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Greenhouse gas emission mitigation potential of rice husks for An Giang province, Vietnam

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ABSTRACT

To evaluate the greenhouse gas (GHG) emission mitigation potential of rice husk utilization, a life cycle inventory analysis was conducted for 18 scenarios. The allocation of fuels, other than rice husks, was decided based on the current demand for and supply of rice husks. To prevent the bulky nature of rice husks, briquette production is also discussed. In the power generation scenarios, the differences between two capacities (5 MW and 30 MW) were analyzed. The results of analysis reveal that CH_4 and N_2O emissions from open burning contribute largely to the current GHG emissions. Therefore, ceasing open burning alone has a large GHG mitigation potential. The use of briquettes, even though GHG is emitted during the production stage, can still contribute to GHG emission mitigation as the production is more efficient than rice husk burning or dumping. In the power generation scenarios, most GHG emissions were derived from the combustion process. Therefore, gasification which has a little combustion process is the most efficient GHG mitigator. Both the replacement of grid electricity by generated electricity, and the replacement of diesel oil by pyrolyzed oil show larger GHG mitigation potentials than what could be derived from open burning cessation alone.

1. Background, aim, and scope

Rice is the main agricultural crop cultivated throughout the country in Vietnam. The annual production is approximately 36 million tones, of which more than 50% takes place in the Mekong River Delta in Southern Vietnam [1]. There are many rice mills throughout the area and the high volume of rice husks that are considered as waste after milling are not appropriately treated. Some of them are dumped into the dense canal and river systems, polluting the waters and disturbing the habitat for fish populations. The discarded rice husks decrease the dissolved oxygen seriously by covering the water surfaces, further causing pungent odors, black color and high turbidity in the canals and rivers. These problems generate economic costs by increasing the fees for managing catfish disease and reducing productivity. Communities living along the rivers are also affected through using of polluted water for bathing, washing and drinking. Rice husk dumping into the rivers is still observed today, especially in rural areas, even though the practice is illegal and has been strictly banned in Vietnam. As an alternative to river dumping, mill owners are burning the excess husks in the open air which is becoming increasingly prevalent. This causes not only respiratory disease but also severe fire accidents. Many countries have introduced new regulations to restrict field burning of rice husks [2]. However, in Vietnam, there still remains to be

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seen any policies or support by the Vietnamese government to treat or use rice husks economically responsibly.

Rice husks are defined as renewable energy resource which can mitigate greenhouse gas (GHG) emissions and used in this way, instead of as waste, will mean less pollution; further due to the husk's low sulfur and heavy metal contents [3]. Converting rice husks into heat, steam, gas or liquid fuels would benefit countries that have no conventional energy resources [2]. Promoting the use of rice husks by the energy sector would curb local environmental problems, such as rice husk dumping and open burning, and highlight the benefits of GHG reduction to the community and environment. In Vietnam, several pre-feasibility studies were carried out to install rice husk power plants [4–7], but so far such plants have not been realized. The current low electricity costs and the lack of sufficient incentives for renewable energy are possible limitations [8].

Recently, many innovative biomass-use technologies such as gasification and pyrolysis have been developed. In this study, the potential of rice husks as a renewable energy resource was evaluated, taking into account new technologies as well as conventional uses for rice husks, such as cooking and brick making. The supply and current demand of rice husks were estimated using local statistical data. Based on the results, scenarios for the use of rice husks were developed, and then evaluated from the aspect of GHG mitigation using Life Cycle Inventory Analysis. Finally, an effective utilization of rice husks is proposed.

2. Estimation of rice husk supply and demand

2.1. *Study area*

An Giang province situated in the Mekong River Delta region was selected as the study area, because it has the largest paddy area in Vietnam with 520 000 ha in use [9] and, therefore, it can be a potential market place for rice husk energy production. An Giang has 2.2 million people with a density of 625 persons per km^2 [9]. Within the area, besides the two main branches off the Mekong River, namely the Tien and Hau Rivers, there are a lot of small rivers and canals evenly distributed throughout the area (Fig. 1). An Giang province has one city (Long Xuyen), one provincial town (Chau Doc) and 9 districts (Chau Phu, Chau Thanh, Cho Moi, Phu Tan, Tinh Bien, Tri Ton, Tan Chau, Thoai Son and An Phu), all of which are considered as target regions in this study. There are more than 1000 rice mills, of which more than 200 have larger capacities above 100 t/d [9]. Most rice mills are located on the banks of canals and the two major rivers, taking advantage of the dense water transport network. This province suffers from serious pollution problems from inadequate rice husk waste disposal.

2.2. *Availability of rice husks*

The availability of rice husks depends on the rice production and the proportion of husks in a paddy. In An Giang province,

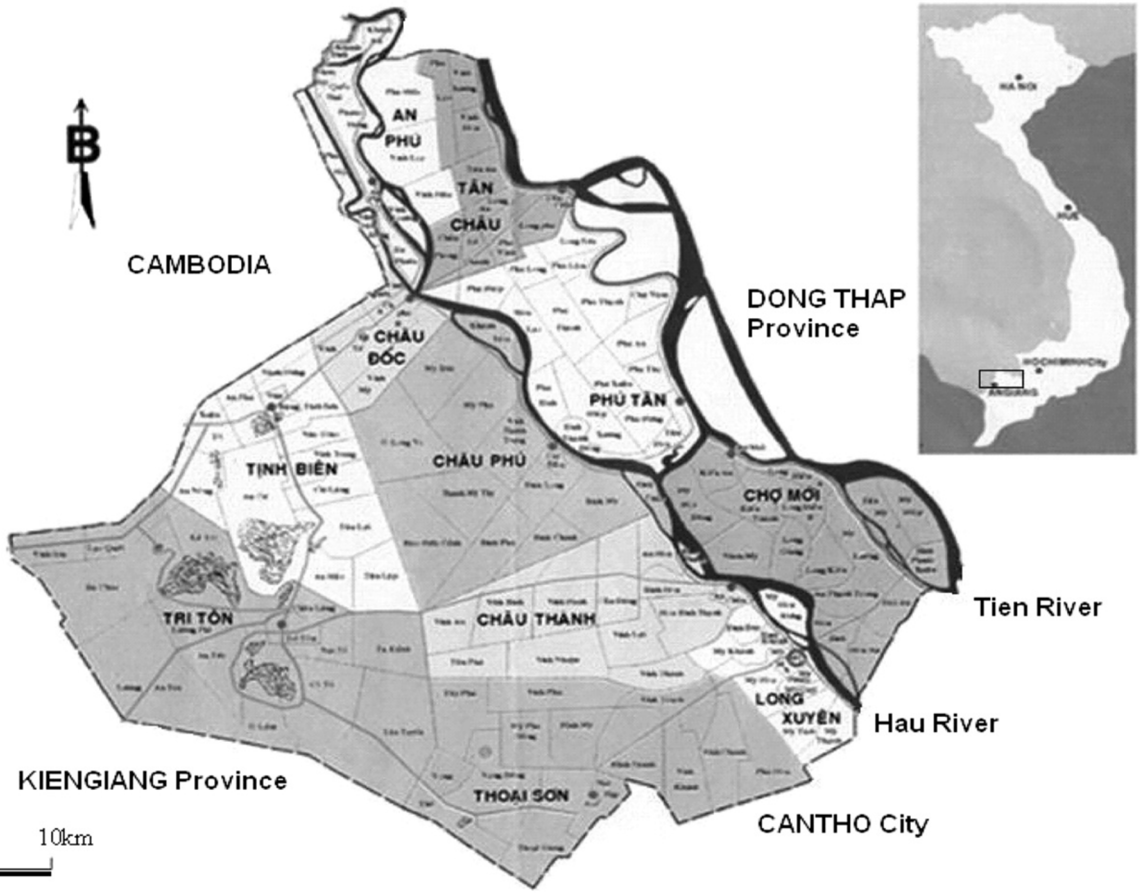


Fig. 1 – Map of An Giang province.

rice is cultivated three times in a year, mainly in the winter–spring season (Feb–Apr), followed by summer–autumn (Jun–Aug) and autumn–winter (Oct–Dec) seasons. The amount of available rice husks was estimated using the statistical data of rice production in each season provided by the An Giang statistic office [9]. Many studies have reported that the proportion of husks in a paddy is 20% [2,3,10–13]. This value was also supported by our interviews with mill owners in An Giang province. Multiplying the proportion (0.2) by the rice production, quantities of rice husks were calculated. The total quantity of rice husks in An Giang province for 2007 was estimated at 620 000 tons per year (t/y), of which 52.5% was generated in the winter–spring season.

2.3. *Current use for rice husks and demand estimation*

2.3.1. *Cooking*

Woods and agricultural residues such as rice husks, rice straws, coffee husks, and bagasse are widely used as fuels for cooking especially in rural areas in Vietnam. The current demand for each fuel for cooking was estimated by multiplying the number of households using a type of fuel in An Giang province [9] by the average household fuel consumption in Vietnam [14]. As shown in the first column (A) in Table 1, fuel wood is mainly used for cooking fuel in rural areas, whilst liquid petroleum gas (LPG) is the main energy source for cooking in urban areas. In total, 65% of households rely on fuel wood for cooking whereas only 7% of households use rice husks [9]. In practice, each household uses various fuels in combination not just one type of fuel. However, due to data availability, it was assumed that each household used mainly one type of fuel. When fuel consumptions (B) in urban and rural areas are compared, more amounts of fuels are used per household in rural areas. This is mainly caused by the difference in family sizes. The average persons per household are 4 and 6 in urban and rural areas, respectively [9]. The total rice husk demand for cooking in An Giang province is estimated at 53,100 t/y, accounting for 8.6% of the rice husk supply.

2.3.2. *Brick kiln*

In the Mekong River Delta, the use of rice husks for brick making and in other local industries is widely spread because of lower prices, local availability and reliability of supply. It was found that 0.4 kg of rice husks are needed to produce one brick, through interviews with brick kiln owners in An Giang province. According to the An Giang statistical office, 400 million bricks are produced annually [9]. From these data, the amount of rice husks used in brick kilns are estimated at 160 000 t/y, accounting for 25.8% of the rice husk supply.

Table 1 – Cooking fuel use and total fuel consumption.

Fuel type	(A) Number of household [9]		(B) Fuel consumption, [kg/household] [40]		Total consumption (A × B) [1000 t/y]		
	Urban	Rural	Urban	Rural	Urban	Rural	Total
LPG	63 371	56 262	357	604	22.62	33.98	56.61
Coal	2488	2321	816	1380	2.03	3.20	5.23
Wood	43 822	237 236	1083	1831	47.46	434.38	481.84
Rice husk	14 040	15 863	1300	2197	18.25	34.85	53.10

In total, 213 000 t/y of rice husks are utilized and the excess (407 000 t/y) rice husks (65.6%) are disposed. The scenarios evaluated in this study use these estimated values of rice husk supply and current demand.

3. Preparations for life cycle inventory analysis

3.1. *Alternative uses for rice husks*

The simplest way to use rice husks is direct combustion for heat energy, which is popular in rural households in developing countries. Combustion in a furnace is a traditional and well-established technology, however, combustion efficiency is quite low compared to other methods for generating energy [15]. Electricity generation using steam engines through combustion is another technology already applied in many developing countries [16]. Gasification has been considered as an alternative energy generating technology with a higher efficiency than direct combustion. The gases synthesized from rice husk in a gasification system, such as CO, H_2 and volatile hydrocarbons, can be used for electricity generation using internal combustion engines and generators. Separately from the technologies of electricity generation, liquid fuel production by pyrolysis is another stream. The produced bio-oil can replace diesel oil and new engine systems for this oil have been developed all over the world [17].

One of the critical disadvantages of using rice husk is managing its bulky volume. To overcome this disadvantage, briquettes produced by compressing rice husks, can be applied here. This technology has already been used in many developing countries as well as in Vietnam. The technologies and uses of rice husks taken into consideration in this study are summarized and shown in Fig. 2.

3.2. *Data preparation for inventory analysis*

3.2.1. *Direct combustion in cooking and brick making*

Direct combustion is the most common technical option for rice husks as a source of energy. Currently, as already estimated in 2.3, only a small quantity of rice husks is used in household cooking and brick making. As energy demand for household cooking increases, surplus rice husks can be promoted as a fuel alternative which is affordable and easy to obtain. The greenhouse gas emission mitigation can be achieved by utilizing rice husks in place of the fossil fuels. In this study, it is assumed that rice husks or briquettes can replace liquid petroleum gas (LPG), coal and fuel wood for household cooking and brick making. Some GHG emissions from rice husk utilization are a consequence of CH_4 and N_2O emissions during combustion. Emission from rice husk transportation for domestic use is negligible because people usually obtain the rice husks from neighborhood mills using bicycles or water boats.

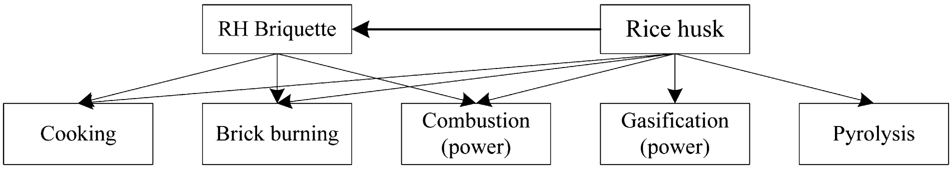


Fig. 2 – Uses for rice husks and rice husk briquettes.

When fuel replacement is considered, the lower heating value (LHV) and combustion efficiency of a cooking stove should be taken into account. Those values reported in previous papers are summarized in the first and second columns (a & b) in Table 2. Some previous studies have reported rice husk LHV values as shown in Table 3. The lowest LHV value was seen for the Vietnamese case [18] which accounted for Vietnam being selected as a model for this study. Multiplying the LHV by the stove efficiency, the modified LHV including stove efficiency was estimated (Table 2 (c)). Based on the modified LHV, the replacement factor among fuels was then calculated (Table 2 (d)).

In the case of brick making, the furnace efficiency for each fuel – LPG, coal, fuel wood, rice husk, briquette – was not available, therefore, the requisite amount of fuel for the production of one brick was used instead: 0.3 kg of coal [19] or 0.18 kg of fuel wood [14]. The briquette is assumed to be equitable to the fuel wood value.

The total GHG emission from household cooking and brick making in An Giang province was estimated with the equation as follows:

$$Em_{GHG} = \sum (F_i \times Ef_i)$$

Where:

Em_{GHG}: GHG emissions [t CO_{2eq}/y]

F_i: consumption of fuel i [t/y] (i: coal, LPG, fuel wood, rice husk, and briquette)

Ef_i: GHG emission factors of fuel i [t CO_{2eq}/t fuel] (with Global Warming Potential, tCO_{2eq}/t GHG (CH_4: 21; N_2O: 310 – IPCC, 2006))

The default GHG emission factors for stationary combustion stated by the Intergovernmental Panel on Climate Change IPCC (2006) were summarized and used as shown in Table 4.

Table 2 – Estimated replacement factors based on stove efficiency and LHV.

Fuel	(a) Cooking stove efficiency [%]	(b) Low heating value [MJ/kg]	(c) Modified LHV (incl. stove efficiency) (a × b), [MJ/kg]	(d) Replacement factor (incl. stove efficiency) [kg/kg]
LPG	60[14,41]	47.3[28]	28.4	0.06
Coal	22[14,41]	20.7[28]	4.55	0.34
Fuel wood	17[14,41]	15.6[28]	2.65	0.59
Rice husk	12[14,41]	13.0	1.56	1.00
Briquette	17[42]	16.3[43]	2.77	0.56

For a rice husk briquettes, the greenhouse gas emission factor is assumed to be same as that of fuel wood.

3.2.2. *Power generation by combustion or gasification*

The most popular combustors for biomass applications are stoker-fired and fluid bed designs. The fluid bed boilers have long been available for capacities ranging from 15 to 715 MW. Bubbling fluid bed boilers tend to be limited to the lower size range, whilst circulating fluid bed boilers are applicable to any capacity [17]. Besides the combustors, the selection of generating machinery also depends on capacity. While steam engines are available in the capacity range from 50 kW to 1 MW, steam turbines can cover the range from 0.5 MW up to more than 500 MW [20]. According to Bhattacharya et al. (1999), the combustion efficiencies of rice husk power generation using steam turbines for the capacities 29 MW, 2.5 MW and 1 MW are 31.3%, 15% and 13%, respectively [21]. A feasibility study in Vietnam also showed that the efficiency of a rice husk combustion power plant is 25% for 27 MW capacity [8]. The decrease in efficiency is usually observed when the

Table 3 – Moisture content and lower heating value of rice husk.

References	Moisture [%]	LHV [MJ/kg]
[44]	5.7	14.2
[45]	8.6	15.8
[46]	12.4	14.5
[11]	9.4	15.0
[18]	8.8	13.0

Table 4 – GHG emission factors for stationary combustion in residential areas [28].

Fuels	GHG emission from combustion [28] [kg CO_{2eq}/kg fuel][a]	GHG emission from production phase [kg CO_{2eq}/kg fuel]	Total GHG emission [kg CO_{2eq}/kg fuel]
LPG	2.990	0.230[47]	3.220
Coal	2.160	0.110[29]	2.270
Fuel wood	0.118	0	0.118
Rice husk	0.100	0	0.100
Briquette	0.123	0.060[b]	0.183

a The data shown in IPCC [kg CO_{2eq} MJ] are converted using LHVs.
b Calculated from electricity consumption through interview result in An Giang (17/Sept/2008).

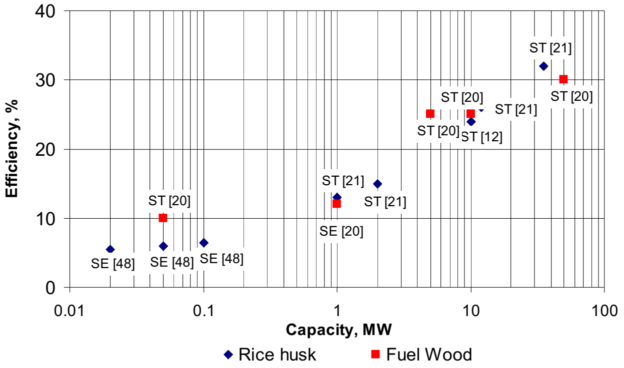
capacity becomes smaller. Mahin (1989) showed that a 100 kW power generation system only has 7% efficiency [22]. The relationships between capacity and efficiency reported in previous studies are summarized and shown in Fig. 3. In the case of fuel wood combustion, the efficiency is higher than that for rice husks. The reported values are 28% at 5 MW [23] and 29.8% at 25 MW [24] for fuel wood. According to the OECD report, the efficiency of biomass combustion can be 30–35% in the 5 MW–25 MW range [25].

Like the combustion process, the gasification system also shows various efficiencies depending on capacity. The gasification of coal is now well-established, and biomass gasification is attracting attention and developing rapidly. Gasifiers have been designed in various configurations, however, only the fluid bed type is put to practical use in the range of capacities 2.5–150 MW [17]. For the generating machinery, gas engines and gas turbines are usually used. The efficiencies reported in previous studies are summarized in Fig. 4. According to Yin et al. [26], the efficiencies of rice husk gasification for 200 kW and 1 MW capacities are 12% and 17%, respectively. Bergqvist et al. [8] reported the efficiency to be 16% for 3 MW capacities. In the case of fuel wood gasification, the efficiency can reach 30–40% in the 10–30 MW range [25].

In this study, the fluidized bed systems equipped with steam and gas turbines were the technologies assumed for the combustion and gasification processes. The assumed capacities and efficiencies are summarized in Table 5. Two capacities, 5 MW and 30 MW, were considered. Briquettes can be applied only to in combustion scenarios, assuming the efficiency is the same as fuel wood.

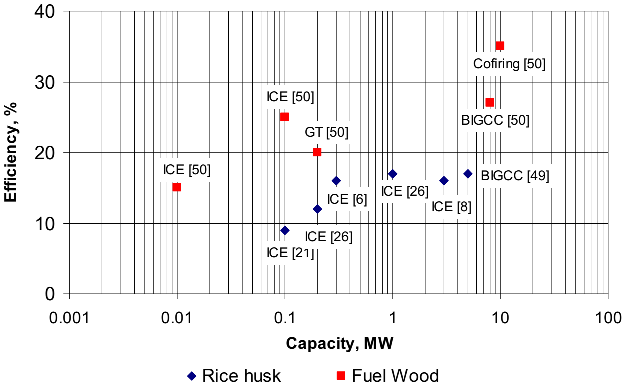
The GHG emission from the combustion process is derived from three components: (1) use of residual oil in the combustion start-up process, (2) N_2O and CH_4 emissions during combustion and (3) transportation by motor boats. Replacing national grid electricity with electricity generated from rice husk and briquette was counted as a GHG reduction.

It is reported that 500–600 L residual oil is needed for each start-up [27]. In deciding the frequency of operation, the operational condition of the power plant must be taken into account. If operation time is limited to approximately 15 h per day, a daily start-up is required, causing larger GHG emissions. Therefore, continuous operation is preferable. In this study, operating a system 5000 h with 5 breaks per year is applied which was adopted by a rice husk power plant in Thailand following a Clean Development Mechanism (CDM) feasibility study [27].



ST: Steam turbine; SE: Steam engine

Fig. 3 – Biomass combustion power plant combustion efficiencies.



ICE: Internal combustion Engine; BIGCC: Biomass gasification combined cycle; GT: Gas turbine

Fig. 4 – Biomass gasification power plant combustion efficiencies.

CH_4 and N_2O are emitted during the combustion process in a power plant. Combustion is defined as controlled combustion as applied in industries, and IPCC emission factors for industrial combustion were applied [28].

The transport emission depends on transport distance which was calculated in the following order: (1) the number of potential power plants was calculated based on plant capacity and rice husk supply, (2) the area for one plant was calculated, (3) the radius was used as the average distance traveled from mill to the power plant assuming that the power plant and rice mills are located at the center and at the circumference, respectively, and (4) trip frequency was determined by the distance and motor-boat capacity.

Generated electricity can replace national grid electricity. Net power generation is defined as the power remaining after subtracting the parasitic power from the gross power generation. Parasitic power is the power consumed by the plant or system itself and is assumed to be 10% of the gross power generated [21]. The carbon intensity of national grid electricity was calculated based on the total electricity generated (69 074 GWh) and fuel consumed for electricity generation during 2007 [18]; the fuel breakdown is anthracite coal (3646 ktoe), diesel oil (821 ktoe) and natural gas (4916 ktoe). The IPCC emission factors for stationary combustion in the energy industries [28] and emission from production of these

Table 5 – Capacities and combustion efficiencies for power generation plants.

Feedstock	Technology	Capacity [MW]	Efficiency [%]
Rice husk	Combustion	5	15
		30	25
	Gasification	5	16
		30	30
Briquette	Combustion	5	25
		30	30

fuels were applied as followed; 4.1 g CO_{2eq}/MJ for anthracite coal [29], 3.3 g CO_{2eq}/MJ for diesel [30], and 0.81 g CO_{2eq}/MJ for natural gas [31]. The carbon intensity was estimated at 0.459 kg CO_{2eq}/kW h, which is rather small due to a higher dependence (42.2%) on hydro power in Vietnam [18].

The basic data and GHG emission factors applied for the power generation plants are listed in Tables 6 and 7.

3.2.3. *Fuel production by pyrolysis*

Pyrolysis is a type of energy recovery process which generates char, oil and gas products, all of which have potential uses [32]. Pyrolysis liquid is different from conventional diesel fuels but this oil has been reported to be a good performance oil [17]. In the pyrolysis process, GHG emission is derived from (1) nitrogen gas for fluidizing, (2) zeolite as a catalyst, (3) electricity use and (4) transportation, and GHG mitigation can be achieved by replacing diesel oil with the produced oil.

For production of nitrogen gas and the zeolite catalyst, the inventory data offered by JLCA (Life Cycle Assessment Society of Japan, Japan Environmental Management Association for Industry) were modified and adopted in this study. The electricity input to nitrogen gas production is 0.271 kW h/kg, which is equivalent to 0.114 kg CO_{2eq}/kg based on carbon intensity in Vietnam. To produce 1 kg of fluid catalytic cracking (FCC) catalyst, 0.180 kW h electricity, 0.476 m^3 natural gas and 17.7 kg steam are needed. The local GHG emission factor for steam production is not available. Therefore, the total GHG emission for 0.935 kg of FCC offered by JLCA was applied for the following calculations.

Taking into account the difference in LHVs between bio-oil (28.15 MJ/kg) [10] and diesel oil (43 MJ/kg) [28], 1 kg of bio-oil can replace 0.65 kg of diesel oil. GHG emission factors, 0.74 kg CO_{2eq}/kg [33] and 3.24 kg CO_{2eq}/kg [30] for, respectively, diesel oil production and combustion were used in calculations. The yield of liquid oil from rice husks was set at 20% with catalytic treatment [10]. All data applied to the pyrolysis process are summarized in Table 8.

3.3. *Scenarios*

Based on rice husk supply and current local demands, the following scenarios were set up. The scenario description and fuel allocation in each scenario are shown in Tables 9 and 10, respectively. The total supply was fixed at 620 000 t/y as estimated in 2.2.

S0 is defined as the baseline scenario, in which case the current use and disposal of rice husks is applied. Current demands for cooking (8.6%) and brick making (25.8%) were maintained, and the excess (65.6%) was considered treated by open burning. At this present time some rice husks are still being dumped into the river instead of being burnt, therefore, this baseline setting may over-estimate GHG emissions. However, open burning of all excess rice husks was assumed here due to the recent and severe increase in open burning, triggered by the prohibition of river dumping by law.

It was assumed that the current use of rice husks, based on their affordability would not dramatically change. Therefore, current demand figures were maintained in some scenarios. In S1, it was assumed that the current demands are maintained and all excess rice husks are used for cooking. As rice husks are more affordable than other fuels, the priority of replacement is set as following order: coal, LPG, and finally,

Table 6 – Basic data for power generation plants.

Categories		Applied data	Data sources
Operation	Operating time	5000 h/y	CDM in Thai [27]
Start-up	Frequencies	5 times/y	″
	Residual oil use	600 L/one start-up	″
	Density of residual oil	0.89 kg/L	Standard unit conversion factor
Transportation	Boat capacity	RH[a]: 10 t/boat	Interview in An Giang (17/Sept//2008)
		RHB[b]: 12 t/boat	
	Diesel oil use	0.4 kg/km	″
Replacement by generated electricity		90% (10% for internal use)	[21]

a RH: rice husk.
b RHB: rice husk briquette.

Table 7 – GHG equivalent emission factors for power generation plants.

Categories		Emission factors	Unit	Data sources
Operation	RH combustion	0.024	kg CO_{2eq}/kg[a]	Agricultural biomass combustion in the energy industries [28]
	RHB combustion	0.031	kg CO_{2eq}/kg[a]	Fuel wood combustion in the energy industries [28]
	Residual oil[b]	3.272	kg CO_{2eq}/kg[a]	Residual oil combustion in the energy industries [28]
Transportation	Diesel oil[b]	3.382	kg CO_{2eq}/kg[a]	Diesel oil mobile combustion in transport [28]
Replacement	Grid electricity	0.459	kg CO_{2eq}/k Wh	Calculated

a Original data shown in kg CO_{2eq}/MJ are converted into kg CO_{2eq}/kg using LHVs.
b The data include GHG emission from production phase – 0.142 kg CO_{2eq}/kg oil [30].

Table 8 – Basic data for pyrolysis plant.

Categories		Applied data	Data source
Plant capacity		3120 t/y	[10]
Operation	Nitrogen gas	6300 m^3/y	″
	Electricity	250 MW h/y	″
	Catalyst	1250 kg/y	″
	Oil yield	20%	″
Transportation	Boat capacity	10 t/boat	Interview in An Giang (17/Sept//2008)
	Diesel oil use	0.4 kg/km	″

fuel wood. The replacement of LPG is adopted mostly in rural areas, because it is more difficult to change the convenience of using LPG in urban lifestyles.

S2 and S3 scenarios for power generation were designed in keeping with current demands. The excess rice husks (65.6%) were assumed to be used for power generation through combustion (S2) or gasification (S3). In association with these scenarios, S4 and S5 were set up assuming that all rice husks are used for power generation through combustion (S4) or gasification (S5). The alternative fuels for cooking and brick making were assumed to be LPG and coal, respectively. As already shown in Table 5, two capacities, (a) 5 MW and (b) 30 MW were considered for the power generation scenarios. Table 11 summarizes the calculated transportation distances adopted here based on the plant capacities.

Table 9 – Scenario description.

Scenario	Technology	Capacity	Feeding stocks	Target rice husk amount
S1	Cooking		Rice husk	Excess *
S1B1			Rice husk briquette	All
S1B2			Rice husk briquette	Excess
S1B3			Rice husk briquette	Excess + cooking
S2a	Combustion power plant	5 MW	Rice husk	Excess
S4a		5 MW	Rice husk	All
S2Ba		5 MW	Rice husk briquette	Excess
S4Ba		5 MW	Rice husk briquette	All
S2b		30 MW	Rice husk	Excess
S4b		30 MW	Rice husk	All
S2Bb		30 MW	Rice husk briquette	Excess
S4Bb		30 MW	Rice husk briquette	All
S3a	Gasification power plant	5 MW	Rice husk	Excess
S5a		5 MW	Rice husk	All
S3b		30 MW	Rice husk	Excess
S5b		30 MW	Rice husk	All
S6	Pyrolysis		Rice husk	Excess
S7			Rice husk	All

*[Excess rice husk] = [All generated rice husk] − [Current demand for cooking and brick making].

S6 and S7 are scenarios for bio-oil production by pyrolysis. All rice husks were assumed used in the S7 scenario, whereas the current demand was maintained for the S6 scenario. Based on the plant capacity (3120 t RH/y), transportation distances for S6 and S7 were estimated at 5.5 and 4.4 km/trip, respectively.

Rice husk briquettes can be utilized only in combustion processes, such as cooking, brick making and power generation using combustion. They cannot be applied to the gasification and pyrolysis processes, which usually require smaller sized material (less than 2 mm) and homogeneous feed-stocks [34]. In S1B1, all rice husks are converted into briquettes and they were allocated to cooking and brick making. In S1B2, the current demands of rice husks for cooking and brick making were maintained, and the excess rice husks were used to make briquettes. In S1B3, the current demands of rice husks for brick making were maintained, and the remained rice husks were used to produce briquettes. There would be some difficulty for consumers to shift from using fuel wood to briquettes due to the higher price of briquettes. On the other hand, the direct advantage of briquettes is their easiness to handle. Therefore, replacing coal and LPG in rural areas with briquettes was assumed to precede that of fuel wood in the briquette scenarios.

Using briquettes for power generation through combustion was also considered. Current demands were maintained in S2B, whereas all rice husks were allocated to briquette production and then used for power generation in S4B; as with S4, the alternative fuels for cooking and brick making are assumed to be LPG and coal, respectively.

4. Results and discussions

Table 12 shows the estimated GHG emissions for the baseline scenario (S0) and scenario considering the domestic uses of rice husks and briquettes. As shown in S0, potentially mitigating GHG depends on the combustion of LPG, coal and fuel wood, and open burning. A large part of the GHG emissions can be reduced by the prevention of open burning, because the emitted CH_4 and N_2O by open burning (0.10 kg CO_2eq./kg rice-husk [28]) contribute to the GHG emission although CO_2 from biomass burning is not counted. Even when GHGs are emitted during the production process, the use of briquettes can mitigate GHG emissions due to their higher density, higher calorific value and higher stove efficiency compared to rice husks.

Fig. 5 shows GHG emission for 1 kWh electricity generation in the S2 and S3 scenarios. The estimated GHG emissions from transportation are smaller than emissions from combustion. This can be due to the use of motor boats and small transportation distances. A significant difference in total GHG emission was observed between gasification and combustion processes. In the gasification process, air can accelerate the process; therefore, no input of fuel for start-up is required. No CH_4 and N_2O emissions during the gasification process also greatly influence the results. GHG emission during gasification is only due to the transportation of rice husks, resulting in smaller GHG emissions overall. In the combustion scenarios, the larger capacity (30 MW) results in higher combustion

Table 10 – Fuel allocation in each scenario.

	[1000 t/y]	S0*	S1	S2	S3	S4	S5	S6	S7	S1B1	S1B2	S1B3	S2B	S4B
Cooking	Rice husk	53	460	53	53	0	0	53	0	0	53	0	53	0
	Briquette	0	0	0	0	0	0	0	0	470	388	438	0	0
	Coal	5.2	0	5.2	5.2	5.2	5.2	5.2	5.2	0	0	0	5.2	5.2
	LPG (urban)	22.6	22.6	22.6	22.6	23.5	23.5	22.6	23.5	22.6	22.6	22.6	22.6	23.5
	LPG (rural)	34.0	12.5	34.0	34.0	35.7	35.7	34.0	35.7	0	0	0	34.0	35.7
	Fuel wood	434	0	434	434	434	434	434	434	339	393	372	434	434
Brick making	Rice husk	160	160	160	160	0	0	160	0	0	160	160	160	0
	Briquette	0	0	0	0	0	0	0	0	120	0	0	0	0
	Coal	0	0	0	0	72	72	0	72	0	0	0	0	72
Power combustion	Rice husk	0	0	407	0	620	0	0	0	0	0	0	0	0
	Briquette	0	0	0	0	0	0	0	0	0	0	0	388	590
Gasification	Rice husk	0	0	0	407	0	620	0	0	0	0	0	0	0
Pyrolysis	Rice husk	0	0	0	0	0	0	407	620	0	0	0	0	0
Open burning	Rice husk	407	0	0	0	0	0	0	0	0	0	0	0	0

*baseline.

Table 11 – Estimated transportation distances in power generation scenarios.

Category	Unit	S2a	S3a	S4a	S5a	S2Ba	S4Ba	S2b	S3b	S4b	S5b	S2Bb	S4Bb
Capacity	MW	5						30					
Efficiency	%	15	16	15	16	25	25	25	30	25	30	30	30
Number of plants (tentatively calculated)	–	8.8	9.4	13.4	14.3	17.6	26.7	2.5	2.9	3.7	4.5	3.5	5.3
Transport distance	km/trip	22.2	21.5	18.0	17.4	15.7	12.8	42.1	38.4	34.1	31.1	35.1	28.5
Total distance	10^3 km/y/plant	102	93	83	75	29	24	699	532	567	431	323	262

Table 12 – GHG emissions in baseline and scenarios related to local uses [unit: 10^5 t CO_{2eq}/y].

Emission sources		S0	S1	S1B1	S1B2	S1B3
Cooking (combustion)	Rice husk	0.05	0.46	0	0.05	0
	Briquette	0	0	0.58	0.48	0.54
	LPG	1.82	1.13	0.73	0.73	0.73
	Coal	0.12	0	0	0	0
	Fuel wood	0.58	0.58	0.46	0.53	0.5
Brick making (combustion)	Rice husk	0.16	0.16	0	0.16	0.16
	Briquette	0	0	0.15	0	0
Briquette production		0	0	0.35	0.23	0.26
Open burning		0.4	0	0	0	0
Total emission		3.13	2.33	2.27	2.18	2.19
Difference from the baseline		–	−0.80	−0.86	−0.95	−0.94

efficiency, hence, smaller GHG emissions per 1 kWh generated is observed in the scenario S2b. In the case of briquette use, GHG emission derived from the production phase is larger than that estimated for during the combustion phase.

The GHG emission from the construction phase was not included in our estimations. As mentioned in Mcdougall et al. (2001) [35], construction GHG emission is usually not taken into account because of its smaller contribution to the total GHG emission. Furthermore, calculating construction GHG emissions involves much uncertainty. In this study, instead of fossil fuel use, biomass is used as main feed-stocks. It means that fuel combustion and other activities can derive smaller GHG emissions in total and excluded GHG emissions from construction phase may contribute to the total GHG emission and may not be negligible. The results without construction GHG emission estimates are shown here to avoid the uncertainty. However, potentially higher estimates of GHG emissions as explained above is also discussed later.

Table 13 shows the total GHG increase from the baseline in power generation scenarios. Compared with the GHG emissions related to the plant operation, the GHG reduction derived by the replacement of grid electricity is much higher, even though the carbon intensity is not so high as explained in 3.2 (ii). If replacement of electricity is not included, some

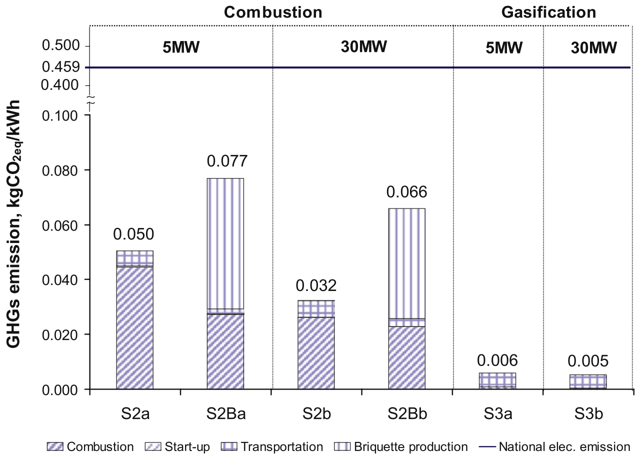


Fig. 5 – GHG emissions per 1 kW h electricity generation a: 5 MW, b: 30 MW, B: briquette.

scenarios (S2B, S4, and S5) cannot achieve the GHG reduction just by the prevention of open burning. Comparing the results between the two capacities (a & b), the scenarios with the larger capacity show larger GHG reduction potentials with the exception of S4B. The gasification process, which possesses higher combustion efficiency than the direct combustion process, can achieve higher electricity production, resulting in the larger GHG mitigation potential. It can be seen when the results of S2(a, b) and S3(a, b) are compared, in which both scenarios assume the same allocation of rice husks.

The GHG emission from bio-oil production is estimated at 0.179 kg CO_{2eq}/kg, which is mainly derived from electricity use during production. As shown in Table 14, higher GHG emissions can be avoided by replacing diesel oil with bio-oil.

Table 14 – GHG change from the baseline in pyrolysis scenarios [unit: 10^5 t CO_{2eq}/y].

Scenario		S6	S7
Cooking (combustion)	Rice husk	0	−0.05
	Briquette	0	0
	LPG	0	0.084
	coal	0	0
	Fuel wood	0	0
Brick making (combustion)	Rice husk	0	−0.16
	Briquette	0	0
	Coal	0	1.63
Bio-oil generation	Electricity	0.15	0.23
	Transportation	0.003	0.0037
	Nitrogen	0.0011	0.0017
	Catalyst	0.0015	0.0023
Diesel oil replacement	Combustion	−1.169	−2.958
	Production	−0.075	−0.1
Diesel oil combustion		0.0026	0.0040
Open burning		−0.4	−0.61
Total difference from S0		−1.49	−1.92

As shown in Fig. 6, all scenarios have GHG mitigation potentials that range from 13 000 to 222 000 t CO_{2eq}/y. The maximum mitigation potential is derived from briquette combustion (S2Bb) and followed by direct gasification (S3b), which, in Vietnam currently accounts for 0.23% of the total GHG emission (98.6 million t/y) [36]. As already discussed, when construction GHG is included, the mitigation potentials shown in scenarios S2–S7 would decrease. The GHG emissions from construction and decommissioning of actual coal-fired power plants were reported as 3.4 g CO_{2eq}/kW h in Japan [37] and 1.1 g CO_{2eq}/kW h in the United Kingdom [38]. If 3.4 g CO_{2eq}/kW h and a productivity lifetime of 20 years were adopted for scenarios S2–S5, the total GHG emission

Table 13 – GHG change from the baseline in power generation scenarios [unit: 10^5 t CO_{2eq}/y].

Technology		Combustion								Gasification			
Capacity		5 MW				30 MW				5 MW		30 MW	
Feedstock		RH		RHB		RH		RHB		RH			
Scenario		S2a	S4a	S2Ba	S4Ba	S2b	S4b	S2Bb	S4Bb	S3a	S5a	S3b	S5b
Cooking (combustion)	Rice husk	0	−0.05	0	−0.05	0	−0.05	0	−0.05	0	−0.05	0	−0.05
	Briquette	0	0	0	0	0	0	0	0	0	0	0	0
	LPG	0	0.084	0	0.084	0	0.084	0	0.084	0	0.084	0	0.084
	Coal	0	0	0	0	0	0	0	0	0	0	0	0
	Fuel wood	0	0	0	0	0	0	0	0	0	0	0	0
Brick making (combustion)	Rice husk	0	−0.16	0	−0.16	0	−0.16	0	−0.16	0	−0.16	0	−0.16
	Briquette	0	0	0	0	0	0	0	0	0	0	0	0
	Coal	0	1.63	0	1.63	0	1.63	0	1.63	0	1.63	0	1.63
Power generation	Combustion	0.098	0.149	0.12	0.183	0.098	0.149	0.12	0.183	0.002	0.003	0.002	0.003
	Start-up	0.0008	0.0012	0.0015	0.0023	0.0002	0.0003	0.0003	0.0005	0	0	0	0
	Transportation	0.012	0.015	0.007	0.008	0.023	0.029	0.015	0.019	0.012	0.015	0.021	0.026
	Electricity replacement	−0.91	−1.39	−1.81	−2.76	−1.52	−2.31	−2.18	−3.31	−0.97	−1.48	−1.82	−2.77
Briquette production		0	0	0.23	0.35	0	0	0.23	0.35	0	0	0	0
Open burning		−0.4	−0.61	−0.4	−0.61	−0.4	−0.61	−0.4	−0.61	−0.4	−0.61	−0.4	−0.61
Total difference from S0		−1.20	−0.33	−1.85	−1.32	−1.80	−1.24	−2.21	−1.86	−1.36	−0.57	−2.20	−1.85

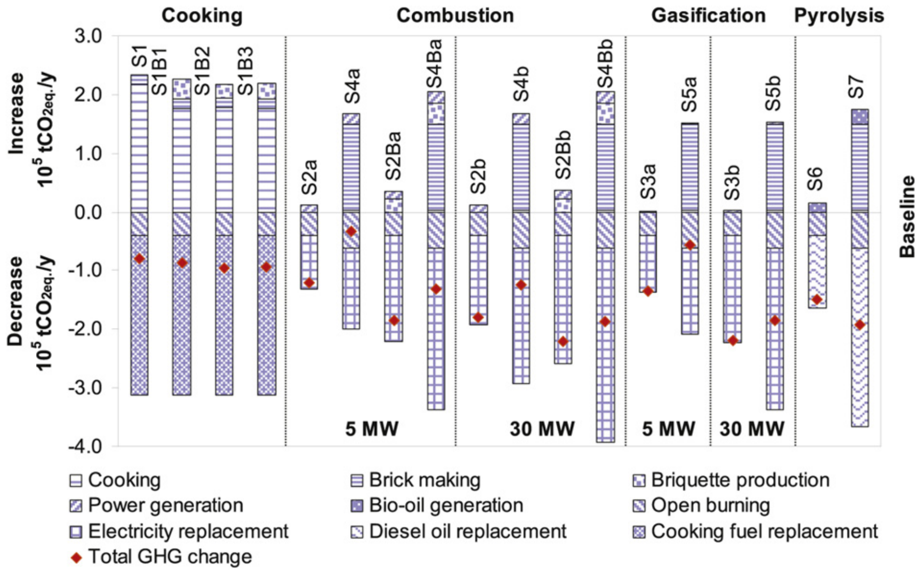


Fig. 6 – GHG emission mitigation potential of all scenarios in comparison with baseline a: 5 MW, b: 30 MW, B: briquette.

mitigation potentials will decrease by 0.66–13.4%. Even the scenario S4a, which shows the lowest GHG reduction, can still gain GHG reduction with the involvement of construction and decommissioning GHG emissions. In the case of bio-oil production, it is also reported that most of the GHG emissions arise from the operation stage and the GHG emissions from construction and decommissioning can be negligible in comparison [39].

5. Conclusions and recommendations

GHG emission mitigation potential using rice husks for energy generation was investigated in this study. Ceasing open burning brings CH_4 and N_2O reduction and contributes to large GHG reductions. Replacing grid electricity or diesel oil with generated by rice husk also involves higher GHG mitigation potential. The introduction of innovative technologies, such as power generation through combustion or gasification, or bio-oil production by pyrolysis, shows higher mitigation potential than that of conventional uses. However, rapid shift to innovative technologies is sometimes quite difficult due to its affordability and residents' acceptances. Our results indicate that the briquette use as a transient technology can also help GHG mitigation. The scenarios outlined in this study can be attractive to consumers, communities and governments from the view point of GHG reduction as well as sustainable energy development in rural areas. Further discussion on economic aspects is also needed for considering the feasibility of each scenario.

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REFERENCES

[1] Vietnam. Vietnam's statistic yearbook. Hanoi, Vietnam: Statistical Publishing House; 2007 (In Vietnamese). p. 830.
[2] Mansaray KG, Ghaly AE, Al-Taweel AM, Hamdullahpur F, Ugursal VI. Air gasification of rice husk in a dual distributor type fluidized bed gasifier. Biomass and Bioenergy 1999;17(4): 315–32.
[3] Natarajan E, Nordin A, Rao AN. Overview of combustion and gasification of rice husk in fluidized bed reactors. Biomass Bioenergy 1998;14(5–6):533–46.
[4] Nguyen NT, Duong HM. Economic potential of renewable energy in Vietnam's power sector. Energy Policy 2009;37(5): 1601–13.
[5] IE. Demonstration of rice husks fired power plant in An Giang province: a pre-feasibility study report. Hanoi, Vietnam: Vietnam Institute of Energy; 2004.
[6] IE. Bagasse and other biomass-fired power plant in Ben Tre sugar company: a pre-feasibility study report. Hanoi, Vietnam: Vietnam Institute of Energy; 2006.
[7] Nguyen VH, Nguyen VS. Clean development mechanism project design documents (cdm–pdd) for pilot grid connected rice husk fueled bio-power development projects in Mekong Delta, Vietnam: second technical report [cited 2009 25th/Sept];. Hanoi: EEPSEA. Available from, www.idrc.ca/uploads/user-S/11624356301Hanh.doc; 2006.
[8] Bergqvist MM, Wardh KS, Das A, Ahlgren EO. A techno-economic assessment of rice husk based power generation in the Mekong River Delta of Vietnam. International Journal of Energy Research 2008;32:1136–50.
[9] An Giang. An Giang's statistics yearbook (In Vietnamese). Hanoi, Vietnam: Statistical Publishing House; 2007. p. 457.
[10] Islam MN, Ani FN. Techno–economics of rice husk pyrolysis, conversion with catalytic treatment to produce liquid fuel. Bioresour Technol 2000;73(1):67–75.

[11] Armesto L, Bahillo A, Veijonen K, Cabanillas A, Otero J. Combustion behaviour of rice husk in a bubbling fluidised bed. Biomass and Bioenergy 2002;23(3):171–9.

[12] Chungsangunsit T, Shabbir HG, Patumsawad S. Environmental assessment of electricity production from rice husk: a case study in Thailand. In: Proceedings of international conference on electricity supply industry in transition: issues and prospect for Asia; 2004.

[13] Abe H, Katayama A, Sah BP, Toriu T, Samy S, Pheach P, Adams MA, Grierson PF. Potential for rural electrification based on biomass gasification in Cambodia. Biomass and Bioenergy 2007;31(9):656–64.

[14] IE. A case study on wood energy data collection and assessment and decentralized wood energy planning in Vietnam. Hanoi, Vietnam: Vietnam Institute of Energy; 2001.

[15] Kapur T, Kandpal TC, Garg HP. Electricity generation from rice husk in Indian rice mills: potential and financial viability. Biomass Bioenergy 1996;10(5–6):393–403.

[16] Bhattacharya SC, Abdul Salam P, Sharma M. Emissions from biomass energy use in some selected Asian countries. Energy 2000;25(2):169–88.

[17] Bridgwater AV, Toft AJ, Brammer JG. A techno–economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable Sustainable Energy Rev 2002;6(3):181–246.

[18] IE. Strategy and masterplan for renewable energy development of Vietnam for the period up to the year 2015, with outlook to 2025. Hanoi, Vietnam: Vietnam Institute of Energy; 2008.

[19] FAO. Tropical forestry action programme Vietnam – fuelwood and energy sectoral review. Food and Agriculture Organization of the United Nations; 1992.

[20] IEA. Biomass combustion and co-firing. Boienergy Task 2003;32.

[21] Bhattacharya SC, Arul Joe M, Kandhekar Z, Abdul Salam P, Shrestha RM. Greenhouse-gas emission mitigation from the use of agricultural residues: the case of rice husk. Energy 1999;24(1):43–59.

[22] Mahin DB. Short communication: economic analysis of a husk-fueled gasifier power plant at a rice mill in Africa. Biomass 1989;19:56–60.

[23] WB. Energy from biomass, a reveiw of combustion and gasificiation technologies. World Bank Technical paper No. 422. Energy Serries 1999.

[24] Kumar A, Bhattacharya SC, Pham HL. Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model. Energy 2003a;28(7):627–54.

[25] OECD/IEA. Biomass for power generation and combined heat and power (CHP). In: IEA energy technology essentials; 2007.

[26] Yin XL, Wu CZ, Zheng SP, Chen Y. Design and operation of a CFB gasification and power generation system for rice husk. Biomass and Bioenergy 2002;23(3):181–7.

[27] UNFCCC. A.T. Biopower rice husk power project in Pichit, Thailand. The Project). 2007 cited Available from, http://cdm.unfccc.int/UserManagement/FileStorage/I2OT9XDEU9M0A8BK5P62P06OG8P24C; 2008 Apr 10.

[28] IPCC. Guidelines for integration greenhouse gas inventories. intergovernmental panel on climate change, Geneva. 2006 cited Available from, http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf; 2007 Dec 27.

[29] Chinh LD, Gheewala SH, Bonnet S. Integrated environmental assessment and pollution prevention in Vietnam: the case of anthracite production. J Cleaner Prod 2007;15(18):1768–77.

[30] Furuholt E. Life cycle assessment of gasoline and diesel. Resour Conserv Recycl 1995;14(3–4):251–63.

[31] Okamura T, Furukawa M, Ishitani H. Future forecast for life-cycle greenhouse gas emissions of LNG and city gas 13A. Appl Energy 2007;84(11):1136–49.

[32] Williams PT, Nugranad N. Comparison of products from the pyrolysis and catalytic pyrolysis of rice husks. Energy 2000; 25(6):493–513.

[33] Pleanjai S, Gheewala SH, Garivait S. Greenhouse gas emissions from production and use of used cooking oil methyl ester as transport fuel in Thailand. J Cleaner Prod 2009;17(9):873–6.

[34] Bridgwater AV, Meier D, Radlein D. An overview of fast pyrolysis of biomass. Org Geochem 1999;30(12):1479–93.

[35] Mcdougall F, White P, Franke M, Hindle P. Integrated solid waste management: a life cycle inventory. 2nd edition. UK: Blackwell publishing; 2001. p92. p.

[36] UNDP. Human development report 2007/2008-Vietnam [cited 2009 Sept/17th]; Available from, http://hdrstats.undp.org/en/countries/data_sheets/cty_ds_VNM.html; 2008.

[37] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 2005;30(11–12): 2042–56.

[38] Odeh NA, Cockerill TT. Life cycle analysis of UK coal fired power plants. Energy Convers Manage 2008;49(2):212–20.

[39] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007; 32(9):1543–59.

[40] IE. A case study on wood energy data collection and assessment and decentralized wood energy planning in Vietnam. Vietnam Institute of Energy; 2001.

[41] FAO. Tropical forestry action programme Vietnam: fuelwood and energy sectoral review [cited 2009 20th/Oct]; Available from, http://www.fao.org/DOCREP/006/AD543E/ad543e00.pdf; 1992.

[42] Svenningson PJ, Hosier R. Biomass briquettes in the Dominican Republic part II: technical analyses. Biomass 1987;13(4):275–91.

[43] Bhattacharya SC, Bhatia R, Islam MN, Shah N. Densified biomass in Thailand: Potential, status and problems. Biomass 1985;8(4):255–66.

[44] Abas B. Rice husk gasification for cogeneration, end-user point-of-view and expectation. In: COGEN Workshop; 1991. Indonesia.

[45] Therdyothin A, Bhattacharaya SC, Chirarattananon S. Electricity generation potential of Thai sugar mills. Energy Sources Part A 1992;14(4):367–80.

[46] Bhattacharya SC. State-of-the-art of utilizing residues and other types of biomass as an energy source. RERIC Int Energy J 1993;15(1):1–21.

[47] Johnson E. Charcoal versus LPG grilling: a carbon-footprint comparison. Environ Impact Assess Rev 2009;29(6):370–8.

[48] Sookkumnerd C, Ito N, Kito K. Financial viabilities of husk-fueled steam engines as an energy-saving technology in Thai rice mills. Appl Energy 2005;82(1):64–80.

[49] Wu CZ, Huang H, Zheng SP, Yin XL. An economic analysis of biomass gasification and power generation in China. Bioresource Technology 2002;83(1):65–70.

[50] Hollingdale A. Recent advances in biomass energy technology in Europe and applications for Southern East Asia [cited 2010 20th/May]; Available from, http://www.nri.org/projects/biomass/conference_papers/recent_advances_in_biomass_energy_in_europe.pdf; 2004.