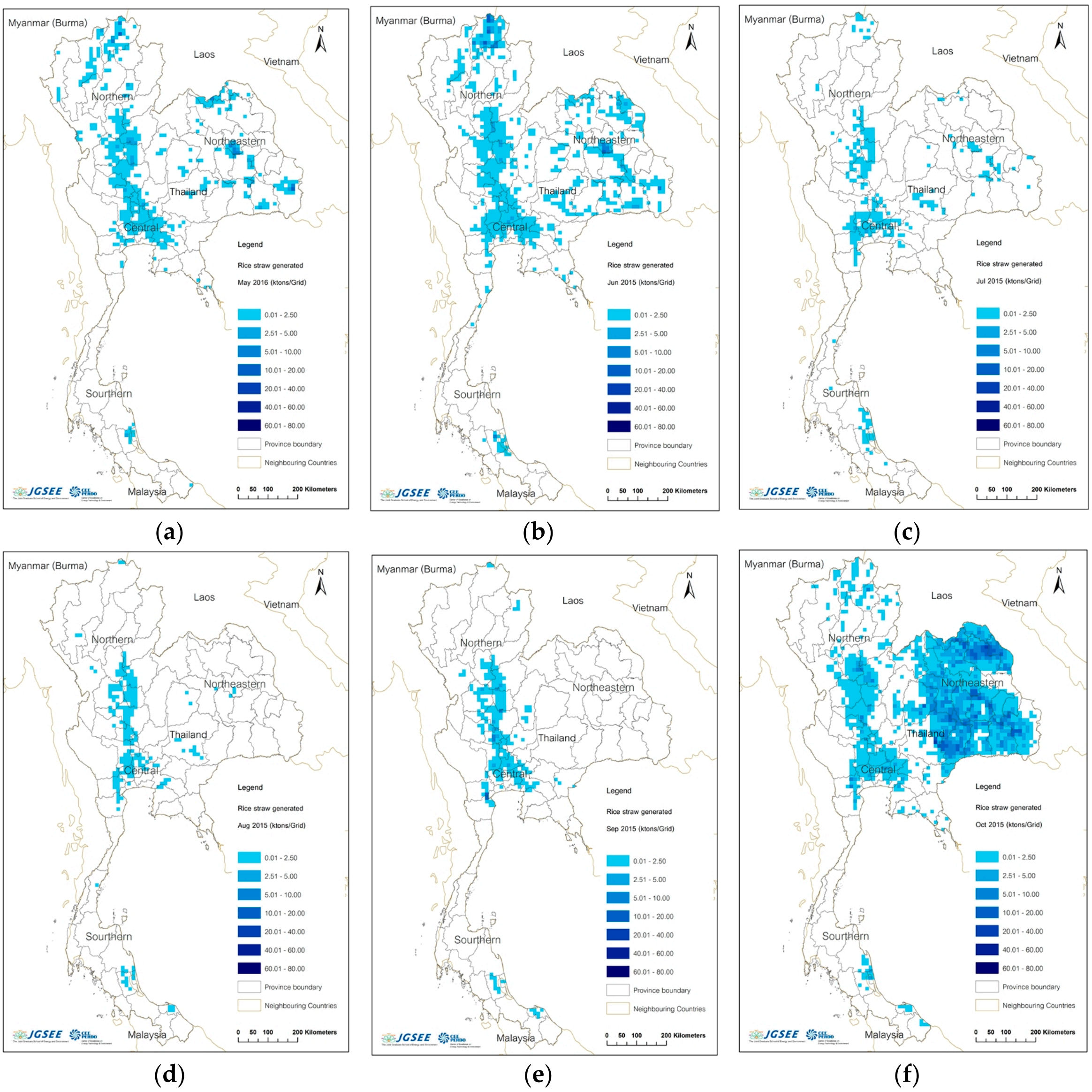
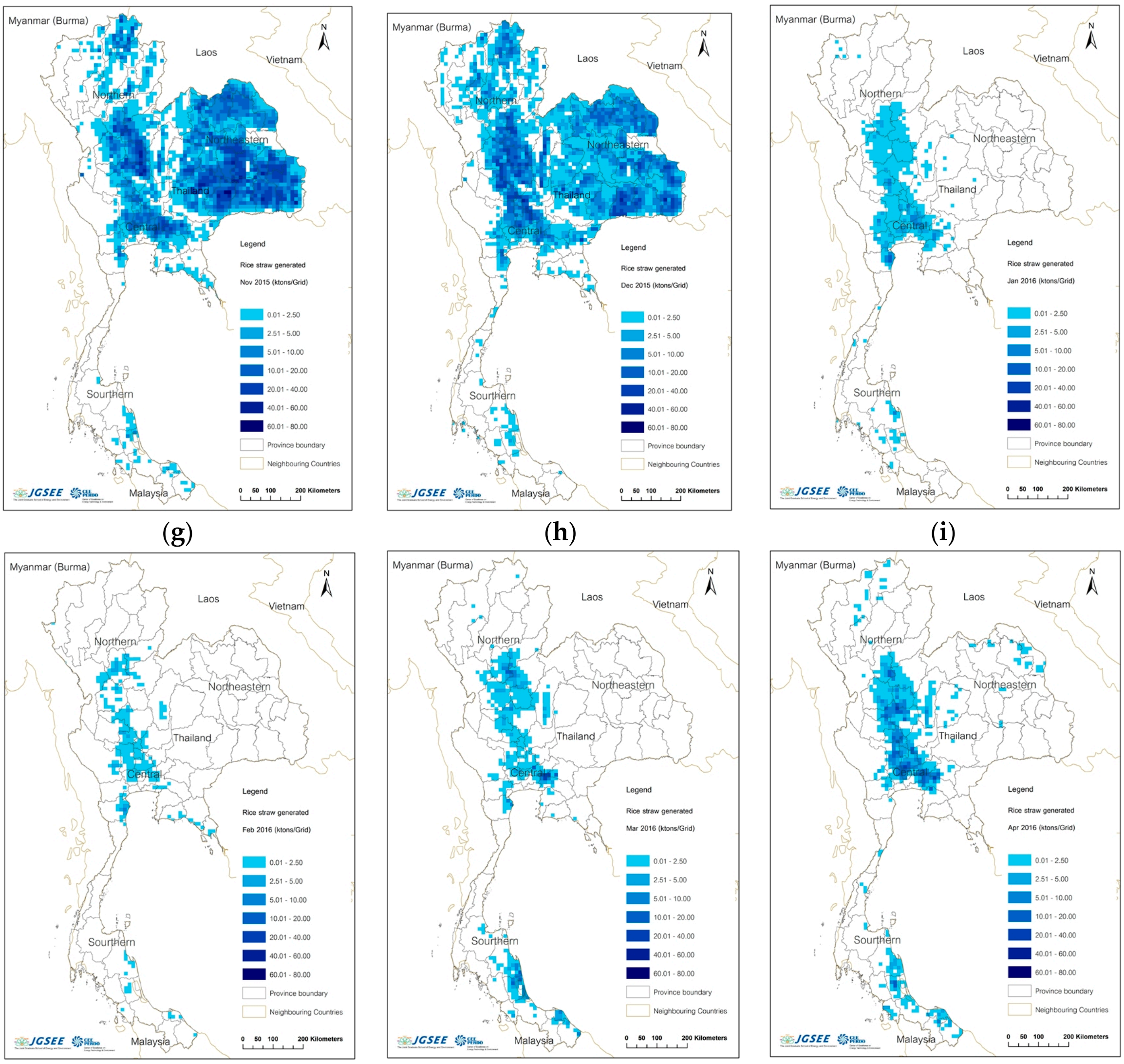


Figure 8. *Cont.*



(**g**) (**h**) (**i**) (**j**) (**k**) (**l**)

Figure 8. Spatial variation of the gross potential of rice straws for each harvesting month, consisting of (**a**) May 2015, (**b**) June 2015, (**c**) July 2015, (**d**) August 2015, (**e**) September 2015, (**f**) October 2015, (**g**) November 2015, (**h**) December 2015, (**i**) January 2016, (**j**) February 2016, (**k**) March 2016, and (**l**) April 2016.

3.2. Net Potential of Rice Straws

On the basis of the information of rice residue management derived from the farmers' surveys, it can be inferred that rice straws left in the fields and rice straws subjected to open-burning have a high potential. According to the gross potential of rice straws and the share of rice straws that remained and burned in the fields, it can be concluded that the amount of rice straws left in the fields was about 5.92 Mt ((6.8 Mt × 23.2%) + (19.2 Mt × 22.6%)). Meanwhile, the amount of rice straws subjected to open-burning was about 6.13 Mt ((6.8 Mt × 29.7%) + (19.2 × 21.4%)). Considering such volumes, along with the baling efficiency, the willingness of farmers to sell rice straws and the suitable time for straw collection (from October to April the following year), the net potential of the rice straw was only about 3.85 Mt, consisting of 1.09, 1.27, 1.46, and 0.04 Mt for the central, northern, northeastern, and southern regions, respectively. On the basis of this information, the net potential of the rice straws was only 15% of the gross potential, which was lower than the values obtained from previous studies in the range of 5.3–9.6 Mt/year [17–20]. The differences in the results are due to the differences in the parameters used. None of the previous studies considered the willingness of farmers, which indirectly affected the potential of the straw collection. In addition, the majority of the previous studies (except for the study of M.K. Delivand et al. [17]) lacked consideration on the collection efficiency.

For the monthly temporal distribution of the rice straw potential, the season of rice straws was from the end of the year to the beginning of the following year (October to April the next year), which is the harvesting period of major and minor rice. The peak of available rice straws was in November and was about 1.64 Mt or 43% of the total rice straw potential, followed by December and April at 1.32 Mt (34%) and 0.34 Mt (9%), respectively. The temporal distribution of rice straw residue potential for energy-related purposes is illustrated in Figure 9.

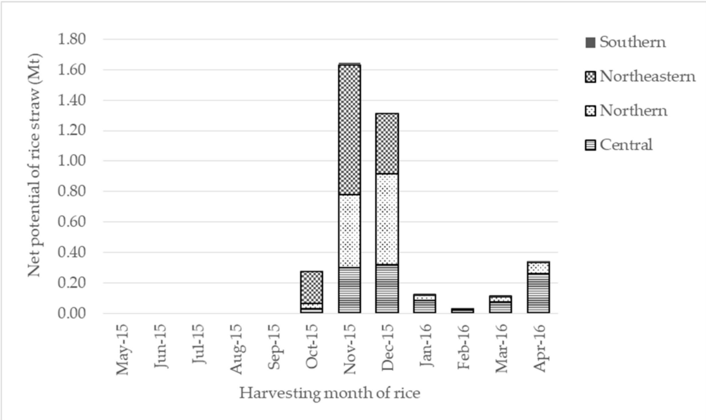
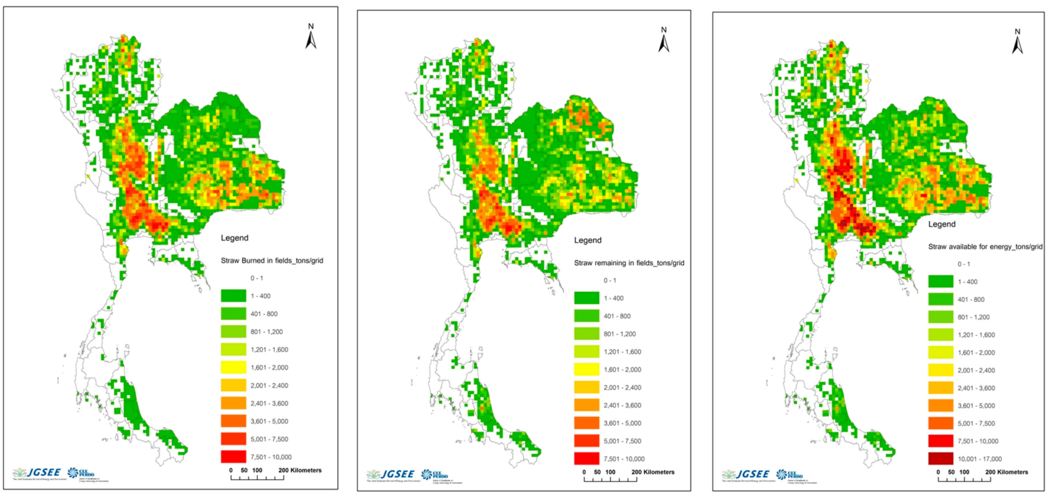


Figure 9. Monthly temporal distribution of the net potential of rice straw residue categorized by region.

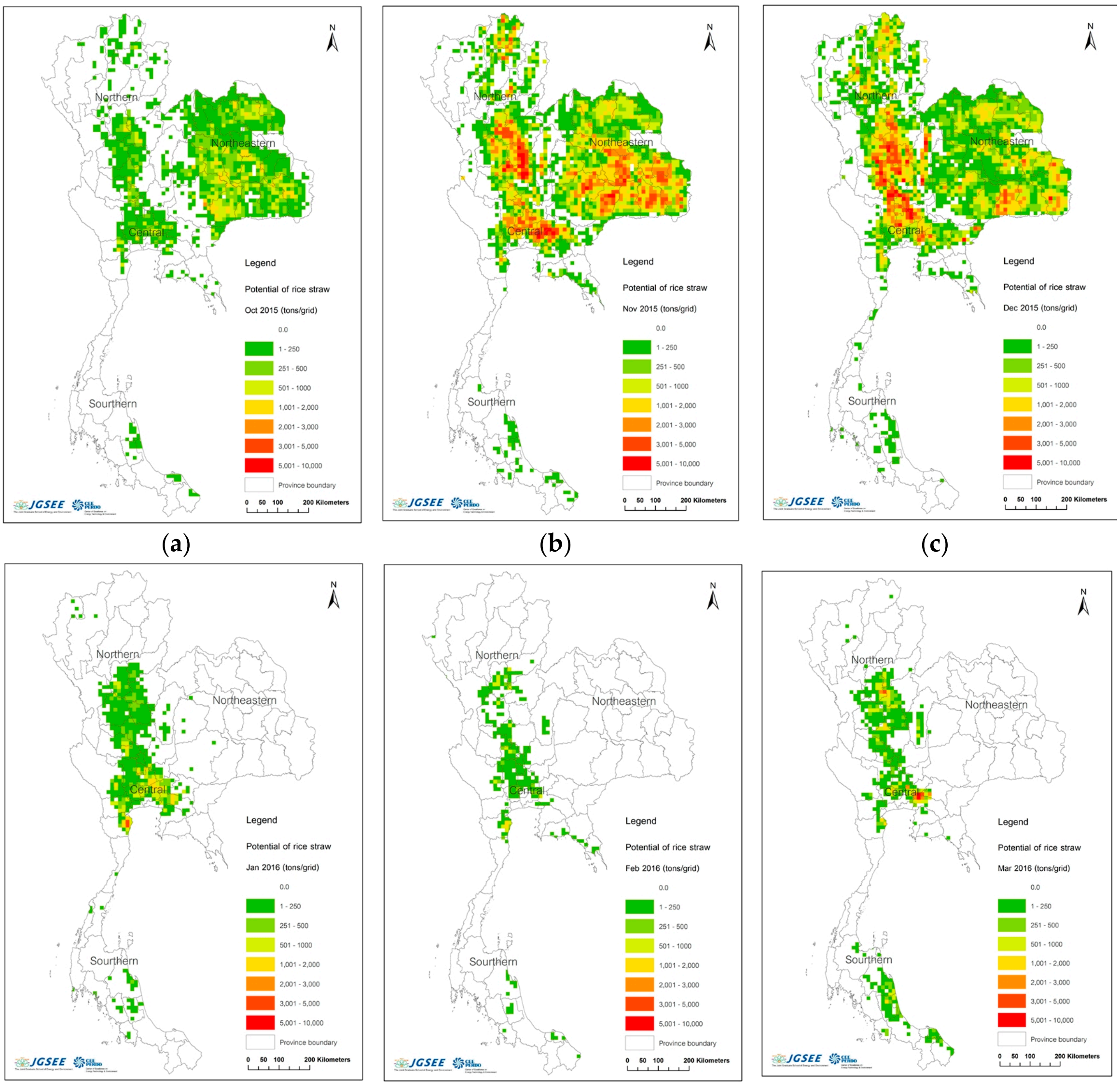
Taking into consideration the spatial distribution of burned rice straws, as demonstrated in Figure 10a, the density of burned rice straws was 5.0–10.0 t/grid (grid size 144 km^2); these were mostly allocated at the central and lower-northern regions of Thailand, the density was only 2.0–5.0 t/grid for the northeastern region. Regarding rice straws that were left in the fields, as presented in Figure 10b, the densities were 5.0–10.0 t/grid for the central region, 2.4–5.0 t/grid for the lower-northern region, and only 1.0–2.4 t/grid for the northeastern region.



(**a**) (**b**) (**c**)

Figure 10. Spatial variation of the net potential of rice straws in Thailand obtained from (**a**) rice straw residue subjected to open-burning, (**b**) unused rice straw residue left in the field, and (**c**) total rice straws available.

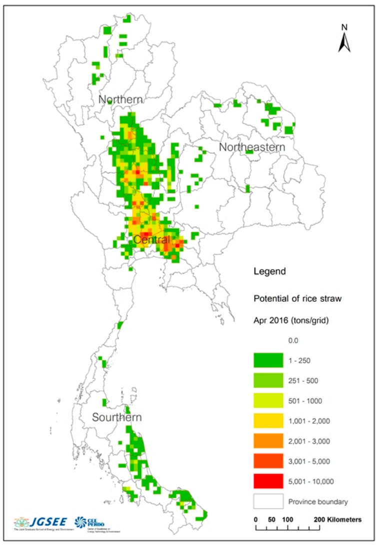
Combining both burned and left rice straws, as demonstrated in Figure 10c, the highest net potential of rice straws was in the central region, at the density of 5.0–17.0 t/grid, followed by the lower-northern region at the density of 5.0–10.0 t/grid, and northeastern region at the density of 2.0–3.5 t/grid. Figure 11 illustrates the monthly spatial and temporal distribution of the potential of the rice straw residue in Thailand, classified by the harvesting month.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 11. *Cont.*



(**g**)

Figure 11. Spatial variation of the net potential of rice straws for each harvesting month: (**a**) October 2015, (**b**) November 2015, (**c**) December 2015, (**d**) January 2016, (**e**) February 2016, (**f**) March 2016, and (**g**) April 2016.

3.3. Potential of Rice Straws for Electricity Generation in Thailand

According to the study of M.K. Delivand et al. (2011) [17], 10 MWe from a biomass power plant requires about 75,789 tons of rice straws per year to be used as fuel (estimated on the basis of 6000 working hours and 23% efficiency of the power plant). Upon taking into consideration the 10% loss from transportation, 84,820 tons of rice straws are required per year. On the basis of this information, the net potential of rice straws for electricity generation was 457.4 MWe, which was allocated to the central, northern, northeastern, and southern regions at 129.5, 150.3, 173.5, and 4.2 MWe, respectively. The results are represented in Table 5.

Table 5. Potential of rice straws for electricity generation in Thailand classified by region and harvesting month.

Region	Potential of Rice Straws for Electricity Generation (MWe)							Total
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	
Central	3.9	35.9	37.9	9.8	2.4	8.8	30.8	129.5
Northern	3.6	57.0	70.9	4.1	1.4	4.5	8.8	150.3
Northeastern	25.3	101.0	46.8	0.0	—	0.0	0.3	173.5
Southern	0.3	1.3	0.7	0.6	0.1	0.6	0.6	4.2
Whole country	33.1	195.2	156.3	14.5	3.9	13.8	40.6	457.4

3.4. Material Flow Diagram

Figure 12 illustrates the material flow diagram of rice straw residue, which was developed from the characteristics of the rice straw management of farmers in Thailand. From the diagram, it can be seen that the total paddy harvested area during the crop season of 2015/2016 was about 7.90 Mha for the period between May 2015 and April 2016. After harvesting, the average density of the rice straws generated was in the range from 2.75 to 4.50 t/ha. On the basis of this rate, the total rice straws generated were expected to be 26.1 Mt. About 56% of the total rice straws generated (15.1 Mt) were used for various purposes, including animal feeding, fermentation, mushroom plantations, and other purposes. Meanwhile, about 20% of the total rice straws generated (5.30 Mt) were left in the field; about 22% (5.70 Mt) were subjected to open-burning. Accordingly, the residue available for use was residue that was left in the field and residue that was subjected to open-burning, which accounted for 42% of the total rice straws generated, or 11.0 Mt. Nonetheless, in order to collect rice straws from the field, the willingness of farmers to perform the baling process and the collection efficiency of the baler machine are necessary to determine the net potential of the rice straws. According to the farmers' survey, 21% of farmers who burned rice residue and 18% of farmers who left rice residue in the field stated that they were not willing to sell rice straws. On the basis of the baling straw experiment, the collection efficiency of the rice straws was 62% for irrigated areas and 42% for rain-fed areas. With this information, the net potential of the rice straws was calculated to be about 3.85 Mt, which could generate 457.4 MWe of electricity or 1331 ktoe of heat.

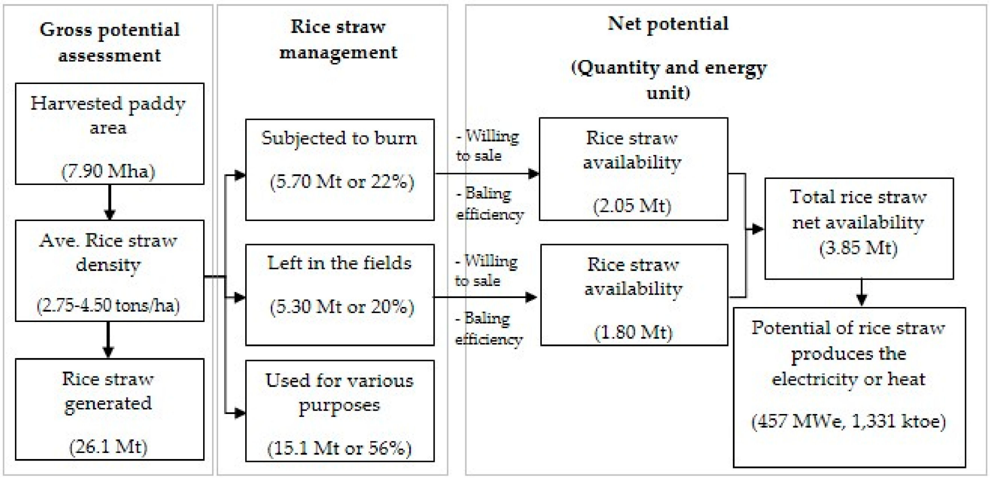


Figure 12. Material flow diagram of rice straw residue for energy-related purposes.

3.5. Efficiency of Supply Materials for Very Small Power Plants in Thailand

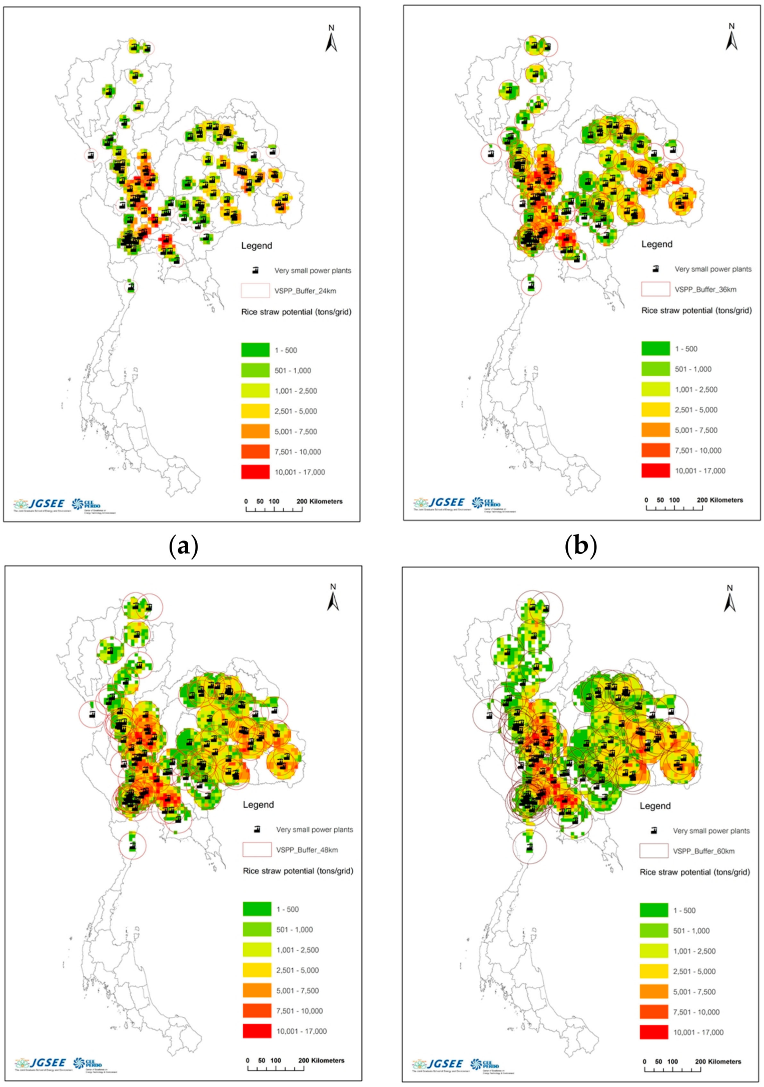
The total capacity of 110 VSPPs in Thailand (except in the southern region) is about 1310 MWe [16]. Meanwhile, the total fuel demand is equal to 12.12 Mt. The highest demand is in the northeastern region, at 5.38 Mt, followed by the central region, at 3.71 Mt. The amount of fuel demand in each region is summarized in Table 6.

Table 6. Fuel demand of very small biomass power plants in Thailand, classified by region.

Region	Number of Biomass Power Plants	Capacity (MW)	Rice Straw Residue Demand (Mt)
Central	33	401	3.71
Northeastern	46	581	5.38
Northern	31	327	3.03
Total	110	1310	12.12

According to the demand and supply of rice straw residue in terms of spatial analysis, the efficiency of supply materials was about 14.2% at the radius of 24 km. This efficiency increased with distance, whereby it reached 29.0% at a radius of 60 km. At a radius of more than 60 km from the VSPP's location, the net potential of the rice straw was about 0.33 Mt, and was classified at 0.22, 0.16, 0.11, and 0.04 Mt in the central, northeastern, northern, and southern regions, respectively. The results are presented in Table 7. Nonetheless, it is also important for investors to consider the transportation cost, which varies by distance. On the basis of the study of M.K. Delivand et al. (2011) [17], the transportation costs of rice straw residue at the distances of 20, 40, and 80 km are anticipated to be $17.07, $18.83, and $20.77 USD/t, respectively.

From the results presented in Figure 13a–d, most VSPPs are located in the area with a high straw density at the range of 7.5–17.0 t/grid for the central and northeastern regions and at 5.0–7.5 t/grid for the lower-northern and upper-northeastern regions. Indeed, most VSPPs use agro-processing residues as a fuel for heat and power production. For instance, rice millers use rice husks to generate energy (heat and power) for personal use, with those remaining are sold to the Provincial Electricity Authority (PEA). An agro-processing factory, such as a rice miller, sugar factory, or cassava factory, are mainly located in the plantation area with the presence of raw materials. However, the limitation of using agricultural products is the aspect of seasonality; it is possible that an agro-processing factory may run out of fuel materials. Hence, rice straw has a high potential to be used as an additional fuel for VSPPs, particularly in the aspect of the reduction of transportation costs.



(c) (d)

Figure 13. Efficiency of supply fuel for very small biomass power plants at various radii: (**a**) 24 km, (**b**) 36 km, (**c**) 48 km, and (**d**) 60 km.

Table 7. Efficiency of supply materials for very small biomass power plants at various radii.

Region	Efficiency of Supply Materials for Very Small Biomass Power Plants							
	Radius at 24 km		Radius at 36 km		Radius at 48 km		Radius at 60 km	
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)
Central	0.52	13.9%	0.73	19.6%	0.82	22.0%	0.85	22.9%
Northeastern	0.68	12.6%	1.16	21.6%	1.53	28.4%	1.71	31.7%
Northern	0.52	17.2%	0.72	23.9%	0.85	28.0%	0.96	31.6%
Whole country	1.72	14.2%	2.62	21.6%	3.19	26.3%	3.52	29.0%

4. Conclusions

This study estimates the gross and net potential of rice straw residue obtained from rice plantations in Thailand from January to December 2015 using remotesensing information combined with farmers' surveys and field experiments. The potential of the rice straws was obtained from the rice straws left or burned in the field that were still available for utilization. The potential of the rice straws was assessed from the gross potential of the rice straws with the share of current utilization for any purposes, the share of farmers who were unwilling to sell rice straw bales, and the collection efficiency deducted.

According to the results, the most suitable period for the collection of rice straw residue was from November to December, which was the period that generated a relatively high amount of rice straws. Moreover, this period is the drying season that is suitable for the baling process. It is also worth noting that the seasonality of the rice straw collection should be contemplated regarding the sustainability of using rice straws as agro-residues. Similarly, the results suggest that the willingness of farmers to perform rice straw baling is important information that should be considered for the sustainability of using agro-residues as feedstock for energy production.

On the basis of the obtained results, the net potential of rice straws is inadequate to achieve the alternative energy target of 5570 MWe by 2036 [2]. To achieve this target, other potential agro-residues, such as sugarcane leaves and cassava rhizomes, which are mostly left in the fields, should be considered as the alternative fuel. For future research, the methodology developed from this study should be extended to examine other agricultural residues, whereby such results will serve as fundamental information for the utilization of agro-residues with the highest efficiency.

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Author Contributions: Penwadee Cheewaphongphan and Agapol Junpen devised the project, the main conceptual ideas and the proof outline and worked out almost all of the technical details, field experiments, and questionnaire surveys, as well as performed the numerical calculations. Agapol Junpen and Orachorn Kamnoet worked on the spatial and temporal distribution of the potential of the rice straws by using the satellite information and GIS program. Agapol Junpen proposed the results in discussions with Savitri Garivait. All authors discussed the results and contributed to the final manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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