Overall Analyses of Using Rice Straw Residues for Power Generation in Thailand- Project Feasibility and Environmental GHG Impacts Assessment

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Abstract: The financial feasibility assessment for rice straw-based power combustion projects of different scale and the environmental LCA are performed for conditions in Thailand. Straw-based cumbustion facilities are financially feasible and profitable, assumed that the specific capital cost is approximately lower than 70,000 Baht/kW$_e$, which can be reached if the capacity of the power plant is 8 MW or greater. The subjective probability of a financially successful 10 MWe straw-based power plant could be as high as 86-90%, whereas, it is as low as 24-32% for an 8 MWe project. Implication of learning rate (LR) shows that the 4th power plant capacity of 10 MWe can compete with an alternative fossil-fuel power plant within 8 years after initiating the first straw-based power combustion project. Furthermore, the effect of Carbon Certified Reduction (CER) revenues can significantly lower the production costs to 2.26 Baht/kWh in a 10 MWe straw-based combustion facility. The life-cycle Green House Gas (GHG) emission reductions indicate that 0.378 tCO_2eq/t straw$_{(db)}$ (0.496 kg CO_2eq/kWh) and 0.683 tCO_2eq/t straw$_{(db)}$ (0.959 kg CO_2eq/kWh) could be avoided if rice straw substitutes natural gas or coal in the power generation sector, respectively. Furthermore, using rice straw as energy source in Thailand could result in considerable annual savings on primary energy imports of around 7-9%.

Key words: Rice straw combustion; Subjective probability; LR; CER; GHG impact.

1. Introduction

Thailand is highly dependent on imported fossil fuels, especially, on the natural gas for power generation. The enormous increase of power consumption, and the limited domestic gas reserves, would lead the country to rely more on imported gas from abroad raising the issue of vulnerability and energy security [1-2]. The use of locally available renewable energy sources is promoted by the Thai government. Rice straw as an energy source has an enormous potential in Thailand [3-4]. The provision of straw energy utilization in the country would result in the mitigation of GHG emission from fossil fuel sources and considerable fossil fuel savings as studied by Refs. [5-8]. However, to tap into this potential renewable source, several hurdles must be taken.

The technological and economic development of renewable energy (RE) systems is required in promoting RE systems in the future [9]. There are various conversion routes to use rice straw as an energy source. Because after rice harvesting, the straw is usually characterized by low moisture content, the direct combustion processes seems to be the favorable paths for utilization [10]. At present, grate boilers followed by steam cycles are favorable compared to other technologies for using straw-fuels, mainly, because they are proven, simple, cheaper, more flexible to the moisture content and particle size, and less sensitive to slagging/fouling [8,11-12]. However, straw-based fuel is known as a difficult fuel, and the experience is required in the design of the steam temperature profiles, and handling the deposit formation in the boilers [11,13-14] depending on the characteristics of the fuel and specification of the technology. The slagging and fouling indices of Thai rice straw is reported to be 0.04 and 0.24, respectively, and is addressed as not very different from rice husk [8], which has been used as a fuel for power generation in the country.

Apart from assessing the fuel parameters and selecting the suitable process chain for the energetic utilization of rice straw, the next step would be to analyze the rational handling of straw from the field to delivery and handling at the plant. This consideration is crucially important in developing straw-based energy facilities, because a large proportion of the operating cost in a biomass energy generation facility are the fuel costs; and the cost analysis of the straw fuel chains seems to be an urgent requirement in logistics management [15]. The straw-based process evaluation should be followed by an evaluation of its possible environmental, economical and social impacts [10]. Since the total costs of a biomass system are determined by local factors such as fuel costs and the cost of labor, thus, the project feasibility should be assessed based on localized conditions in the regions of interest [16]. Interlinks between variables or provisions which may affect the feasibility of the projected straw-based energy facility should be sought; some of these provisions are scaling up, learning rate effect (LR), carbon credits, and uncertainties of the variables. For instance, the impact of the scale on the economic viability of the biomass energy projects is even reported to be more important than the biomass transportation costs [17].

Principally, an overall analysis of the rice straw process chains may promote its use for energy purposes in Thailand. Detailed economic analysis, including the environmental and the likely societal benefits are still needed to be investigated because a high proportion of the rice straw residues are left unused in the fields or are still subject to open field burning in the country. This study focuses on the possibility of the rice straw utilization for power generation in projected straw-based combustion facilities, and aims at performing an overall economic feasibility assessment and environmental impacts analyses of the whole system. In the economic analyses, the logistics and the economies of scale considerations for the straw-based power facilities are reviewed. Subjective probability of the critical variable such as fuel costs, plant factors, and the selling price of the electricity are quantified and the best scale is suggested for the rice straw energy utilization through combustion power plant in Thailand. Then the effect of the learning rate (LR), and the Certified Emission Reduction (CER) revenues on the production costs are discussed. The overall life-cycle GHG impacts of the projects with respect to the total Green House Gas (GHG) emission reductions, fossil fuels and currency savings are also presented. A further study on the societal impacts/benefits of using the rice straw for energy purposes can be viewed in the future work to give a holistic perspective of straw-based energy scenarios.

2. Experimental

The overall analysis of the projected straw-based combustion facilities includes the life-cycle economic analysis as well as the GHG emission impacts of the projects, as shown in Fig. 1.

The analysis is performed for the combusting of the rice straw in the grate boiler followed by the steam turbine to generate electricity. This technology is well developed in Thailand and it is at a relative low investment cost [8]. The feasibility of the projects will be addressed by implication of subjective probability analyses, LR and CER effects, and by the life-cycle GHG impact assessment. The data sources of each of the processes illustrated in Fig. 1 are discussed in the succeeding sections.

2.1. Fuel supply and delivering costs

The fuel supply can crucially determine the economics of the fuel at different scales. A detailed analysis of the rice straw logistics process can influence the feasibility of the rice straw energy use. This study has used the results of a comprehensive rice straw logistics model for Thailand situation, the detail of which can be found in the previous study [15]. In general, the dispersed and bulky characteristics of rice straw urge a management requirement for the collection and transportation of the straw before using it in energy facilities. Baling process is often recognized as the state of art and a current practicable method for collecting the bulky straw in the region. The determination of the annual fuel costs and the catchment area from which rice straw would be collected is estimated through Eqs. (1) and (2) [15], and considerations of the parameters in the equations are explained by Ref. [15].

$$\text{Annual demand}\left(\frac{t}{yr}\right) = \frac{\text{Electrical putput} \times 3.6 \times \text{Plant factor}}{\text{Electrical efficiency} \times \text{Fuel LHV}} \quad (1)$$

$$\text{Area (km}^2\text{)} = \frac{\text{Annual demand for rice straw (t)}}{\text{Straw yield}\left(\frac{t}{km^2}\right) \times \text{Collection efficiency} \times \text{Land efficiency} \times \text{Farmland}} \quad (2)$$

It is required to add the moisture content (11%) and the organic loss portion (10%) to the annual demand of the rice straw, estimated by Eq. (1). The projected rice straw costs for each of the facilities are shown in Table 1.

2.2. Project Investment analysis

The projects' economic analysis is carried out by a developed discounted cash flow model, and the detail of the methodology and data are discussed in Ref. [16]. A correlation cost model on the basis of the general power law is developed for a capacity range of 5 to 50 MWe facilities, and the specific capital costs (Baht/kWe) show a range of 83,000 to 37,000 Baht/kWe for the capacities of 5 to 50 MWe. The total operating costs of the proposed power plants relative to the total project capital costs vary by 23% and 26 % at different scales. A 70% bank loan financial support (7% interest rate, 10-year-payback period) is assumed for all the projects.

The common economic criteria, namely, Net Present Value (NPV), project Internal Rate of Return (IRR), Pay Back (PB) period, and the Cost of generated Electricity (COE) computed for the studied capacities indicate that except the 5 MWe straw-to-electricity combustion projects, the other projects seem to be feasible (see Table 2).

In this study, the feasibility of the projects will be further analyzed through subjective sensitivity analysis, learning rate, CER implications, as well as the GHG emission reduction impacts as shown in the overall methodology in Fig 1.

Table 1. Estimated rice straw costs for the projects.

	Plant capacity MW_e				
	5	8	10	15	20
Average fuel cost (Baht/t) (1)	651	673	685	712	730
Average round trip distance (km)	68	82	89	107	119

(1)Average fuel cost with a standard deviation of ±3%

Table 2. Financial evaluation of combustion project.

Criteria	Plant capacity MW_e				
	5	8	10	15	20
Project NPV (10^6 Baht)	-65	13	120	270	480
Project IRR %; after tax	-	9	12	14	16
PB (year)	-	6.9	6.2	5.8	5.3
COE (Baht/kWh)	3.13	2.83	2.61	2.47	2.34

2.3. Subjective probability analysis

Assigning subjective probabilities can somewhat quantify the judgment about uncertain parameters affecting the project profitability and decisions [18]. The variables such as plant factor, selling price of the electricity, and the fuel costs are identified as the critical values which could switch the decision to another course of action, i.e., don't build the plant. For this purpose, the critical values as they affect the project decision, here NPV, are first obtained. It is then judged whether the actual subjective probabilities are greater or less than these critical values. The following expression, adopted from [18] is used to quantify the subjective probability of the values in Eq. (3).

$$[P\times C_v]+[(1-P)\times A_v]= P(0)+(1-P)(0) \quad (3)$$

where P is the subjective probability of the event, C_v is the critical value that results in the negative NPV; A_v is the actual NPV value (see Table 3), and the right side of the equation relates to the zero expectations or "don't build" the plant decision. The three mentioned critical values are changed so that they result in negative NPV values, and then the probability sensitivity analysis in Eq. (3) is used to quantify the probabilities.

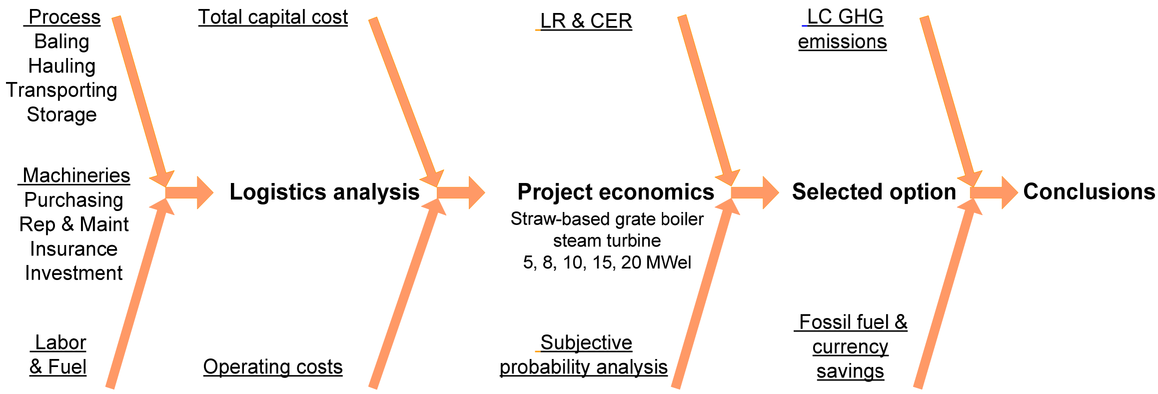

Figure 1. Overall analysis of straw-based combustion projects.

2.4 Learning rate (LR)

For biomass plants producing electricity, there is a significant reduction in the COE due to learning-by-using occurring during the operation of the plant [19]. Learning rate was initially introduced to the aircraft industry in 1936 by T. P. Wright as an attempt to describe the cost estimated based on repetitive production of airplane assemblies. Since then, learning curves have been applied to all types of work [20]. In the energy technologies, unit cost reductions of production as a result of a learning process are expressed as a function of the experience gained from an increase in the production cumulative capacity or output. Despite the importance of the two-factor learning curves (i.e., incorporating both capacity deployment and Research and Developments), commonly, the single-factor model (cumulative capacity) is used because of the extreme data limitations to validate the Research Development and Demonstration (RD&D) factors [21]. More information on learning factor implication in energy technologies are provided in different studies [20,22-24]. The implication of the learning rate is based on the following common form of the single factor learning measure, Eq. (4).

$$C=a\ Cum^{-b} \tag{4}$$

where C is the specific cost of electricity generating in Baht/kWh, "a" and "b" are constants that model the electricity generating cost reduction, and Cum is the cumulative installed capacity.

This equation suggests that each doubling of cumulative production results in a cost reduction of $1-2^{-b}$, which is defined as the learning rate and 2^{-b} is defined as the progress ratio or PR [22]. For biomass combustion projects, PR ratios are reported between 85% to 93% [20,23-24]. The default learning rate of 8% reported in IEA report [23] is used in this work.

2.5 Certified Emission Reductions (CERs)

Developed countries that are unable to meet their emissions standards can offset their emissions by buying CDM-approved CERs from developing countries. Under the Kyoto Protocol, Thailand is able to participate in a trade or purchase of carbon credits in the form of CERs through the CDM [25]. The revenues from carbon offsets, Eq (5), are measured in tones of CO_2 equivalent reductions multiplied in the carbon price.

$$EA_y=SG_y*CEF_{mix\text{-}grid} \tag{5}$$

where EA_y relates to the CO_2-eq emissions avoided through straw-fueled electricity generation in tCO_2/yr, SG_y stands for the elctricity energy that can be generated from the rice straw in MWh/yr, and $CEF_{mix\text{-}grid}$ refers to the national grid carbon emissions factor for Thailand electricity mix-grid that is 0.563 tCO_2-eq/MWh, in 2010 [26]. Then, Eq. (6) is used to calculate the annual carbon emission reduction.

$$CERy=EAy-PEsy \tag{6}$$

where CER_y is the carbon emission reduction in tCO_2/yr, EAy is the emission avoided calcualted through Eq (5) in tCO_2/yr and PEsy is the CO_2-eq emissions due to the straw combustion project in tCO_2/yr. The CO_2 emissions from straw-based fueled power facility is considered neutral, because of the biological carbon sequestration during the growing season. Howere, the CO_2-eq straw-fuel emissions of N_2O and CH_4 gases are borrowed from the Denmark LCI databases [27] that is 513 t CO_2-eq/yr. The revenue from CER can be esmtimated by multiplying the carbon emission reduction, Eq (6) by the price of carbon credit. There is not a fixed carbon trade price and the price is changing daily (see http://www.bluenext.eu/). At the time of the evaluaiton, the price was 11.93 Euro (15.66 USD) per CER. Two CER-sceanrios have been considered:

a) A minimum carbon price of 5 USD/t (1 USD=30.16 Baht) is considered for the likely CER revenues in the study; this conservative assumption is based on the fact that the status and risk of the project can lower the CER price, and it is also similar to the assumption made by [28].

b) A miximum (current) carbon pice of 15 USD/t is analyzed as the best case scenario.

The CER revenue is calculated through Eq (7).

$$CR_e=CER*\ CP \tag{7}$$

where CR_e refers to the carbon revenues in Baht, and CP is the price of CER (151 and 452 Baht per t $CO_{2\text{-}eq}$ reduction for the scenarios "a" and "b", respectively).

According to the currently Thai regulations, the taxation of CER revenues continues to evolve. Although CERs may be exempted from taxation in the future as new incentives for the promotion of carbon trading and the CDM [29-30], an applicable taxation rate of 7% to the CER revenue is included in the anlayses.

2.6 Availability of rice straw for energy use

Five-year statistics (2005-2009) data from OAE (www.oae.go.th) is collected, and the average rice straw availability on the regional basis are calcualted and presented in Table 3 with two scenario considerations:

Scenario 1: Rice straw residues available for energy exploitation on the basis of using of the 50% of the rice straw in the Central regions and 75% of rice straw in the Northern and the Northeastern regions. This consideration is discussed by Ref. [15].

Scenario 2: Rice straw residues available for energy exploitation on the basis of using of 70% of the rice straw in the Central regions and 90% of the rice straw in the Northern and the Northeastern regions.

2.7 Life cycle GHG impacts

The overall GHG emission impacts of rice straw conversion to electricity in combustion power plants are viewed through a life-cycle perspective. Straw is considered as a waste by-product of rice cultivation, therefore, fertilizers and agricultural land use are exempted from the LCA; so are the manufacture of the vehicles, materials, and building constructions; as the amount of energy that go into producing subcomponents of equipment used is found to be insignificant, less than 3% [31], when compared to total energy consumption within the system. Furthermore, the nature of immense data would indicate higher uncertainties as reliance

Table 3. Potential rice straw availability for energy production through two scenarios [(1)].

Region	Average rice production (Mt/year)[(2)]	Straw residues (Mt/yr) SGR: 0.6 at 0.11 MC	Scenario1 [(3)] Straw availability (Mt) (50% Central and 75% North & Northeast)	Scenario 2 [(3)] Straw availability (Mt) (70% Central and 90% North & Northeast)
Central	9.61±0.15	5.76±0.11	1.15±0.02	1.61±0.03
Northern	9.02±0.13	5.41±0.10	1.62±0.03	1.95±0.03
Northeastern	10.76±0.18	6.47±0.14	1.94±0.04	2.33±0.05
Southern	0.91±0.02	0.55±0.02	0	0
Total	30.32±0.40	18.19±0.30	4.72±0.09 **(25.9%)**	5.89±0.12 **(32.4%)**
MWe [(4)]	-	-	**433**	**541**

(1) Straw residues estimation and availability is derived from the previous study [15]
(2) Estimated from 5-year statistics data obtaine from OAE (www.oae.go.th).
(3) Note that a determined 40% collection efficeincy has been included in estimation of the available rice straw residues for energy exploitation in both scenarios
(4) Potential MW electrical generations per year (based on the specification of 10 MWe plants)

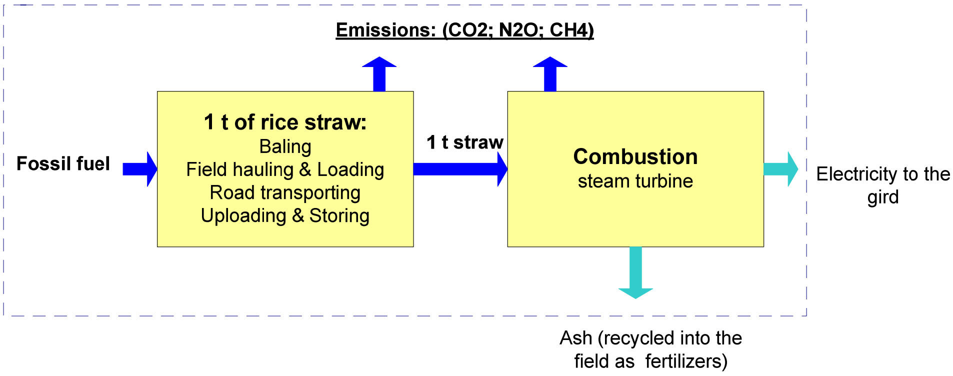

Figure 2. Boundary of the GHG emissions analysis.

Table 4. Probability sensitivity analysis.

8 MWe			10 MWe			15 MWe			20 MWe		
PF (h)	C_v(MB)	P	PF (h)	C_v(MB)	P	PF (h)	C_v(MB)	P	PF (h)	C_v(MB)	P
5500	-11.75	0.22	5520	-15.02	0.89	5212	-25.52	0.91	4967	-19.95	0.96
EP (B/kWh)			EP (B/kWh)			EP (B/kWh)			EP (B/kWh)		
2.52	-39.72	0.24	2.36	-19.56	0.86	2.23	-23.71	0.92	2.12	-15.02	0.97
FP (B/t)			FP (B/t)			FP (B/t)			FP (B/t)		
720	-26.57	0.32	825	-12.89	0.90	926	-10.95	0.96	1037	-17.34	0.97

PF: Plant factor; EP: Electricity selling price; FP: Fuel price; C_v critical value of NPV; P: Probability Sensitivity

upon such data increases [32]. The goal is to investigate the GHG emission consequences of rice straw utilization for energy production by quantifying the following parameters:

1. The life-cycle GHG emissions of the straw-based power generation facilities, and the offsetting emissions from fossil consumptions that would otherwise occur.

2. The potential fossil-fuel savings.

The analysis quantifies emissions of the three primary greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) within the illustrated boundary in Fig 2. One tonne of dry rice straw is considered as the functional unit.

The average emission factors specified to burning of the rice straw in the field is derived from Refs. [7,33-34]. The US life cycle inventory database [36] in which life-cycle emission flows of diesel combustion in combination trucks are provided, are used for the logistics emission analyses. The characterization factor system developed by Intergovernmental Panel on Climate Change (IPCC) explained by [36] is used to weight the various substances according to their efficiencies as green house gases. The life cycle GHG impact of the natural gas or coal power plants is 0.539 t CO_2-eq/MWh [37] or 1.002 [38] t CO_2-eq/MWh, respectively. The estimation of the amount of the potential saved natural gas or coal as well, and the likely avoided GHG emissions through their substitution by rice straw fuel is made based on the assumptions that the LHV, and efficiency of the natural gas or (bituminous coal) power plants, are 47.1 or (26.1) MJ/kg, and 44% or (33%), respectively. The GHG emissions from straw-based combustion power plant are estimated from Danish LCI [27]. Potential avoided GHG emissions due to the logistics of the rice straw in Thailand is found to be around 1 t CO_2-eq per each dry tonne of rice straw [39] when compared to the emissions of its open field burning.

3. Results and discussions

3.1. Project feasibility assessment

Examining the effects of the scale on the COE over the considered range of capacities shows that around 14% reduced COE is expected by each doubling the plant capacity (see Table 2). The assigned subjective probabilities, discussed in section 2.3, can quantify the uncertain parameters which affect the fate of the projects. It should be noted that despite the fact that subjective probability is, by nature, uncertain (it depends on our knowledge or the assumptions of the study), it is considered to be useful for selecting the project options. These probability analyses are presented in Table 4.

The results in Table 4 imply that, for instance, in a 10 MW_e straw-fueled combustion plant, if the probability of the operating working hours at 5520 hr/yr is more than 89%, the selected action is “don’t build” the plant. Similarly, if the probability of the fuel cost at 825 Baht/t is more than 90%, or if the probability of selling the electricity at 2.36 Baht/kWh (fixed tariff) is more than 86%, “don’t build the plant” decision should be selected. Furthermore, the results indicate that the 8 MW_e power plants are riskier than the other three plants, because the subjective probability of “don’t build” the plant is as high as 68-76%. No doubt, higher capacities are more certain in terms of the economic criteria and earnings, but the constraints of the fuel supply and high storage space requirements limit the scale of the straw-based power plants. The subjective sensitivity analysis performed in Table 4, indicates that the probability of the financially successful 10 MWe straw-based power plant could be as high as 86-90%. Therefore, we have selected the 10 MW_e straw-based power projects as a suitable scale for starting electricity generation from rice straw in Thailand, and the further analysis presented in following sections are based on 10 MW_e projected straw-based facilities.

3.2 The effect of Learning rate in reducing specific electricity generation from rice straw combustion

The results of the economies of scale suggest that up-scaling is probably one of the main mechanisms behind cost reductions in the straw-fueled boiler technology. It is reported that the most cost-effective biomass-to-energy applications are those relatively large scales (30-100 MWe) [40], but the constraints of the fuel supply and storage space as mentioned earlier can not be overlooked. For this reason, biomass power facilities can not usually compete against the conventional fueled power plants. On the other hand, the results of this work show that as the capacity of the plant increases, there is a relative decrease in the electricity generating cost. Thus, based on the project economics evaluation and the subjective probability sensitivity analysis discussed in section 3.1, we have focused on the results of 10 MWe straw-fueled combustion plants.

Attempt is made to answer the following question: Can rice straw-based electrical combustion facilities compete against conventional fuel power plants? Assuming an average electricity producing price of 2.20 Baht/kWh for fossil power plants [41-42], this study suggests that, under the assumptions of this study, at the plant capacity of around 25 MWe (see Fig. 3), the rice straw-fuel combustion power facilities would compete against conventional-fuel power capacities which seems to be unrealistic considering the fuel supply constraint.

Accepting the assigned 8% LR as discussed in section 2.4, one can expect that the cost of electricity generation from a 10 MW_e straw fueled-power plant decreases to around 2.20 Baht/kWh when the cumulative installed capacity of straw-based power capacities reach to 40 MW_e (4^{th} plant at capacity of 10 MWe) as shown in Fig 4. It should be noted that an average LR of 4% is suggested by Ref. [42] for electricity generating from fossil-fuels which occur over 30 years. However, this study ignores the learning rate of COE from fossil-fuel power plant in short term.

The learning rate application for straw-based power combustion technologies can use the scenarios for cumulative installed capacities over time to provide insight into future cost development paths. Using the learning rate given above, and assuming that straw fueled power combustion plants would start in 2014, and there would be an increase in installed capacity of 20% per year, the cost of the generated electricity could be approximately 2.21 Baht/kWh in 2022. This would correspond to around 4 straw-fueled power plants of 10 MW_e installed within 8 years, and, at least, until then the projected rice straw-based combustion power plants require supporting incentives. It should be noted that the learning rates are in no way exact but can be regarded as a suitable guess to be used in energy systems analysis [42]. Considering that the growth in installed capacity remains limited, the implication of learning rate is only possible if incentives for the construction of new plants are properly given on time.

3.3 The effect of CER on the plant profitability

The effect of carbon emission reduction credits on the project profitability (i.e. NPV, IRR, PB period, and COE) is shown in Table 5. This effect is due to offsetting 34,010 t CO_2-eq per year.

Table 5. Effect of CER scenarios on the profitability of the 10 MW_e combustion project

Criteria	Base value	Economics criteria	
		Scenario-a*	Scenario-b*
NPV	120 million-Baht	+37% variation	+ 110% variation
IRR %	12	13	15
PB- Year	6.2	5.9	5.4
COE-Baht/kWh	2.61	2.52	2.35

*Scenario-a: Minimum CER of 151 Baht or 5 USD per t CO_2-eq reduction
*Scenario-b: Maximum CER of 452 Baht or 15 USD per t CO_2-eq reduction

This reduction in emissions could lead to an additional annual income for the project of about 5 or 15 million Baht if a credit price of 151 or 425 Baht per tonne CO_2-eq reduction is achieved. In the best case scenario (maximum CER credits), the combustion project can achieve an appealing profitability (IRR≥11%) at the debt to equity ratio of approximately 1 to 3, i.e. 30% bank loan and 70% equity, which consequently reduces the COE to 2.26 Baht/kWh (almost compatible with the COE of the fossil-fuel power plants).

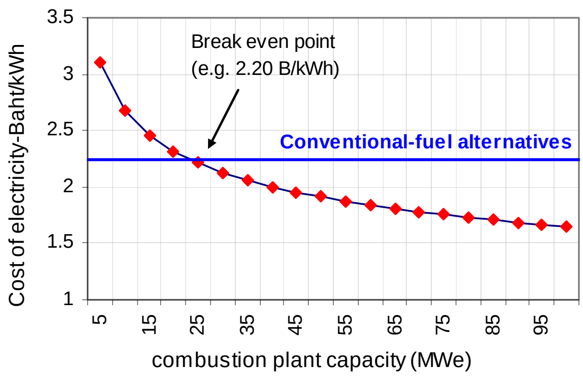

Figure 3. Minimum needed capacity for a straw fuel power facility to compete with a fossil fuel alternative.

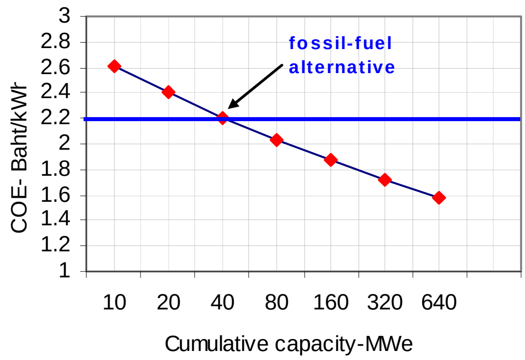

Figure 4. Effect of learning rate on the COE reduction of 10 MW_e straw-fuel combustion plants.

3.4 Life-cycle greenhouse gas emission impacts of substituting rice straw for fossil-fuel in electric generation

Burning the rice straw in power plants can lower GHG emissions and contribute to improved energy security. Based on the input data explained in section 2.7, the GHG emission impacts of the rice straw combustion process and the offsetting GHG emissions due to the replaced fossil-fuel are shown in Tables 6 and 7.

Table 6. Life-cycle CO_2-eq emissions per tonne $straw_{(db)}$ in combustion route.

Process chains	Life cycle GHG emissions		
	$kgCO_2$-eq/t $_{straw(db)}$	gCO_2-eq/MJ	kg CO_2-eq/kWh_e
Logistics	24	1.912	0.035
Grate boiler combustion	6	0.460	0.008
Total emissions	30	2.372	0.043

Note: 1 tonne of the dry-based rice straw is converted to 681 kWh gross electricity (i.e. 0.681 kWh/ kg $straw_{db}$) or 0.613 kWh net electricity per kg straw db

As per the results of Table 7, substituting the natural gas or coal fuels with rice straw fuels for power generation would result in a considerable fossil fuel savings and a lower GHG emission (CO_2, N_2O, CH_4). The statistical data for the imported quantities of the natural gas and coal fuels to Thailand obtained from EPPO [43] indicate that in 2010, 15.93 Mt coal (total value

Table 7. Avoided GHG emissions from substituted fossil-fuel.

Power generation by fuel type	Avoided GHG emissions			Saved fossil-fuel
	$kgCO_2$-eq/kWh_e	t CO_2-eq/t $_{straw\ db}$	% CO_2-eq (1)	
Natural gas	0.496	0.368	92.0	152 m^3/t $_{straw\ db}$ (2)
Imported Coal	0.959	0.683	95.7	0.285 t/t $_{straw\ db}$

(1) In case of substituting fossil-fuels with rice straw-fuel
(2) 0.118 t natural gas/t straw (On the basis of density of 0.777 kg/m^3)

Table 8. Contributions of rice-straw-fueled power generations to GHG emission reductions and fossil fuel savings.

Scenario "1"- 433 MW electrical generations from rice straw										
Yearly GHG avoidance				Yearly natural-gas savings			Yearly imported coal savings			
$MtCO_{2eq}$/yr		% (1)		importation	Currency savings		Importation	Currency savings		
NG(2)	coal	NG	coal	Mm^3/yr	bB/yr (3)	% (4)	Mt/yr	bB/yr	%(4)	
2.31	3.53	0.83	1.27	593.09	6.02	7.15	1.11	2.57	6.96	
Scenario "2"- 541 MW electrical generations from rice straw										
Yearly GHG avoidance				Yearly natural-gas savings			Yearly imported coal savings			
$MtCO_{2eq}$/yr		%		importation	Currency savings		Importation	Currency savings		
NG	coal	NG	coal	Mm^3/yr	bB/yr	%	Mt/yr	bB/yr	%	
2.88	4.42	1.04	1.59	741.02	7.52	8.93	1.39	3.21	8.70	

(1) Estimated based on Thailand's yearly GHG emissions of 277.51 million tonne as of 2010[42]
(2) Natural gas
(3) Annual billion Baht savings of the imported natural gas-fuels or coal
(4) Currency savings with respect to the avoided imported natural gas or avoided imported coal per year.

of 36.94 billion Baht) and 8,300 Mm^3 natural gas (total value of 84.21 billion Baht) is imported to the country. Thus, the specific value of 1 tonne of the imported coal and 1 m^3 of the imported natural gas can be estimated as 2319 Baht and 10.15 Baht, respectively. By taking into account the data provided above, the whole perspective of straw-fueled electricity generations in terms of the annual GHG emissions from logistics and straw burning in the power plant, imported natural gas-fuel savings or imported coal-fuel savings, avoided GHG emissions due to the substitution of the natural-gas-fuel or the coal-fuel which would otherwise are burned to generate electricity are shown in Table 8.

An investigation of the results in Table 8 shows that projection decentralized straw-fueled power plants would contribute to the savings on the conventional fuel consumptions and imports, as well as to a reduction of GHG emissions. The proportion of the annual projected straw-fueled power generating compared to the total power generation in 2010 (152,954 GWhe [44]) is 1.74-2.17% for scenario "1" and "2", respectively. The results in Table 8 indicate that, for instance in case of generating 433 MW electricity from rice straw, it is expected to have a GHG emission reduction of approximately 2-3.5 million t per year which is equivalent to around 1-1.3% reduction of the total annual country's GHG emissions. This emission reduction is due to the avoided GHG emissions from non-open-field burning of rice straw residues (only CH_4 and N_2O contributions) and those avoided due to the substituted natural gas or coal fuel-burnings to generate the equivalent electricity. In addition to the mitigation of GHG emissions, around 7% (in scenario 1) and 9% (in Scenario 2) of the annual currency spending on the importation of the equivalent natural gas or coal fuels into the country could be saved, respectively.

4. Conclusions

The GHG environmental analyses and the financial feasibility assessment of different scale are performed for rice straw-based power combustion projects. Straw-based combustion facilities are financially feasible and profitable assumed that the specific capital cost is approximately lower than 70,000 Baht/kW_e. This means the 8 MWe or greater capacity plants. The results of subjective probability analyses indicate that the riskier projects are those that probability of "don't built" the plant is greater than 50%. The subjective probability of a financially successful 10 MWe straw-based power plant could be as high as 86-90%, whereas, it is as low as 24-32% for an 8 MWe project. Although, the bigger capacities (15 and 20 MWe plants) show a favorable subjective probability indicators, but due to the constraints of straw fuel supply and storage space, 10 MWe straw-based power projects seems to be a suitable project scale for future power plants.

The effect of the learning rate as a tool to analyze the reduction of the generated electricity with increasing the cumulative installed capacities for a rice straw-based combustion power plant indicate that the COE of a 10 MW_e straw fuelled-power plant would decrease to around 2.21 Baht/kWh when the cumulative installed capacity reaches to 40 MW_e, i.e. the 4th plants. At this COE level, the straw-based power combustion plant can compete with the alternative fossil-fuel plant.

The effect of CERs on the profitability of the 10 MWe project shows that an additional annual income of about 5 to 15 million Baht can be expected, and the desired profitability can be achieved at lower debt to equity ratio which consequently reduces the COE to 2.26 Baht/kWh.

Life cycle GHG emissions of the straw combustion process chain (logistics and combustion) indicate that 30 kg CO_2eq/t $straw_{(db)}$ or 0.043 kg CO_2eq/kWh would be released into the atmosphere in case of burning the straw in a 10 MW_e combustion plant. However, 92-96% of CO_2-eq emission reductions could be achieved; i.e., 0.368 tCO_2eq/t $straw_{(db)}$ (0.496 kg CO_2eq/kWh) and 0.683 tCO_2eq/t $straw_{(db)}$ (0.959 kg CO_2eq/kWh) could be avoided if rice straw is substituted with the natural gas or coal fuels in the power generation sectors, respectively. This would result in the saved fossil fuels of 152 m^3, or 0.285 t coal per 1 tonne of dry base rice straw. Totally, the GHG emission reductions would be around 2-4 million tonns per year (1-2%) due to using of 4.7 Mt rice straw residues (26% of the total rice-straw residues), and 5.9 Mt rice straw residues (32% of the total rice straw residues) to generate 433 MW and 541 MW electricity generation, respectively. A significant savings on primary energy importations (7-9%) could be gained for the country from rice straw-based power generations through combustion systems. The overall analysis need to be followed by the societal impact assessment which can be viewed in the future work.

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