Scenarios for Sustainable Biomass Use in the Mekong Delta, Vietnam

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Abstracts: By conducting a survey of energy demand in rural industries of the Mekong Delta in Vietnam, this study aimed to: (i) estimate current and future energy demands of rural industries; (ii) identify the most available biomass source for energy production; and (iii) develop and assess biomass utilization scenarios with different system scales and conversion technologies. The results showed that rice husk and straw are the most available biomass sources for energy production in the Mekong Delta. Depending on the type of technology and the scale of the system, electricity produced from such biomass sources could be used to satisfy demands within the community, and the excess energy produced could be sold to the national grid. A set of indicators, including the specific cost and greenhouse gas (GHG) emissions of usable energy, total GHG emissions, and GHG marginal abatement cost were used to assess the economic and environmental benefits of several biomass utilization scenarios. All the scenarios in which grid-based electricity was replaced by biomass-based electricity have lower specific usable energy costs and GHG emissions, resulting in negative values of the marginal GHG abatement cost. Among the scenarios we considered, medium-scale systems offer better economic and environmental benefits than small-scale systems. Gasification-based systems have a lower environmental impact but a higher cost for usable energy than steam turbine systems.

Key Words: biomass, material flow, conversion technology, rural industry, Mekong Delta.

1. Introduction

Economic growth and improved living standards are directly or indirectly related to the increased use of energy in Vietnam [1]. The primary energy demand is projected to grow annually at 3.9%, from 38 million tons of oil equivalent (MToe) in 2008 to 109 MToe by 2030. Vietnam is expected to become a net energy importing economy after 2020 [2]. Considering the desirability of sustainable development, the Vietnamese government is now making great efforts to seek the development of alternative energy sources, such as solar, wind, and other renewable energy, especially biomass [3].

Although biomass has been an important energy source in Vietnam, a comprehensive database of current and predicted biomass sources is not available. National statistics and previous studies provide an aggregated energy outlook on a national scale, but they cover neither details on the composition of biomass resources nor provincial-scale conditions. This lack of information on current biomass resources makes it difficult for policy makers and businesses to design an effective energy plan and to identify opportunities for investment.

Our study in 2009 [4] revealed the preliminary material flow of biomass sources in the residential and rural industrial sectors of the Mekong Delta, and projected the amount of unused biomass based on three cases of urbanization. In the study, the data on biomass demand in the residential sector was obtained from our household survey in 2007. In contrast, the data for the industrial sector was based mainly on preceding research over the last decade [5-6], because our survey did not cover current and future industrial energy demand.

Our previous study considered the on-site open burning of rice straw for fertilizer as a material supply end-use, even though it has been recognized as a key driver of global climate change [7]. Since the use of rice straw for power production is cleaner than on-site open burning for all tracked pollutants [8], this study considers rice straw as an alternative biomass source for energy production.

By conducting an energy demand survey in the Mekong Delta's industrial sector and revising our original estimate of the biomass material flow [4], this study aimed to: (i) estimate the current and future energy demands of rural industries in the Mekong Delta; (ii) identify the type and quantity of the most available biomass source for energy production in the Mekong Delta; and (iii) develop and assess biomass utilization scenarios assuming various system scales and conversion technologies. As this study focuses on the development and assessment of sustainable biomass utilization scenarios, we used only the mean value of the urbanization ratio over the last decade (2.5%/year) for estimating future biomass production and use in the study area. Assessment of these scenarios would provide the Vietnamese government and energy policy-makers with useful insights and implications for sustainable biomass utilization systems in the Mekong Delta region of Vietnam.

Future development of a biomass utilization system is highly uncertain and is determined by driving forces, such as socioeconomic development and technological changes. The scenario approach was used to explore unpredictable features of change in these driving forces. In principle, the scenarios were not predictions, but they were developed on the basis of different assumptions about the forces driving change and their possible interactions [9]. The scenarios provide alternative plausible systems of biomass use by considering both technology and system scale for the assessment of their economic and environmental effects. The framework for developing and assessing biomass utilization scenarios is summarized in Figure 1.

2. Unused biomass sources in the Mekong Delta

2.1 Energy demand in rural industries

A total of 109 enterprises in An Giang and Tien Giang provinces were surveyed by direct interviews in 2008 to collect data on energy demand and biomass use in the industrial sector, which includes brick kilns, rice mills, and homemade alcohol production (Table 1). Other industries, such as wood processing, mushroom production, and bran drying, were also investigated, but we could not collect enough samples for analysis. Except for homemade alcohol production, rural industries are normally grouped into clusters of several enterprises and are located along river banks to facilitate the transportation of materials and products by boat.

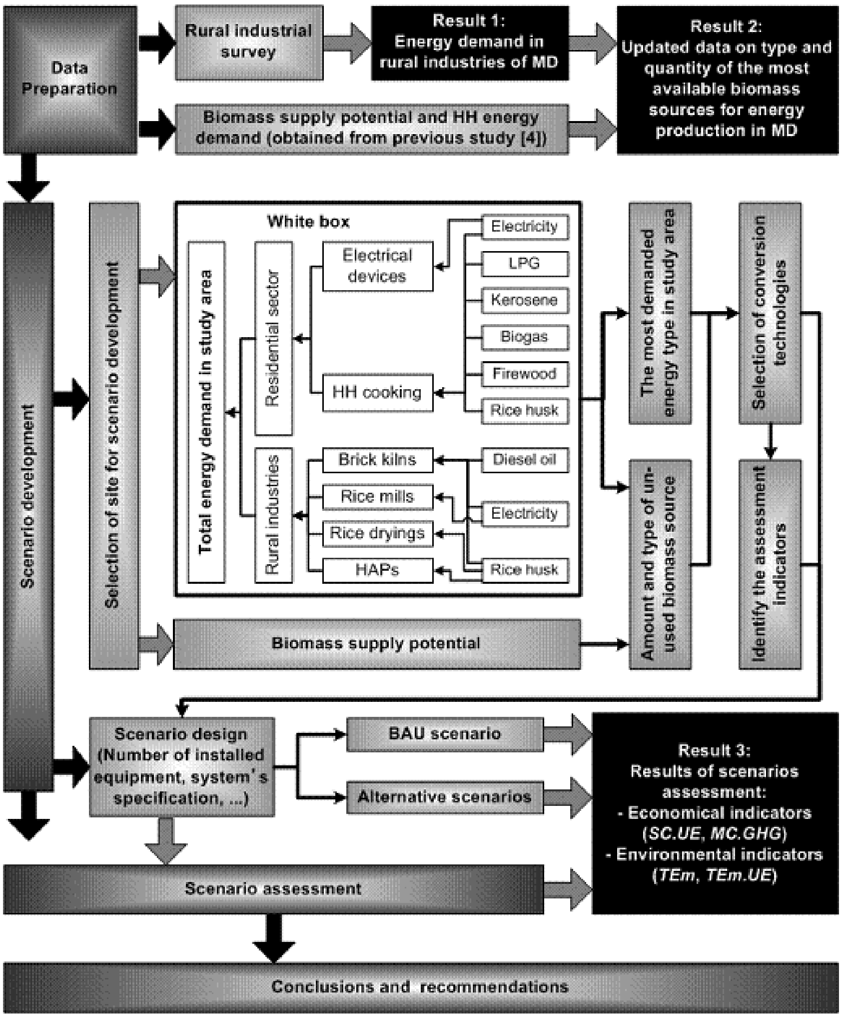

Figure 1. Research framework.

Table 1. Energy demand in surveyed industries in 2008.

	Brick kilns			Rice millings			Homemade alcohol productions		
	Unit	Mean	Std	Unit	Mean	Std	Unit	Mean	Std
Sample number	76			20			10		
Capacity	10^6 pieces/year	1.9	1.2	10^3 T/year	18.0	14.5	10^3 L/year	56.5	38.3
Specific energy demand									
- Rice husk	kg/piece	0.4	0.1	-			kg/L	1.7	1.0
- Electricity	Wh/piece	6.0	2.1	kWh/T	24.4	8.2	-		
- Diesel oil	10^{-3} L/piece	1.1	0.4	-			-		

2.1.1 Brick kilns

The term "brick kilns" refers to traditional-brick making enterprises, which are widespread in rural areas surrounding the Mekong Delta. They are characterized by the use of annular kilns, which use rice husk as their main energy source for brick-firing [10]. These kilns have a low energy efficiency of around 35%, long batch operation, and highly polluting emissions [11,12]. Each enterprise may own several small-scale kilns, which have an average annual capacity of 400,000 pieces/kiln. Electricity and diesel oil are also used in the brick shaping process.

2.1.2 Rice mills

"Rice mills" refer to enterprises that dehusk and polish rice. Almost all such mills in the Mekong Delta are small- or medium-scale enterprises. Their output consists of one main product (milled rice) and several by-products, such as husks, bran, germ, and broken kernels. Until the last 20 years, most rice mills used a diesel engine to run the milling machines [13]. However, since the national electricity grid has been expanded, all the mills now use electricity in the production process, with an average consumption of 24.4 kWh per ton (T) of milled rice (Table 1).

2.1.3 Homemade alcohol production

Homemade alcohol production refers to the production of rice wine, the traditional form of alcohol, communally produced in rural areas of Vietnam [14]. Rice wine is made household scale by the conversion of rice through steaming, inoculation with a starter, mashing, and fermentation processes. In the Mekong Delta, the main type of energy demand for homemade alcohol production is heat, which is obtained from the direct combustion of rice husk in small-scale stoves. The energy efficiency of the stoves, which is defined as the ratio of useful heat to the energy potential in the burned fuel, is assumed to be the same as that for household cooking:10%.

2.1.4 Rice drying

Rice drying is an important activity for maintaining the quality of rice during the rainy season. As the survey was conducted during the dry season, we were unable to collect samples from rice drying enterprises. The data related to rice drying in this analysis were obtained from the literature and our 2007 study [4,15-16]. Several rice drying techniques are available in the Mekong Delta. Depending on the technology used, the energy efficiency of rice husk burning stoves can reach 60%, with a total drying time of 6–8 hours/batch. The amount of husk consumption for rice drying is 60 kg/T dried rice.

2.2 Changes in unused biomass sources

The Mekong Delta possesses abundant sources of biomass, which are mainly due to agricultural production and land-use conditions. Since recoverable husbandry manure and woody biomass were found to be fully used within the residential sector [4], this study concentrates on agricultural residues, especially rice husk and rice straw. Changes in both supply and demand are taken into account to estimate the amount of unused rice husk and rice straw in the Mekong Delta.

2.2.1 Changes in the supply side

The theoretical rice straw and rice husk production was estimated by multiplying the residue-to-product ratio (T residue/ T product) by the amount of rice production. Our previous study [4] pointed out that, over the years 2010–2030, economic development and urbanization processes would result in the expansion of urban land and the reduction of agricultural land. Under the urbanization rate of 2.5% per annum, the agricultural land in Mekong Delta would be reduced by 20.0% by 2030 [4]. Therefore, even if the paddy production was assumed to remain constant at 6.1T/ha, total rice production in the Mekong Delta would be 18.2, 20.9, 18.8 and 13.6 million ton (MT), respectively in 2007, 2010, 2020 and 2030 (Table 2). The theoretical residue- to-product ratios of rice husk and rice straw were assumed to be constant at 0.2 and 1.9 T residue/T product [15]. However, due to limiting factors such as disease burning, preferred incorporation, and poor straw conditions, not all of the farm-based residues that are grown would be available for harvest [17]. The maintenance of crop residues on farmland is important agronomically because these can increase the amount of organic matter in the soil and reduce soil erosion, thereby improving soil quality and increasing crop yield [17]. Several studies have assessed the amount of crop residue required to maintain the amount of organic matter in the soil and to control soil erosion. The results show that while 20–40% of the residues can be removed from farms, a removal level of 50% or more would likely result in a measurable decrease in organic soil carbon [18-19]. Therefore, in contrast to our previous study, at most 40% of the produced farm-based residues will be considered as a removable source for energy production and other competing uses. The amounts of rice straw available for energy production in 2007, 2010, 2020, and 2030 were estimated to be 13.8, 15.9, 14.3, and 10.3 MT, respectively (Table 2). In contrast, we assumed that 100% of processing-based residues, which are usually available in large quantities and ready for consumption, can be used. The amount of rice husk available for energy production would be 3.8, 4.4, 4.0, and 2.9 MT, respectively, in 2007, 2010, 2020, and 2030 (Table 2).

2.2.2 Changes in the demand side

Current and future demand in the residential sector was estimated on the basis of the household survey in 2007 [4], but we recalculated the rice husk supply from households based on the industrial survey in 2008 (Table 1) using the following assumptions.

Brick kilns

Under a new policy of the national government, traditional brick kilns would continue their production until 2015 [20]. After 2015, these enterprises may continue their work if improved kilns are established. Most of the proposed improved kilns still use rice husk as the main energy source because of its abundance in the Mekong Delta. By 2030, the specific rice husk demand for brick firing is expected to be 0.3 kg/brick [11]. Brick demand in the Mekong Delta is assumed to remain at 250 bricks/capita/year, which is also the projected national demand [21]. The share of handicraft products in the total brick production will drop from 80% in 2007 to 50% by 2030 [12,21]. The total rice husk demand for handicraft brick firing is therefore expected to be 1.3 in 2007 and 0.9 MT in 2030.

Rice drying

All the drying equipment surveyed in the Mekong Delta had been newly installed and operated between 2000 and 2009. Thus, we assumed that the amount of rice husk used for rice drying would not change until 2030. As a result of reduced rice production, the total amount of rice husk needed for rice drying would decrease from 0.4 MT in 2007 to 0.3 MT in 2030.

Table 2. Agricultural biomass supply, demand, and its unused amount in Mekong Delta.

			2007	2010	2020	2030
Population (10^6 person) [4]			17.3	19.1	21.3	23.2
Household number (10^6 households) [4]			3.9	4.2	5.0	5.8
Main product production	Rice (10^6 T) [4]		18.2	20.9	18.8	13.6
	Traditional brick (10^6 pieces)		3,451.2	3,588.6	3,273.5	2,898.8
	Homemade alcohol production (10^6 L)		12.7	14.1	15.7	17.1
Agricultural residues						
Supply potential (10^6 T)	Rice residues	Rice husk	3.8	4.4	4.0	2.9
		Rice straw	13.8	15.9	14.3	10.3
	Others [4]		2.0	2.2	3.6	5.9
Demand (10^6 T)	Rice husk	Household sector	1.0	1.0	1.0	0.7
		Brick kilns	1.3	1.3	1.1	0.9
		Rice dryings	0.4	0.4	0.4	0.3
		Homemade alcohol productions	21.6×10^{-3}	23.9×10^{-3}	26.7×10^{-3}	29.1×10^{-3}
	Rice straw		1.4	1.6	1.4	1.0
	Others [4]		1.5	1.6	2.4	3.4
Un-used (10^6 T)	Rice husk		1.1	1.6	1.5	1.0
	Rice straws		12.4	14.3	12.9	9.4
	Others		0.5	0.6	1.2	2.5
	Total		14.0	16.5	15.6	12.9

Homemade alcohol production

We assumed that the annual alcohol consumption in Vietnam would be constant until 2030 at 2.4 liter (L) per adult, of which 1.0 L is homemade wine [14]. The proportion of adults (population more than 15 years old) in the Mekong Delta is expected to be the same as the national average of 73.7% [22]. Rice husk demand for homemade alcohol production will increase from 21.6 thousand tons (kT) in 2007 to 29.1 kT in 2030.

In addition to rice husk, 10.0% of removable rice straw will be used for competing purposes, such as animal bedding and mushroom production [4]. The total rice husk demand for rural industries and other uses in the Mekong Delta is summarized in Table 2.

2.2.3 Changes in unused agricultural residues

Rice straw and rice husk are the dominant biomass resources in the Mekong Delta, accounting for 72.9–88.6% and 7.9–9.7%, respectively, of total unused agricultural residues in 2007–2030 (Table 2). Since almost all rice mills are incorporated into groups of several plants, rice husk has become the most promising biomass source for energy production. Therefore, we consider rice husk and straw as the two main feedstocks when we develop scenarios for sustainable biomass use in the Mekong Delta.

3. Scenario development and assessment methods

3.1 Site for scenario development

An Giang province is located in the Long Xuyen Quadrangle at the center of the Mekong Delta. It is the largest paddy producer in Vietnam, with a total production of 3.0 MT per year. We selected the Cho Moi district, the most intensive rice milling, rice drying, and brick production area in An Giang, as a case study to examine biomass utilization scenarios.

3.2 Current and projected energy demand in Cho Moi district

The current and projected energy demand in Cho Moi district were estimated using the framework shown in the white box in Figure 1 and the assumptions described in the following subsections.

3.2.1 Residential sector

The fuel demand for cooking ($ED_{RS\text{-}it}$, mass unit) and electricity demand for electrical appliances ($ED_{RS\text{-}devices.t}$, kWh/year) can be estimated using Equation 1 and Equation 2.

$$ED_{RS-it} = \frac{ED_{it} \times HH_t \times 45}{LHV_i} \quad (1)$$

$$ED_{RS-devices.t} = ED_{et-devices} \times HH_t \quad (2)$$

ED_{it} : Demand for i in t (kgoe/household/year)
$ED_{et\text{-}devices}$: Per-household electricity demand for electrical devices in t (kWh/household/year)
HH_t : Number of households in t (households)
LHV_i : Lower heating value of i (MJ/mass unit)
i : Fuel type (LPG, electricity, kerosene, biogas, rice husk, firewood)
t : Estimation year
45 : Constant for converting kgoe to MJ

Cooking energy

The energy demand per household for cooking in Cho Moi district was assumed to be 682 kgoe/household/year in 2007, the same as that in the rural households of Mekong Delta provinces [4]. The distribution of fuel type used for cooking, which was obtained from a household survey in 2007, and the energy efficiencies of several cookstoves (ε, %) [23] are shown in Table 3.

Table 3. Distribution of per household energy demand in 2007.

Type of fuel	Actual demand (ED_{i2007})		ε (%)	Usable demand
	kgoe/year [4]	%	[23]	(kgoe/year)
LPG	32.4	4.8	55.0	17.8
Electricity	64.0	9.4	70.0	44.8
Kerosene	0.8	0.1	45.0	0.4
Biogas	26.4	3.9	55.0	14.5
Rice husk	67.4	9.9	10.0	6.7
Firewood	491.0	72.0	10.0	49.1
Total	682.0	100.0		133.3

The projected future energy demand for cooking used the following assumptions:

- Cho Moi district's share of the total population in the Mekong Delta will remain at 2.1%, the average ratio for the past five years [24].
- The household size (number of people per household) will be the same as that of rural households in the Mekong Delta [4].
- The total usable energy for cooking, which is estimated by multiplying the actual energy demand and efficiency of cookstoves (ε) will be 135.0 kgoe/household/year, almost the same as the current value.
- Electricity consumption for household cooking will increase at the same growth rate as in electrical devices [4].
- Although kerosene will not be used, starting 2010, the use of LPG and the installation of biogas systems will expand to replace conventional solid biomass sources.
- Results of multiple regressions, which are based on data collected during our household survey in 2007, demonstrated the siginificant correlation between per-capita income, household size and biomass used for cooking (multiple R=0.77, R^2=59.30%, R_{adj}^2=58.54%, P=0.000) [4]. Therefore, due to the significant increase of per-capita income and the reduction of household size, the share of biomass used in the total energy for cooking is assumed to decrease by 2.4%/year and reach 46.2% by 2030 [4], and mainly due to the transition of firewood utilization to other types of new and clean energy. Rice husk demand for cooking is assumed to remain at 10.0% of the total biomass.

Electricity for electrical devices

In 2007, the per capita income at the current prices in Cho Moi district was 12.4 million VND [25], equivalent to 7.1 million VND at constant 1994 prices. This value is almost the same as that for the Mekong Delta in 2007 [26]. We therefore assumed that the current and future $ED_{et\text{-}devices}$ in Cho Moi district would be the same as those of rural households in the Mekong Delta. By 2030, per-household electricity demand in the residential sector of Cho Moi district will reach 1,397 kWh/household/year, with an average annual growth rate of 1.8% from 2007 to 2030 [26].

3.2.2 Rural industries

Energy demand in rural industries ($ED_{IS\text{-}it}$, mass unit) can be estimated using Equation 3.

$$ED_{IS-it} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(ED_{it-j} \times PR_{jt}\right) \quad (3)$$

$ED_{it\text{-}}$: Specific demand for i in t in j per unit of final product
Pr_{jt} : Amount of final product of j in t (brick: pieces; rice: T; homemade alcohol: L)
j : Handicraft brick making, rice milling, rice drying, and homemade alcohol production

We assumed that $ED_{it\text{-}j}$ in Cho Moi district would be the same as that of the Mekong Delta, as described in Table 1 and section 2.2.2. The current and future values of Pr_{jt} were based on the following assumptions.

Brick kilns

In 2007, An Giang had 1,630 handicraft brick kilns, of which 983 were located in Cho Moi district [27]. The average production capacity was 400,000 pieces/kiln/year. We assumed that all brick produced in An Giang would be used to satisfy demand within the province. Cho Moi district's share in the total brick production in An Giang will remain at 59.8%, the same as in 2007.

Rice milling

Statistical data from the last five years [24,28] were used to estimate the Pr_{jt} of rice mills in Cho Moi district. The average ratio of milled rice production to total raw paddy production has been stable at 61.7% and is expected to remain unchanged until 2030. Milled rice production in Cho Moi district is expected to be 5.0% of the total production in the Mekong Delta.

Rice drying

Presently, one-third of the rice produced in the Mekong Delta is harvested during the rainy season and dried by a mechanical system that uses rice husk as an energy source [15]. We assumed that this situation would continue in the Cho Moi district over the projection period.

Homemade alcohol production

The quantity of rice husk consumed for homemade alcohol production can be projected by multiplying the amount of alcohol produced by specific energy consumption values, which are expected to be constant over the projection period (Table 1). We assumed that homemade alcohol products in Cho Moi district are used to satisfy the demand within the district. The per capita homemade alcohol demand is expected to be the same as that in other rural areas of the Mekong Delta, 1.0 L/adult/year. The estimated current and future energy demand in Cho Moi district are summarized in Table 4.

Table 4. Total annual energy demand for residential and industrial sector in Cho Moi district.

Energy type	Unit	2007	2010	2020	2030
Electricity	10^3 GWh	165.8	185.8	246.0	325.1
LPG	10^3 T	2.6	3.4	4.6	7.8
Kerosene	10^3 L	73.7	0.0	0.0	0.0
Diesel oil	10^3 L	334.3	173.3	0.0	0.0
Biogas	10^6 m^3	4.8	6.3	8.1	10.1
Rice husk	10^3 T	161.3	151.4	125.8	100.8
Firewood	10^3 T	119.4	117.0	105.0	51.6

3.3 Unused rice residues

To estimate the amount of unused rice residues in Cho Moi district, we used the same assumptions for the supply potential applied to rural areas of the Mekong Delta (section 2.2). Due to the expansion of urban areas, which results in the reduction of agricultural land [4], the total unused rice residue in Cho Moi district would increase until 2010, with an average growth rate of 6.5%/year, while a reduction of 2.4%/year is expected from 2010 to 2030. By 2030, the amount of unused rice residue in Cho Moi district is expected to reach 178.4 kT (Table 5), of which the percentages of rice husk and straw are 19.2 and 80.8%, respectively. If the lower heating values of rice husk and straw are 11,400 and 14,000 MJ/T [4], the maximum energy potential from rice residues in the Cho Moi district would reach 2,408.7 GJ by 2030.

3.4 Scenario development

Several scenarios will be examined on the basis of the available technological options and the amount of unused rice residue to identify solutions for sustainable biomass use in the Mekong Delta. In this study, we define "sustainable biomass use" as a method, which uses available biomass sources optimizing the material use, energy flow, and economic benefits, while the effects on soil quality and the environment are of an acceptable degree.

3.4.1 Description of the scenarios

In all the scenarios considered, the current trend for biomass use continues until 2010. After 2010, the trend will be extended in a base scenario [the "business as usual" (BAU) scenario], while three types of technologies: a small-scale gasification system (SC-A); medium-scale gasification system (SC-B); and a medium-scale steam turbine system (SC-C), will be examined as alternative scenarios (Figure 2). To minimize the feedstock transportation distance, all of the biomass-based power plants will be installed arround the Hoa An–Hoa Binh communes (project area) in the centralized rice milling and brick-making areas of Cho Moi district. The distance for rice husk transportation is thus counted as zero, whereas that of straw transportation to the center of the project area is 15.0 km. The heat and electricity that are produced will be first used to cover the demands of the rural industries of Cho Moi district and households in the project area. Excess electricity will be sold to the national grid. The installed equipment for each scenario is decided on the basis of the energy efficiency of the technology used and the amount of rice residue used for energy production, which corresponds to 50%, 75%, and 100%, respectively, of the unused rice residues of the Cho Moi district in 2030.

System specifications

Technical and economic data for the installed systems were collected from manufacturers and similar existing projects. The claimed investment costs of gasification-based systems vary from 400 to 5,000 EUR/kWe [29-30], whereas that of steam power plants is almost the same as that in the literature (1,300 EUR/kWe) [31]. In this study, the investment cost and system's specifications were obtained from a feasibility analysis of similar projects in Tien Giang province [31-32] (Table 6). Construction work for the new systems is expected to begin in 2010. All installed systems will operate in full-load mode by 2020.

Methodologies for scenario assessment

Clean, efficient energy conversion technologies can be identified using a set of indicators. A current technology and an alternative that is expected to replace the existing one in the near term can be compared. In this study, the specific usable energy cost (*SC.UE*), total GHG emissions (*TEm*), specific GHG emissions (*TEm.UE*), and GHG marginal abatement cost (*MC.GHG*) were used to assess the performance of the designed scenarios. *SC.UE* and *TEm.UE* are presented on the basis of MJ of usable energy (MJ_{UE}), and *TEm* and *MC.GHG* are based on the mass unit of CO_2 equivalent ($CO_{2\text{-eq}}$). We counted the emissions of several GHGs, such as CH_4, CO_2, and N_2O, which can be converted to $CO_{2\text{-eq}}$, using the global warming potential conversion factor [33].

Table 5. Supply, demand and unused rice residues in Cho Moi district (kT/year).

	Supply potential			Demand			Unused residues		
	Husk	Straw	Total	Husk	Straw	Total	Husk	Straw	Total
2007	203.4	220.0	423.4	161.3	22.0	183.3	42.0	198.0	240.0
2010	213.5	253.5	467.0	151.4	25.4	176.8	62.1	228.1	290.3
2020	189.9	225.5	415.4	125.8	22.6	148.3	64.2	202.9	267.1
2030	135.0	160.3	295.3	100.8	16.0	116.9	34.2	144.2	178.4

Table 6. Specifications of designed alternative scenarios.

	Unit	SC-A			SC-B			SC-C		
		A50	A75	A100	B50	B75	B100	C50	C75	C100
Amount of feedstock	kT	89.2	133.8	178.4	89.2	133.8	178.4	89.2	133.8	178.4
Electrical efficiency	%	16.0	16.0	16.0	16.0	16.0	16.0	15.0	15.0	15.0
Electricity output	GWh/year	50.9	76.3	101.7	50.9	76.3	101.7	47.7	71.5	95.3
System capacity	kW_e	380	380	380	3,000	3,000	3,000	3,000	3,000	3,000
Number of installed equipment	Unit	16	24	32	2	3	4	2	3	4
Investment cost	10^3VND/kW_e	17,547.6			15,484.9			31,998.7		
Non-fuel operation and maintenance cost	% (*)	16.7			13.2			3.2		
Biomass cost	10^3VND/T	100.0			100.0			100.0		
Biomass transportation cost	10^3VND/T/km	2.0			2.0			2.0		
Benefit from heat	VND/kWh_e	0.0			7.0			11.7		
Benefit from ash sale	VND/kWh_e	0.0			0.0			323.7		
Cost of straw balling	10^3VND/T	1,672.0			1,672.0			1,672.0		

Note: Exchange rate: 1EUR = 22,460VND
(*) Ratio of maintenance cost over investment cost

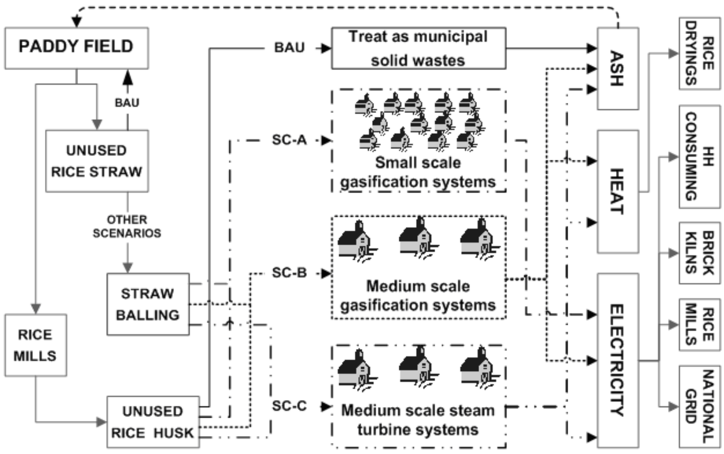

Figure 2. Frame work for system design.

Specific usable energy cost (SC.UE)

SC.UE (VND/MJ_{UE}) values can be estimated as follows.

$$SC.UE_t = \frac{\sum_{i=1}^{n} EC_{it} + \sum_{i=1}^{n} ET_{it} - BE_t}{\sum_{i=1}^{n} D.UE_{it}} \quad (4a)$$

$$EC_{it} = ED_{it} \times SEC_{it} \quad (4b)$$

$$ET_{it} = ED_{it} \times Trans.\cos t_{it} \times FT_i \quad (4c)$$

$$BE_t = (E_{biomass-t} - ED_{RS-et} - ED_{IS-et}) \times E_{SP} \quad (4d)$$

$$D.UE_{it} = ED_{it} \times LHV_i \times \varepsilon_k \quad (4e)$$

EC_{it} : Cost of *i* in *t* (VND/unit)
ET_{it} : Transportation cost of *i* in *t* (VND/unit)
BE_t : Benefit from electricity sales in *t* (VND/year)
$D.UE_{it}$: Usable demand for *i* in *t* (MJ/year)
SEC_{it} : Specific energy cost of *i* in *t* (VND/unit)
$Trans.cost_{it}$: Specific transportation cost of *i* in *t* (VND/unit/km)
FT : Transportation distance of *i* (km)
$E_{biomass-t}$: Biomass-based electricity production in *t* (kW/year)
ED_{RS-et}, ED_{IS-et}: Residential and industrial electricity demands in *t* (kW/year)
E_{SP} : Price at which electricity is sold to national grid (VND/kW); assumed to be 850 VND/kWh [39]
ε_k : Energy conversion efficiency (%)
k : Type of cook stove or kiln or furnace (rice drying furnace, traditional furnace, brick kilns, several type of cook stoves)

The ε values for cook stoves in the residential sector is shown in Table 3. The ε values of rice drying furnaces, traditional furnaces, and improved brick kilns are 60.0, 35.0, and 45.5%, respectively [11]. Since the transportation cost for fossil-based energy was included in its market price, we considered only the cost for rice husk and straw.

Based on the 2007 survey results, the market price for LPG, rice husk, and firewood in Cho Moi district was 19,000.0×10^3, 100.0×10^3, and 200.0×10^3VND/T, respectively. However, households have to pay only 50% and 30% for consumed rice husk and firewood, whereas the rest was freely gathered from surrounding areas. Therefore, $SEC_{rice\ husk}$ and $SEC_{firewood}$ in the residential sector were estimated to be 50.0×10^3 and 60.0×10^3 VND/T, respectively. $SEC_{kerosene}$ and

$SEC_{diesel\ oil}$ in 2007 were 13.7×10^3 and 12.1×10^3 VND/L. To estimate *SC.UE*, we assumed that the market price of all energy types, except electricity, would not change over the study period.

The current $SEC_{e\text{-}grid}$, which refers to the *SEC* of grid-based electricity, is different in the residential and industrial sectors. In the industrial sector, the average $SEC_{e\text{-}grid}$ was 930 VND/kWh. Because of the common practice of electricity resale in rural households of the Mekong Delta [34], the $SEC_{e\text{-}grid}$ in the residential sector was around 1,000.0 VND/kWh. Such electricity resale will not occur after 2020, when the electricity coverage rate is expected to reach 100.0% [4]. Therefore, $SEC_{e\text{-}grid}$ will decrease and reach 930.0 VND/kWh by 2030.

During the study period, biomass-based electricity is expected to replace grid-based electricity. The *SEC* value of biomass-based electricity ($SEC_{e\text{-}biomass}$, VND/kWh) can be estimated by Equation 5. The numerator of Equation 5, which refers to the capital for the entire life cycle of the system, can be estimated using the input parameters presented in Table 6.

$$SEC_{e-biomass} = \frac{I + OM + F + ET - CHP - RHA + SBC}{P \times 24 \times 350 \times L} \quad (5)$$

I	: Investment cost (VND)
OM	: Non-fuel operation and maintenance cost (VND)
F	: Fuel cost (VND)
CHP	: Benefit gained from produced heat (VND)
RHA	: Benefit gained from saleable rice husk ash (VND)
SBC	: Cost of straw baling (VND)
P	: Net power production capacity of system (kWe)
L	: Lifetime of system (years); *L* = 20 years
24 and *350*	: Operating hours per day and days per year

The average $SEC_{e\text{-}biomass}$ in SC-A, SC-B, and SC-C are 750.3, 624.2, and 290.7 VND/kWh, respectively, 19.3–68.7% lower than the current official tariff. The low $SEC_{e\text{-}biomass}$ for SC-C is due to the significant benefit provided by ash sales. If this benefit were excluded, the $SEC_{e\text{-}biomass}$ in SC-C would be 630.9 VND/kWh, almost the same as that of SC-B.

Total greenhouse gas emissions (TEm)

TEm ($TCO_{2\text{-}eq}$) can be estimated by summing the GHG emissions from the residential and industrial sectors. In principle, two main factors contribute to *TEm*: emissions from fuel or electricity consumption and emissions from transportation activities [35] (Equation 6). However, because the fuels consumed in the residential sector are normally supplied by retailers in the vicinity, we assumed that emissions related to fuel transportation in the residential sector need not be considered.

$$TEm_t = Em_{RS-t} + Em_{ISFC-t} + Em_{ISFT-t} + Em_{SOB-t} - Em_{ES-t} \quad (6a)$$

$$Em_{RS-t} = \sum_{i=1}^{n} SEF_{RS-it} \times ED_{RS-it} \times HH_t \quad (6b)$$

$$Em_{ISFC-t} = \sum_{i=1}^{n}\sum_{j=1}^{m} SEF_{ISFC-ijt} \times ED_{IS-ijt} \times \Pr_{jt} \quad (6c)$$

$$Em_{ISFC-t} = \sum_{i=1}^{n}\sum_{j=1}^{m} SEF_{ISFT-ijt} \times FT_{ijt} \times \Pr_{jt} \quad (6d)$$

$$Em_{SOB-t} = R_{OP-t} \times SEF_{SOB} \quad (6e)$$

$$Em_{ES-t} = (E_{biomass-t} - ED_{RS-et} - ED_{IS-et}) \times (SEF_{e-grid} - SEF_{e-biomass}) \quad (6f)$$

$Em_{RS\text{-}t}$	: GHG emissions from residential sector in *t* (T $CO_{2\text{-}eq.}$)
$Em_{ISFC\text{-}t}$	: Emissions from fuel consumption in industrial sector in *t* ($TCO_{2\text{-}eq}$)
$Em_{ISFT\text{-}t}$	: Emissions from transportation in industrial sector in *t* ($TCO_{2\text{-}eq}$)
$Em_{SOB\text{-}t}$	: Emissions from open burning of rice residues in *t* ($TCO_{2\text{-}eq}$)
$Em_{ES\text{-}t}$	: Reduction due to replacement of grid-based by biomass-based electricity ($TCO_{2\text{-}eq}$)
$SEF_{RS\text{-}it}$	: Specific emissions during consumption of *i* in *t* in residential sector ($TCO_{2\text{-}eq}$/unit of fuel consumed)
$SEF_{ISFC\text{-}ijt}$	: Specific emissions during consumption of *i* for *j* in *t* ($TCO_{2\text{-}eq}$/unit of fuel consumed)
$SEF_{ISFT\text{-}ijt}$	: Specific emissions during transportation of *i* for *j* in *t* ($TCO_{2\text{-}eq}$/km)
$R_{OP\text{-}t}$	: Amount of open-burned rice residues in *t* (T)
SEF_{SOB}	: Specific emissions during open burning of rice residues ($TCO_{2\text{-}eq}$/T)
$SEF_{e\text{-}grid}$	: Specific emissions of grid-based electricity production ($TCO_{2\text{-}eq}$/kW)
$SEF_{e\text{-}biomass}$	: Specific emissions of biomass-based electricity production ($TCO_{2\text{-}eq}$/kW)

Emissions from fuel used

Fuel consumption in the residential sector of Cho Moi district is related mainly to cooking activities. The *SEF* values of LPG, kerosene, and biogas stoves are 107.9, 157.4, and 2.8 $gCO_{2\text{-}eq}$ per unit of fuel consumed, respectively [23]. For other stoves that use solid biomass such as firewood or rice husk, the *SEF* values vary depending on the type of stove. The *SEF* values of firewood and rice husk consumption using traditional stoves are 12.1 and 7.5 $gCO_{2\text{-}eq}/MJ_{UE}$, whereas those of improved stoves are 10.1 and 4.0 $gCO_{2\text{-}eq}/MJ_{UE}$, respectively.

In the industrial sector, diesel oil and rice husk are the two most commonly used fuels. This study used the default values from the diesel oil combustion guideline of UNEP [33]. $SEF_{rice\ husk}$ is estimated at 4.0 $gCO_{2\text{-}eq}/MJ_{UE}$, which is same as that of an improved cook stove in the residential sector. For rice husk transportation, a value of 35.0 $gCO_{2\text{-}eq}$/T/km was used based on data from NTM [36].

Emissions from electricity used

$SEF_{e\text{-}grid}$ can be estimated by dividing the country-specific emission factor ($EF_{country}$) by the efficiency of electricity transmission/distribution (η). $EF_{country}$ varies over time depending on the fuel mix for power generation and can be estimated annually using APERC data on power generation and GHG emissions for Vietnam [2]. In the next few years, several small-scale hydropower plants and a nuclear power plant will be commissioned in Vietnam, which will help reduce $SEF_{e\text{-}grid}$ from 442.6 $gCO_{2\text{-}eq}$/kWh in 2007 to 418.9 and 345.3 $gCO_{2\text{-}eq}$/kWh in 2010 and 2020, respectively. After 2020, because of limited hydropower supply capacity, $SEF_{e\text{-}grid}$ will increase and reach 403.1 $gCO_{2\text{-}eq}$/kWh by 2030. The value of η is expected to increase from 0.87 in 2006 [37] to 0.9 by 2030, with a growth rate of 0.2%/year.

We assumed that the *SEF* values for biomass combustion and transportation in biomass-based power plants were the same as that of the industrial sector. SC-A and SC-B have the same value of $SEF_{e\text{-}biomass}$, which is expected to reach 107.6, 54.6, and 28.1 $gCO_{2\text{-}eq}$/kWh by 2030 in the cases of 50, 75, and 100% biomass used, respectively. For SC-C, the $SEF_{e\text{-}biomass}$ values in C50, C75, and C100 are expected to be 112.9, 56.4, and 28.1 $gCO_{2\text{-}eq}$/kWh, respectively.

Emissions from open burning of straw

No data are available on GHG emissions from open burning of straw in Vietnam. Instead, we used data measured in the neighboring countries (Thailand, India, and the Philippines). Based on that data, 1.0 kg of open-burned straw will discharge 1.2 g of CH_4 and 0.07 g of N_2O, or 37.5 $gCO_{2\text{-eq}}$, to the atmosphere [38].

Specific greenhouse gas emissions (TEm.UE)

TEm.UE ($gCO_{2\text{-eq}}/MJ_{UE}$) values can be estimated by dividing *TEm* by the total demand for usable energy (*D.UE*).

Greenhouse gas marginal abatement cost (MC.GHG)

The use of renewable energy sources in the alternative scenarios that we examined would contribute in reducing GHG emissions more when compared to that in the BAU scenario. However, the deployment of renewable technologies requires remarkably higher initial investment for the same amount of energy output. Therefore, we used the *MC.GHG* ($VND/kgCO_{2\text{-eq}}$) values (Equation 7), which indicate the cost of eliminating an additional unit of GHG for scenario assessment.

$$MC.GHG = \frac{SC.UE_{Alternatives} - SC.UE_{Base}}{TEm.UE_{Base} - TEm.UE_{Alternatives}} \times 1000 \quad (7)$$

4. Results and Discussion

4.1 Results

4.1.1 Specific usable energy cost values

In 2007, the *SC.UE* value was 77.9 VND/MJ_{UE}. From 2007 to 2030, the *SC.UE* value in the BAU scenario is expected to increase continuously at a growth rate of 1.2%/year. In contrast, owing to the application of new power plants as well as benefits from selling surplus produced biomass-based electricty, the *SC.UE* values of the alternative scenarios are expected to decrease significantly from 2010 to 2020, and then increase slightly after that. By 2030, SC-B and SC-C will have lower *SC.UE* values than those in 2007 (Figure 3a).

Depending on the technologies used and the ratio of unused biomass utilized for energy production, the average *SC.UE* differs among the scenarios (Table 7). Those that can produce electricity at a lower $SEC_{e\text{-}biomass}$ would have a lower *SC.UE*. Furthermore, if 50% of the unused biomass were utilized, the estimated *SC.UE* values would be 1.1–1.9 times higher than that for 100% utilization.

4.1.2 Greenhouse gas emissions

Total greenhouse gas emission values

The *TEm* values were estimated from 2007 to 2030 using Equation 6. A continuous reduction in *TEm* from 2007 to 2030 was observed for all the scenarios; the lowest reduction rate was found in the BAU scenario at 0.5%/year (Figure 3b). The estimates showed that, by 2030, only A50, B50, and C50 will have positive *TEm* values, whereas the other alternative scenarios will have negative values.

The total *TEm* values between 2007 and 2030 ($TEm_{accumulated}$, $kTCO_{2\text{-eq}}$) were estimated to assess the environmental impacts of each scenario. From 2007 to 2030, if no biomass-based power plant is installed (BAU), $TEm_{accumulated}$ in the project area would reach 794.6 $kTCO_{2\text{-eq}}$, whereas it would be mitigated to 96.4–632.0 (SC-A), −76.1–459.5 (SC-B), and −15.7–483.4 (SC-C) $kTCO_{2\text{-eq}}$ (Table 7).

Specific greenhouse gas emission values

Investment in new biomass-based power plants will help reduce *TEm.UE* in the area. In the BAU scenario, *TEm.UE* is expected to decrease from 47.0 to 40.1 $gCO_{2\text{-eq}}/MJ_{UE}$ from 2007 to 2020, and then increase to 47.1 $gCO_{2\text{-eq}}/MJ_{UE}$ by 2030. In contrast, all the alternative scenarios showed significant reduction by 2030 (Figure 3c).

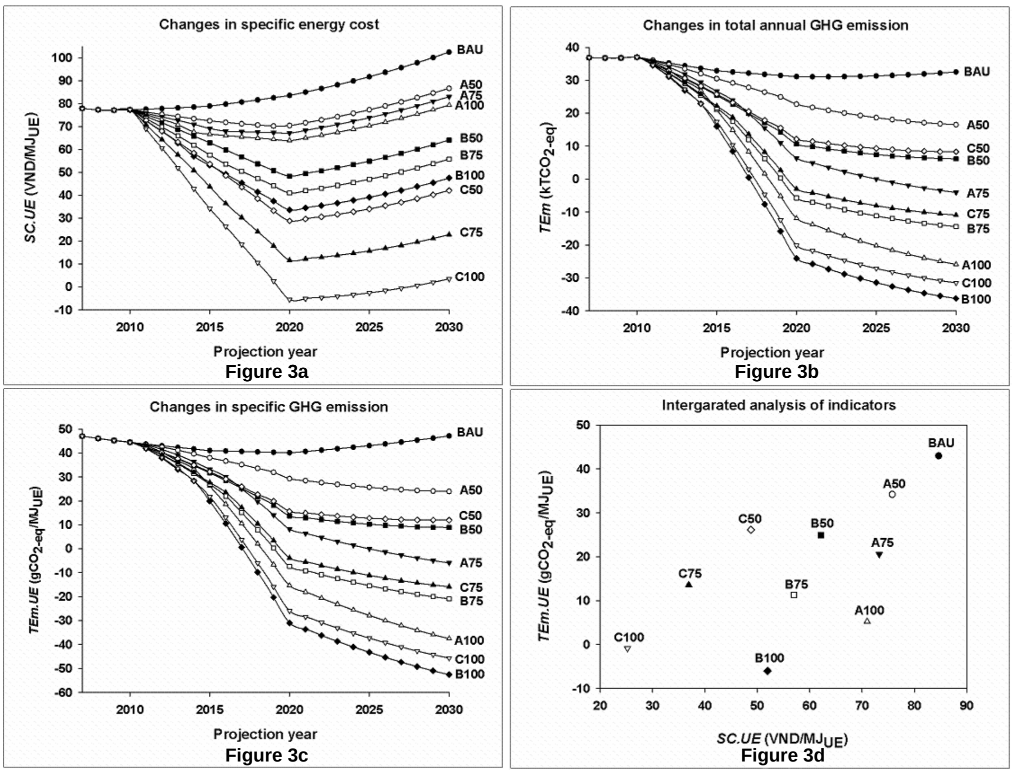

Figure 3. Indicators for scenario assessment.

Table 7. Estimated data for scenario assessment – Average values for the period 2007–2030.

Indicators	Unit	BAU	SC-A			SC-B			SC-C		
			A50	A75	A100	B50	B75	B100	C50	C75	C100
SC.UE	VND/MJ_{UE}	84.6	75.8	73.3	71.0	62.1	57.0	52.0	48.8	36.9	25.2
$TEm_{accummulated}$	$kTCO_{2\text{-eq}}$	794.6	632.0	380.3	96.4	459.5	207.7	−76.1	483.4	259.9	−15.7
TEm.UE	$gCO_{2\text{-eq}}$/ MJ_{UE}	43.0	34.2	20.6	5.2	24.9	11.2	−6.0	26.2	13.6	−0.9
MC.GHG	VND/kg $CO_{2\text{-eq}}$		−1,005.8	−505.2	−361.4	−1,239.9	−870.8	−666.7	−2,127.2	−1,621.5	−1,354.9

The average *TEm.UE* values of the BAU and alternative scenarios were estimated to compare their environmental impacts. The results showed that all the alternative scenarios had a lower *TEm.UE* than the BAU scenario, indicating that the use of biomass-based power plants can reduce environmental impacts as compared with existing systems. However, variations in the technologies and amounts of biomass used would result in varying *TEm.UE* values. A higher ratio of biomass used for energy production and a larger system capacity would lead to a lower *TEm.UE*. Additionally, a system developed on the basis of gasification technology (SC-B) has the potential to produce energy at a lower *TEm.UE* compared to that of a system based on steam turbine technology (SC-C) (Table 7).

4.1.3 Greenhouse gas marginal abatement cost values

MC.GHG represents the cost to reduce by one unit the amount of GHG emitted to the atmosphere. With the use of new technologies and considering all the alternative scenarios, the estimated $SEC_{e\text{-}biomass}$ values are lower than the current national tariff, resulting in negative *MC.GHG* values (Table 7). Of the three technologies considered, SC-C produces biomass-based electricity at the lowest price and consequently will have the lowest *MC.GHG*. In contrast, SC-A has the highest $SEC_{e\text{-}biomass}$ and *MC.GHG* values.

4.2 Discussion

Agricultural residues, in particular rice husk and straw, can be used in biomass-based power plants to produce electricity and heat for residential and industrial consumption. By reviewing the available technologies, this study examined direct combustion using steam turbine and gasification technologies under different conditions. Gasification systems have a wide range of capacities, so we developed both small- and medium-scale systems. *SC.UE*, *TEm*, *TEm.UE*, and *MC.GHG* values were used as assessment indicators for each scenario.

4.2.1 Specific usable energy cost values

We developed rice residue utilization scenarios based on Bergqvist's proposal for Tien Giang province [32]. In Bergqvist's study, the systems were designed to meet the power demand from individual mills and/or groups of scattered rice mills using their own rice husk as feedstock. However, because the feedstock supply is small, the projects still depend on ash sales. In our study, the system is designed at the community level, and the feedstock for energy production consists of rice husk from rice mills and removable rice straw from paddy fields. The electricity produced is used mainly to meet industrial and residential demands within the project boundary, whereas the excess is expected to be sold to the national grid. The systems are profitable both with and without ash sale revenues. Estimated $SEC_{e\text{-}biomass}$ values were 19.3–68.7% lower than the current tariff. If the selling price of biomass-based electricity is 850 VND/kWh [32], the estimated *SC.UE* values in the alternative scenarios would be 10.4–70.2% lower than that of the BAU scenario.

4.2.2 Total greenhouse gas emission, specific greenhouse gas emission and greenhouse gas marginal abatement cost values

Kumar [39] assessed the GHG mitigation potential of biomass energy technologies in Vietnam by substituting fossil-based power plants using Long-range Energy Alternatives Planning System (LEAP) model. The system was designed on the basis of technology packages consisting of used wood, baggasse, rice husk, and coal (in a co-firing plant) as feedstock. The *MC.GHG* value of such packages was recognized as -45.59×10^{-3} US dollars (equivalent to −750.4 VND) per $kgCO_{2\text{-eq}}$ reduced. In contrast, our alternative scenarios use rice husk and straw as feedstock. Using such biomass sources for electricity production helps reduce GHG emissions during the power generation process and also reduces CH_4 and N_2O emissions, thus reducing the total GHG emissions from the open burning of straw. The estimated values for *MC.GHG* in our alternative scenarios are therefore 2.0–2.7 times lower than those proposed by Kumar [39].

4.2.3 Implications for sustainable biomass use

The *SC.UE* and *TEm.UE* values of the designed scenarios were integrated to compare the economic and environmental impacts of the technologies used (Figure 3d). Like those of Bergqvist, our results indicate that using a medium-scale biomass-based power plant is economically and environmentally preferable. The *SC.UE* values for SC-B and SC-C, which were developed on the basis of medium-scale biomass power plants, were 18.1–26.8% and 35.6–64.5% lower, respectively, than those of a small-scale system (SC-A). Also, the *TEm.UE* values of SC-B and SC-C were 23.4–215.4% lower than the corresponding cases in SC-A (Table 7).

Although SC-B and SC-C were designed at the same system scale, different conversion techonologies showed different economic and environmental effects. Medium-scale steam turbine power generation (SC-C), which show the lowest *MC.GHG* values (Table 7), could be considered the most cost-effective option. In 2009, the Ministry of Natural Resources and Environment of Vietnam issued a new National Technical Regulation on Industrial Emissions [40], which specified area-based coefficients for estimating industrial air emission standards. Systems or enterprises located in more urbanized areas should apply a lower air emission coefficient and comply with stricter requirements on environmental performance. Therefore, in the urbanized areas, investment priority should be given to gasification technology (SC-B) for greater reduction in GHG emissions.

Variations in the amount of rice residue used for energy production would yield different economic and environmental effects. Figure 4 shows the variation in energy cost-saving potential and GHG reduction potential per unit of usable energy under different rice residue utilization ratios (50 to 100%). Regardless of the technology used, a higher utlization ratio would lead to more economic and environmental benefits. SC-B is expected to have the highest potential for GHG reduction. In SC-A, the enhancement of the utilization ratio from 50 to 100% can increase the GHG reduction potential by a factor of 4.3 and the energy cost-saving potential by a factor of 1.5. In contrast, with the same range of variation in the rice residue utilization ratio, SC-C may realize both GHG reduction (2.6 times) and energy cost saving (1.7 times).

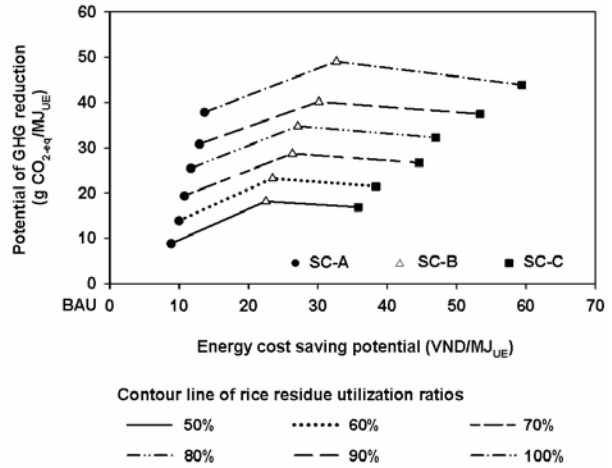

Figure 4. Impacts of different rice utilization ratios on economical and environmental benefits of alternative scenarios.

4.2.4 Sensitivity analysis

Uncertainties in the input data for assessment require us to examine the economic benefit of the scenarios. We investigated the magnitude of these uncertainties by a sensitivity analysis. Bergqvist [32] examined the same system at a smaller project scale and pointed out that investment cost is the most critical parameter for all plant options. Our results showed that lower investment and feedstock costs would result in a lower $SEC_{e\text{-}biomass}$ and therefore reduce the *SC.UE* values. SC-A and SC-B are less affected by variations in investment and feedstock costs than SC-C. If these costs are reduced by 10.0%, the *SC.UE* values of SC-A and SC-B would decrease by 1.0–5.7%, whereas that of SC-C would decrease by 1.6–10.1%.

In contrast, the estimated *SC.UE* values depend strongly on the E_{SP} value of the electricity produced. If E_{SP} is reduced by 10.0%, the *SC.UE* value would increase by 0.1–17.1%. Until now, the Vietnamese government does not have an adequate policy or regulations to purchase power from small power producers. Although Electricity of Vietnam (EVN) purchases electricity from several private power producers, the contracts are negotiated case by case [41]. In some cases, the E_{SP} value of electricity from private producers is around 0.04 US dollar/kWh, almost the same as $SEC_{e\text{-}biomass}$ for SC-B and SC-C (without ash sale revenue), and 10.7% lower than that of SC-A. If such a price were applied to our scenarios, investing in biomass-based power plants becomes unattractive, even though they have significant environmental benefits.

Furthermore, our results suggested that if more rice residue were used, more electricity would be produced, which might provide more economic benefit (Figure 3a). However, the amount of rice residue available for energy production is indirectly related to land use and urbanization [4]. The scenarios in this study were developed on the basis of mean urbanization ratio during the last decade, 2.5%/year. If the maximum urbanization ratio (4.0%/year) [4] were applied, the amount of rice residue available for energy production would be less than that assuming mean urbanization, which may affect the benefits of biomass power plants. For example, the estimated *SC.UE* values in SC-A, SC-B, and SC-C would increase by 2.0–4.0%, 5.5–12.5%, and 14.9–56.4%, respectively, and the *TEm.UE* values are expected to be 15.5–347.2% higher than that assuming mean urbanization.

Finally, technological innovations can improve the efficiency of power plants, improving the benefits of an entire system. When a 10% increase in system efficiency is added to each scenario to examine its effects, the economic benefits in SC-A and SC-B are less affected by variations in system efficiency than that in SC-C. For example, a 10% efficiency improvement would increase the *SC.UE* of SC-C by 11.4–43.5%, but it would increase that of SC-A and SC-B by only 4.6–13.0%. In addition, a 10% improvement in efficiency would enhance the environmental benefits by 6.2–102.5% (SC-A), 8.8–182.1% (SC-B), and 7.5–70.6% (SC-C), which implies that the environmental benefits of SC-B are more strongly associated with improved efficiency.

6. Conclusions

Current and future energy demand in the Mekong Delta was estimated by conducting a survey of the energy demand in the industrial sector. Furthermore, our study indicated the most available biomass sources for energy production. In addition to the BAU scenario, we developed nine alternative scenarios with different technologies and scales for biomass-based energy production. Then, we assessed these scenarios using a set of indicators: specific usable energy cost (*SC.UE*), total GHG emissions (*TEm*), specific GHG emissions (*TEm.UE*), and GHG marginal abatement cost (*MC.GHG*).

First, the study showed that electricity and heat energy obtained from rice husk burning in furnaces, kilns, or stoves are the energy sources highly in demand by the Mekong Delta's rural industries in both the present and the future.

Second, rice husk and straw used as fuel for biomass-based power plants are dominant biomass resources in the Mekong Delta, which account for 72.9–88.6% and 7.9–9.7%, respectively, of total unused agricultural residues in 2007–2030. The electricity produced from such plants can be used not only to meet residential and industrial demands within the project area but also for sale to the national grid.

Third, the assessment of biomass utilization scenarios showed that all the alternative scenarios have lower *SC.UE* and *TEm.UE* values than the BAU scenario and that the values of *MC.GHG* are in negative, from −361.4 to −2,127.2 $VND/kgCO_{2\text{-eq}}$. During 2007–2030, the use of biomass-based power plants could potentially reduce emissions by 162.6–870.7 $kTCO_{2\text{-eq}}$, equivalent to 20.5–109.5% of total GHG emissions in the study area over the same period of time.

We examined the economic and environmental impacts of the alternative scenarios through sensitivity analysis with different system scales, different types of conversion technologies, different conversion efficiencies, and variation in the amount of biomass used. Regardless of the technology type, a higher utlization ratio would increase the economic benefits by 1.5–1.7 times and the environmental benefit by 2.6–4.3 times. The SC-B scenario would cause lower environmental impact (5.2–85.0%) but after less economic benefits (21.4–51.5%) than the SC-C scenario.

The SC-C with the lowest *MC.GHG* values would be considered as the most cost-effective technology to choose for sustainable biomass use in the Mekong Delta. However, in more urbanized areas with stricter requirements for environmental performance, an investment priority should be given to gasification technology (SC-B) for greater reduction in GHG emissions.

In this study, a set of biomass utilization scenarios were developed on the basis of many assumptions and estimations regarding biomass availability, system specifications, and revenues from biomass power generation systems. First, the potential biomass supply depends on the ratio of removable crop residues for energy production, the speed and extent of urban growth, and fluctuations in the international rice market, which change domestic rice production patterns. Of these factors, the ratio of removable residues for energy production was determined by agronomic data such as soil type, cropping system, and management practices [42]. Since no empirical agronomic data is available in the Mekong Delta, we used data obtained from previous studies conducted in other countries [18-19]. Second, when estimating system revenues such as *SC.UE* or *MC.GHG* values, we assumed that the market price of all energy types except electricity would not change over the studied period. However, except for coal, the demands for fossil fuels in Vietnam have been covered by imports [2]. Thus, their prices are susceptible to changes in oil prices worldwide, and the economic benefit from biomass power generation systems will also change depending on fossil fuel prices. Finally, obtaining government subsidies and applying to the Clean Development Mechanism (CDM) scheme were not considered in our scenario assessment. With such additional schemes, which allow greater benefits from biomass use systems, alternative scenarios may be more competitive as well as attractive to policy makers and investors. Our future work will take into account these factors and schemes to improve the credibility and feasibility of the scenario assessment.

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