Doctoral Dissertation

# Evaluation of the Potentials for Development of Ethanol Production from Rice Straw in Vietnam

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## Abbreviations and Acronyms

| | |
|---|---|
| ABO: | Asia Biomass Office |
| AEC: | Advanced Ethanol Council |
| AIST: | The National Institute of Advanced Industrial Science and Technology |
| CDM: | Clean Development Mechanism |
| DFC: | Distance Fixed Cost |
| DOE: | The United States Department of Energy |
| EERE: | Energy Efficiency and Renewable Energy |
| ETBE: | Ethyl Tertiary Butyl Ether |
| EtOH: | Ethanol |
| FFVs: | Flex Fuel Vehicles |
| FY: | Fiscal Year |
| GBEP: | Global Bioenergy Partnership |
| GHGs: | Green House Gases |
| GoV: | Government of Vietnam |
| IEA: | International Energy Agency |
| JICA: | Japan International Cooperation Organization |
| JST: | Japan Science and Technology Agency |
| LCA: | Life Cycle Assessment |
| MAFF: | Ministry of Agriculture, Forestry and Fisheries |
| MRD: | Mekong River Delta |
| NREL: | National Renewable Energy Laboratory |
| OECD: | The Organization for Economic Co-operation and Development |
| OPEC: | Organization of the Petroleum Exporting Countries |
| PCs: | Production Costs |
| RD&D: | Research, Development and Deployment |
| Ropt: | Optimal Radius (imply optimal plant capacity) |
| RPR: | Residue to Product Ratio |
| RRD: | Red River Delta |
| SHF: | Separate Hydrolysis and Fermentation |
| SSF: | Simultaneous Saccharification and Fermentation |

# Abstract

Our dependence on limited fossil fuel energy resources negatively impacts the environment and economy by affecting the issues such as global warming and oil crisis. One of the solutions to this problem is to use biomass energy - renewable and carbon neutral source of energy. Vietnam is well-known for its exporting crude oils and import refined oils, in which gasoline is main imported product. To reduce dependence in gasoline import and address environmental concerns, since 2007, Vietnamese government has promoted bioethanol production and thus, large production of ethanol mainly from cassava has sharply increased since 2009. The current biomass for producing ethanol is also food source for humans and animals, therefore it has been blamed for causing food insecurity, land use change. To avoid these problems, the recent trend for sustainable production of bio-ethanol is to use inedible biomass that can be converted to fermentable sugars for ethanol production, which is called lignocellulosic biomass (forest-agricultural residues, and dedicated crops).

In Vietnam, up to date non-commercialized biomass energy (wood chips, agricultural residues) has accounted for more than one third of total primary energy consumption. This type of energy is mainly used in rural areas for cooking and heating (Vietnam Energy Report, 2012). Traditional use of biomass is ineffective in terms of energy and harmful to the environment and population's health and resulting in highest share of $CO_2$ emission from residential sector (31% of total $CO_2$ emission in all sectors in 2010). Extra amount of biomass also creates environmental pollution in some regions with intensively agricultural activities. It can be realized that if this non-commercialized biomass is converted to

bioethanol, Vietnam will not only reduce gasoline import, eliminate $CO_2$ emission in residential sector and transportation sector but also resolve environment pollution in rural areas and increase income for farmers. To date, technologies for lignocellulosic ethanol production have not yet been ready for commercial production. Major challenges are to improve ethanol yield and to reduce energy consumption and enzyme cost. Additionally, the need for high capital investment and delivered biomass costs make it more difficult to compete with gasoline or even with other traditional bio-ethanol costs. However with recent improvements in developing technologies and on-going researches to overcome technological challenges, it is anticipated that lignocellulosic ethanol will be widely produced in developing countries with abundant-supplied biomass in the near future.

In 2009, within the project "Sustainable Integration of Local Agriculture and Biomass Industries", to promote sustainable development of the rural regions with supports from JICA and JST, a pilot plant for producing ethanol from rice straw was built in the South of Vietnam for promoting research and developing technologies for cellulosic ethanol production. Nevertheless, to realize the potentials for cellulosic ethanol production, additional concerns other than conversion technologies should be addressed, such as delivered cost of biomass, plant capacity, and above all, the assumed production costs - PCs.

The objective of this study is to assess the potentials for the practical production of ethanol from rice straw on the basis of quantity, distribution and farm-plant's gate costs of biomass; the optimum facility's capacity for minimizing the ethanol PCs; estimated ethanol PCs at different scenarios and potentials for reduction in ethanol PCs in Vietnam compared with Japan via techno-economic analysis. Techno-economic analysis is one of vital tools to determine the economics through production cost and cost contribution. Up to date, most of techno-economic studies of ethanol production from lignocellulosic biomass have been conducted in developed countries (Japan, the U.S, France, etc.) as they have developed demonstration plants for lignocellulosic ethanol production. In this research, such kind of study for the case of Vietnam has been completely conducted from investigating the rice straw available for sustainable production of ethanol, density, farm-plant‟s gate cost, and the optimal facility size for minimizing ethanol production cost to techno-economic analysis. This research is an unprecedented attempt in developing countries where technical data from demonstration-scale production process have not yet been available and even rare in the developed nations. The idea of developing the equation for calculation of optimal facility size is unique and applicable for any bio-renewable energy projects which collect biomass residues from surrounding farms.

The data used for the calculation of agricultural residue quantity were the average value of crop production over five years (2005–2009) in Vietnam. The amount of crop residue generated (dry mass) was estimated on the basis of the data for crop production, residue-to-product ratio (RPR), and moisture content of biomass. Annually, Vietnam has produced approximately 83 Mt year$^{-1}$ of agricultural residues from food and cash crops, and this huge amount has been mainly generated from rice production. Analysis of quantity, distribution, current practices, and chemical characteristics of these residues, rice straw (approx. 50 Mt year$^{-1}$) appears as the most promising feedstock for cellulosic bioethanol industry. Practically, 10-25 Mt year$^{-1}$ of rice straw could be available for sustainable ethanol production. Vietnam was divided into six administrative regions with different agricultural pattern, designated regions 1, 2, 3, 4, 5, and 6. In all these regions, rice is main crop, thus rice straw is the main agricultural residue. Region 6, the Mekong River Delta accounted for 52% of the total amount of rice straw generation followed by the Red River Delta (region 1), accounting for 17% of the total.

The Mekong River Delta region has appeared as the most intentivelly argricultural region and will be the best location for seting up ethanol plants in Vietnam. The current utilization of rice residues, promising potential of using rice straw for ethanol production was discussed in this region. Rice production in this region was by far predominant in comparison to other crops, and generated an abundant supply of rice straw (approx. 26 Mt year$^{-1}$). Considering the possible collection and other uses of rice straw, we assumed that 50% of the rice straw generated annually could be available for ethanol production. The analysis of the distribution of rice straw by season and sub-region in the Delta showed a great potential of feedstock supply for bioethanol plants in the region. Rice straw is provided mainly from the two main harvest seasons of spring and autumn rice. The areas with high densities of rice straw supply (from 6.2 to 11.7 dry t ha$^{-1}$ year$^{-1}$) are located along the upper and mid-banks of the Hau and Tien Rivers in the following sub-regions: An Giang, Can Tho, Hau Giang, Kien Giang, Dong Thap, Vinh Long, Long An, and Tien Giang. According to our estimation, the potential of rice straw ethanol production in the Delta could be 1661 ML year$^{-1}$, or up to 3296 ML year$^{-1}$, applying the current rice-straw ethanol production technologies from Japan, with ethanol yield from rice straw was 1.25 to 2.5 L dry kg$^{-1}$ of rice straw without or with xylose fermentation, respectively. This amounts of ethanol could substitute for 25.7% to 51% of the total 2008 gasoline consumption in Vietnam.

Rice straw is abundant in Vietnam but is mainly concentrated in the Mekong River Delta and the Red River Delta regions on the basis of rice straw quantity and density. Considering both field-level and landscape level factors, the available densities of rice straw for sustainable ethanol production in 6 administrative regions of Vietnam named 1, 2, 3, 4, 5, and 6 were estimated to be 69, 6.8, 14, 3.9, 12, and 108 dry t $km^{-2}$, respectively. The difference in rice straw densities results in different costs of delivered rice straw by region.

Delivered cost of biomass (farm-plant's gate costs of biomass) contributes to a major share in ethanol PCs. To know the delivered cost of biomass is vital for considering the feasibility of a bioethanol project. A model for collection and handling rice straw from Thailand was applied to estimate the delivered cost of rice straw in Vietnam. The delivered rice straw cost in Vietnam varied from 20.5 to 65.4 \$ dry $t^{-1}$ with the transportation distances of 0 to 120 km.

To minimise the overall production costs, it is crucial to choose the optimal facility size for minimal production costs. In the bioenergy industry, selection of the optimal facility size must consider the effect of a number of tradeoffs. The savings resulting from the "economics of scale" are offset by the increased cost of transportation of the feedstock. Based on the reasonable approaches, an equation for calculation of the radius of optimal biomass collection area - $R_{opt}$ (imply optimal plant capacity) was developed and applied for calculating the optimal plant size by region. Regions 1 and 6 were found to be the optimal locations for ethanol production, with economical facility sizes of 112.5 and 195 ML $year^{-1}$, respectively. Consequently, the feedstock supply radius was 50 and 48 km for regions 1 and 6, with the total cost of feedstock and fixed cost per litre of ethanol of \$0.244 and \$0.224, respectively. The above-calculated results represent for a case study at present time. The developed equation for calculation of $R_{opt}$ can be applicable to determine the optimal facility size required for the biomass to be transported from the surrounding areas and to predict the change in optimal facility size with the changes of various conditions.

Based on the optimal plants can be built in different regions, to economically practical production, optimal ethanol plants in the Mekong River Delta and Red River Delta are expected to be constructed and the amount of ethanol produced from these two regions (502.5 ML $year^{-1}$) is capable to replace 9.8% of the country's gasoline imported in 2009.

Techno-economic analysis was used to estimate PCs and the cost component distribution, trends for the reduction of ethanol production costs from rice straw in Vietnam were compared with those in Japan. With current technologies developed by AIST applied to the designed production process, the PCs for the plants on the scale of 15 ML $year^{-1}$ in Japan and Vietnam were 2.28 \$ $L^{-1}$ and 1.45 \$ $L^{-1}$, respectively. Feedstock, enzyme, energy and investment costs were the main contributors to the PC. However, the significance of these cost components" contributions was different in each country. In Japan, the dominant cost component was rice straw cost (35.3% of the total cost). Vietnam has much lower rice straw prices, so the impact of improvements in ethanol yield (rice straw component, conversion yields) was not as significant when compared with their impact in Japan. The improvement in solid concentration of material in the hydrothermal pre-treatment step and using residues for power generation substantially reduce the PC, especially in Vietnam where energy costs account for the second largest contribution to the PC, following only enzyme costs. The potential for building larger ethanol plants with low rice straw costs can further reduce the current production cost in Vietnam. The current production cost for an optimal plant size of 200 ML $year^{-1}$ was 1.19 \$ $L^{-1}$. For the future scenario, considering improvements in pre-treatment, enzyme hydrolysis steps, specific enzyme activity, and applying residues for energy generation, the production costs in Japan and Vietnam can be significantly reduced to 1.54 \$ $L^{-1}$ and 0.88 \$ $L^{-1}$, respectively, for a plant size of 15 ML $year^{-1}$. The ethanol production cost can reach 0.45 \$ $L^{-1}$ for a plant size of 200 ML $year^{-1}$ in Vietnam. These data indicated that the cost-competitiveness of ethanol production can be realised in Vietnam with future improvements in production technologies and the specific activity of enzymes for hydrolysis. The cost-competitive production of ethanol from rice straw in Japan would not be viable in the future without a substantial reduction in rice straw cost.

The research results provided useful data and showed good potentials for reducing ethanol PCs in Vietnam. The sensitive analysis of cost components in ethanol PCs suggested the research orientation in development technologies to reduce rice straw ethanol PC in Vietnam. Additional discussion showed potentials for expected environmental, socio-economic benefits of rice straw ethanol production, as well as concerns related to sustainable production and use of rice straw ethanol; how to promote the development of industrial production of ethanol from rice straw in Vietnam. This study is expected to be a valuable document to assist interested parties and bio-energy policy makers during the initial stage of evaluating the potential for development of a cellulosic ethanol facility in Vietnam. The methodologies of this work can be a fundamental tool for economic analysis of ethanol production from rice straw at any certain time.

# Chapter 1

## Introduction

### 1.1 Bioethanol production and utilisation: Current status and development trends

Challenges of increasing oil prices, global warming has forced the world to look for renewable energy (biofuels, wind or solar energy, etc.), which is unlimited energy source and carbon- neutral.

Bioethanol (ethanol produced from biomass) is the most widely use biofuel today. It gradually replaces petroleum fuels, mainly in transport sector, and significantly decreases net $CO_2$ emission.

According to the statistical data of 2010, the transportation sector produces about 25% of global energy-related $CO_2$ emission and accounts for roughly 50% of global oil consumption (OECD/IEA, 2010). Therefore, bioethanol has been seen as one of the most feasible options for reducing carbon emission and dependency on fossil fuel.

Over the last decade, bioethanol is the major biofuel produced. Global bioethanol production increased rapidly, from 17.25 billion liters in 2000 to over 68 billion liters in 2008 and 86 billion liters in 2010, shown in Table 1.1. With new government policies in most countries in the America, Asia, Europe supporting biofuels, total global ethanol demand could grow to exceed 125 billion liters by 2020 (Balat and Balat, 2009). In 2010, the United States (U.S) produced by far more bioethanol than any other country, following by Brazil. Together, the U.S and Brazil produced over 86% of the world bioethanol.

**Table 1.1** World fuel bioethanol production by country or region, 2010.

| **Region** | **Year 2010 (million gallons)** |
|---|---|
| North & central America | 13720.99 |
| Europe | 1208.58 |
| South America | 7121.76 |
| Asia | 785.91 |
| Oceania | 66.04 |
| Africa | 43.59 |
| **Total** | **22946.87**<br>**(86 billion L)** |

| **Individual Countries** | **Year 2010 (million gallons)** |
|---|---|
| United States | 13230.00 |
| Brazil | 6577.89 |
| European Union | 1039.52 |
| China | 541.55 |
| Canada | 290.59 |

Source: World fuel ethanol production (Biomass energy data book, 2010).

Bioethanol is mainly used as transportation fuels. Ethanol is used to increase octane number and improve the emissions quality of gasoline. In many countries, such as the U.S, Brazil, China, Thailand, ethanol is mostly blended with gasoline to form an E10 blend, called 'gasohol' (10% ethanol and 90% gasoline). This gasohol is substituting for gasoline and burned in traditional combustion engines without any modifications. With engine modification (flex fuel vehicles - FFVs), bioethanol can be used at higher levels, for example, E85 (85% ethanol, 15% gasoline). To date, pure ethanol or E100 is only used in Brazil for some designated engines (Balat and Balat, 2009). Other way of using bioethanol is in the form of Ethyl Tertiary Butyl Ether (ETBE), which is produced in the reaction between bioethanol and isobutylene derived from petroleum. ETBE is an excellent gasoline additive because it has high octane number than ethanol and is easily handled as it is not hygroscopic like ethanol.

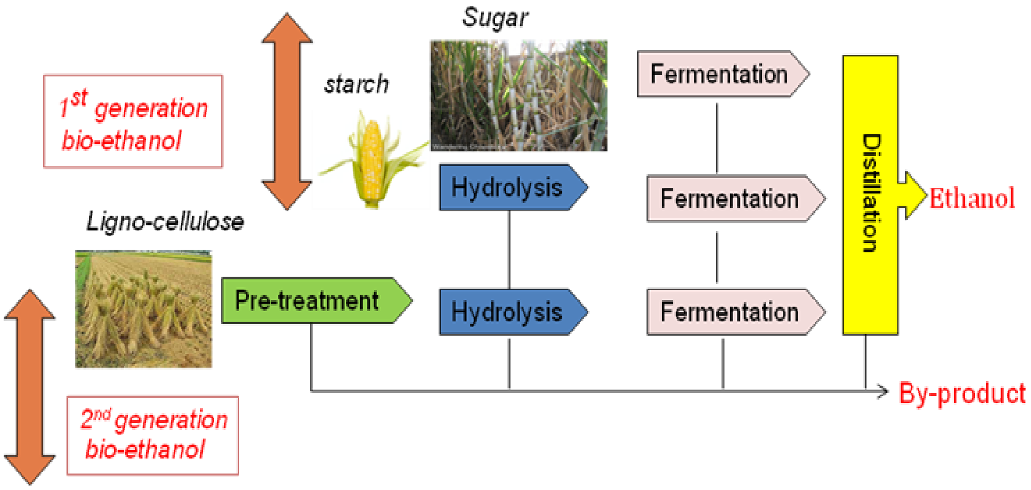


**Figure 1.1** Diagram for ethanol production from biomass.

Presently, commercial bioethanol is produced from sugary or starchy biomass such as, sugarcane (Brazil), corn (the U.S), sugar beet, wheat (Europe) cassava, sweet sorghum (Asia). This ethanol is called first-generation ethanol. The production process (shown in Figure 1.1) is similar with traditional wine production process, however ethanol is collected at higher concentration (>99.0 wt%) to be used as fuel. Though more and more emerging and developing countries have already successfully developed the first-generation bioethanol industry, this fuel has been blamed for food crisis as the main material (feedstock) used for this industry is also food and feed for human and animal.

For sustainable production of bioethanol, the feedstock has been gradually shifted from edible to inedible biomass, that is lignocellulosic biomass (such as agricultural residues, trees and grasses). Ethanol produced from lignocellulosic biomass is called the second-generation ethanol or lignocellulosic ethanol. From this type of biomass, sugars are extracted via pretreatment and hydrolysis steps, thus production technologies are more complicated (shown in Figure 1.1).

While the production of first-generation bioethanol is in an advanced state regarding both processing and infrastructure, second-generation technologies are mainly in a pilot and demonstration stages and not yet operated commercially. The main obstacles for commercially production of second-generation bioethanol are high initial investment costs and high costs for the end-product compared to gasoline or first-generation bioethanol.

With strong policies in developed countries, investments in RD&D in second-generation biofuels have been increased in OECD countries. Some companies have reported they would start commercial production of second-generation biofuels within the coming years (Choren Co., Poet Co.), but they still depend on subsidies to be economically visible for some years to come. So far, only few developing and emerging countries (Brazil, China, India, Thailand, Vietnam, and Indonesia) are undertaking RD&D in second-generation bioethanol. According to The World Energy Outlook by IEA, 2009, the second-generation biofuels will not penetrate the market on a fully commercial scale earlier than 2015.

## 1.2 Technologies for ethanol production from lignocellulosic biomass

There are 2 main conversion routes to produce lignocellulosic ethanol as follows:

1. Bio-chemical route: this process based on enzymatic hydrolysis of lignocellulosic biomass through a variety of enzymes that break the biomass into sugars, then these sugars are fermented into ethanol.

2. Thermo-chemical route: this route starts with gasification of biomass under high temperature, pressure to produce a synthetic gas (syngas). This syngas is converted to ethanol using catalyst.

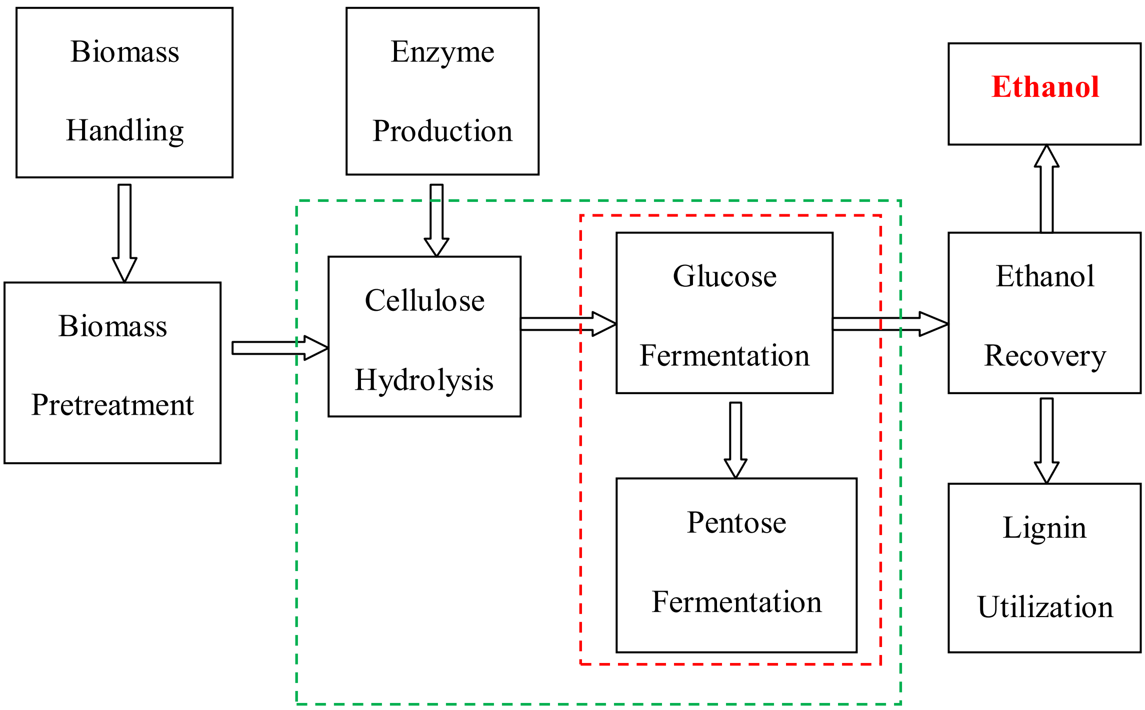


**Figure 1.2** Lignocellulosic ethanol production process (bio-chemical route).

Though, bio-chemical route has been considered as promising future option. Many RD&D have been taken to improve technologies for this route. Within this study, those technologies are introduced. Figure 1.2 shows the basic steps in production of ethanol from lignocelullosic biomass. Some steps can be combined as shown in dashed line rectangles.

**Process description**.

1. *Biomass handling*: this step reduces the size of biomass to make it easier to handle and to make the ethanol production process more efficient. For instance, agriculture residues go through a grinding process and wood goes through a chipping process to achieve a uniform particle size.

2. *Biomass pretreatment*: In this step, the hemicellulose fraction of the biomass is broken down into simple sugars. The complex hemicellulose sugars are converted to a mix of soluble pentose ($C_5$) sugars (xylose, arabinose), and soluble hexose ($C_6$) sugars (manose, galactose, glucose). A small portion of the cellulose is also converted to glucose in this step. Technologies used for this step are variable, named chemical pretreatment (acid or alkaline, oxidising agents are used), hydrothermal treatment (steam, high pressure and temperature ($160^0$-$180^0$C), biological treatment (using a mixture of microorganism to pre-decompose the biomass), or combined pretreatment. Technologies for pretreatment have been researched to improve efficiency of the process and save energy.

3. *Enzyme production*: the cellulase enzymes that are used to hydrolyse the cellulose fraction of biomass are produced in this step (onsite enzyme production). Alternately, the enzymes might be purchased from commercial enzyme companies.

4. *Cellulose hydrolysis*: in this step, the remaining cellulose is hydrolyzed to glucose. Cellulase enzymes are used to break the chain of sugars that make up cellulose, releasing glucose. This step is also called saccharification because it produces sugars.

5. *Glucose fermentation*: glucose is converted to ethanol by yeast or bacteria through a process called fermentation. Fermentation is a series of chemical reactions that convert sugars to ethanol in the microorganism's cells.

6. *Pentose fermentation*: the hemicellulose fraction of biomass is rich in pentose sugars. Of them, xylose is the most prevalent pentose released during biomass pretreatment step. In this step, xylose is fermented using *Zymomonas mobilis* or other genetically engineered yeast or bacteria.

7. *Ethanol recovery*: Fermentation solution combined from pentose and glucose fermentation steps is called fermentation broth. In this step, ethanol is separated from other components in the broth by distillation. To get anhydrous ethanol (>99 wt %), dehydration is needed to remove water from rectified ethanol.

8. *Lignin utilization*: lignin and other byproducts of the biomass-to-ethanol process can be used to produce the electricity required for the ethanol production process. Burning lignin actually creates more energy than needed and selling electricity may help the process economics.

***Technological challenges***: Converting lignocellulosic biomass to ethanol is currently too expensive to be used on a commercial scale. Researchers are working to improve the efficiency and economics of the ethanol production process by focusing their efforts on the three most challenging steps (Hamelinck *et al*., 2005; Binod *et al*., 2010):

- *Pretreatment biomass*. Recalcitrant structure of lignocellulosic biomass is difficult to be broken down. Technologies for pretreatment have been researched to improve efficiency of the process and save energy.
- *Cellulosic hydrolysis*. The crystalline structure of cellulose (homo-polymer of ß-1,4 glucose) make it difficult to hydrolyze to simple sugars ready for fermentation. Researchers are developing enzymes that work together to efficiently decompose cellulose.
- *Pentose fermentation*. While there is a variety of yeast and bacteria that ferment hexose sugars, most of them cannot easily ferment pentose sugars, which limits ethanol production from cellulosic biomass. Researchers are using genetic engineering to design microorganisms that can efficiently ferment both $C_6$ and $C_5$ sugars at the same time.

## 1.3 Lignocellulosic biomass for ethanol production: definition, composition, and categorization

### 1.3.1 Definition

Lignocellulosic biomass refers to plant dry matters. It is the most abundantly available raw material on earth and widely recognized as the most potential feedstock for sustainable ethanol production. According to Claassen *et al.*, 1999, lignocellulosic biomass accounts about 50% of world biomass and its annual production was estimated in 10-50 billion tons. Thus this type of biomass is considered as the endless source for renewable energy production.

Ethanol produced from this biomass is called lignocellulosic biomass or the 2nd generation ethanol to distinguish from the first generation ethanol, which has been produced from sugary and starchy biomass (sugarcane, corn, cassava, rice, etc.)

### 1.3.2 Composition

Chemically, lignocellulosic biomass is composed of carbohydrate polymers (cellulose, hemicellulose), and aromatic polymers (lignin). These carbohydrate polymers are tightly bound to lignin and make the biomass into a rigid structure (Carroll and Somerville, 2009). Carbohydrate polymers composed of $C_5$ and $C_6$ sugars that can be fermented to ethanol.

- Cellulose (40-60% of the biomass) is a linear homo-polymer of several hundred to over ten thousand $\beta$(1–>4) linked D-glucose units. In hydrolysis or saccharification, the polymer is broken down to monosugar - glucose, ($C_6$ sugar or hexose). The orientation of linkages and additional hydrogen bonding make the polymer rigid and difficult to break.
- Hemicellulose (20-40%) consists of several heteropolymers. These polymers are highly branched by various $C_5$ and $C_6$ sugars: mainly xylose ($C_5$ sugar), and further arabinose ($C_5$ sugar), galactose, glucose, and manose (all $C_6$ sugars). It also contains small amount of non-sugar such as acetyl groups (Lynd *et al.*, 1999). Because of its branched, amorphous nature, hemicellulose is relatively easy to be hydrolyzed.
- Lignin (10-25%) is a large complex polymer of phenyl propane and methoxyl groups. Lignin encrusts the plants cell walls and cements the cells together. Lignin is degradable by chemical processes to produce higher value products, such as organic acids, phenols, vanillin, and fuel additives. However, presently lignin is deployed only for power generation (Hamelinck *et al.*, 2005).

**Table 1.2** Typical lignocellulosic biomass compositions (% dry basic) (adapted from Mosier *et al*., 2005).

| Feedstock | Glucan (cellulose) | Xylan (hemicellulose) | Lignin |
|---|---|---|---|
| Corn stover | 37.5 | 22.4 | 17.6 |
| Corn fiber | 14.28 | 16.8 | 8.4 |
| Pine wood | 46.4 | 8.8 | 29.4 |
| Poplar | 49.9 | 17.4 | 18.1 |
| wheat straw | 38.2 | 21.2 | 23.4 |
| Switch grass | 31.0 | 20.4 | 17.6 |
| Office paper | 68.6 | 12.4 | 11.3 |

### 1.3.3 Categorization of lignocellulosic biomass

Lignocellulosic biomass can be categorized into 4 groups, depending on source of biomass (Hamelinck *et al*., 2005).

- Agricultural residues: corn stover, rice straw, cane bagasse, etc.
- Dedicated crops: Eucalyptus, switch grass, prairie grass, Miscanthus, etc.
- Wood residues: tree branches, thinning wood; wood chips, sawdust, etc.
- Municipal paper waste.

According to Sanchez and Cardona (2008), prospective lignocellulosic materials for fuel ethanol production can be divided into 6 main groups:

- Crop residues: cane bagasse, sweet sorghum bagasse, corn stover, wheat straw, rice straw, rice husks, barley straw, olive stones and pulp.

- Hardwood: aspen, poplar, etc.
- Softwood: Pine, cedar, spruce, etc.
- Cellulose waste: newsprint, waste office papers, recycle paper sludge.
- Herbaceous biomass: alfalfa hay, switch grass, reed canary grass, coastal Bermuda grass, Thimothy grass.
- Municipal solid wastes.

To date, many lignocellulosic materials have been tested for bioethanol production in different countries in the world: wood and forestry waste, wood chips from cedar and pine, sawdust, poplar, eucalyptus, corn stover, cane bagasse, sweet sorghum bagasse, wheat straw, barley straw, rice straw, switch grass, alfalfa, and recycled paper (Sanchez and Cardona, 2008) .

Composition of biomass plays an important role in ethanol yield. Biomass composition varies by many factors, such as types of biomass, growth area, used fertilizers, time of harvesting and storage conditions. Some typical lignocellulosic biomass compositions are shown in Table 1.2. Biomass with high content of glucan and xylan, will be a better choice for higher ethanol yield.

### 1.4 Situation of research and development of lignocellulosic ethanol worldwide

To cope with dependency on fossil fuels and the increasing emission of GHGs, bioethanol represents one of the most prominent options to replace fossil fuels due to possibility of blending with gasoline and using in the existing cars. However, the first generation of commercially available bioethanol suffers from its reliance on food crops and concern about direct and indirect effects on land use. Thus, the sustainable production of bioethanol from cellulosic biomass is expected to become one of the most credible alternatives within a few years.

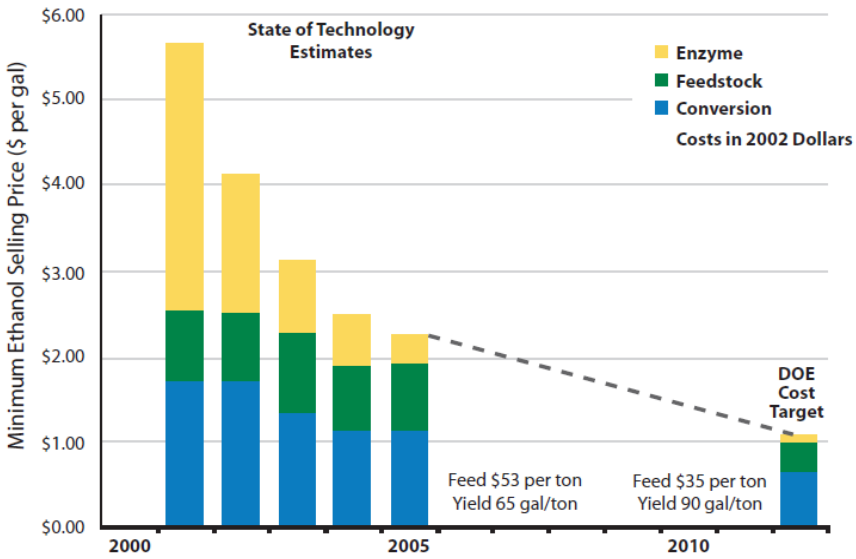


**Figure 1.3** Progress toward cost target of 1.07$/gallon for biochemically produced ethanol in the United States. (NREL, 2007).

Significant efforts in research, development and demonstration (RD &D) are being undertaken worldwide, especially in industrialized countries with the most substantial progress made in the United States, where the government support is more important than in any other country worldwide (Gnansounou, 2010; NREL, 2012). Pilot and demonstration plants existed for proving the technology and working out economic and technical issues prior to scale-up but no commercial-scale facilities exist even today that can provide easily replicable models (Biotechnology Industry Organization - BIO, 2011).

The main obstacle for lignocellulosic ethanol is high initial investment costs as well as higher costs for end product compared to gasoline and other first generation bioethanol (OECD/IEA, 2010). The framework of the R&D technologies on lignocellulosic ethanol include: improvement of the ethanol yield, high ethanol concentration during fermentation, improvement of pretreatment techniques, finding effective yeasts for fermentation of both $C_5$ & $C_6$ sugars, production of cheaper and more effective enzymes, effective utilization of by-products, and achievement of process integration. Research works on each of these issues have been undertaken in different institution worldwide using different types of lignocellulosic biomass for ethanol production, for example, corn stover in the U.S, rice straw and soft wood chips in Japan, soft and hard wood, grass in Europe countries, agricultural residues in Asia (Asian Biomass Office, 2011a; NREL, 2012).

In emerging and developing countries, such as Brazil, China, India, Thailand, etc. still mainly in the stage of R&D, pilot plants have set to promote research on production of lignocellulosic ethanol.

Demonstration stage of lignocellulosic ethanol has existed mostly in developed nations of North America, Europe and in Japan. These demonstration projects use different type of feedstock, technologies and set different targets to reduce production costs, (shown in Table 1.3). The United States is recognized as the leading country in the global race to produce lignocellulosic ethanol with aggressive mandates for production and use of cellulosic biofuels. In 2002, the U.S Department of Energy (DOE) set a target to produce ethanol cost of 1.07 $/gallon and aimed to archive this goal by 2012 (Figure 1.3). Up to date, the United States has significant improvement in technologies to reduce production cost to 2$/gallon today, enzyme cost are down to 20% in the last decade (Advanced Ethanol

Council-ACE, 2013). The cellulosic biofuel industry in the United States has almost reached the commercial development phase, however high capital risk from OPEC induced price distortion, constrained blending market, policy uncertainty continues to slow the rate of development (Advanced Ethanol Council - AEC, 2013). Contrary to the case of the United States, in Europe the research works remain fragmented despite the efforts made by the European Union. The actual deployment of lignocellulosic ethanol in Europe will depend on the opportunities cost of biomass and prices of first generation ethanol and gasoline (Gnansounou, 2010).

In Asia, Japan is the leading country in development of advanced technologies for lignocellulosic ethanol. Japanese government intends to promote cellulosic ethanol production in Asia with Japanese technologies (Kawamura, 2009). In Japan, after the Great East Earthquake and subsequent nuclear accident happened, the biomass industrialization strategy was drawn as principle to create regional green industry and fortify an independent and distributed energy supply system. Oil refineries were required to produce a certain amount of biofuels during FY 2011 around 210,000 kl up to 500,000 kl (crude oil equivalent) in FY 2017 (MAFF, 2013). In which, ethanol from rice straw or thinned wood will account for a big share of it if appropriate technical development is achieved. According to Japanese Biomass Policy in 2007, to develop technologies to produce ethanol in great quantity from soft cellulose waste (rice straw, wheat straw), since 2009, Japanese government has funded 4 projects named "Soft cellulose utilization projects" for four organizations (Taisei Corporation, Sapporo Breweries Ltd; Akita Agricultural Public Corporation, Kawasaki Plant System Ltd; Biomaterial in Tokyo Ltd; Mitsubishi heavy Industry Ltd), consequently, four pilot plants for production ethanol from rice and wheat straws with capacities from 3.7 to 200 L $day^{-1}$ had constructed in Eniwa city, Hokkaido; Katagami city, Akita Prefecture; Kashiwa city, Chiba prefecture; and Akashi city, Hyogo prefecture.

According to the news released by Reuters in May of 2013, Japan's Kawasaki Heavy Industries Ltd., had developed technology to produce ethanol from rice straw at a cost that is competitive with imported ethanol made from food products. The production cost would be total of 40 JPY $L^{-1}$ or 80 JPY $L^{-1}$ with or without subsidies for cost of gathering straw waste from rice farming in Japan. The cost of 80 JPY $L^{-1}$ is much lower than the cost of importing ethanol from Brazil, ranging from 80 to 100 JPY $L^{-1}$. However the spokeswoman of the company said it has no specific plans for commercial production, and the technology would be competitive in countries with sufficient biomass resources and lower labor costs such as Brazil and Southeast Asian nations.

**Table 1.3** Main cellulosic ethanol demonstration plants in the world. (Output capacity >1000 t year$^{-1}$). (Monot and Porot, 2013; Gnansounou, 2010)

| Plant owner | Location | Input capacity (t year$^{-1}$) | Capacity (t year$^{-1}$) |
|---|---|---|---|
| **European countries** | | | |
| Clariant (ex Sud Chemie) | Straubing, Germany | Agriculture residues, wheat straw | 1000 |
| Abengoa Bioenergy, Biocarburantes Castilla y, Leon, Ebro Puleva | Babilafuente, Salamanca, Spain | 25 000 t/year (barley/wheat straw, corn stover) | 4000 |
| Inbicon (Dong Energy) Kalundborg | Denmark | 30 000 t/year (wheat straw, other lignocellulosics) | 4300 |
| Beta Renewables (JV Chemtex (M&G), TPG, Novozymes) | Crescentino, Italy | Non-food biomass (giant cane, wheat straw) | 40000 |
| **North America countries** | | | |
| IOGEN Corporation | Ottawa, Ontario, Canada | 30 t/d (wheat, barley and oat straws) | 1600 |
| BP (Jennings Demo Facility) | Jennings, LA,US | Sugarcane bagasse, switch grass, wood products | 4180 |
| Blue Sugars Corporation | Upton, Wyoming, US | 33 500 t/y (bagasse, wood) | 4500 |
| **Other countries** | | | |
| Kirin Brewery | Japan | | 8000 |
| Bioethanol | Japan | | 1000 |
| Sandong Longlive Bioenergy | China | | 3000 |
| Sandong Wande | China | | 8000 |
| Shandong Xueling Starch | China | | 3000 |
| Thai Roong Ruang Energy | Thailand | | 25000 |

### 1.5 Published works related to ethanol production from rice straw

According to FAO statistics, 2007, world annual rice production was about 650 million tons. Every kilogram of grain harvested is accompanied by production of 1-1.5 kg of rice straw. It gives an estimation of about 650-975 million tons of rice straw produced per year globally. More than half of global produced rice straw is from Asian countries, as rice is widely grown crop in China (30%), India (21%), and followed by Vietnam, Myanmar, Thailand, and the Philippines. In Asia, rice straw is the major field-based residue, equal to 668 million tons annualy and this amount could produce the theoretically 282 billion liters of ethanol (Binod *et al.*, 2010). However, due to limitation of rice straw such as low bulk density, slow degradation in soil, an increasing proportion of rice straw undergoes field burning as a common way of disposition. This waste of energy is added to the great demand for reducing GHGs emission as well as air pollution (Gaddle *et al.*, 2009). As climate change is extensively recognised as a threat to the sustainable development, there is growing interest in alternative uses of agricultural residues for energy applications. During last decade A number of works on ethanol production from rice straw have been increased significantly with notable contributions of researches from Asian countries, where rice is main crop.

Most of researches in universities and institutions worldwide have focused on developing conversion technologies in each step of the whole production process (pretreatment step, fermentation, saccharification, utilization of lignin, a by-product of the ethanol production process) to optimize conditions for the production process, reduce energy consumption and PC. Collection of rice straw is laborious and its availability is limited to harvest time, thus some works on logistics of collection, baling, transportation and storage rice straw have been conducted. Technologies and methods in baling, handling rice straw have reduced delivered cost of rice straw.

The potential of ethanol production from rice straw was researched in South East Asia. The total ethanol produced from rice straw in 6 countries in Southeast Asia can reach maximum of 23.8 billion L, or more than 30 % gasoline consumption can be substituted by ethanol produced from rice straw (Yano *et al*., 2009). The recent technologies applied for ethanol production process, from 1 dry ton of rice straw can obtain 125 L- 250 L ethanol with or without $C_5$ sugar (xylose) fermentation, respectively.

To understand the PC of ethanol produced from rice straw, studies on techno-economic analysis of ethanol from rice straw are rare as the production technologies are still un-matured in many countries and few pilot plants are existed. The latest research from Japan reported high ethanol production cost, around 1.8 $\$L^{-1}$ as the high delivered cost of rice straw, energy consumption, and small plant‟s capacity (Yanagida *et al*., 2010).

However, recent advances in enzyme technology for conversation biomass into sugars; development of energetic microorganisms that efficiently convert both $C_5$ and $C_6$ sugars into ethanol; innovative pretreatment technologies as well as technologies for saving energy and production of value-added products developed in the world have brought significant progress in lignocellulosic ethanol research (Binod *et al*., 2010). With the advance of these technologies and other sophisticated technologies and their efficient combination, the process of bioethanol production from rice straw will be proved to be a feasible technology in very near future.

## 1.6 Bioethanol production and consumption in Vietnam

For years, Vietnam produced bioethanol mainly for brewery and chemical industries, from starch materials such as rice, sweet potato, and from sugarcane molasses. The plants' capacity was small, and the total country's ethanol output was only 76 million liters in 2005. Bioethanol production in Vietnam has been sharply increased since 2010, the government of Vietnam (GoV) approved the scheme on development of biofuel up to 2015, with a vision to 2025 (with efforts to develop alternative fuels to partially replace conventional fossil fuels, thus contributing to assuring energy security and environmental protection (Decision No. 177/2007/QD-TTG, 2007). Since 2007, the GoV has provided incentives for investments on biofuel production projects. Companies investing in bioethanol production have received preferential treatments such as income-tax exemptions, tariff exemption on materials, imported equipments, and subsidies for renting land over the next 20 years.

Table 1.4 shows the list of bioethanol plants with capacity of more than 50 ML/year. Some of these plants have been operating since 2010. The bioethanol plants located across the country and the main raw material for ethanol production are cassava, sugarcane molasses. Not all of these plants produce fuel ethanol, some of them are producing bioethanol for other uses: as medicine, main material in brewery industry and solvent in many other industries.

In concern with the government's Biofuel Development Program, some large-scale plants which produce more than 50 million liters of bioethanol a year are in operation, with the construction of other plants moving forward as well (Table 1.4). The total production capacity is planned to reach 822.7 million liters (660,000 tons) by 2013. With such production capacity Vietnam will adequately be able to cover its production target of 250,000 tons for 2015 (Asia Biomass Office, 2010 and 2011b).

According to Vietnam News, On August 1st, 2010, E5 (a mixture of 5% ethanol and 95% unleaded gasoline A92) has been selling at 20 filling stations located in 5 major cities. It is expected to broaden the network of E5 supply at 4,300 points nationwide in the next two years. However, up to date, only 150 of 12,000 petrol stations nationwide have sold the E5 bio-fuel. The reasons are lack of government mandate, customer are not confident to use a new fuel that they do not know much about its benefit, and incentives for bioethanol consumption are not so much significant. Weak domestic demand on bioethanol has forced bioethanol companies export ethanol to neighbouring countries (the Philippines, Singapore) with low prices and some bioethanol plants have delayed their production, or do not produce with their full capacities. Consequently, the delay had negatively impacted on the region's socio-economic developments, farmers were very worried that they could not sell cassava to the factory. To deal with this hardship, Vietnamese Government has announced that it would make E5 compulsory from late 2014 in certain built-up ethanol plant's areas and nationwide from December 2015. It is forecasted that ethanol producers will have a stable market with better sales and farmers will no longer suffer huge volume of unsold cassava (Vietnam News, 2011a; 2011b and 2013).

**Table 1.4** Bioethanol plants in Vietnam, updated to 2012 (Biofuel database in East Asia by ABO; Le *et al*., 2011 and Vietnam News).

| Number | Company | Productivity (ML/year) | Situation |
|---|---|---|---|
| 1 | Dong Xanh Joint Stock Company | 125 | In operation |
| 2 | Tung Lam Company Ltd. | 70 | In operation |
| 3 | Joint Stock Company Petrol.& Biofuel | 100 | In operation |
| 4 | Midlands Central biofuel Joint Stock Company | 100 | In operation |
| 5 | VN Oil Company | 100 | In operation |
| 6 | Tan Phat Joint Stock Company | 50 | Under construction |
| 7 | Dakto Bio-ethanol factory | 65 | In operation |
| 8 | Thao Nguyen Joint Stock Company | 100 | Start operation in 2012 |
| 9 | Thai Viet Joint Stock Company | 62.7 | Start operation in 2013 |
| 10 | Dai Viet Joint Stock Company | 50 | Start operation in 2013 |
| Total | | 822.7 | |

## 1.7 Vietnam energy and government policies supporting development of renewable energy

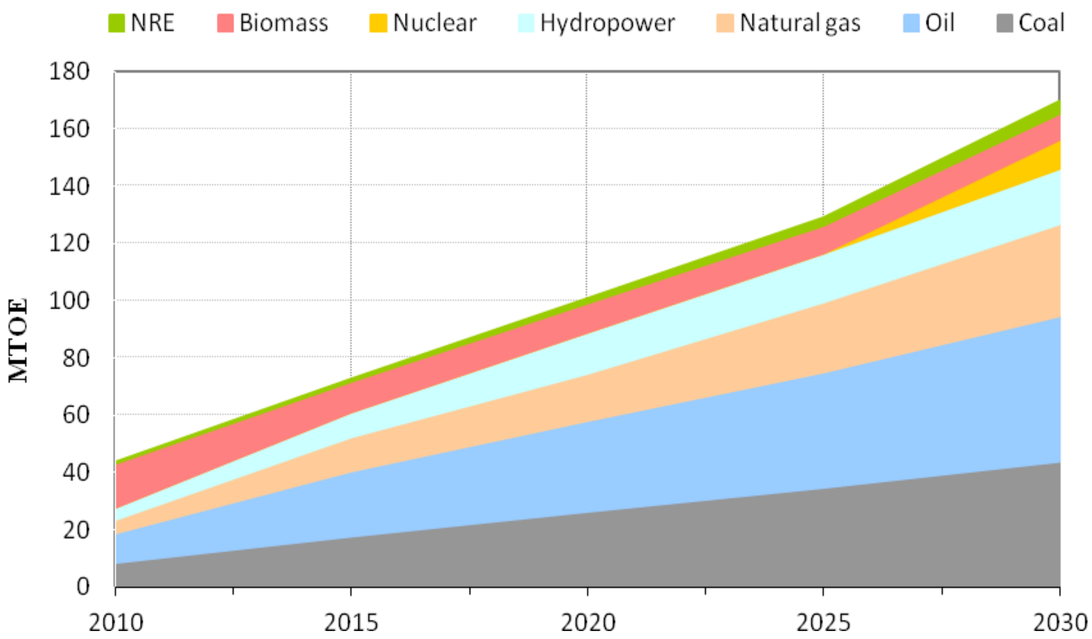


**Figure 1.4** The scenario of energy consumption in Vietnam up to 2030 (Adapted from Vietnam Institute of Energy, 2012).

In the last decade, fast industrialization and the socio-economic development of Vietnam lead to its rapidly growing energy consumption. The country was a net energy exporter during 1990-2010, and currently has been a net energy importer. An increased dependency on fossil fuels is foreseen. The scenario of increasing energy consumption has been anticipated (Figure 1.4) (Vietnam Institute of Energy, 2012), in which, Vietnam's targets to diversify energy sources, such as nuclear power and renewable energy, increase share of these types of energy in total commercial primary energy and reduce traditional use of biomass energy.

The followings are energy and environmental policies that support the development of renewable energy (Biomass Business Opportunities Vietnam, 2012; TM Do and D Sharma, 2011):

1. Decision 1208/QD-TTG by prime minister (approved on July 21, 2011). Title: National power development plant period 2011-2030 (master plan VII). One of the objectives is to increase the share of renewable energy in total commercial primary energy from 3% in 2010 to 5% in 2020 and 11% in 2050.

2. Decision 2149/QD-TTG by prime minister (approved on Dec 17, 2009). Title: National strategy on comprehensive management of solid wastes for period up to 2025, vision to 2050. The objectives include recycling, reuse and energy recovery from solid wastes.

3. Decision 1855/QD-TTG by prime minister (approved on July 27, 2007). Title: National energy development strategies for Vietnam up to 2020, outlook to 2050.

4. Decision 18/QD-BTC (approved on July 18, 2008). Title: Promulgation of regulation on avoided cost tariff and standardized power purchase agreement for small renewable energy power plants.

5. Decision 58/2008/TTLT-BTC/BTN&MT (approved on July 4, 2008). Title: Guideline on implementation of some articles of decision No.130/2007/QD-TTG on financial incentives for CDM projects. The target are regulations on price subsidy for products from CDM projects, including electricity produced from wind, solar, geothermal, tide, and methane gas.

6. Decision 177/QD-TTG by prime minister (approved on Nov 20, 2007). Title: Bio-energy development study report for period up to 2015, outlook to 2025. the objectives are: in 2010: developments of models for experimenting and using of bio-energy, meeting 0.4% of gasoline and oil demand in country; in 2015: production of ethanol and vegetable oil is 250,000 tons, meeting 1% of gasoline and oil demand in country; in 2025: production of

ethanol and vegetable oil is 1.8 million tons, meeting 5% of gasoline and oil demand in country.

7. Decree 04/2009/ND-CP (approved on January 14, 2009). Title: Decree on incentives, support on environmental protection activities. The decree included regulation on incentives, support on land, capital; tax exemption, reduction of tax, fees for environmental protection activities; price subsidy, support for products from environmental activities. In the list of products with incentives, there is energy generated from waste treatment.

8. Law No 52/2005/QH 11 (approved on Nov 29, 2005). Title: Environmental protection law-2005. Related contents are: environmental protection actions which encourage development, use of renewable energy, GHG emission reduction; development of clean energy, renewable energy and environmental products; organizations or individuals who invest in development, use of clean energy, renewable energy, production of environmental friendly products get support from the state on tax, investment capital, and land for project construction.

### 1.8 Rational and Research targets

Realizing the importance of energy in sustainable economic development, Vietnam has prioritized investment into developing energy sector, in which, diversifying energy supply sources is one of the main targets. So far, all the R&D projects involving in development and utilization renewable energy have received support from the government (Do and Sharma, 2011).

Total primary energy consumption in Vietnam has strongly depended on biomass (wood, agricultural residues). Share of biomass energy has accounted for more than one third of total energy consumption during the last decade. This non-commercialized energy is traditionally use in rural areas, and 80% of households in rural areas has used biomass for cooking and heating. Traditional use of biomass is ineffective in term of energy and harmful to the environment and human health. Extra amount of waste biomass also creates environmental pollution in some regions with intensively agricultural activities. Thus, GoV has schemed to gradually convert biomass to renewable energy, such as biofuels, electricity by the government to ensure energy security and mitigate environment pollution.

Since 2007, several projects have been conducted to produce electricity from biomass, such as rice husks, sugarcane bagasse with small to medium scales. Many other types of biomass have not been used. Bioethanol production from agricultural residues could be one of the most appropriate renewable energies for Vietnam to be developed. As Vietnam has strongly depended on imported gasoline, and this situation still lasts long as oil refinery industry in Vietnam is incapable. Ethanol is a good additive to gasoline, partly reducing gasoline import and is widely used in transport sector. According to the statistical data of 2010, transport sector accounted for 22% of total energy consumption and produced 16.4% of the country $CO_2$ emission. Bioethanol production from agricultural residues can significantly reduce gasoline import, $CO_2$ emission, increase income for farmers, create jobs, and especially provide an environmentally friendly way to deposit biomass in rural areas.

In 2009, Vietnam has cooperated with University of Tokyo to develop a project titled "Sustainable Integration of Local Agriculture and Biomass Industries" in 5 years which designate outputs as developing the key technologies for bio-refinery processes including production technologies of bioethanol from lignocellulosic biomass. Within the project, a pilot plant supported by JICA and JST for producing ethanol from rice straw was built in the South of Vietnam for promoting research and developing technologies for cellulosic ethanol production using the abundant biomass supplies from the Mekong Delta area. Nevertheless, to promote cellulosic ethanol production in Vietnam, additional concerns other than conversion technologies should be addressed. Based on the above mentioned, I undertook research, titled **"Evaluation of the Potentials for Development of Ethanol Production from Rice Straw in Vietnam"**, with the following targets:

1. Discover the availability of agricultural residues (rice straw, rice husks, sugarcane bagasse, cassava waste, etc.) for ethanol production in Vietnam based on the annual-generated amount, current application of these residues, and point out the appropriate type of residues for ethanol production, that is rice straw.
2. Propose the best location to set up ethanol facilities based on quantity, density, availability, and distribution by region/season; and assuming the amount of ethanol can be locally produced.
3. Estimate delivered rice straw costs; calculation of the ethanol facility"s size (facility"s capacity) could be built and propose optimal plant size to minimize ethanol production cost by region in Vietnam.
4. Sensitivity estimation of ethanol PCs via techno-economic analysis to foresee the ethanol PCs in Vietnam and discussion on how to reduce PCs.
5. Discuss on expected environmental socio-economic benefits, as well as concerns related to sustainable production and use of rice straw ethanol; how to promote industrial production of ethanol from rice straw in Vietnam.

This research is an unprecedented attempt to assumed ethanol PCs from rice straw in Vietnam via Techno-economic analysis. The idea of developing equation for calculation of Ropt (optimal radious of biomass collection area) is unique and applicable for any bioenergy projects which collect biomass residues on surrounding farms.

This work is expected to provide useful information for interested parties and bio-energy policy makers during the initial stage of evaluating the potentials for development of cellulosic ethanol facilities in Vietnam.

**1.9 Frame works of the study**

The research was divided into 6 Chapters and the relation between these Chapters was shown in Figure 1.5. Five main objectives were implemented in the Chapters 2 - 6. The results of this study have been published in several International Journals in the field of Renewable Energy.

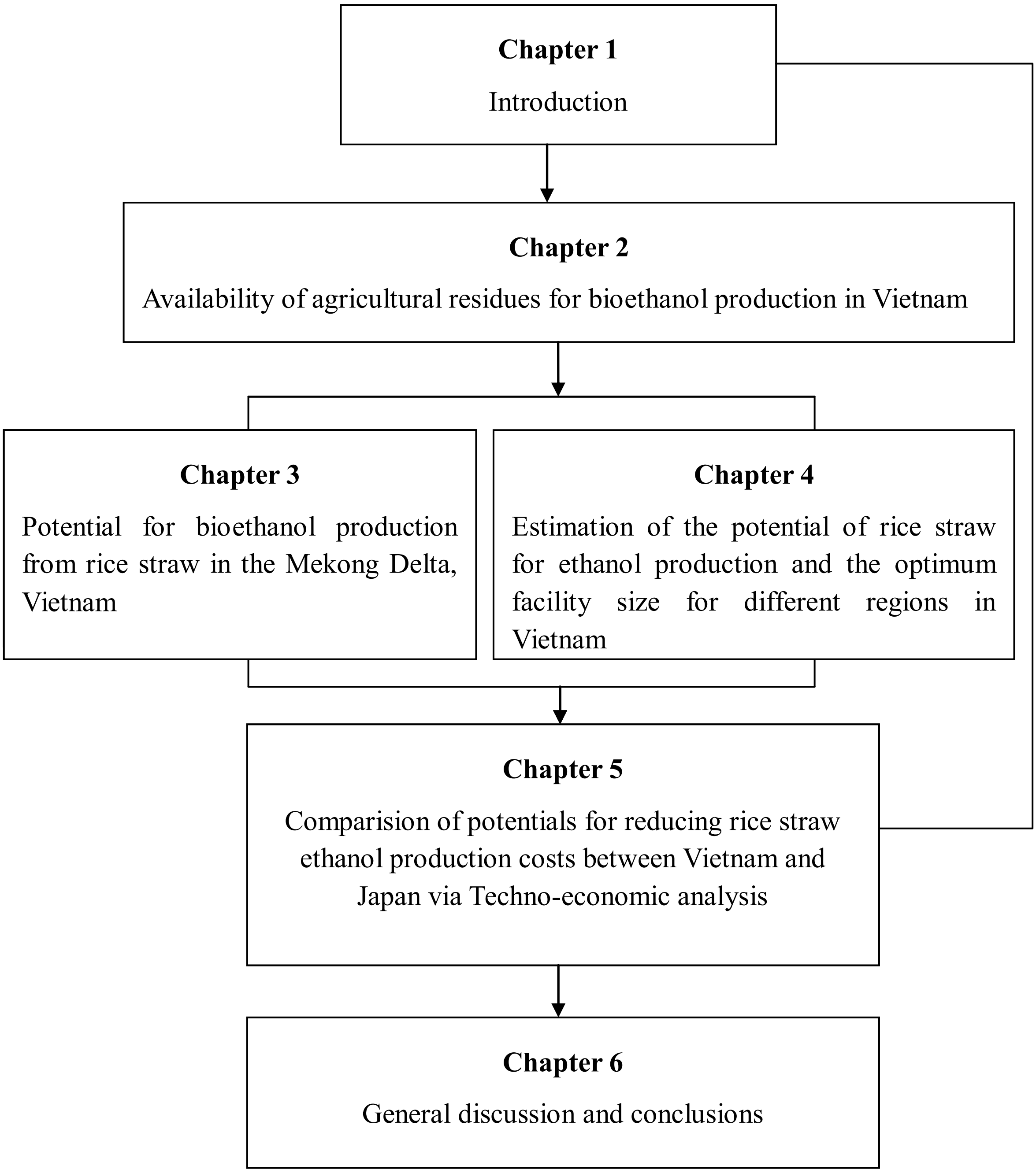


**Figure 1.5** Frame works of the study.

# Chapter 2

## Availability of agricultural residues for bioethanol production in Vietnam

### 2.1 Introduction

Among all type of residues, agricultural residues could form an important feedstock in the initial phase of building the second generation bioethanol industry as their suitable compositions for ethanol production, ready availability and non-reliance on additional land use or the development of specific cultivation techniques. Furthermore, agricultural residues are produced on every farm, huge amount of unused residues has harmed to the environment and thus utilization of agricultural residues as bioenergy creates opportunities (job, additional income for farmers) and will benefit the environment.

Vietnam is an agriculture-based economy, thus agricultural residues is abundant. Most studies in Vietnam related to biomass potential focus on theoretical potentials only. For instance, it is reported that Vietnam produced about 92 million tons (Mt) of crop and forest residues in 2002, which could be converted to 28 $Mm^3$ of ethanol or 13 Mt of gasoline equivalent. This volume is more than enough to displace the current gasoline consumption (Mibrandt and Overend, 2008). According to one report, the total rice straw and sugarcane bagasse generated in Vietnam could be used to produce around 5,090 million liters (ML) of ethanol (Yano *et al.*, 2009). Other reports have demonstrated the great potential of lignocellulosic biomass in Vietnam for the production of fuel or energy (Truong and Cu, 2004; Chau, 2005; Man, 2007). These reports assumed that all generated residues are available for bioenergy production, and would result in a maximum potential for the entire country. In practice, not all generated residues can be used for biofuel production because of scattered abundance and diversion to other uses (e.g., animal fodder, fertilizer, and domestic heating and cooking).

This study will assess the availability of agricultural residues for bioethanol production based on annual generation of residues by type, current utilisation of these residues; then, designate the suitable type of residue for bioethanol production in Vietnam in regard to abundant-available quantity, concentrated distribution, and suitable composition.

## 2.2 Materials and methods

The amount of crop residue generated (dry mass) was estimated on the basis of the data for crop production, residue-to-product ratio (RPR), and moisture content. The RPR is a crop-specific estimator which, when multiplied by the crop yield, identifies the actual amount of residue produced by a unit of harvested crop (Sofer and Zaborsky, 1981).

There were no substantial changes in crop-planted areas in last several years. The data used for the calculation of agricultural residue quantity are based on the average value of crop production over five years (2005–2009) obtained from the Statistical Yearbook of Vietnam 2009. The values for the crop residue ratio and moisture content varied with crop varieties, cultivation conditions, and harvesting methods. This study applied the values used for the estimation of crop-residue production in Asian countries (Matsumura *et al.*, 2005; Koopmans and Koopejan, 1997).

For the information involved in biomass utilization, data have been collected in a systematic and active way. The author has accessed the website as well as visited most leading organizations in the field and agricultural regions for background information and data.

### 2.3 Agricultural residues: generation and current utilization

#### 2.3.1 Cash crops' residues

Coconut and coffee are two important cash crops in Vietnam in value and quality, thus it is expected that processing of these crops could create a large amount of residues. The annual generation and current practices of their residues is shown in Table 2.1.

- *Coconut*: Vietnam is the world largest exporter of coconuts for fresh consumption, with high demand coming from China. Vietnam has 130,000 ha coconut plantations and harvests around 700 million nuts yearly. Coconut cultivation is concentrated in the Mekong Delta, which generates 84% of the nation's total production. 31% of annual nuts has been processed to coconut candy and desiccated coconut for internal export; 30% nuts processed to coconut candy for local market; 32% raw nuts exported internationally (husk removed locally), 7% raw nuts sold locally for consumption.

**Table 2.1** Summary of the generation and current practices of coconut and coffee residues in Vietnam.

| Crop | Planted area (ha) (yield- t $ha^{-1}$) | % of resource is residue or waste | Generation (ton) | Current practices |
|---|---|---|---|---|
| *Coconut* | 130,000 ha<br>13 t/ha, 84% area is located in the Mekong Delta | 30% weight is husk, plus leave and bark it is 6.5 t/ha of fuel wood | Husk: 975 t<br>Fuel wood: 1.6 Mt<br>Pith:1 Mt | 100% shell: activated carbon or use as fuel<br>96% husk: processed into coir |
| *Coffee* | 500,000 ha<br>(1.8 t/ha). 7% Arabica (in the North), 93% Robusta (in the Central Highlands) | 15% of the dried cherry weight | 135,000 t | Combusted, fertilizer, dumped |

Source: Biomass Business Opportunities Vietnam - March 2012.

The residues from nut processing are husk and shell. Shells are practically 100% utilized, either for production of activated carbon or as fuel for domestic or industrial thermal application. 96% of coconut husks are processed into coir, which is the fibrous material and used for making ropes, mats, nets and a variety of products (Table 2.1). The by-product of making coir is a fine dust called pith. Pith is applied as a plant growing material and soil conditioner, however an approximate amount of 80,000 tons is dumped into the Mekong river, thus , creates an environmental burden (Biomass Business Opportunities Vietnam, 2012).

- *Coffee*: Vietnam today ranks as the world‟s second largest coffee producer, after Brazil (Vietnam Agricultural Outlook Conference, 2011). Coffee is the second most important export commodity in Vietnam in value and quantity (FAO Statistic, 2010). There are 500,000 hectares of coffee plantations in Vietnam. This is made up of 93% Robusta concentrated in the central highlands and 7% Arabica grown in the north. The majority of Vietnamese coffee is harvested between the months of October and January. 85% of the coffee production is carried out by small holders (typically less than 2 hectare land tenure) and 15% is state-owned (larger farms). In Vietnam three different processing technologies are used; wet processing for Arabica, semi-wet or dry processing for Robusta. The objective of each process is to remove husk and flesh from the cherry, which in turn becomes the coffee bean. The different processing technologies produce residues with different characteristics in regard to moisture and composition. Coffee residues represent 15% of the cherry weight when dried. Average coffee yield per hectare is 1.8 tons, thus there is 270 kg of residues per hectare resulting in 135,000 tons total in Vietnam (Table 2.1). Current practices of husk disposal are either burned out in the open or disposed along ways and countryside, either as a fertilizer or just left on the road. In semi-wet processing systems, water is reutilized and sludge is used as fertilizer. No integration of the residue into the productive chain energy supply in Vietnam has been identified; therefore within wet and semi-wet processing utilization of sludge for biogas and electricity generation is a promising opportunity, particularly in Arabica. Residues from dry processing coffee beans are sometimes used as a primary fuel source for coffee driers at some small-scale facilities.

### 2.3.2 Annual food crops' residues

Table 2.2 shows the quantity of residues generated annually from food crops. Residues generated from rice cultivation account for 74.7% of the total residues. This rice cultivation residue comprises rice straw and rice husk at levels of 49.6 Mt (62.5%), and 9.7 Mt (12.2%), respectively. This rice straw quantity is 5-fold bigger than that in the case of Japan (9.6 Mt), and almost double of that for Thailand (32.9 Mt) and Myanmar (34.4 Mt) (Matsumura *et al.*, 2005; Yano *et al.*, 2009). The huge amount of rice straw generated inVietnam, mainly comes from the Mekong River Delta (50%) and Red River Delta (18%) - the two largest rice production regions in Vietnam. Rice is harvested in three seasons of spring, autumn and winter. After rice, sugarcane and corn contributed to a quite large amount of residue. Other crops produce much smaller quantities of residues than these main crops (rice, sugarcane, and corn); thus, these minor residues can be neglected for their contribution to the total of agricultural residues.

- *Rice*: Vietnam is the second biggest rice exporter in the world. During the last 5 years, rice production in Vietnam has increased steadily, reaching approximately 40 Mt of paddy in

2010.

Rice straw and rice husk are residues from harvesting and processing of rice production. While rice straw is mainly left in the fields after harvesting, and is not utilized to nearly the same extent, rice husk is produced in thousands of rice mills all over the country and currently used in many different ways. Traditionally, rice husk is used for domestic cooking, as fuel for brick kilns. Recently, several projects utilising rice husk for power generation have been developed. Six 10MW rice husk-fired power plants in provinces of the Mekong Delta region have been developed. Each 10MW rice husk power plant consumes 85,000 tons of rice husks per year (Biomass Business Opportunities Vietnam, 2012). In the last 5 years, production of rice husk briquettes have become more common, supplying fuel for small and medium industries boilers in Vietnam. In Mekong Delta region paddy drying systems consume about 100,000 tons of rice husks. Recent works are underway to develop rice husk gasification systems for use in brick kilns and instead of direct combustion.

**Table 2.2** Annual generation of crops' residues by type.

| Crop | Residue type | Residue ratio | Moisture content [%] | Generation (dry $10^3$ ton $year^{-1}$) | Share [%] |
|---|---|---|---|---|---|
| Rice | straw | 1.5 | 15 | 49,592 | 62.5 |
| | husk | 0.267 | 2.37 | 9,658 | 12.2 |
| Corn | stalk | 2.0 | 15 | 7,123 | 9.0 |
| | cob | 0.273 | 7.53 | 1,058 | 1.3 |
| Cassava | husk | 0.2 | 11.11 | 745 | 0.9 |
| | stalk | 1.14 | 11 | 1,395 | 1.8 |
| Sweet potato | stalk | 0.2 | 25 | 1,217 | 1.5 |
| | peeling | 0.03 | 50 | 122 | 0.2 |
| Sugarcane | bagasse | 0.29 | 50 | 2,333 | 2.9 |
| | tops/leaves | 0.3 | 10 | 4,345 | 5.5 |
| Groundnut | husk | 0.477 | 8.2 | 220 | 0.3 |
| | straw | 2.3 | 15 | 984 | 1.2 |
| Soya-bean | straw | 2.5 | 15 | 389 | 0.5 |
| | pod | 1.0 | 15 | 156 | 0.2 |
| Total | | | | 79,336 | 100 |

Rice straw was used for domestic cooking in rural areas in the past, but improved living conditions have ended this practice. Nowadays, rice straw is utilised for cattle feeding, pig bedding, mushroom cultivation, potato planting, and soil incorporation or bio-fertilizer. However the ratio of using rice straw is just from 10-25% depending on the regions (Truc and Ni, 2009; Biomass Business Opportunities Vietnam, 2012). A huge amount of rice straw is inappropriately deposited by burning on the fields or dumping in the river, and creating environmental burden.

- *Sugarcane*: The production of sugarcane in Vietnam has steadily decreased in the past 10 years with plantation areas dropping from 344,000 ha in 1999 to 266,000 ha in 2010 as the result of low demand of feedstock for sugar factories. In Vietnam, sugarcane is harvested once a year in the north and twice a year in the south. Leaves are stripped off during cane stalk harvesting and left on the field to dry to be burned later. Tops of sugarcane is used for feeding cattle or reused for planting. Bagasse is residue recovered as by-product during sugar processing. Current utilisation of bagasse in Vietnam is almost 100%, being used as fuel for process heat or electricity generation in sugar industry.
- *Corn*: Corn production in Vietnam has increased progressively during the last 10 years as the results to increasing demand of animal feed. Corn production increases from 2 Mt in 2000 to 4.6 Mt in 2010. The main producing regions are the north-east (50%) and the south-east (10%) of Vietnam with the remainder scattered throughout the country. The main production seasons are from December to April and from April to August. After corn is harvested, the top part of the corn stalk is used for animal feed. Other residues such as corn cob and stalk are used as cooking fuel.

## 2.4 Rice straw - the most promising residue for ethanol production: quantity and its composition

Among all types of residues, amount of residues generated from cash crops (coconut and coffee) is quite small compared to other crops' residues, but these residues are concentrated at processing plants, so easily be collected for utilization. However, most of coconut residues are currently used, thus could not be available for ethanol production.

Coffee's residue with low moisture content has been used for boiler, residue from semi-wet or wet processing is not suitable for production of ethanol in regard to its high moisture content and low carbohydrate ratio in its composition. For residues from annual crops, as described above, rice straw is the only residue can be available at huge amount for ethanol production.

Rice straw has characteristics that make it a potential feedstock for fuel ethanol production. It has high cellulose and hemicellulose contents that can be hydrolysed into fermentable sugars. Chemical composition and theoretical ethanol yield of rice straw is shown in Table 2.3 (Binod *et al.*, 2010). Practical ethanol yield of rice straw with the latest technology developed in Japan is 0.25 (L kg $dry^{-1}$).

Cellulose and hemicellulose are two components can be converted to ethanol, high percentage of cellulose is  a good potential for high ethanol yield. Theoretical yield of ethanol from rice straw is 110 gallon/dry ton, higher than that from forest thinning (81.5 gal/ dry t), slightly lower than that from bagasse (111.5), corn stove (113) and mixed paper (116.2), and lower than from corn grain 124.4 gal/ dry t (feedstock for the first EtOH generation).

Considering its abundant-available supply, concentrated distribution at the two delta regions, as well as its suitable composition for ethanol production, rice straw becomes the most promissing potential feedstock for ethanol production among agricultural residues in Vietnam. Theoretically, as approximately 20% rice straw is used for other purposes, 80% of the total rice straw generated, or approximately 40 Mt is avalable for ethanol production per year. However, depending on the landscape and field level factors (the collection fraction subject to environmental restrictions; accessibility or weather inhibiting factors) , the amount of rice straw can be practically used for ethanol industry will be in the rage of 20-50% of the total generated quantity or 10-25 Mt per year (Kunimitsu and Ueda, 2013).

**Table 2.3** Chemical composition and theoretical ethanol yield of rice straw (Binod *et al*., 2010).

| | |
|---|---|
| Cellulose | 32-47 % |
| Hemicellulose | 19-27 % |
| Lignin | 5-24 % |
| Theoretical ethanol yield | 0.42 (L/kg dry)<br>or 110 (gal/Mt dry) |

## 2.5 Conclusion

Agricultural residues, together with wood and charcoal play an important source of energy in Vietnam. This biomass energy is mainly used at households and small industries located in rural areas. Small amount of agricultural residues is used for other purposes, such as making fertilizer, material, animal feed, etc. Recently, with the increasing of living standards, less biomass used for cooking or heating in rural areas, instead it is used for power generation.

Annually, Vietnam has approximately 83 Mt of agricultural residues from food and cash crops, and this huge amount is mainly generated from rice production. Analysis of current practices, distribution, and characteristics of these residues, rice straw appears as the most promising feedstock for bioethanol industry. Practically, 10-25 Mt of rice straw can be available for ethanol production per year.

# Chapter 3

# Potential for bioethanol production from rice straw in the Mekong Delta, Vietnam

## 3.1 Introduction

The Mekong Delta region is recorgnised as the most intensively agriculture-activity region of Vietnam, with huge amount of agricultural products and labor force (more than 80% of its population engaging in farming).

The intensive agricultural activities in this region demand high energy consumption and create environmental problems related to agricultural wastes. Vietnamese goverment has conducted the program named "Sustainable Integration of Local Agriculture and Biomass Industries" to promote utilization of agricultural wastes as model energy (heat, power, biofuels from biomass) to meet the local energy demand for its own scale business, industries, and transportation as well as to reduce environmental pollution caused by the waste biomass (News from JICA Vietnam Office, 2009). The Mekong Delta region is selected as a model pilot. To date, only rice husk, and catfish fat have been used for heat, power and biodiesel production in this region. Rice straw is proposed as feedstock for ethanol production, and a pilot plant for ethanol production from rice straw was launched at Ho Chi Minh City University of Technology with support from JICA (Japan International Cooperation Agency) and JST (Japan Science and Technology Agency) in 2010 (Kunimitsu and Ueda, 2013). The pilot plant is a facility to help Vietnamese scientists in to develop and test key technologies for rice straw ethanol production process.

To contribute for successful implementation of bioethanol production from rice straw in the Delta, this research aims to assess the potentials for ethanol production from agriculture residues in this region on the basis of availability, sub-region, and seasonal distribution of such residues, and practically estimate ethanol production potential. In addition, this study can contribute to the effective planning and implementation of rural energy intervention programs in the Mekong Delta.

## 3.2 Materials and methods

- Based on statistical data of agriculture production and the current utilization of its residues, promissing potential of rice straw for ethanol production was discussed in the Mekong Delta
- The amount of crop residue generated (dry mass) was estimated on the basis of the data for crop production, residue-to-product ratio (RPR), and moisture content (as showed in the methodology of Chapter 2).
- This study assumed 50% of total amount of generated rice straw can be available for ethanol production, density of available rice straw was calculated by dividing the available amount of rice straw for ethanol production in each sub-region by the area of that sub-region. Rice production by season was used for discussion of rice straw distribution by season.
- The amount of ethanol that can be produced from a dry ton of residue will depend on the composition of the crop residues and the ethanol production methods.

By experimental studies performed at Biomass Technology Research Center (BTRC), AIST Chugoku, Japan, the experimental rice-straw ethanol yield was determined to be 0.126

(L dry $kg^{-1}$). An ethanol production technique based on milling pretreatment and enzymatic hydrolysis was developed (Yano *et al.*, 2009).

The theoretical ethanol yield was calculated by the U.S. Department of Energy (DOE), which assumed that both hexose and pentose sugars are fermented; therefore, ethanol can be produced from rice straw at a rate of 111.5 gallons per dry ton. Depending on the feedstock and the process, the actual yield could be anywhere from 60% to 90% of the theoretical value (Theoretical Ethanol Yield Calculator by ENERGY Efficiency and Renewable Energy (EERE) of DOE. For this study, we assumed an ethanol yield of 60% of the theoretical yield, which would result in 65.9 gallons per dry ton of rice straw, or 0.25 (L dry $kg^{-1}$).

### 3.3 Results and Discussion

#### 3.3. 1 Agricultural production and biomass utilization in the Mekong Delta

The Mekong Delta is one of six administrative units of Vietnam, located in the southern tip of the country, where the Mekong River approaches and empties into the sea through a network of distributaries. Thus, the Delta is endowed with important natural resources: fertile soil and water. This region covers an area of 40,602 $km^2$, 64% of which is used for agricultural production and aquaculture. The population of the region is around 17 million, 80% of whom are engaged in agricultural production (Cuulong Delta Rice Research Institute, 2011).

The comparison of the annual crop production in the Delta with that of the entire country is shown in Table 3.1. Rice produced in this region accounts for more than 50% of the total Vietnamese rice output and is more than that produced in other countries such as the

Philippines (15.97 Mt) or Japan (10 Mt) (Matsumura *et al*., 2005; Lauria *et al*., 2005). The Delta possesses a favorable equatorial climate for agricultural production, especially for rice cultivation. About 1.7 million ha of the region is under rice cultivation, and most of this area uses the triple rice crop system. Therefore, the total rice-planted area in the Mekong Delta is 3.859 million ha, which corresponds to more than 50% of the rice-growing area in Vietnam, with an average yield of more than 5 tons $ha^{-1}$. This region is also famous for sugarcane production and accounts for one third of the total annual sugarcane output in Vietnam.

**Table 3.1** Annual crop production in Vietnam and the Mekong Delta (General Statistics Office, 2009).

| Crop | Planted area [$10^6$ ha] | | Production [$10^6$ ton] | | % of the total country"s crop output |
|---|---|---|---|---|---|
| | Whole country | Mekong Delta | Whole country | Mekong Delta | |
| Rice | 7.414 | 3.859 | 38.725 | 20.682 | 53.4 |
| Maize | 1.126 | 0.041 | 4.531 | 0.230 | 5.1 |
| Sweet potato | 0.162 | 0.013 | 1.324 | 0.242 | 18.3 |
| Cassava | 0.558 | 0.007 | 9.396 | 0.107 | 1.1 |
| Sugarcane | 0.271 | 0.065 | 16.128 | 5.084 | 31.5 |
| Groundnut | 0.256 | 0.014 | 0.534 | 0.043 | 8.1 |
| Soya-bean | 0.192 | 0.007 | 0.269 | 0.016 | 5.8 |

In addition to annual crops, perennial crops such as coconut are abundant in the Delta: 60% of the 130,000 ha coconut plantations in Vietnam is located in this region. Annually, around 3 Mt of coconut residue is generated, and mostly exploited for producing handicrafts, exported fibers, charcoal, growing materials, etc. (Truong and Cu, 2004). However, the most abundant source of biomass in the Delta is mainly from rice cultivation (Tu *et al*., 2010). Rice husks and sugarcane bagasse have been the main agricultural residues used for energy supply in the Delta. Approximately 80% of the bagasse generated is used for the production of electricity, heat, and steam in sugar plants and small mills (Institute of Energy, Vietnam, 2006). Rice husks are used as the main energy source in brick kilns, homemade alcohol production, rice dryers, and power co-generation plants. It was reported that the electricity and heat energy obtained from rice-husk burning in furnaces, kilns, or stoves are in high demand by the Mekong Delta"s rural industries, in both the present and the future (Tu *et al*., 2010). Currently, rice straw and other agricultural wastes are not popularly used for energy supply and have been dumped into rivers or burnt openly in the fields, causing environmental problems in the region. Thus, technologies to convert agricultural wastes into energy have been promoted to satisfy the energy demands within the community of the Delta and conserve the environment.

### 3.3.2 Agriculture residue generation and distribution of the most potential residue for ethanol production in the Mekong Delta

#### 3.3.2.1 Agriculture residue generation

Table 3.2 shows the quantity of residue generated annually. Residues generated from rice cultivation account for 90% of the total residues, and represent the major part of the total agricultural residues in the Mekong Delta. This rice cultivation residue comprises rice straw and rice husks at levels of 26 Mt (75%), and 5.4 Mt (15%), respectively. This rice straw quantity is more than double that in the case of Japan (9.6 Mt), and equal to 75% of rice straw generated in Thailand (32.9 Mt) and Myanmar (34.4 Mt) (Matsumura *et al*., 2005; Yano *et al*., 2009). The huge amount of rice straw generated in the 4 million ha area indicates that the density of rice straw is higher in this region than in the other regions and countries. After rice, sugarcane contributed a quite large amount of residue. The quantities of sugarcane tops/leaves and bagasse annually generated are 1.37Mt (4%) and 0.74 Mt (2.1%), respectively. Other crops produce much smaller quantities of residues than these main crops (rice and sugarcane); thus, these minor residues can be neglected for their contribution to the total of agricultural residues.

**Table 3.2** Annual agricultural residue generation in the Mekong Delta.

| Crop | Production [$10^3$ ton $year^{-1}$] | Residue | Residue ratio | Moisture content [%] | Residue generation [dry $10^3$ ton $year^{-1}$] |
|---|---|---|---|---|---|
| Rice | 20682 | Straw | 1.5 | 15 | 26,370 |
| | | Husk | 0.267 | 2.37 | 5,391 |
| Maize | 230 | Stalk | 2 | 15 | 391 |
| | | Cob | 0.273 | 7.53 | 58 |
| | | Husk | 0.2 | 11.11 | 41 |
| Sweet potato | 242 | Stalk | 1.14 | 11 | 246 |
| Cassava | 107 | Stalk | 0.2 | 25 | 16 |
| | | Peeling | 0.03 | 50 | 2 |
| Sugarcane | 5084 | Bagasse | 0.29 | 50 | 737 |
| | | Tops/leaves | 0.3 | 10 | 1373 |
| Groundnut | 43 | Husk | 0.477 | 8.2 | 19 |
| | | Straw | 2.3 | 15 | 84 |
| Soybean | 16 | Straw | 2.5 | 15 | 34 |
| | | Pod | 1 | 15 | 14 |
| Total | | | | | **34,774** |

#### 3.3.2.2 Availability and distribution of rice straw

As mentioned above, rice husks and bagasse mostly have been used for heat, steam, and electricity generation in rural industries and other power cogeneration plants in the Delta. Considering its abundant supply as well as its suitable composition for ethanol production, rice straw will be a potential feedstock for ethanol production in the region.

In the Mekong Delta, most of rice straw generated has been either plowed in or burned directly on the field. It was stated that more than 80% of the generated rice straw is burned on fields (Truc and Ni, 2009). Some rice fields have no rice straw collected, especially in the winter rice season. Another paper reported that only 10% of the collected rice straw is used for the feeding and bedding of cattle or buffaloes, mushroom cultivation, composting, while 90% of the remainder is used for energy supply (Tu *et al.*, 2010). Even though burning adds a considerable amount of ash to the soil and improves its fertility, it causes air pollution. Thus, large amounts of generated rice straw should be collected in part for ethanol production. Considering the possibility of collection and other uses, we assumed that 50% of the rice straw generated each year could be used for sustainable ethanol production.

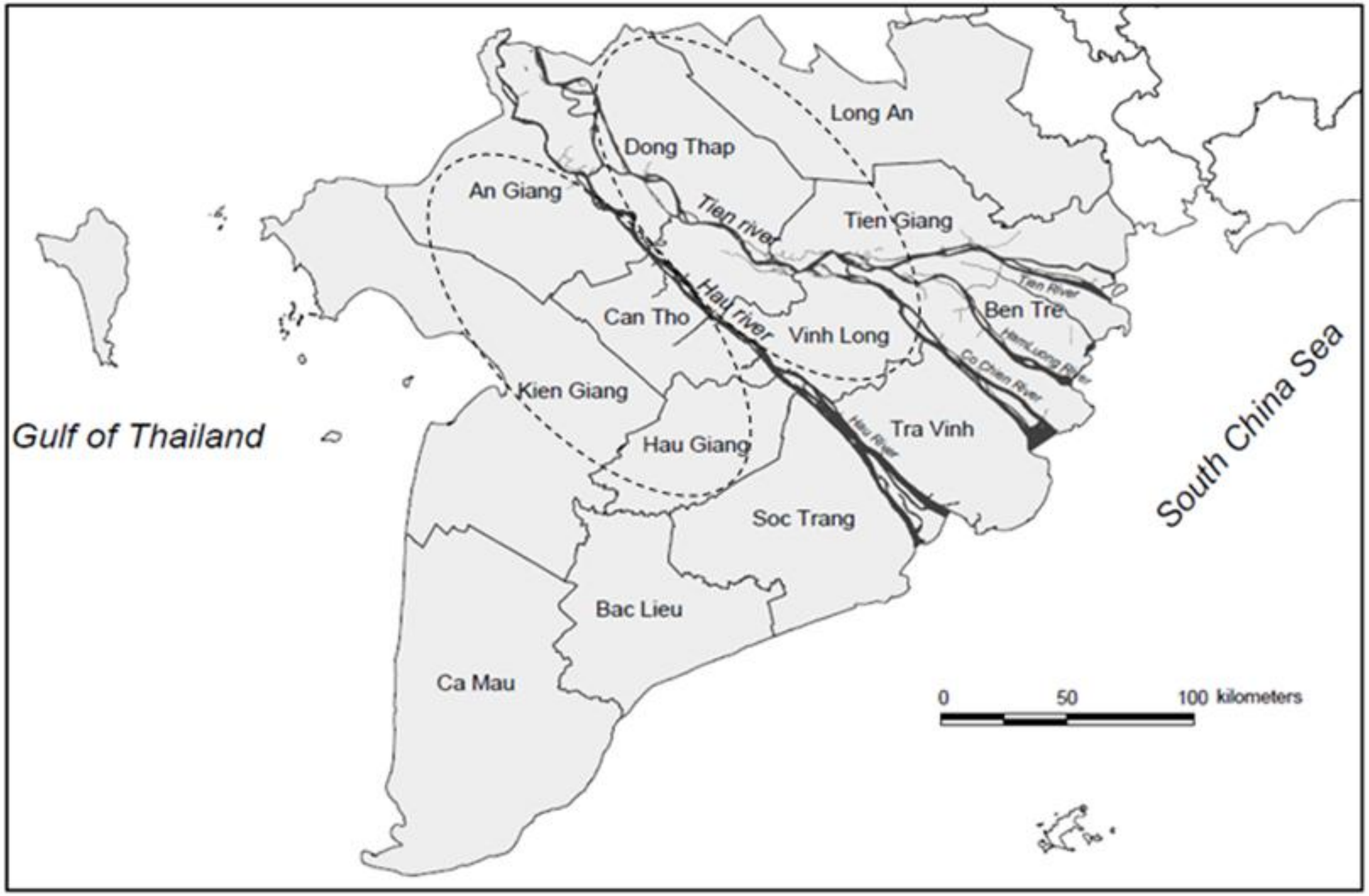


**Figure 3.1** Sub-regions in the Mekong Delta, Vietnam. (Mekong Delta map, 2011)

**Table 3.3** Annual rice straw availability for ethanol production in the Mekong Delta by sub-region.

| Sub-region | Area [$10^3$ ha] | Rice straw [dry $10^3$ ton $year^{-1}$] | | |
|---|---|---|---|---|
| | | Generation | Availability | Share [%] |
| Long An | 449.4 | 2,637 | 1,319 | 10 |
| Tien Giang | 248.4 | 1,846 | 923 | 7 |
| Ben Tre | 236 | 527 | 264 | 2 |
| Tra Vinh | 229.5 | 1,319 | 659 | 5 |
| Vinh Long | 147.9 | 1,319 | 659 | 5 |
| Dong Thap | 337.5 | 3,428 | 1,714 | 13 |
| An Giang | 353.7 | 4,219 | 2,110 | 16 |
| Kien Giang | 634.6 | 3,956 | 1,978 | 15 |
| Can Tho | 140.2 | 1,846 | 923 | 7 |
| Hau Giang | 160.1 | 1,319 | 659 | 5 |
| Soc Trang | 331.2 | 2,110 | 1,055 | 8 |
| Bac lieu | 258.5 | 1,055 | 527 | 4 |
| Ca Mau | 533.2 | 791 | 396 | 3 |
| Mekong Delta | 4060.2 | 26,370 | 13,185 | 100 |

The amounts of rice straw could be used annually for ethanol production in the Delta and its sub-regions are shown in Table 3.3. The total amount of available rice straw for ethanol production in the Delta is around 13.2 Mt year$^{-1}$, this amount is even greater than the total rice straw generated each year in other countries such as Korea and Japan (Matsumura *et al*., 2005; Kim *et al*., 2010). The Mekong Delta region is divided into 12 provinces and one municipality (Can Tho) - or 13 sub-regions (Figure 3.1) (Mekong Delta map, 2011). The available amount of rice straw is different in each sub-region. An Giang, Kien Giang, Dong Thap, and Long An have more rice straw than do the other sub-regions, and they account for 16%, 15%, 13%, and 10% of the total rice straw in the Delta, respectively. The quantity of available rice straw in An Giang alone is 2.1 Mt year$^{-1}$, which corresponds to almost the same as the total rice straw generated in Malaysia (2.2 Mt year$^{-1}$) (Yano *et al*., 2009).

To consider the high potential of rice straw as a feedstock supply for ethanol production, assessment of the rice straw density by location (sub-region) and season is essential for the proper planning of activities that precede actual utilization. Such activities include locating ethanol plant building sites, as well as collection, transport, and storage.

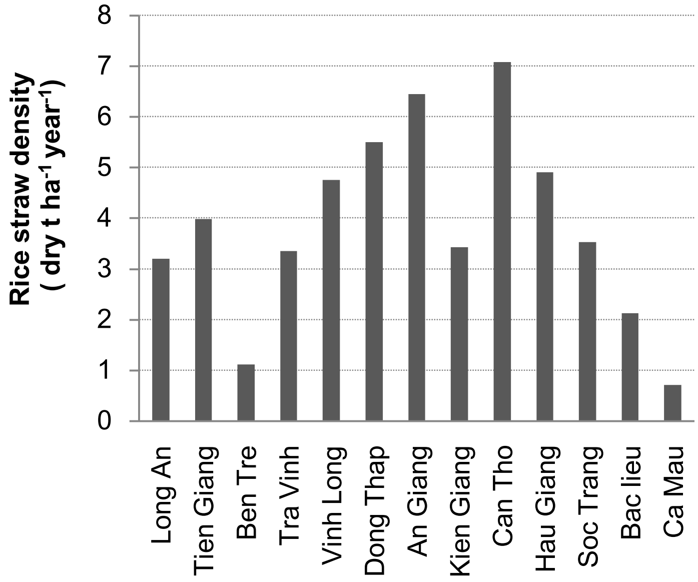


**Figure 3.2** Density of available rice straw for ethanol production by sub-region.

The distribution of the available rice straw is represented by the sub-regional rice straw densities (mass/area/year, Figure 3.2). Rice straw is available in high density in Can Tho, An Giang, Dong Thap, Hau Giang, Vinh Long, and Tien Giang, ranging from approx. 4 to 7 tons $ha^{-1}$ $year^{-1}$. Because these sub-regions have high percentages of land use and good soil for rice cultivation, rice yields are more than 6 tons $ha^{-1}$. However, the contribution of rice straw amounts from each sub-region varies because of the disparity in their total areas. Can Tho is the municipality in the Delta, with the highest density of rice straw available for ethanol production (7 tons $ha^{-1}$ $year^{-1}$), but it has a lower amount of rice straw than other sub-regions. An Giang could be considered as the best site in terms of the total amount as well as the high density of rice straw for ethanol production.

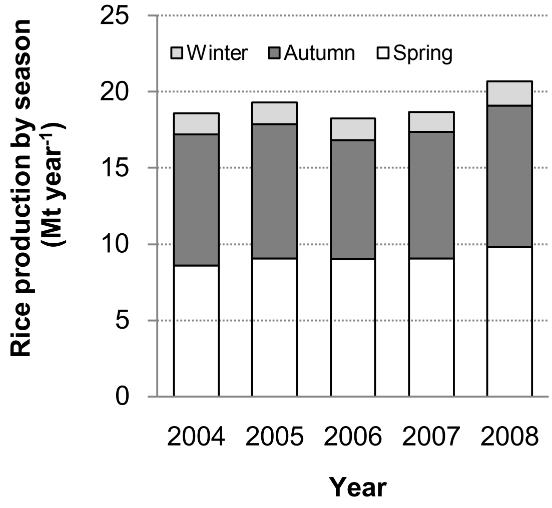


**Figure 3.3** Rice production by season in the Mekong Delta.

In summary, large rice-planted areas with high potential for rice straw collection are located along the upper and mid-banks of the two main rivers, the Tien River and the Hau River (see the dash-circle areas in Figure 3.1). These areas belong to sub-regions: An Giang, Can Tho, Hau Giang, Kien Giang, Dong Thap, Vinh Long, Long An, and Tien Giang. These sub-regions have fertile soil and water from the rivers and are less affected by seawater intrusion due to high tides, floods, and inundation. The annual flooding season in the Mekong Delta lasts for five months, between July and November, primarily in the lower parts of the Delta (Ninh, 2008).

There are three rice seasons in the Mekong Delta: winter, autumn, and spring. The seasonal distribution of rice straw is shown via rice production by season (Figure 3.3). The winter, autumn, and spring rice seasons represent about 7%, 45%, and 48%, respectively, of the total annual rice output in the Delta. Winter rice season starts in the rainy season, in July or August, and ends at the close of the rainy season in November or December. Local rice varieties with low yields (4 tons $ha^{-1}$) that are adapted to deep water are grown in this season. The spring rice season starts at the end of rainy season (November–December) and yields the first harvest in February or March. The autumn rice season starts in May or June and is harvested in mid-August or September. Rice straw generated in the winter season accounts for just 7% of the total supply and is less efficiently collected because of deep water. The rice straw supply is mainly from the rice harvest seasons of spring and autumn, particularly from February to September (Cuulong Delta Rice Research Institute, 2010). Thus, rice straw generated during this time could be collected for ethanol production and other uses. Two main rice-straw-supply seasons per year are considered advantageous because fewer storage yards would be required to ensure a constant supply of feedstock throughout the year, as compared to other countries that have one rice season per year.

### 3.3.3 Estimation of bioethanol production from rice straw

Rice straw has several characteristics that make it a potential feedstock for ethanol production. It has high cellulose (32-47 wt%) and hemicellulose (19-27 wt%) content that can be readily hydrolyzed into fermentable sugars (Nagalakshmi *et al.*, 2010). Additionally, an advantage of rice straw often contains non-structural carbonhydrates, such as starch, sucrose and soluble reducing sugars, that can be defined as readily-recoverable sugars for ethanol fermentation (Binod *et al.*, 2010). Table 3.4 shows the estimates of ethanol production potential from rice straw in the Mekong Delta and the substitution potential of this ethanol for gasoline consumption based on energy content. Depending on the ethanol yield basis applied, the estimated ethanol potential from rice straw in the Mekong Delta could be 1661 ML (case 1) or 3296 ML per year (case 2).

**Table 3.4** Annual potential of ethanol production and gasoline substitution from rice straw.

| | Ethanol yield ($L\ dry\ kg^{-1}$) | Ethanol production (ML) | Gasoline Equivalent (ML) |
|---|---|---|---|
| Case 1 | 0.126 | 1,661 | 1,108 |
| Case 2 | 0.245 | 3,296 | 2,197 |

In case 1, we applied the authentic experimental result - the ethanol yield from rice straw of about 0.126 L dry $kg^{-1}$. This yield is similar to the yields obtained in some Japanese bioethanol plants that use rice straw as feedstock. At the Hokkaido Soft Cellulose Project Plant, the ethanol yield is around 0.126 (v/w) or 0.126 L dry $kg^{-1}$ of rice straw. This plant uses an alkaline pretreatment, cellulase for saccharification, and yeast for ethanol fermentation of glucose, with no xylose fermentation (personal communication).

In case 2, the estimation applied an ethanol yield of 60% of the theoretical yield, about 0.245 L dry $kg^{-1}$. This ethanol yield is almost the same as that obtained at the Soft Cellulose Bioethanol Plant in Akashi, Kobe, Japan. In this plant, 245 L of ethanol can be produced from one dry ton of rice straw, or the ethanol yield is 0.245 L dry $kg^{-1}$. The hydrothermal method is used for pretreatment. After milling, the rice straw is pretreated using steam at 130–300°C and 10 MPa. This pretreatment can automatically separate lignin, and hemicellulose into soluble and insoluble fractions (mainly cellulose). Subsequently, saccharification and ethanol fermentation of hexose and pentose sugars are separately conducted. The efficacy of xylose utilization was confirmed (personal communication).

According to these estimates, the quantity of ethanol potentially produced from rice straw in the Mekong Delta may substitute for an amount of imported gasoline of 1108 ML in case 1 and 2197 ML in case 2. The total gasoline consumption in Vietnam in 2008 was 3405 thousand tons or 4310 ML (100% imported) (IEA Energy Statistic, 2011). In other words, the ethanol production potential from rice straw in this region may substitute for 25.7% to 51% of the total gasoline consumption in Vietnam, as can be seen from 2008 statistics. Applying the case 1 (0.126 L ethanol dry $kg^{-1}$), ethanol produced from rice straw in An Giang alone can reach 265 ML $year^{-1}$. This level of production can meet the target of the Vietnamese government for producing biofuels by 2015, without using food crops such as sugarcane and cassava that have been cultivated for ethanol production (Binh, 2009).

Though rice-straw ethanol yields used for the estimations in this research can be practically achieved at some pilot ethanol plants in Japan, the cost of ethanol produced in Japan is still high for fuel use. Some of the reasons are the high costs of enzymes and rice straw, and the small scale of ethanol production. The rice straw price in Japan was estimated to be about 15 JPY dry $kg^{-1}$ (87 JPY = 1 USD) or 172 USD dry $ton^{-1}$ in 2010, including transportation fees (Yanagida *et al*., 2010). For the amount of rice straw collected in one hectare of paddy field in the Mekong Delta (about 9 dry tons), the current purchase price ranges from 72 to 82 USD for feeding cattle and mushroom cultivation or 8 to 9 USD dry ton$^{-1}$ (not including transportation fees) (Vietnam News, 2011c). Thus, rice-straw costs in the Delta are by far cheaper than those in Japan. Additionally, the substantial amount of rice straw for large-scale ethanol production and low labor costs for bioethanol plant operation could reduce ethanol production costs in the region. To verify this expectation, a techno-economic analysis for bioethanol production from rice straw in this region should be conducted.

The rice-straw ethanol yields used for estimating the ethanol production potential in the present study seem to be more conservative than those used in a previous study (Kim and Dale, 2004). With the development of advanced techniques for more efficient hydrolysis and fermentation, the ethanol production potential from rice straw in this region could surpass our estimation. The ethanol production process employing rice straw will be a feasible technology in the near future (Park *et al*., 2011).

### 3.4 Conclusion

The potential of ethanol production from rice straw in the Mekong Delta was assessed on the basis of feedstock availability and distribution. Rice production in the Mekong Delta was predominant in comparison to other crops, and generated an abundant supply of rice straw (26 Mt year$^{-1}$). Rice straw accounted for 75% of the total agricultural residues generated in the Delta. With its substantial availability as well as its suitable composition for ethanol production, rice straw can be the main feedstock for ethanol production in this region. Considering the possible collection and other uses of rice straw, we assumed that 50% of the rice straw generated annually could be used for sustainable ethanol production. The analysis of the distribution of rice straw by season and sub-region in the Delta showed a great potential of feedstock supply for bioethanol plants in the region. Rice straw is abundant, and provided mainly from the two main harvest seasons of spring and autumn rice. The areas with high densities of rice straw supply are located along the upper and mid-banks of the Hau and Tien Rivers in the following sub-regions: An Giang, Can Tho, Hau Giang, Kien Giang, Dong Thap, Vinh Long, Long An, and Tien Giang.

According to our estimation, the potential of ethanol production in the Delta could be 1661 ML year$^{-1}$, or up to 3296 ML year$^{-1}$ (without or with xylose fermentation, respectively), using current rice-straw ethanol production technologies of Japan. This amounts of ethanol could substitute for 25.7% to 51% of the total 2008 gasoline consumption in Vietnam. This research showed a high potential for ethanol production from rice straw in the Mekong Delta, resulting in the promotion of rural development and polution reduction caused by agricultural waste. As rice straw is readily available, non-reliant on additional land use, and produced on almost every farm, it thus offers the opportunity for the farmer to profit from ethanol production. Promoting ethanol production from rice straw in the Delta will contribute to the sustainable integration of local agriculture and bioenergy production as well as to the energy security of the entire country.

# Chapter 4

## Estimation of the potential of rice straw for ethanol production and the optimum facility size for different regions in Vietnam

### 4.1 Introduction

The global production of ethanol from biomass resources has been increasing dramatically, from 17.25 billion litres in 2000 to 46 billion litres in 2007 (Balat and Balat, 2009). The utilisation of bioethanol as a gasoline substitute is a potential solution in mitigating the effects of greenhouse gas emissions and reducing the dependence on fossil fuels, which are becoming depleted and rising in price. However, using food crops, such as sugarcane, corn, grains, and cassava, for ethanol production will ultimately be limited by land availability, government policy, and alternative uses for these agricultural products (Sainz, 2009). The trend for sustainable ethanol production is to shift the feedstock from edible crops to inedible biomass, such as lignocellulosic biomass (e.g., wood residue, rice straw, and corn stover), which can be converted to fermentable sugars. Rice straw is plentiful and available in many agriculture-economic countries in Asia. Traditionally, open-field burning is the common practice for the disposal of rice straw, although this practice is soon to be prohibited for environmental reasons; hence, using rice straw as a feedstock for bioethanol production can potentially provide a significant portion of transport fuels globally and contribute to the promotion of rural development with fewer environmental impacts (Gaddle *et al*., 2009; Binod *et al*., 2010). Modern conversion technologies for producing cellulosic biomass are under development, and major technological advances have set the stage for a significant expansion of cellulosic ethanol industries during the next few years.

The Vietnamese government has promoted bioethanol development since 2007 (Vietnamese Government Decision No.177/2007/QD-TTG), and ethanol is presently primarily made from cassava and sugarcane molasses to produce the E5 (gasoline with 5% ethanol) that is sold at filling stations across the country. For sustainable biofuel production, the Vietnamese government supports several research programs and lignocellulosic ethanol production projects (News from JICA Vietnam Office, 2009). Rice straw accounts for approximately 62.5% of the total agriculture residues in Vietnam and has been considered as a potential feedstock for ethanol production. To have a broad view of the feasibility of ethanol production from rice straw, initial concerns other than conversion technologies should be addressed. Existing studies for producing cellulosic ethanol primarily focus on feedstock production and conversion technology to minimise the production costs. To minimise the overall production costs, bioenergy development and deployment decisions need to consider the delivered feedstock cost and the optimal facility size for minimal production costs. Thus, the aims of this research were to explore the feasibility cost competiveness of ethanol production from rice straw in Vietnam via the regional distribution of rice straw, its available density for ethanol production, and the delivered rice straw cost; in addition, we further conducted an analysis of the optimal facility size by region.

In the bioenergy industry, selection of the optimal facility size must consider the effect of a number of tradeoffs. The savings resulting from the "economics of scale" are offset by the increased cost of transportation of the feedstock (Aden *et al.*, 2002; Gan and

Smith, 2011). There are several simulation studies that have proposed equations for calculating optimal facility size, but these are complicated and require many input data that are not suitable for the present study (Nguyen and Prince, 1996; Aden *et al.*, 2002). The determination of optimum facility size is independent of the other logistics of feedstock cost, such as payments to farmers and the baling, handling, and storage costs of the straw (distance fixed cost, DFC) (Cameron *et al.*, 2007). For this study, our approach was that an optimal facility size exists when the total of the capital investment (fixed cost) and the transportation cost of the feedstock per unit ethanol production is minimal. The per-unit feedstock transportation cost depends on certain factors, such as the winding nature of the road and hauling cost, whereas the per-unit fixed cost depends on the payback period and scale factor. To understand the effects of these factors on the optimal facility size and to predict the changes in the optimal radius of the collection area ($R_{opt}$) in the future, an equation for the theoretical calculation of $R_{opt}$ was also developed, where $R_{opt}$ determines the optimal facility size.

This work is expected to provide useful information to assist interested parties and bioenergy policy makers during the initial stage of evaluating the potential for development of a cellulosic ethanol facility in Vietnam.

## 4.2 Material and methods

### 4.2.1 Estimation of the rice straw quantity, distribution and available rice straw density for ethanol production by region

- Rice straw quantity: The amount of rice straw generated was estimated from the data for rice production, residue to product ratio (RPR) and moisture content (Risser, 1981). In the literature, the RPR value for a rice crop varied from 1 to 1.6 with different moisture contents (Koopmans & Koppejan, 1997). In this study, we applied an RPR value of 1.5 and a moisture content of 15%.

- The data for the rice production, rice yield, rice planted area, and total area of each region in Vietnam were obtained from the Statistical Yearbook of Vietnam 2009. The average rice straw distribution was calculated as the amount of rice straw divided by the total area.

- Estimation of the available rice straw density for ethanol production: The available rice straw in an area depends on both field and landscape level factors. Therefore, the available density of rice straw was calculated using the following equation (Perlack and Turhollow, 2003; Leboreiro and Hilaly, 2011):

$$D = Y_s \cdot F_c \cdot F_d \cdot F_p \cdot F_a \cdot 100 \quad (1)$$

Where „$D$" is the available rice straw density (dry t km$^{-2}$ year$^{-1}$); „$Y_s$" is the rice straw yield (dry t ha$^{-1}$) (amount of rice straw divided by the rice-planted area); „$F_c$" is the collection fraction subject to environmental restrictions; „$F_d$" is the rice-planted area density (ratio of rice-planted area to total area); „$F_p$" is the proportion of farmers selling the material; and „$F_a$' is the accessibility and/or weather inhibiting factors. In Vietnam, there are two or three rice harvest seasons per year, depending on the region. In this study, we assumed that the values of $F_c$, $F_p$ and $F_a$ were 0.7, 0.8, and 0.3, respectively, for all of the regions.

### 4.2.2 Estimation of the delivered rice straw cost in Vietnam

The delivered cost of rice straw was broken down into farmer payments, baling costs, handling costs (e.g., staking on the field edge and loading and unloading the trucks), and transportation costs. Approximately 80-90% of the amount of rice straw generated was disposed of by open-field burning, however, in some periods of the year, rice straw has a market value (in the field) of around 7 USD ($) dry $t^{-1}$ for cattle feed and mushroom cultivation (Vietnam News, 2011b). This price was applied as the cost of farmer payments.

In Vietnam, rice straw is transported in a loose condition. To use rice straw as a feedstock for bioenergy industries, it should be baled to reduce the transportation costs. We applied the baling and handling cost data from Thailand, where the fuel and labour costs are similar to those in Vietnam. The rice straw is baled to achieve a size of 1.2 × 0.5 × 0.4 (m) – 40 kg for a wet, basic, moisture content of 11%. The baling cost and handling costs were \$9 $t^{-1}$ and \$4.5 $t^{-1}$, respectively (Delivand *et al.*, 2011). The transportation costs depend on such variables as the transportation distance, feedstock moisture, bale density, and road quality. The technical standard for design of rural roads on connecting rural district-commune-village-hamlet-fields in Vietnam was referred (Vietnam Government Decisions, 2010 and 2011) such as road width, weight and speed limit of vehicles for transportation, etc. as well as the opinions from experts in transportation sector to assume the type of truck that can be applicable for delivering rice straw from fields to the facility's gate. As such, we assumed that each truck has a volume capacity of 78 $m^3$ and a loading weight of 6 tons, for the transport of feedstock to an ethanol facility at a cost of \$2 $km^{-1}$ (Vietnam Government Decision, 2011). As mentioned above, the rice straw bale density was 40 kg $bale^{-1}$ (0.24 $m^3$), for a wet, basic, moisture content of 11%. This type of truck can carry 150 bales with the weight of 6 tons, volume of 36$m^3$. Therefore, the hauling cost per-unit weight-distance (Hc) was given by the following equation:

$$Hc = 2(\$\ km^{-1}) / [6\ (ton) \times (1 - 0.11)] = \$0.375\ dry\ t^{-1}\ km^{-1} \quad (2)$$

This study used a hauling cost per distance that was independent of the transportation distance. Thus, the following equation is introduced:

$$\text{Transportation cost / dry ton of feedstock} = Hc \times \text{transportation distance (km)} \quad (3)$$

In calculating the transportation cost of the feedstock, a simple model was applied that assumed a circular collection area, with a facility at the centre; no discrete farm locations were considered, and it was assumed that the farmland was uniformly distributed. The average transportation distance from fields to the facility gate was given by the following (Nguyen and Prince, 1996; Huang *et al.*, 2009):

$$\text{Average transportation distance} = 2/3 \cdot R \cdot \tau\ \text{(km)} \quad (4)$$

Where $R$ is the radius of the collection area (km); and $\tau$ is the tortuosity factor (ratio of the actual distance travelled in a straight-line distance).

The tortuosity factor can be as low as 1.27 for developed agricultural regions, where the area is laid out in a rectangular grid over a flat terrain, and as high as 3.0 for poorly developed regions (Overrend, 1982). In the present study, we assumed $\tau = 1.5$ for a base case. From Eqs.

(3), (4), the per-unit feedstock transportation cost was given by the following:

Per-unit transportation cost ($\$L^{-1}$) = $2/3 \cdot R \cdot \tau \cdot Hc/Y$ (5)

Where „$Y$“ is the ethanol yield (L dry $t^{-1}$). In this study, we applied an ethanol yield of 250 L dry $t^{-1}$. This ethanol yield from rice straw is obtained using recently developed technologies and is equal to 60% of the theoretical yield (Yanagida *et al.*, 2010).

### 4.2.3 Capital investment for developing a cellulosic ethanol facility and the per-unit fixed cost

Capital investment refers to the money to purchase fixed assets, such as land, equipment, buildings, and installation costs. The actual capital investments of cellulosic ethanol plants were obtained from the project data reported to the IEA Bioenergy Task 39 (Bacovsky *et al.*, 2010). The derived capital investment for different sizes of commercial facilities, from 5 to nearly 400 million litres (ML) per year, were used to develop a mathematical equation showing the relationship between the capital investment (fixed cost) and facility size. The equation was as follows:

$$y = a \cdot x^{\alpha} \quad (6)$$

Where „$y$“ is the fixed cost of the facility (Million USD- M$); „$x$“ is the facility size (ML $year^{-1}$); „$a$’ and „$\alpha$“ are specific coefficients; $\alpha$ is also called scale factor, $0<\alpha\leq 1$ (Leboreiro and Hilaly, 2011).

This equation was used to predict the fixed cost of an ethanol facility of a specific size. From the equation, the per-unit fixed cost is ($\$L^{-1}$) can be calculated as $n{\cdot}x^{\alpha-1}/T$, where „$T$“ is the payback period (years). We assumed a payback period of 20 years for a base case.

### 4.2.4 Development of an equation for the theoretical calculation of $R_{opt}$

A simple model was applied that assumed a circular collection area with a facility at the centre; $D$, $Hc$, $DFC$, $Y$, $T$, $a$, $\tau$, and $\alpha$ were constants in such a case. The supposition is that:

Production cost = distance fixed cost of feedstock (DFC) + feedstock transportation cost + fixed cost (7)

For simplicity and without a loss of generality, this supposition can be flexible, if needed, and other components of the conversion cost (e.g., fuel, labour costs) may be added into the production cost. These costs are scale-independent and have no effect on the calculation of $R_{opt}$.

Feedstock amount (Mt) = $\pi \cdot R^2 \cdot D$ ($D$ is calculated in million tons) (8)

Product amount or facility size (ML year$^{-1}$) = $\pi \cdot R^2 \cdot D \cdot Y$ (9)

Per-unit feedstock distance fixed cost (\$/L) = DFC/$Y$ (10)

Total fixed cost per year (M\$ year$^{-1}$) = $a \cdot (\pi \cdot R^2 \cdot D \cdot Y)^{\alpha}/T$ (11)

Per-unit fixed cost (\$/L) = $a \cdot (\pi \cdot R^2 \cdot D \cdot Y)^{(\alpha-1)}/T$ (12)

From Eqs. (5), (7), (10), (12), it is interpolated that:

Per-unit production cost (\$/L) = DFC/$Y$ + $2/3 \cdot R \cdot \tau \cdot Hc/Y + a \cdot (\pi \cdot R^2 \cdot D \cdot Y)^{(\alpha-1)}/T$ (13)

The difference of per-unit production cost approaches zero when $R$ approaches $R_{opt}$. Hence, it follows that:

d(per-unit production cost)/d$R$ = $2/3\tau \cdot Hc/Y + (a/T) \cdot (\pi \cdot D \cdot Y)^{(\alpha-1)} \cdot 2(\alpha-1) \cdot R^{(2\alpha-3)} = 0$ (14)

$R_{opt}^{(2\alpha-3)} = -2/3\tau \cdot Hc/[Y \cdot (a/T) \cdot (\pi \cdot D \cdot Y)^{(\alpha-1)} \cdot 2(\alpha-1)$ (15)

$$R_{opt}=\{[3(1\text{-}\alpha)\cdot a\cdot(\pi\cdot D)^{(\alpha\text{-}1)}\cdot Y^{\alpha}]/(Hc\cdot\tau\cdot T)\}^{[1/(3\text{-}2\alpha)]}\ \text{(here, } 3\text{-}2\alpha\geq 1) \quad (16)$$

### 4.3 Results and Discussion

#### 4.3.1 Rice straw in Vietnam: Regional distribution and available density for ethanol production

Vietnam was divided into six administrative regions (Figure 4.1), designated regions 1, 2, 3, 4, 5, and 6, respectively. In this study, the rice straw distribution was assessed for these locations. The total rice straw generated in Vietnam was estimated to be approximately 50 dry million tons (Mt) (Table 4.1). This amount is much more than that in other countries, such as Thailand (32.9 Mt) or Myanmar (34.4 Mt) (Yano *et al.*, 2009). Region 6, the Mekong River Delta, accounts for 52% of the total rice straw generation and is followed by the Red River Delta (region 1), accounting for 17% of the total. The rice straw amount is high in the two Deltas because of the higher rice-planted area and rice yield compared to the other regions.

The available rice straw densities for ethanol facilities in regions 1, 2, 3, 4, 5, and 6 were estimated to be 69, 6.8, 14, 3.9, 12, and 108 dry t $km^{-2}$, respectively (Figure 4.2). This estimation showed an abundant rice straw supply for ethanol production in the two Deltas of Vietnam. A high density of feedstock can reduce the total cost of the feedstock, via a reduced transportation cost. This issue will be discussed more in Section 4.3.4.

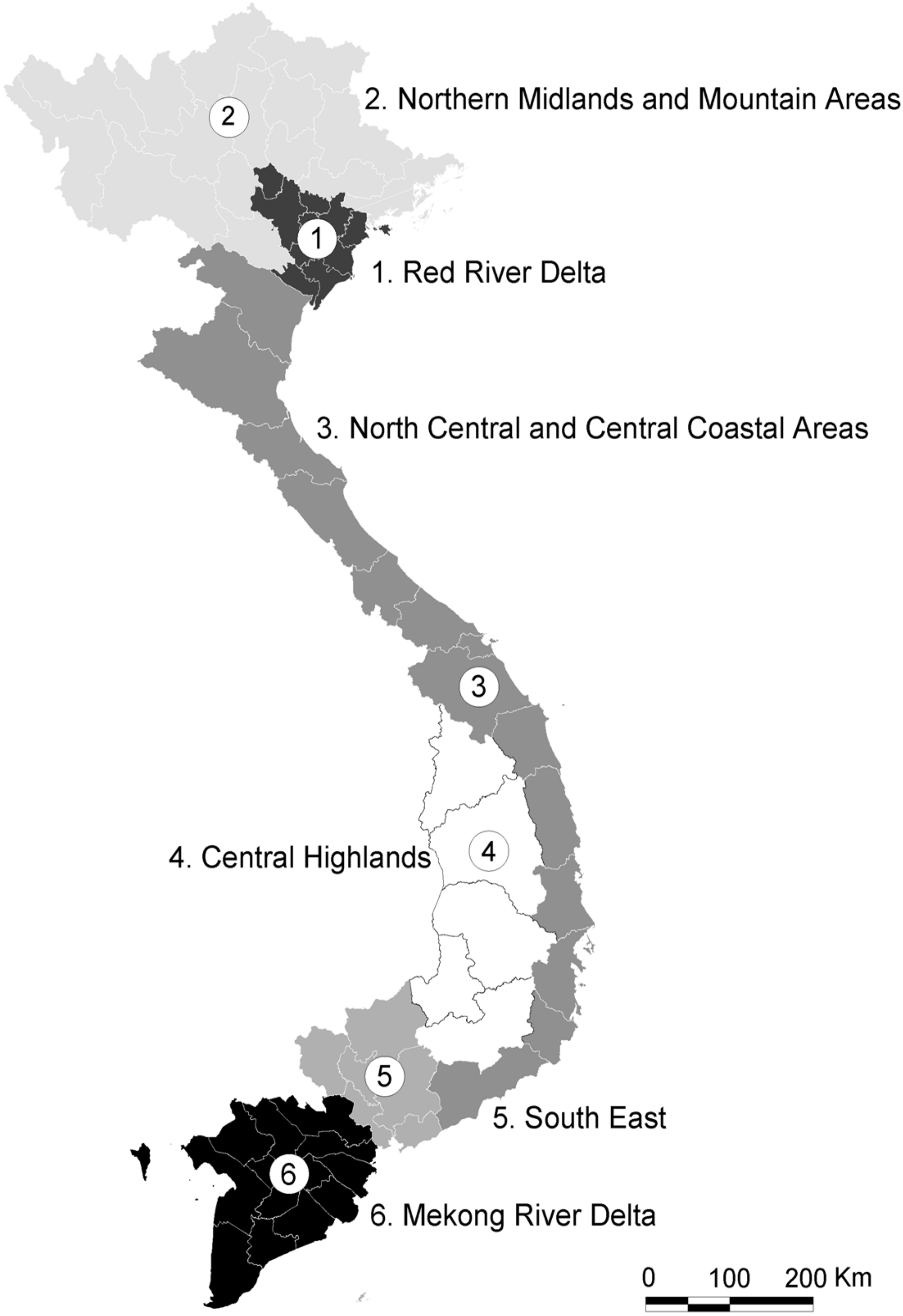


**Figure 4.1** Regions in Vietnam.

**Table 4.1** Rice straw generation and regional distribution in Vietnam.

| Region | Total area ($10^3$ ha) | Rice-planted area ($10^3$ ha) | Rice production ($10^3$ ton) | Rice straw amount (dry $10^3$ t $year^{-1}$) |
|---|---|---|---|---|
| Red River Delta (1) | 2106.3 | 1155.4 | 6796.3 | 8665.3 |
| Northern Midlands and Mountain Areas (2) | 9533.7 | 669.9 | 3047.1 | 3885.1 |
| North Central and Central Coastal Areas (3) | 9588.6 | 1221.6 | 6252.0 | 7971.3 |
| Central Highlands (4) | 5464.1 | 213.6 | 994.3 | 1267.7 |
| South East (5) | 2360.5 | 306.7 | 1322.4 | 1686.1 |
| Mekong River Delta (6) | 4051.9 | 3872.9 | 20483.4 | 26116.3 |
| **Whole country** | 33105.1 | 7440.1 | 38895.5 | **49591.8** |

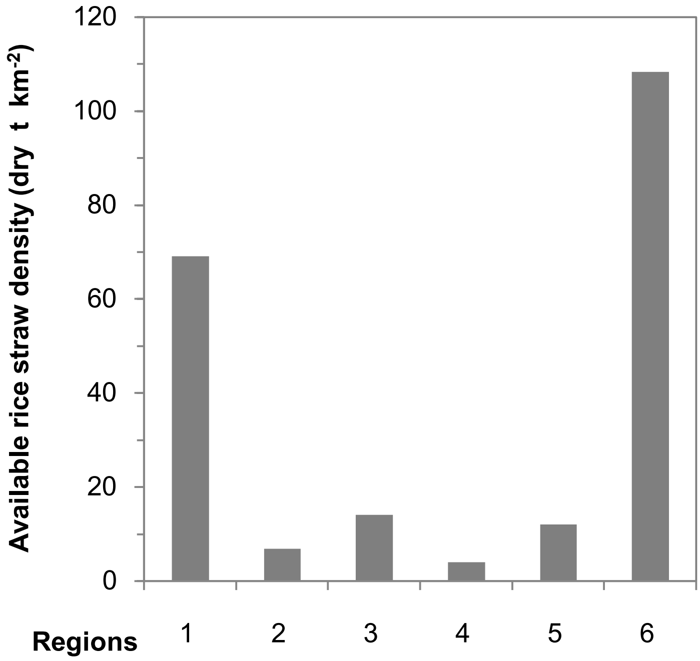


**Figure 4.2** Available rice straw density for ethanol production by region.

### 4.3.2 Estimation of the delivered rice straw cost

Feedstock cost represents an important portion of cellulosic ethanol production, approximately 35%-50% of the production cost (Hess *et al*., 2007). Reducing the feedstock cost is one of the means by which to make cellulosic ethanol cost-comparative with petroleum-derived fuels. The amount of rice straw collected in one hectare of paddy field in the Mekong River Delta (about 9 dry tons) is currently purchased at the price of 1,200,000 - 1,600,000 VND, equivalent to 60 -80 $ (Vietnam News, 2011b). Thus, we assumed the average cost of rice straw in the field around \$7 dry ton$^{-1}$. Therefore, the total cost of payment to the farmer, bailing (\$9 dry ton$^{-1}$), and handling (\$4.5 dry ton$^{-1}$) was estimated to be 20.5 \$ dry t$^{-1}$ (distance fixed cost).

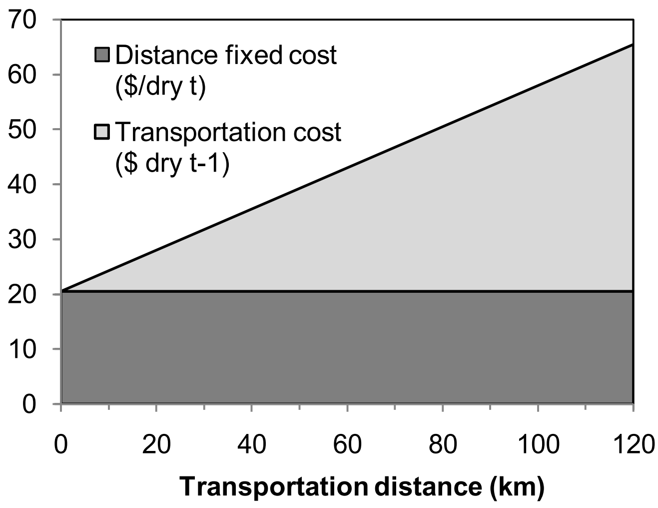


**Figure 4.3** Analysis of rice straw cost.

The hauling cost was estimated to be 0.345$ dry $t^{-1}$ $km^{-1}$. Thus, the delivered cost of the rice straw varied from 20.5 to 65.4 $ dry $t^{-1}$, with a transportation distance of 0 to 120 km (Figure 4.3). A low bulk density of the rice straw causes the transportation cost to be a large proportion of the delivered feedstock cost. This estimation showed a lower cost of biomass for ethanol production in Vietnam, as compared to that in developed countries such as Japan (delivered rice straw costs 15,000 JPY dry $t^{-1}$ within radius of collection area of 50 km) Yanagida *et al.*, 2010; Leboreiro and Hilaly, 2011). The cheap labour costs for collecting and handling of biomass were the main reason for the low cost of biomass in Vietnam.

### 4.3.3 Capital investment for a cellulosic ethanol facility

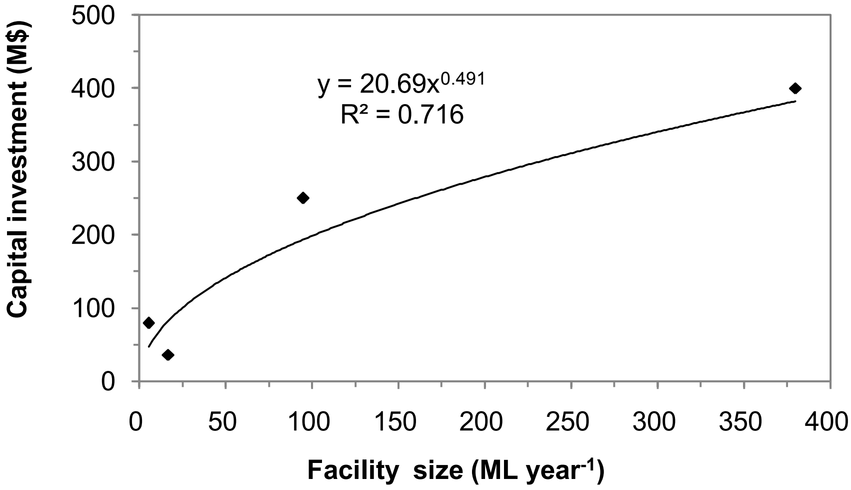


**Figure 4.4** Capital investment as a function of facility size.

Capital investment is an exponent function of bioenergy plant size (Aden *et al*., 2002). According to the project data reported to the IEA Bioenergy Task 39, facilities for commercially bio-chemical conversion of lignocellulosic biomass to ethanol with the capacities of 13,000; 4,200 ; 75,000; 300,000 tons ethanol year$^{-1}$ were invested 36; 79; 250; 400 million $, respectively (Bacovsky *et al*., 2010). These four datasets were used to develop the equation showing the relationship between the capital investment and facility size, with a degree of fit ($R^2$) > 0.7 (Figure 4.4). From the equation, the capital investment increased as a function of facility size, indicating that the per-unit fixed cost will drop dramatically for large-scale operations. This economics of scale is further illustrated in Figure 4.5. In the biorefinery industries, the following formula is currently used:

New Cost/Original Cost = (New Size/Original size) $^{\text{scale factor}}$

The exponent is called the scale factor. According to Aden *et al*., (2002), the scale factor usually ranges from 0.6 to 0.8 for bioenergy facilities. In this study, the scale factor used (0.491) is lower than the reported ones. Thus, the capital investment for an ethanol facility may be lower than the normal estimation due to the use of datasets originating from commercial cellulosic-ethanol facility projects.

### 4.3.4 Optimal facility size by region

Depending on the shape and size of each region (Figure 4.1), the biomass supply radius in regions 1, 2, 3, 4, 5, and 6 was limited to 50, 120, 25, 70, 70, and 70 km, respectively. Based on the different available densities of the rice straw for ethanol, as shown in Figure 4.2, the maximal facility sizes in regions 1, 2, 3, 4, 5, and 6 were estimated to be 112.5, 75, 7.5, 15, 45 and 412.5 ML $year^{-1}$, respectively, with an ethanol yield of 250 L dry $t^{-1}$. To be economically recognised, choosing an optimal facility size to reduce production costs is an important measure.

The relationship between the cost components and facility size by region is shown in Figure 4.5. Facility size increases lead to a reduction of per-unit fixed cost. However, an increase in the facility size leads to an increase in the per-unit feedstock transportation costs. In the regions with low biomass densities, the transportation costs increase sharply due to the dramatic increase in biomass supply areas needed to meet the feedstock demand when the scale increases.

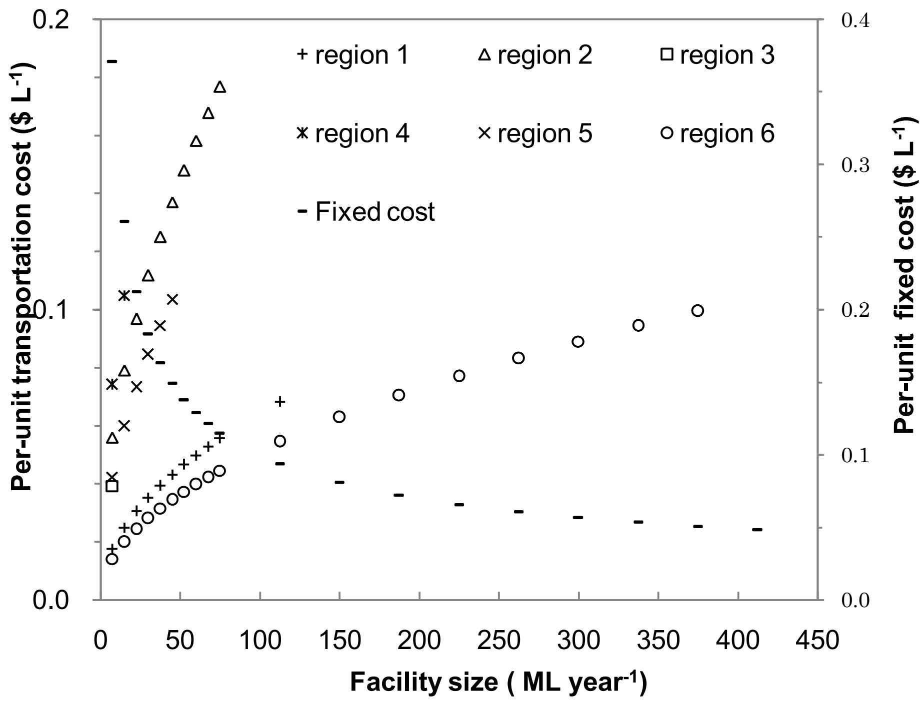


**Figure 4.5** Fixed cost and feedstock transportation cost as functions of facility size.

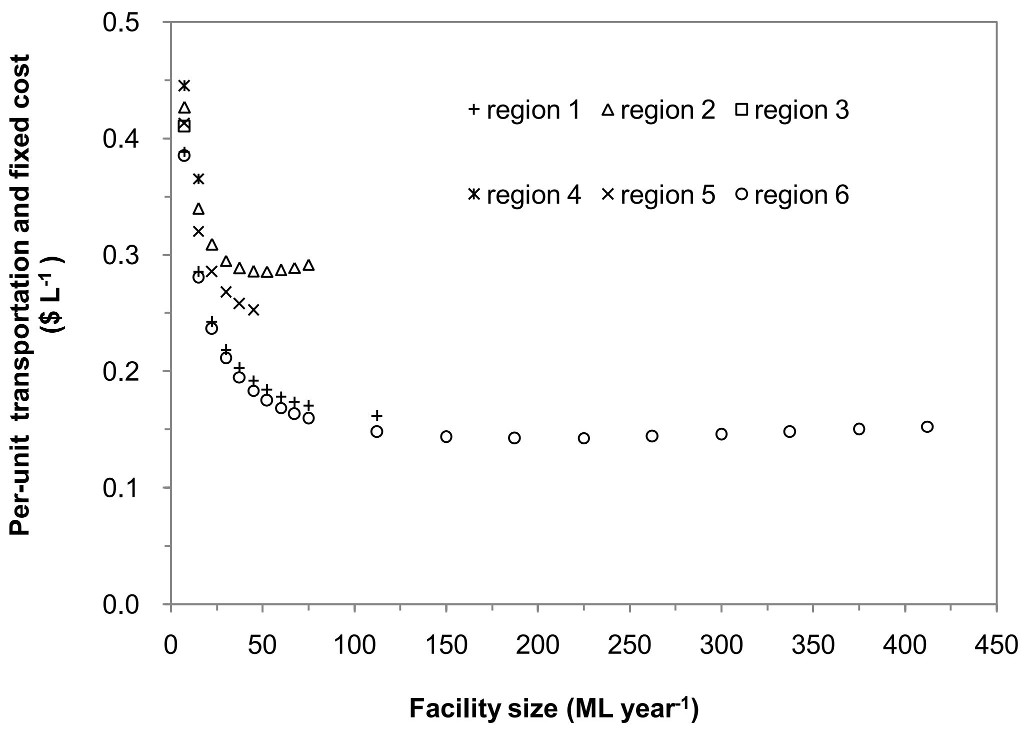


**Figure 4.6** Selection of optimal facility size by region.

Reduction in the fixed cost from the economics of scale is offset by increases in the feedstock transportation cost. Thus, an optimal facility size is found by minimising the total feedstock transportation and fixed costs, in particular, or the total production cost in general. The optimal facility size for each region is depicted in Figure 4.6. Normally, there is a peak that shows the minimal production cost, and, in this figure, it is clearly shown that the optimal facility size in regions 2 and 6 is 50 and 195 ML year$^{-1}$, respectively. In other regions, the optimal size of the facilities could not be established, as the maximal biomass supply radius is smaller than the optimal supply radius or the rice straw supply is not sufficient to meet the feedstock demand for the optimal facility size. Thus the most economic scale should be the maximal size, with 112.5, 7.5, 15, and 45 ML year$^{-1}$ for regions 1, 3, 4, and 5, respectively. From this result we calculated the $R_{opt}$ via the available rice straw supply density. Thus, the optimal feedstock supply radii in regions 2 and 6 were 96.2 km and 48 km, respectively. The $R_{opt}$ value increases with decreasing biomass density (from Eq. (16)). From Figure 4.6 and Eq. (16), it is observed that, at a fixed facility size, a high density of feedstock decreases the per-unit production cost. In this case study, the Mekong River Delta showed the greatest potential for developing an ethanol facility with the lowest production cost, followed by the Red River Delta, with estimated optimal facility sizes in the two regions of 195 and 112.5 ML year$^{-1}$, respectively. From Figure 4.6, the sums of the feedstock transportation cost and fixed cost per litre of ethanol in regions 1 and 6 are 0.162 and 0.142 \$ L$^{-1}$, respectively. The distance fixed cost of the rice straw was estimated at 20.5 \$ dry t$^{-1}$. Therefore, the total per-unit feedstock cost and fixed cost in regions 1 and 6 are estimated 0.244 and 0.224 \$ L$^{-1}$

ethanol, respectively, at their optimal facility sizes. The feedstock and fixed costs account for the major portion of the total production cost, approximately 45% in the case of a 2010 facility start-up in the U.S that set a target to produce ethanol from corn stover at a price of 1.07 $ per gallon (Gal) (0.276 $ $L^{-1}$) using a biochemical conversion process with an ethanol yield of 89.7 Gal/ dry US ton corn stover (375L dry $t^{-1}$) (Aden *et al*., 2002). In Vietnam, the fuel ethanol produced from cassava with 99.5% purity is presently purchased at the free on board price of 0.97 $ $L^{-1}$ (Vietnam News, 2011a). Therefore, it is promising that cellulosic ethanol production from rice straw in the two deltas of Vietnam can be deployed in the near future when the advanced technologies have been proven to be technically and economically feasible.

### 4.3.5 Impacts on the optimal facility size

The optimal biomass supply radius ($R_{opt}$) determines an optimal facility size. Eq. (16) was used to predict the relative change in the optimal facility size in regard to the impact of factors such as the tortuosity factor, transportation cost per distance, payback period and scale factor. The Mekong River Delta is chosen as the base case, and feedstock density and ethanol yield are kept constant for all of the cases. According to Eq. (16), the optimal feedstock supply radius decreases with an increase in the hauling cost per distance ($Hc$), the tortuosity factor ($\tau$) and the payback period ($T$). The relative change in the $R_{opt}$ in a change of scale factor ($\alpha$) is difficult to deduce from the equation but is demonstrated in Figure 4.7.

The data shown in the figure confirmed the direction of the changes in the $R_{opt}$ due to the change in the values of $Hc$, $\tau$, $T$, as discussed above. The scale factor is a complicated function of $R_{opt}$, if $\alpha = 1$, $R_{opt} = 0$, or no economics of scale. In this case study, with $8.5 < \alpha < 1$, $R_{opt}$ decreases with an increase in the scale factor; with $0 < \alpha \leq 0.85$, $R_{opt}$ increases with an increase in the scale factor. The latter result is contrary to some studies but consistent with study reported by Jenkins (Jenkins, 1997; Leboreiro and Hilaly, 2011; Gan and Smith, 2011). $\alpha$ and $R_{opt}$ are co-variant or contra-variant depending on input data (interpolation from Eq. (16)).

More importantly, Figure 4.7 depicts the magnitude of the impact of the mentioned factors. The remarkable exponential change in the $R_{opt}$ with a change in each of the factors, $Hc$, $\tau$, $T$, and $\alpha$, is shown. In particular, $R_{opt}$ seems to be the most sensitive to the scale factor. Essentially, this analysis showed the following:

If $\tau$ or $Hc$ is low, the transportation cost is reduced, and the biomass collection area should therefore be expanded to reduce the production cost. If the payback time is shortened, the per-unit fixed cost will increase; therefore, the large-scale facility is an option to reduce the production cost. In practice, the scale factor ranges from 0.6 to 0.8; in this case, if the scale factor increases, the facilty size should be increased to minimise production costs. In the future, hauling costs will increase and the capital investment will decrease when more facilities are developed, thus, the optimal biomass supply radius will be decreased, or the optimal facility sizes will be smaller than the currently estimated ones.

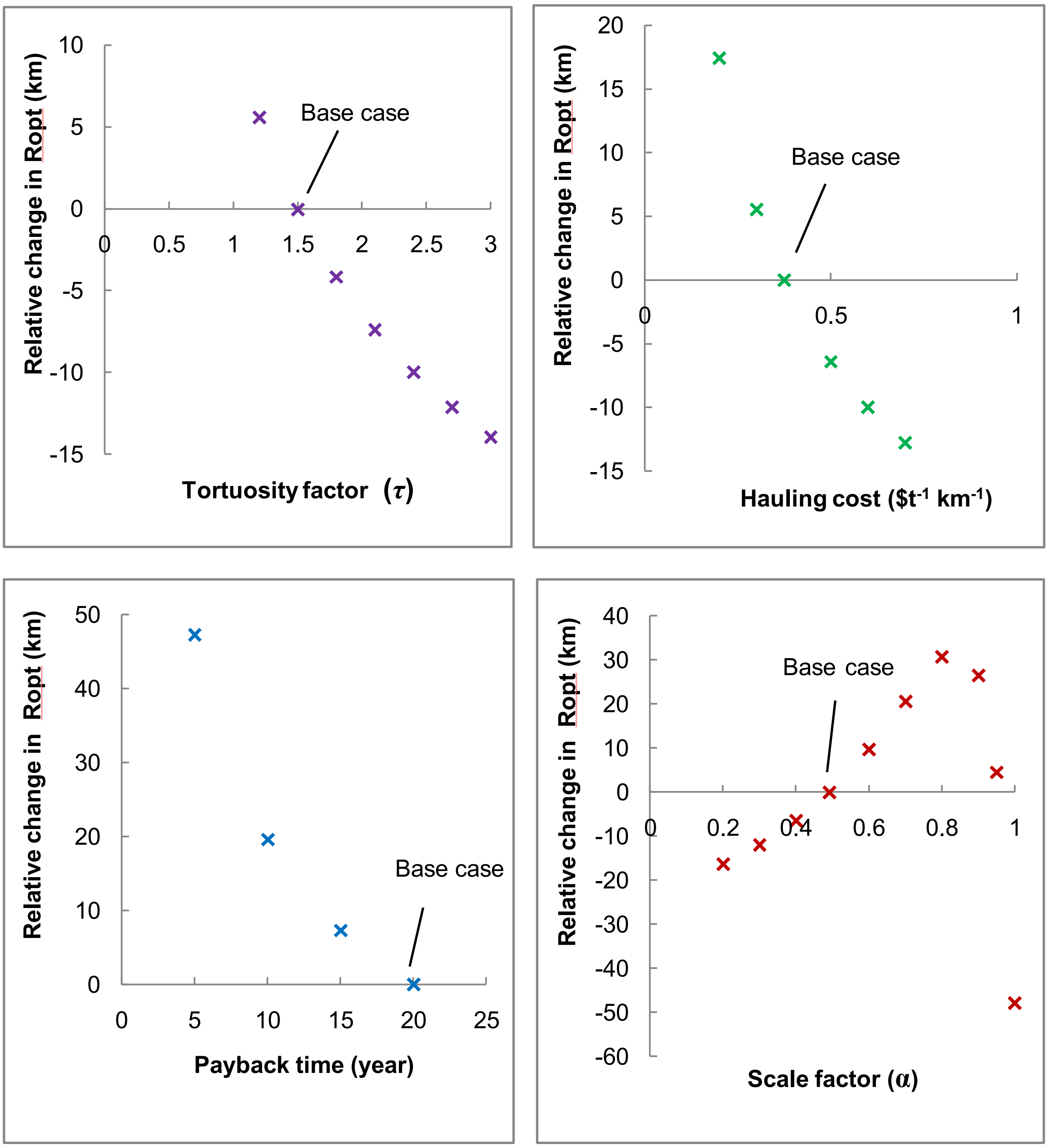


**Figure 4. 7** Relative change in optimal feedstock supply radius vs. various factors.

Determining the facility size remains a site-specific task (i.e., considering the feedstock density, tortuosity factor, and transportation costs) and a mission related to investment (i.e., considering the fixed cost and payback time). Eq. (16) is applicable to all bioenergy facilities for calculations of the optimal biomass supply radius or the optimal facility size that is required for the biomass to be transported from the surrounding areas.

#### 4.3.6 Estimation of ethanol amount can be practical produced in Vietnam

To answer an important question that how much rice straw ethanol can be produced in Vietnam, it is definitely not easy. According to several studies, the amount of ethanol produced from biomass just simply converts from the total biomass generated, multiple with percentage of biomass that can be sustainable use, then multiple with the conversion rate of biomass to ethanol. Most of this studies assumed that the percentage of biomass can be used is from 20% to 50 % of total generated amount (considerable ecosystem function and other uses), thus the results seemed to be too optimistic in many cases, as the amount of ethanol production after all depends on the number of ethanol plants and their capacities.

In this study, the practical ethanol amount can be produced in Vietnam based on a number of optimal facilities can be built in regions and their capacities after a long run to calculate the optimal plant size for minimizing the production cost.

Table 4.2 shows the optimal facilities sizes by region, based on size and shapes of land, a number of optimal facilities are calculated. After that, ethanol amount produced was calculated for each region and for the whole country. Production cost consists of delivered cost of biomass, capital investment (fixed costs) and operating cost. Operating cost is constant for all plant sizes, thus the total of fixed cost + delivered rice straw cost ($ $L^{-1}$ ethanol) was represented to show the changes in ethanol production costs in different regions.

**Table 4.2** Estimation of ethanol amount can be yearly produced in Vietnam.

| Region | Optimal plant size ($MLyear^{-1}$) | Ropt (km) | Number of optimal plant by region | Delivered cost of rice straw | | Total of fixed cost + delivered rice straw cost ($\$L^{-1}$ EtOH) | Yearly ethanol production ($MLyear^{-1}$) |
|---|---|---|---|---|---|---|---|
| | | | | ($ dry $t^{-1}$) | ($\$L^{-1}$ EtOH) | | |
| Red River Delta **(1)** | 112.5 | 45.5 | 1 | 37.6 | 0.150 | 0.244 | 112.5 |
| Northern Midlands and Mountain Areas **(2)** | 52.5 | 98.8 | 2 | 57.5 | 0.230 | 0.368 | 105 |
| North Central and Central Costal Areas **(3)** | 7.5 | 26.2 | 6 | 30.3 | 0.121 | 0.492 | 45 |
| Central Highlands **(4)** | 15 | 70 | 2 | 46.7 | 0.187 | 0.448 | 30 |
| South East **(5)** | 45 | 69.1 | 1 | 46.4 | 0.186 | 0.335 | 45 |
| Mekong River Delta **(6)** | 195 | 48 | 2 | 38.7 | 0.154 | 0.224 | 390 |
| **Whole country** | | | | | | | **727.5** |

The total of ethanol produced through the country is roughly estimated of 727.5 ML $year^{-1}$. This amount could replace 14.2% of the total gasoline consumed in Vietnam as the IEA statistical data of year 2009. In year 2009, Vietnam imported 4045 thousand tons of gasoline, equal to 5126.7 ML, 100% gasoline consumption amount is imported. However, the production costs of ethanol may differ from 0.02 -0.268 $\$L^{-1}$ depending on the capacities of plants and the location of plants (interpolated from Table 4.2). The deviation in production cost by region is more than 0.1 $\$ L^{-1}$ (10% of target production cost) should be carefully considered, as the target of ethanol production cost is not more that gasoline imported cost, around 1.0 $\$ L^{-1}$ as the data of year 2012. Hopefully, with the fast growing of bio-industries, the investments costs can be reduced by time, the deviation of ethanol production costs by region can be shorten. According to this calculation, just 5% of the total generated rice straw in Vietnam is exploited for practical ethanol production, this assumption is by far lower than the previous study in Chapter 3 and other publications.

In the current scenario, to the economically practical application, only optimal ethanol plants in the Mekong river delta and Red river delta should be constructed and the amount of ethanol produced from these two regions of 502.5 ML $year^{-1}$ is capable to replace 9.8% of the country's gasoline imported in 2009 by mixing with gasoline to use as gasohol 5% (E5).

### 4.4 Conclusions

Rice straw is abundant in Vietnam but is mainly concentrated in the two delta regions (regions 1 and 6). The available densities of rice straw for ethanol production in regions 1, 2, 3, 4, 5, and 6 were estimated to be 69, 6.8, 14, 3.9, 12, and 108 dry t $km^{-2}$, respectively. The delivered rice straw cost varied from 20.5 to 65.4 $ dry $t^{-1}$ with the transportation distances of 0 to 120 km. Regions 1 and 6 were found to be the optimal locations for ethanol production, with economical facility sizes of 112.5 and 195 ML $year^{-1}$, respectively. Consequently, the feedstock supply radius was 50 and 48 km for regions 1 and 6, with the total cost of feedstock and fixed cost per litre of ethanol of $0.244 and $0.224, respectively. The above-calculated results represent for a case study at present time. The developed equation for calculation of $R_{opt}$ is applicable to determine the optimal facility size required for the biomass to be transported from the surrounding areas and to predict the change in optimal facility size with the changes of various conditions.

Our findings show the economic potential of using rice straw as feedstock for ethanol production in two delta regions in Vietnam and roughly estimate the optimal plant size by region. In practice, the feedstock supply area is not limited by the region‟s border. Thus, site-specific factors at high resolution, such as the available feedstock density, tortuosity factor, and transportation costs, are necessary for decision making regarding the location and optimal size of ethanol facilities.

Presently, based on the optimal plants in different regions, the total rice straw ethanol can be produced in Vietnam yearly was 727.5 ML $year^{-1}$. This amount can replace 14.2 % of total gasoline imported in 2009. In the short-term period, to economically practical application, only optimal ethanol plants in the Mekong River Delta and Red River Delta should be constructed and the amount of ethanol produced from these two regions (502.5 ML year$^{-1}$) is capable to replace 9.8% of the country's gasoline imported in 2009 by mixing with gasoline to use as E5 gasohol.

This work provides useful tool and information in determining the location, optimal sizes of ethanol plants by region in Vietnam, and assumption of ethanol quantity can be economically produced from rice straw.

# Chapter 5

## Comparison of the potentials for reducing rice straw ethanol production costs between Vietnam and Japan via techno-economic evaluation

### 5.1 Introduction

Ethanol from biomass has become an increasingly popular alternative to gasoline as one option to reduce dependence on oil and mitigate global warming. Bio-ethanol is commercially produced on a moderate scale (approximately 80 million tons worldwide in 2010) mainly from sugar cane, corn, and other starchy biomass sources (Balat and Balat, 2009). However, this first generation bio-ethanol has been blamed for causing food insecurity. Therefore, more sustainable ethanol production strategies have been investigated, including shifting feedstock from edible to inedible biomass or lignocellulosic biomass (Hamelinck *et al*., 2005; Sassner *et al*., 2008).

In Asian countries where rice is a staple food, rice straw is a promising alternative to edible feedstock for bio-ethanol production because of its abundance, relatively low cost, and attractive composition (Sanchez *et al*., 2008; Park *et al*., 2011). Rice straw is the major agricultural residue in Japan (approximately 10 Mt year$^{-1}$) and Vietnam (approximately 50 Mt/year); in both countries ethanol production from this biomass source has been promoted (Roy *et al*., 2012). A previous study discovered the potential for using rice straw as feedstock in ethanol production in Vietnam as rice straw is mainly concentrated in two Delta regions that would be fully available for ethanol production. Thus, the country has the potential to build ethanol plants with optimal capacity of up to 200 million L year$^{-1}$ with low rice straw costs (including transportation fees).

Techno-economic analysis is used to understand the viability of liquid bio-fuel production processes, determine the economics of bio-fuel production and indicate the impact of process advances, different feedstock components, etc. Since the mid-80‟s, the volume of techno-economic analysis of second generation ethanol has increased significantly with notable research and development contributions from the US and, to a lesser extent, Europe and Japan (Kazi *et al*., 2010; Yanagida *et al*., 2010). These studies revealed various results dependent on the applied technologies, the types of feedstock (corn stover, switch grass, hard and soft wood chips, etc.), plant capacity, and the high uncertainty about economic drivers and crude oil price, etc. These studies indicated that feedstock and capital investment costs are the major factors in ethanol production costs. Therefore, a lower cost of feedstock and the potential for larger scale production significantly reduce production costs; these factors make the techno-economic analyses of bio-ethanol sensitive to the location of the ethanol plant.

Japan is one of the leading countries in the world promoting bioethanol production from rice straw and has developed the advanced technologies for production processes. Some pilot plants have operated to produce ethanol from rice straw with support from the Japanese government via subsidised policies. A recent study in Japan estimated rice straw ethanol production costs under various scenarios. Despite a future scenario with rice straw cost reduced to 30%, bio-ethanol production is not economical and competitive when compared with other traditional bio-ethanol production processes unless innovative technologies, renewable energy policy and stake holder participation are considered (Roy *et al*., 2012).

A pilot plant for producing ethanol from rice straw with financial and technological support from the Japan International Cooperation Agency (JICA) and Japan Scientific Technology (JST) has been operating in Vietnam, and the country set an ambitious target for industrial production of ethanol from rice straw in the implementation of rural energy intervention programs. Presently, Vietnam is still in the early stage of developing key technologies for producing ethanol from lignocellulosic biomass. Thus, which technologies should get priority to be improved and the anticipation of production costs with advanced technologies are top concerns to shorten the way for promoting rice straw ethanol production in Vietnam.

Vietnam has both a lower cost of rice straw and the potential to build a higher capacity ethanol plant when compared with Japan. This study compared the production costs of rice straw ethanol in Vietnam and Japan based on currently developed technologies in Japan that have proven to be economic and environmentally friendly, such as hydrothermal pre-treatment and enzymatic hydrolysis. To determine how changes in feedstock, labour, energy costs and plant capacities affect ethanol production costs and the cost component distribution, trends for the reduction of ethanol production costs from rice straw in Vietnam were compared with those in Japan. A sensitivity analysis on ethanol production costs with respect to some parameters was performed to assess the impact of the rice straw composition and technological improvements on the production costs in each country. Additionally, ethanol production costs at the optimal plant size were approximated to a model of future scenario, showing default data based on process assumptions and forecasting the cost competitiveness of rice straw ethanol with first generation bio-ethanol and gasoline in Vietnam and Japan.

This work will provide invaluable guidance to research, investment and policy endeavours in developing commercial ethanol production from rice straw in Vietnam in the near future and serve as a useful reference for countries in Asia with agriculture-dependent economies.

## 5.2. Key technologies for ethanol production from lignocellulosic biomass and development trends

The first attempt at commercializing a process for ethanol from wood was done in Germany in 1898. The process was able to produce 7.6 liter of ethanol per 100 kg of wood waste, which used diluted acid to hydrolyze the cellulose to glucose. Up to date, this conversion rate has increased to more than 25 liter per 100 kg wood waste in Japan which used thermal hydrolysis instead. However, the production process has been not profitable yet because of some difficulties:

(i) The resistant nature of lignocellulosic biomass to breakdown;

(ii) The variety of sugars which are released when hemicellulose and cellulose are broken

(iii) The need to find or genetically engineer organisms to efficiently ferment these sugars to ethanol.

Although the basic biochemical process (mentioned in Chapter 1) for production of ethanol from lignocellulosic is well understood, it consists of four major unit operations: (1) pretreatment, (2) hydrolysis, (3) fermentation, and (4) ethanol recovery/distillation. Detail technologies for these unit operations have been developed with respect to reduce production cost and environmental affects. In this part, key technologies of major steps and development trends are introduced.

### 5.2.1 Pretreatment technology

Because of rigid structure of lignocellulosic biomass (wood, grass, agricultural residues), an effective pretreatment is needed to liberate the cellulose from the lignin seal and its crystalline structure to make it accessible for a subsequent hydrolysis step (Mosier *et al.,* 2005). By far, most pretreatments are done through physical or chemical means. To achieve higher efficiency, both physical and chemical pretreatments are required. Physical pretreatment is often called size reduction to reduce biomass physical size (by cutting and then ball milling, or wet disc milling, etc.). Chemical pretreatment is to remove chemical barriers so the enzymes can have access to cellulose for microbial destruction.

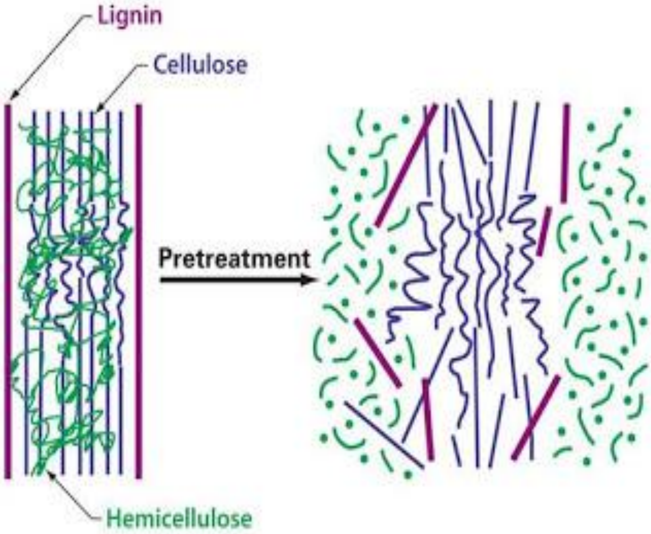


**Figure 5.1** Pretreatment of lignocellulosic biomass. (Adapted from Hsu *et al*., 1980)

To date, a number of options have been investigated for pretreatment of biomass including acid hydrolysis, steam explosion, hydrothermal, ammonia fiber expansion, sulfite pretreatment to overcome recalcitrance of lignocellulose (SPORL), (Mosier *et al.,* 2005) alkaline wet oxidation and ozone pretreatment (Klinke, 2004). Besides effective cellulose liberation, an ideal pretreatment has to minimize the formation of degradation products because of their inhibitory effects on subsequent hydrolysis and fermentation processes (Olsson and Hahn-Hägerdal, 1996). The presence of inhibitors not only further complicate the ethanol production but also increase the cost of production due to entailed detoxification steps. Even though pretreatment by acid hydrolysis is probably the oldest and most studied pretreatment technique, it produces several potent inhibitors including furfural and hydroxymethyl furfural (HMF) which are by far regarded as the most toxic inhibitors present in lignocellulosic hydrolysate (Palmqvist and Hahn-Hägerdal, 2000). Ammonia fiber expansion (AFEX), and hydrothermal treatment are promising pretreatments with no inhibitory effect in resulting hydrolysate (Lynd, 1996)

After pretreatment, all or part of hemicellulose is solubilized. The soluble sugar products are primarily xylose, and further mannose, arabinose, and galactose. A small portion of cellulose can also be converted to glucose (Figure 5.1). The product is filtered and pressed, solid (lignin + cellulose) go to the cellulose hydrolysis, and liquids (containing the sugars) go directly to a fermenting step.

The variety of pretreatment technologies of biomass has led to the development of many flowsheet options for bioethanol production.

### 5.2.2 Hydrolysis technology

The cellulose molecules are composed of long chains of sugar molecules. In the hydrolysis process, these chains are broken down to free the sugar, before it is fermented for ethanol production. The chemical reaction of hydrolysis process is given as follows:

$$(C_6H_{10}O_5)n \quad + \quad nH_2O \quad \rightarrow \quad nC_6H_{12}O_6$$

There are two major cellulose hydrolysis processes: a chemical reaction using acids, or an enzymatic reaction. Dilute acid may be used under high heat and high pressure, or more concentrated acid can be used at lower temperatures and atmospheric pressure. A decrystalized cellulosic mixture of acid and sugars reacts in the presence of water to complete individual sugar molecules (hydrolysis). The product from this hydrolysis is then neutralized and yeast fermentation is used to produce ethanol. However, a significant obstacle to the dilute acid process is that the hydrolysis is so harsh that toxic degradation products are produced that can interfere with fermentation. Using concentrated acid would give a very high sugar yield (90%), not produce nearly as many fermentation inhibitors, but critical for economical viability of this process is to minimize the amount of acid, hence it must be separated from the sugar stream for recycle by simulated moving bed (SMB) chromatographic separation, or continuous ion exchange to be commercially attractive. Furthermore the required equipments are more expensive than those with diluted acid pretreatment.

Enzymes known as cellulase catalyze, breakdown of cellulose into glucose for ethanol fermentation. Because enzymes are highly specific in the reactions that they catalyze, formation of by-products as evidenced in dilute acid hydrolysis is avoided, and waste treatment costs are reduced. Furthermore, enzymatic reactions take place under mild conditions and achieve high yields with relatively low amounts of catalysts. Enzymes have the further advantage in that they are naturally occurring compounds which are biodegradable and environmentally benign. Advances in enzyme-based technology for ethanol production have been substantial over the years, and as a result, ethanol production costs have been reduced considerably. Thus, large-scale application of ethanol production through enzymatic hydrolysis of lignocellulosic biomass is now beginning to appear economically advantageous.

Enzyme supply: is a complex mix of enzymes (cellulase, hemicellulase) that work together synergistically to attack typical parts of the cellulose and hemicelluloses fibers. Cellulase and hemicellulase belong to the large glycosyl hydrolase family of enzyme. Cellulase is a mixture of at least 3 key enzymes: endoglucanase, exoglucanase, and *ß*-glucosidase. Hemicellulase includes endo-1,4*ß* -D-xylanase, 1,4*ß* -D-xylosidases, *α*-L-arabinofuranosidases, acetyl xylan esterases, etc. Enzyme cost accounts for major part of production cost mainly due to poor activity of cellulase (Sainz, 2009). The enzymatic hydrolysis has currently high yields (75-85%) and improvements are still projected (85-95%) as the research field is only a young decade (Hamelinck *et al.*, 2005). Enzyme can be produced on-site or purchased from commercial enzyme industries. Moreover, using enzyme can reduce energy, and equipment costs compared to using acid in hydrolysis.

### 5.2.3 Fermentation technology

The followings are bio-chemical reactions in fermentation step:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

$$3C_5H_{10}O_5 \rightarrow 5C_2H_5OH + 5CO_2$$

$C_6$ and $C_5$ sugars → Ethanol + Carbonic gas

The $C_6$ and $C_5$ sugars can be converted to ethanol by either simultaneous saccharification and fermentation (SSF) or separate enzymatic hydrolysis and fermentation (SHF) processes. SSF is more favored because of its low potential costs (Wyman, 1994). It results in higher yield of ethanol compared to SHF by minimizing product inhibition. One of the drawbacks in this process is the difference in optimum temperature of the hydrolyzing enzymes and fermenting microorganisms. Most of the reports states that the optimum temperature for enzymatic hydrolysis is at 40–50$^0$C, while the microorganisms with good ethanol productivity and yield do not usually tolerate this high temperature. This problem can be avoided by applying thermo- tolerant microorganisms such as *Kluyveromyces marxianus*, *Candida lusitaniae*, and *Zymomonas mobilis* or mixed culture of some microorganisms like

*Brettanomyces clausenii* and *Saccharomyces cerevisiae* (Golias *et al*., 2002; Spindler *et al.,* 1988).

Several approaches have been examined for hydrolysis of cellulose and fermentation of mono sugars to ethanol. Recently, engineered yeasts *Saccharomyces cerevisiae* have been described efficiently fermenting xylose (Matsushika *et al*., 2009), and arabinose, (Becker and Boles, 2003) and even both together (Karhumaa *et al.,* 2006). Yeast cells are especially attractive for cellulosic ethanol processes because they have been used in biotechnology for hundreds of years, and are tolerant to high ethanol and inhibitor concentrations and can grow at low pH values to reduce bacterial contamination.

**5.2.4 Product recovery/distillation**

Typically, ethanol concentrations of 3-12% result from fermentation of the hemicellulose and cellulose fractions into ethanol. In addition, there are leftover solid materials such as lignin, enzymes, un-reacted cellulose and hemicellulose, yeast, and various salts in the fermentation broth. The entire mixture can be fed to a distillation (beer) column to concentrate the ethanol in the overhead product, while water and solids exit from the bottom of the device. The enriched ethanol stream can then pass to a second rectification column for concentration of the ethanol-water mixture to the azeotrope composition of about 95% by weight ethanol. The bottoms from the first column can be further concentrated by centrifugation or other processes to provide a high solids content material that can be used as a boiler fuel. It is necessary to break the ethanol- water azeotrope if anhydrous ethanol is needed for blending with gasoline. This can be done by utilizing a third component, such as benzene or cyclohexane, in a ternary distillation column. Molecular sieves such as corn grits could also be used to preferentially absorb the ethanol or water phase of the mixture. Pervaporation membranes that are permeable to only one of the components, such as water, while retaining the ethanol, could be used to concentrate ethanol. At present, distillation with a third component and molecular sieves are typically used in commercial operations (Wyman, 1994).

## 5.3 Material and methods

A process for ethanol production from rice straw was designed, as shown in Figure 5.2, by considering the economic efficiency and environmental sustainability of lignocellulosic ethanol production technologies that have been researched and developed in Japan (Cardona and Sanchez, 2007; Gnansounou and Dauriat, 2010). A diagram of all equipment in the plant for energy consumption calculation is shown in Figure 5.3. The process comprises five main steps:

① Rice straw shredding to reduce the size to ≤ 2 mm for pre-hydrolysis.

② A pre-treatment step using hydrothermal treatment technology.

③ Enzymatic hydrolysis (enzymatic saccharification).

④ Co-fermentation of $C_5$ and $C_6$ sugars to ethanol via recombinant yeast, *Saccharomyces cerevisiae*.

⑤ Distillation of the fermentation broth to ethanol (92.5 wt %).

Solid residues after distillation will be considered for energy production depending on the energy and economic efficiency of the process conditions (this step was placed in a dashed rectangle in Figure 5.2 and Figure 5.3).

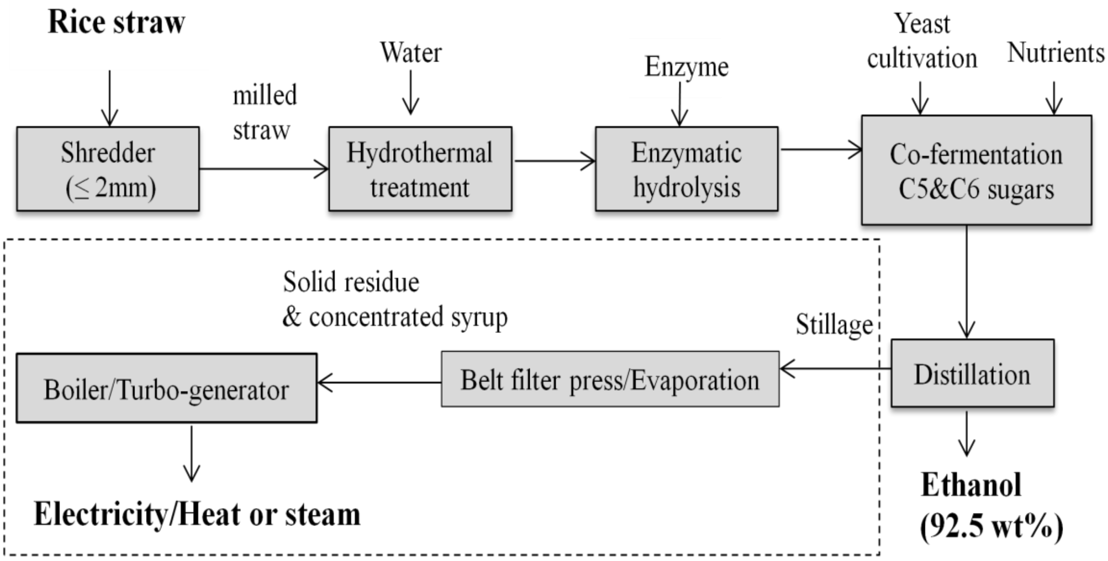


**Figure 5.2** Process flow diagram of bio-ethanol production.

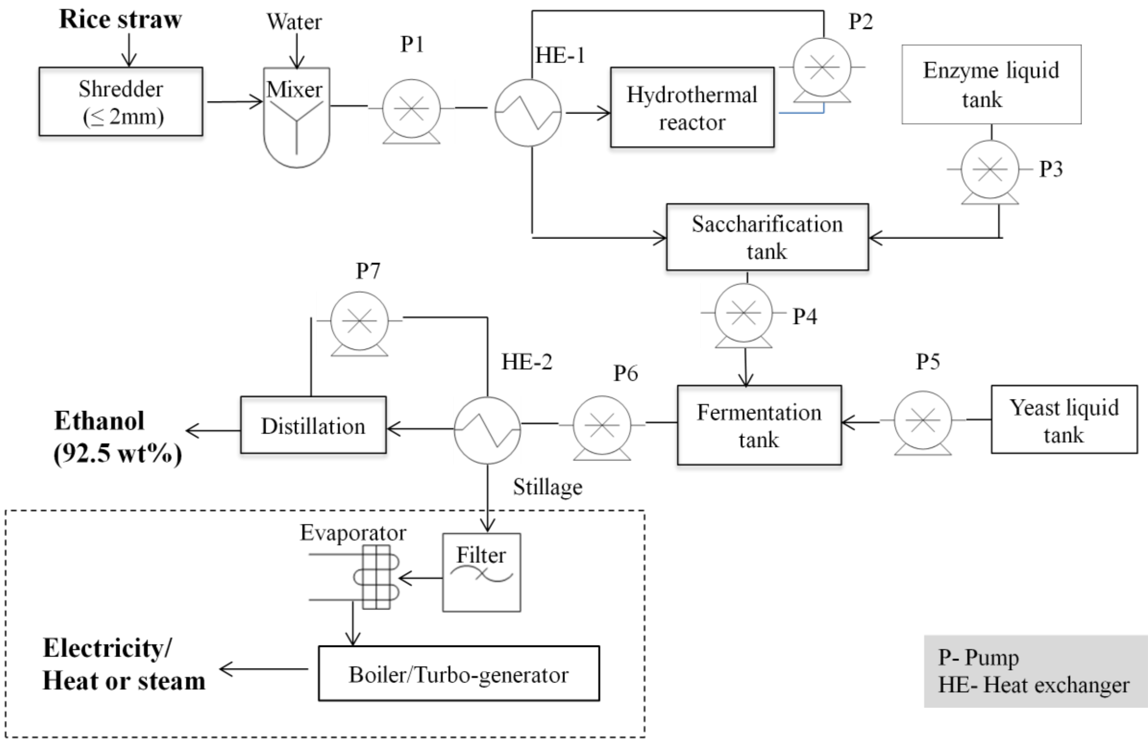


**Figure 5.3** Equipment diagram of the bio-ethanol plant.

### 5.3.1 Specific conditions for mass and energy balances

Rice straw components and plant sizes were set as follows:

- Raw material: rice straw with a moisture content of 15 wt%. Composition of rice straw (on a dry basis) was: glucan 34.4 wt%, xylan 13.6 wt%, lignin 24.1 wt%, and ash 17.7 wt%. The theoretical yields of glucose (Glu) and xylose (Xyl) were 382.2 and 154.5 mg/g of dry rice straw, respectively (Inoue and Yoshimura, 2009).
- Plant size: based on the results of previous studies, the optimal size for rice straw ethanol plants in Japan and Vietnam were set at 15 ML/year and 200 ML/year, respectively. The plants were operated for 24 hr/day and 300 days/year.

Process conditions: data from experiments at laboratories and bench plants at AIST Chugoku, Japan were applied for setting the process conditions of the base case to estimate current ethanol production cost (Matsushika *et al*., 2009; Binod *et al*., 2010). The process conditions for the future case were set based on ethanol production cost reduction targets (Aden *et al*., 2002; Rodriguez *et al*., 2009). The detailed conditions of the process are shown in Table 5.1. The process flow, mass and energy balances were used to calculate operating costs.

**Table 5.1** Process conditions.

| Process step | Base case | Future case |
|---|---|---|
| Hydrothermal pre-treatment | $180^0C$, 3 MPa, initial solid concentration 10 wt%; heat recovery as heat rejection temperature is $50^0C$ | Initial solid concentration 20% |
| Enzymatic hydrolysis | Cellular enzyme 28 mg/g-dry rice straw, equal to 10 FPU/g-dry straw. Reaction time of 72 hr, at $45^0C$<br>% fraction converted to product after hydrolysis:<br>Glucan to glucose: 86% (glucose yield)<br>Xylan to xylose: 66% (xylose yield) | 2 –fold increasing in specific enzyme activity, (10 FPU/g-dry rice straw).<br>Glucose yield: 95%<br>Xylose yield: 75% |
| Co-fermentation<br>$C_5$ and $C_6$ sugars | Seed solution ($KH_2PO_4$, $(NH_4)_2SO_4$, $MgSO_4.7H_2O$, and recombinant yeast at 0.10, 0.10, 0.05, and 4.00 wt%, respectively) accounts for 10% of total fermentation solution. Fermentation at $30^0C$, 24 hr.<br>Fermentation rate: Glucose to ethanol: 90%<br>Xylose to ethanol: 90% | *The same with the base case* |
| Distillation | Ethanol distillation yield 99%<br>Product: ethanol 92.5 wt% | *The same with the base case* |
| Residues for energy generation | Not included | The residues: solid cake and syrup with a moisture content of 40 wt% and 60 wt%, respectively. The total energy gain from residues includes: power 10% (efficiency 95%), and heat 90% (efficiency 80%) |

### 5.3.2 Cost analysis

Net ethanol production costs were estimated that included investment costs (depreciation or fixed cost), rice straw costs, fixed operating costs (labour and maintenance costs), and variable operating costs (other materials and energy costs). The assumptions made for the economic evaluation are:

Total capital investment (equipment costs + installation costs + site development + home office + construction fee + other costs) was estimated based on the equation shown in Chapter 4: $Y = 20.695X^{0.49}$ where "Y" is the total capital investment (millions of US $); "X" is plant size (in million litres (ML) of ethanol/year). When residues are used for energy generation, this capital cost will be increased by 34.2% to account for added equipment costs (Kazi *et al*., 2010). Maintenance cost per year: 3% of total capital investment (TCI).

**Table 5.2** Other costs of materials and energy .

| List of material or energy | Price |
|---|---|
| $KH_2PO_4$ ($/kg) | 9.35 |
| $(NH_4)_2SO_4$ ($/kg) | 0.61 |
| $MgSO_4.7H_2O$ ($/kg) | 0.84 |
| Heavy oil ($/GJ) | 19.67 |
| Electricity ($/kWh) | 0.16 (0.06) |
| Running water ($/m$^3$) | 0.26 |
| Yeast - on site production ($/ton) | 15.97 |
| Enzyme - on site production ($/kg) | 3.9 |

*In brackets: price in Vietnam.*

- Plant life: 20 years, with a straight-line depreciation cost per year = TCI/20.
- Labour cost: In Japan, the following equation was applied: $A = 1.17\times(B/20)^{0.27}$ where "A" is labour cost and "B" is plant size (ML/year) (Yanagida *et al*., 2010).
- In Vietnam, labour cost was assumed to be 10 times less than in Japan.
- Rice straw cost (including transportation cost): In Japan, 15 JPY dry $kg^{-1}$ or $194.8 dry $ton^{-1}$ for a plant size of 15 $MLyear^{-1}$. In Vietnam, prices were set as 26, 28.5, 34, 36, 40, and 44 $ dry $ton^{-1}$ for plant sizes of 15, 50, 100, 150, 200, and 250 $MLyear^{-1}$, respectively.
- Other material and energy costs (Table 5.2) were from vendor quotes or published documents (AGC Chemicals, 2011). All costs were updated to 2012 with an exchange rate of 1 US $ = 77 JPN = 21,000 VND.

## 5.4 Result and discussion

### 5.4.1 Ethanol production cost – current scenario

A process designed using current technologies (the base case) was used to predict current ethanol production costs in Vietnam and Japan. The production costs per litre of ethanol produced, both the total and partial costs, are shown in Figure 5.4. The distribution of cost components are shown as percentages of total cost in Figure 5.5.

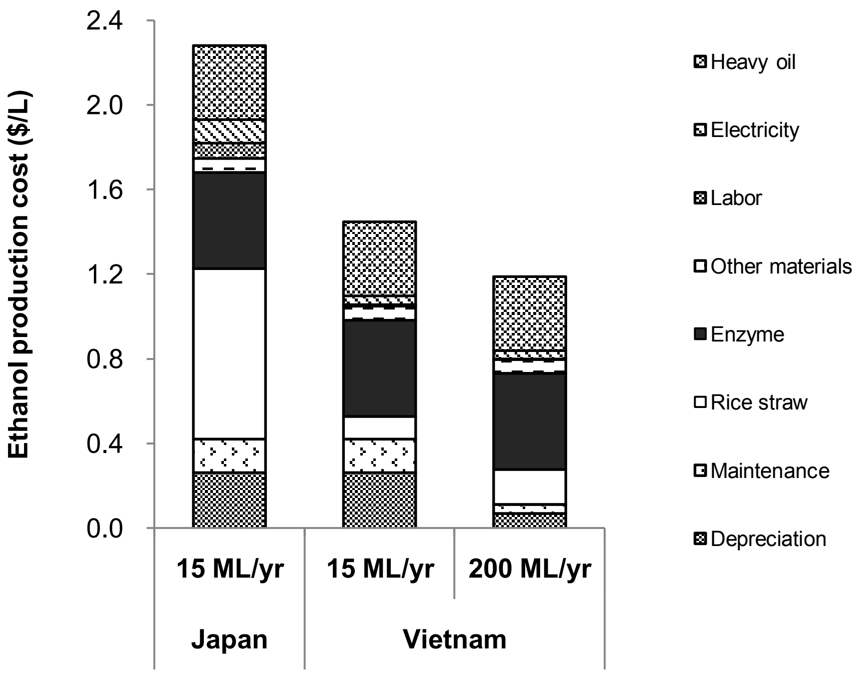


**Figure 5.4** Estimated ethanol production cost under the current scenario.

As mentioned in previous studies, the production cost strongly depends on raw material (feedstock) and plant size (Aden *et al*., 2002; Roy *et al*., 2012). In Japan, with its target to produce ethanol from rice straw at a plant size of 15 ML/year (Roy *et al*., 2012), the estimated PC was 2.28 $/L. In Vietnam, with the same plant size, the estimated PC was 1.45 $ $L^{-1}$ because of the cheaper cost of rice straw in Vietnam when compared with Japan. The potential to build larger plant sizes because of the abundant rice straw supply in Vietnam holds even more promise to reduce production cost. A scale of 200 ML $year^{-1}$ has been proposed as the optimal plant size in Vietnam, with an estimated PC of just 1.19 $$L^{-1}$. Therefore, if ethanol is produced in Vietnam, the production cost will be reduced to 44% when compared with production cost in Japan. Although Vietnam possesses cheaper labour and electricity costs when compared with Japan, these costs contribute to a small share of the total cost; the reduction in PC in Vietnam is mainly due to the lower cost of rice straw and the larger plant size. However, this PC is much higher than the fuel ethanol market price in Vietnam, 0.97 $\$L^{-1}$ (Vietnam news, 2011a), so the current PC should be reduced further to be cost-competitive with first generation ethanol.

Compared to other previous studies, the estimated production costs in this study are more realistic as the capital investment and enzyme costs were higher and based on recent project data (Kazi *et al*., 2010; Gnansounou and Dauriat, 2010).

As shown in Figure 5.5, the main cost components of the production cost in Japan for a plant size of 15 ML/year are in the following order, progressively reducing in share: rice straw (35.3%), energy (heavy oil + electricity) (20.2%), enzyme (19.9%), and capital investment (depreciation and maintenance) (18.4%). In Vietnam, this order is changed at a plant size of 200 ML year$^{-1}$ as follows: enzyme (38.2%), energy (32.7%), rice straw (13.9%), and capital investment (9.5%). Thus, the strategies used to achieve more economical ethanol production should be different in each country.

In Japan, as in other developed countries, raw material is the biggest component in PC; therefore, reducing this cost is the most important for the reduction of PC. Vietnam possesses the potential for building a larger scale plant with low rice straw costs that can eliminate the worries for large components costs from investment and feedstock.

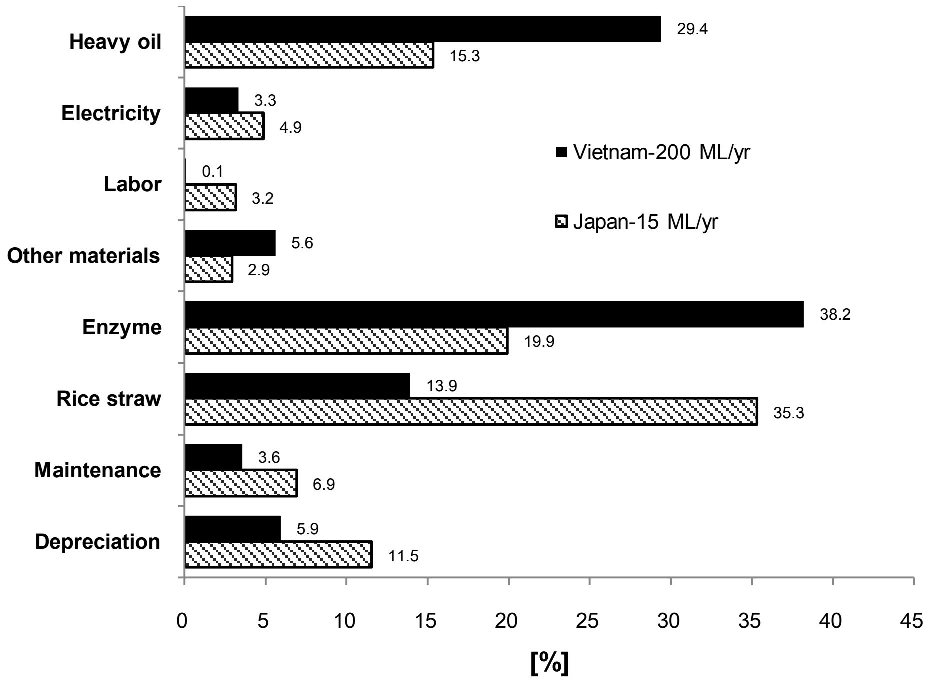


**Figure 5.5** Production cost contribution chart.

For process designs that utilise hydrothermal pre-treatment and enzymatic hydrolysis, energy and enzyme costs are large components of PC (Yanagida *et al*., 2009; Hideno *et al*., 2012). In this study, the first priority for reducing PC in Vietnam is the enzyme cost; it is the largest cost component of the total production cost. Reducing energy consumption is the second most important component in reducing ethanol production costs for both countries. Therefore, innovative technologies that reduce energy and enzyme costs per litre of ethanol produced are indispensable. In this study, enzyme costs were applied as on-site enzyme production costs to eliminate the expenses for broth concentration, enzyme stabilisers and transportation, effectively reducing enzyme production costs. In this case, increasing the specific enzyme activity to lower enzyme loading in the production process is the sole method for reducing the enzyme cost per litre of ethanol produced. As reported, increasing the specific enzyme activity is the target in enzyme industries not only for reduction in PC but also in reducing $CO_2$ emission (Roy *et al.*, 2012).

Capital investment accounts for a large share of PC in both countries. However, in Vietnam, large-scale plants can be built, partially alleviating the cost burden from capital investment.

### 5.4.2 Sensitivity analysis

Sensitivity analyses were performed on important parameters to provide information on the potential for PC reduction in each country.

#### 5.4.2.1 The impact of rice straw composition and conversion yields

Feedstock composition (especially the main components that can be converted to ethanol) and the efficacy of conversion technologies are parameters that impact the ethanol yield, and consequently the PC. Table 5.3 shows how changes in rice straw composition (represented as change in theoretical yields of fermented sugars) and saccharification yields lead to changes in ethanol yield and PC (Figure 5.6). For the base case, rice straw composition was applied from a nominal variety (Inoue *et al.*, 2011). In Japan, *Koshihikari* is the most popular rice variety that has theoretical yields of 432.2 and 212 mg/g dry straw for Glu and Xyl of after 5 days of harvest, respectively (Kumagai *et al.*, 2007; Park *et al.*, 2011). Thus, ethanol yield can be increased to 287.5 L dry $t^{-1}$. Improvement in sugar yields through the saccharification step also substantially increase ethanol yield (Table 5.3).

**Table 5.3** Rice straw composition and ethanol yield.

| Theoretical yield of fermented sugars (mg/g dry rice straw) | Saccharification yield | Fermentation yield | Ethanol yield (L dry $t^{-1}$ rice straw) |
|---|---|---|---|
| Glucose: 382.2<br>Xylose: 154.5<br>(*nominal variety*) | Glu - 83%,<br>Xyl - 66% | 90% | 241.7 (base case) |
| | Glu - 95%,<br>Xyl - 75% | 90% | 276.1 |
| Glucose: 432.2<br>Xylose: 212<br>(*Koshihikari*) | Glu - 83%,<br>Xyl - 66% | 90% | 287.5 |
| | Glu - 95%,<br>Xyl - 75% | 90% | 328.3 |

As shown in Figure. 5.6, increasing ethanol yields resulted in decreasing the PC as the feedstock and variable operating costs decreased, while other cost components such as fixed operating and investment costs are unchanged. In Japan, PC decreased more significantly with higher ethanol yield because the feedstock cost per litre of ethanol more substantially decreased when compared with Vietnam. Thus, when the feedstock is a large component of PC, improvements in feedstock composition and conversion yields are important factors in reducing PC.

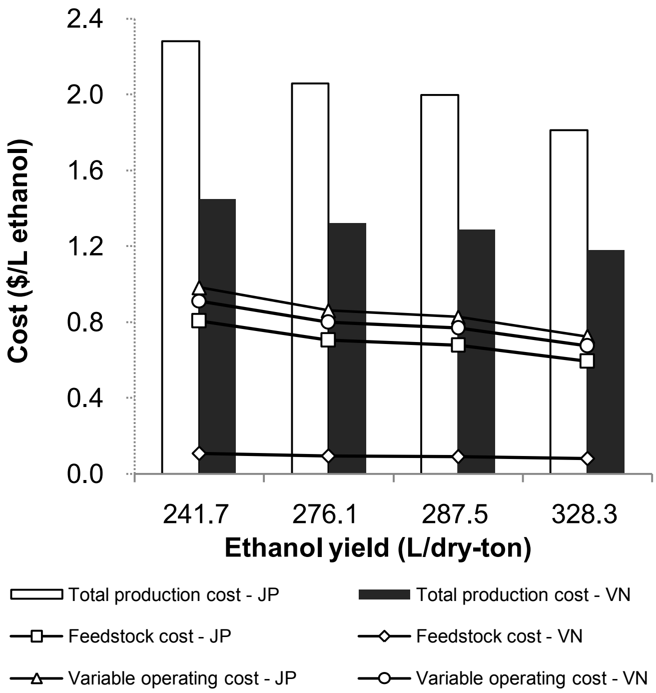


**Figure 5.6** Impact of ethanol yield on ethanol production cost.

#### 5.4.2.2 The impact of solid concentration for hydrothermal pre-treatment and utilisation of residue for energy generation

To reduce energy costs, improvement in the solid concentration for pre-treatment is an important target because energy consumption decreases in the pre-treatment and distillation steps as the ethanol concentration in the fermenter increases (Gnansounou and Dauriat, 2010). Additionally, as residue concentrations in the stillage increase, the residues are considered for energy generation depending on the trade-off between energy gain and increasing cost of capital investment. The heat and power generated from the residues supply energy to ethanol plants and thus reduce energy costs (electricity and heavy oil).

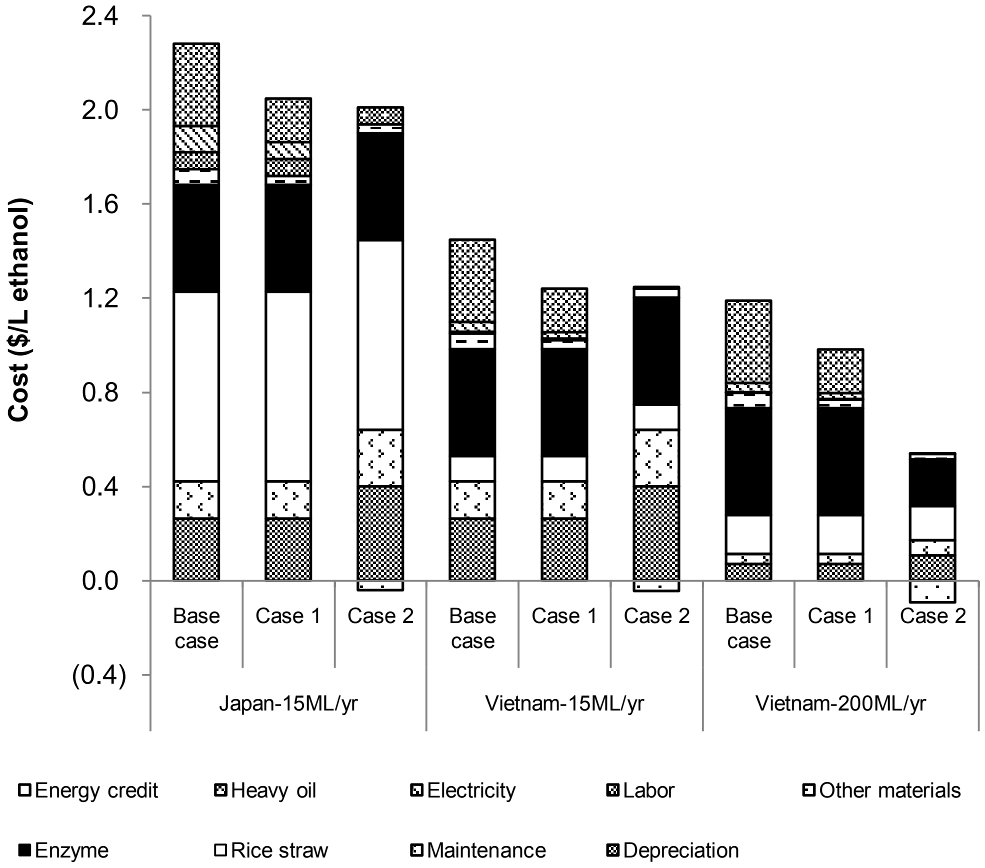


**Figure 5.7** Changes in ethanol production costs with respect to increasing solid concentration for hydrothermal treatment and energy generation from residues.

The impact of solid concentration for pre-treatment on the PC and cost components is shown in Figure 5.7. The cost of the base case with 10% solid concentration was compared with cases with 20% solid concentration without and with use of residues for energy generation (cases 1 and 2, respectively). In case 1, the PC significantly decreases because of the reduction in energy cost, particularly the cost of heavy oil. The PC was more reduced in case 2 when compared with the base case because of the benefit of using residues for energy generation, despite the significant increase in the investment cost. In case 2, heat and power generated surpasses the energy demand of the ethanol plant, and the excess electricity produced is sold “to the grid” returns as an energy credit.

In Japan, with a plant size of 15 ML/year, the PC was reduced by 10.2% and 13.7% compared to the base case for cases 1 and 2, respectively. In Vietnam, the potential for reduction of PC was much higher than in Japan by improving the solid concentration for pre-treatment, especially if the plant size is scaled-up. With a plant size of 15ML $year^{-1}$, the PC was reduced by 14.4% and 16.9% for cases 1 and 2, respectively. With a plant size of 200 ML $year^{-1}$, those reductions increased to 17.5% and 34% for cases 1 and 2, respectively. As shown above, energy costs account for a large share of the PC, especially in Vietnam. The reduction in energy consumption by increasing the solid concentration for pre-treatment is much more effective at reducing the PC in Vietnam when compared with Japan.

#### 5.4.2.3 The impact of plant size (in Vietnam)

Vietnam possesses a large rice straw supply for ethanol production, so the plant size can be as large as 450 ML $year^{-1}$ in the Mekong Delta region. The potential for further PC reduction based on plant capacity is shown in Figure. 5.8. The base case production process was applied for estimation of PC. The PC was divided into feedstock and non-feedstock cost. How the change in plant size causes changes in PC and its cost components is shown in Figure. 5.8. When plant sizes increase, feedstock costs increase and non-feedstock costs decrease, especially investment costs (Aden *et al*., 2002). The nature of this trade-off is demonstrated in the figure.

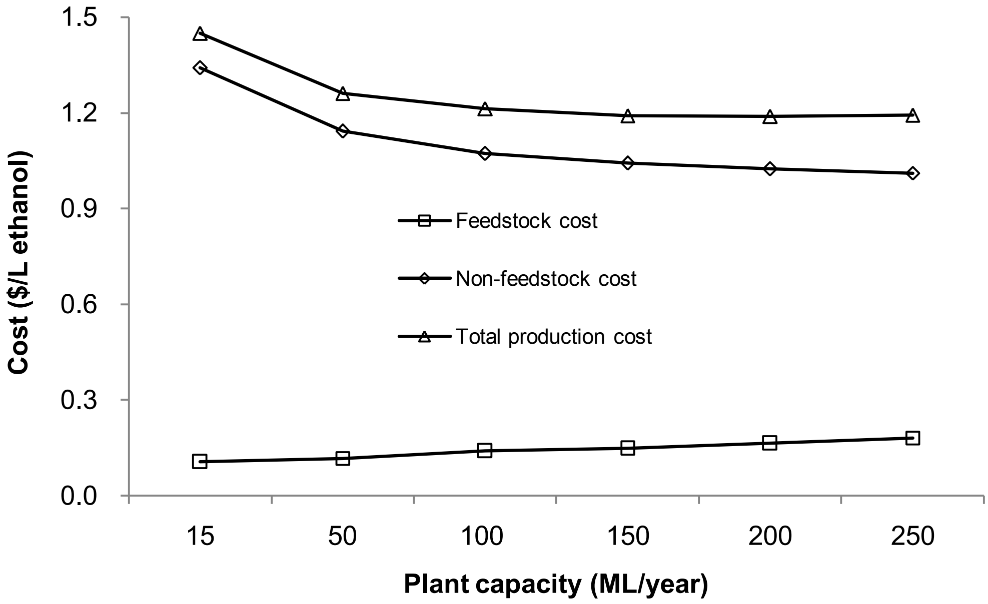


**Figure 5.8** Impact of plant size on ethanol production cost in Vietnam.

The production cost under the current scenario was substantially reduced when the plant size was increased from 15 to 200 MLyear$^{-1}$, but slightly reduced when the plant size increased from 150 to 200 MLyear$^{-1}$, and starts increasing when the plant size exceeds 200 ML year$^{-1}$. These data confirm the optimal plant size for Vietnam, as shown in a previous study, is 200 ML year$^{-1}$. However, if rice straw is not as available as assumed, the optimal plant size could be in the range of 150-200 ML year$^{-1}$.

### 5.4.3 Ethanol production cost - Future scenario

Ethanol production costs estimated for the future scenario with technological improvements in pre-treatment, enzyme hydrolysis, low enzyme load because of increased specific enzyme activity, and residues for energy generation is shown in Figure. 5.9.

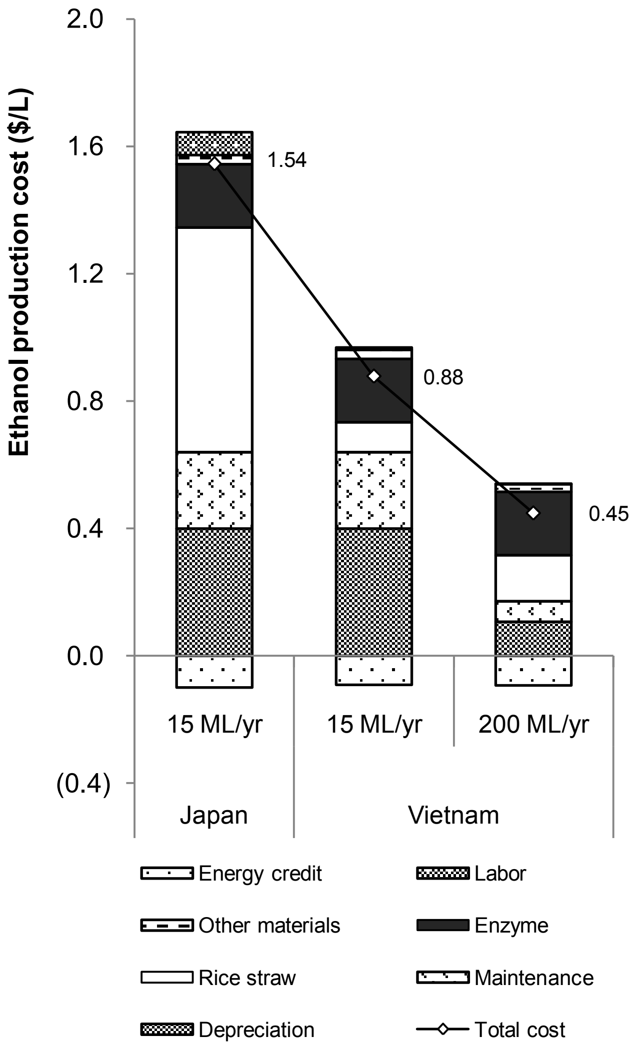


**Figure 5.9** Future ethanol production costs in Vietnam and Japan.

In Japan, the current production cost can be reduced to 1.54 $\$L^{-1}$ in the future scenario, but this cost is still higher than the recent target for production of cellulosic ethanol with a cost of 100 JPY/L or 1.30 $\$L^{-1}$ (Yanagida *et al., 2009).* The analytical results in this study are consistent with previous studies that conducted techno-economic analysis of rice straw ethanol production in Japan, (Yanagida *et al.*, 2010; Roy *et al.*, 2012). Rice straw is the largest contributor to the total production cost. The high costs of rice straw and capital investment are the main obstacles for economical ethanol production in Japan.

In Vietnam, ethanol production cost can be reduced to 0.88 $\$L^{-1}$ and 0.45 $\$L^{-1}$ for plant sizes of 15 MLyear$^{-1}$ and 200 MLyear$^{-1}$, respectively. The benefits of low rice straw cost and larger plant size will reduce the PC sharply with the improvement in production technologies and high specific enzyme activity when compared with the base case. The estimated ethanol production costs from rice straw in Vietnam are much lower when compared with a recent study‟s estimate of corn stover ethanol production, 1.36 – 2.30 $ per litre of gasoline equivalent [LGE] in some probable scenarios (Kazi *et al.,* 2010). These data show a promising future for industrial ethanol production from rice straw in Vietnam. Innovative technologies for improving production processes are critical for the cost competitiveness of rice straw ethanol in Vietnam

## 5.5 Conclusion

With current technologies applied to the designed production process, the PCs for the plants on the scale of 15 ML year$^{-1}$ in Japan and Vietnam are 2.28 $\$ L^{-1}$ and 1.45 $\$ L^{-1}$, respectively. Feedstock, enzyme, energy and investment costs are the main contributors to the PC. However, the significance of these cost components‟ contributions is different in each country.

In Japan, the dominant cost component is rice straw cost (35.3% of the total cost). Vietnam has much lower rice straw prices, so the impact of improvements in ethanol yield (rice straw component, conversion yields) is not as significant when compared with that in Japan. The improvement in solid concentration of material in the hydrothermal pre-treatment step with using residues for power generation can substantially reduce the PC, especially in Vietnam where energy costs account for the second largest contribution to the PC, following only enzyme costs. The potential for building larger ethanol plants with low rice straw costs can further reduce the current production cost in Vietnam. 1.19 $ L^{-1}$ is the current production cost for an optimal plant size of 200 ML year$^{-1}$.

For the future scenario, considering improvements in pre-treatment, enzyme hydrolysis steps, specific enzyme activity, and applying residues for energy generation, the production costs in Japan and Vietnam can be significantly reduced to 1.54 $ L^{-1}$ and 0.88 $ L^{-1}$, respectively, for a plant size of 15 ML year$^{-1}$. The ethanol production cost can reach 0.45 $ L^{-1}$ for a plant size of 200 ML year$^{-1}$ in Vietnam. These data indicate that the cost-competitiveness of ethanol production can be realised in Vietnam with future improvements in production technologies and the specific activity of enzymes for hydrolysis. The cost-competitive production of ethanol from rice straw in Japan would not be viable in the future without a substantial reduction in rice straw cost.

# Chapter 6

## General discussion and conclusions

### 6.1 Originality and research contribution

Fuel ethanol production from lignocellulosic biomass (second-generation bioethanol) has received attention worldwide and being considered as an alternative to the conventional bioethanol produced from sugary and starchy-derived biomass which has been blamed for causing land used change and food insecurity. Countries in Asia, such as China, India, Thailand, Vietnam, Japan, etc. where rice straw is the major agricultural residues, are interested in producing fuel ethanol from rice straw. Japan is the leading country in developing the advanced production technologies, but the higher cost of rice straw and the lower plant capacity are hurdles for economic production of rice straw-derived ethanol. These matters can be solved in the Asian developing countries with the abundant supply of rice straw and the lower labour costs, thus industrial production of rice straw ethanol is expected to be realized in the near future.

The research described in this thesis was originated from interest about the potentials for the implementation of industrial ethanol production from rice straw in Vietnam. To understand the potential for practical production of a product, besides the mature technologies required, other concerns such as biomass cost, plant capacity, and above all, assumed ethanol PCs should be addressed. Techno-economic analysis is one of vital tools to determine the economics through production cost and cost contribution. Up to date, most of techno-economic studies of ethanol production from lignocellulosic have been conducted came from developed countries (Japan, the U.S, France, etc.) as they have developed demonstration plants for lignocellulosic ethanol production. In this research, such kind of study for the case of Vietnam was completely conducted from investigating the rice straw available for sustainable production of ethanol, density, farm-plant"s gate cost, and the optimal facility size for minimizing ethanol production cost to techno-economic analysis. This research is an unprecedented attempt in previous studies in developing countries where technical data from demonstration-scale production process have not yet been available and even rare in the developed nations. The idea of developing the equation for calculation of optimal facility size is unique and applicable for any bio-renewable energy projects which collect biomass residues on surrounding farms, and should ensure that all the input data such as yield of product (Y), scale factor of plant (α), and plant life (T) and other parameters must be collected correlatively and appropriately.

The research results provided useful data and showed good potentials for reducing ethanol PCs in Vietnam through choosing optimal location, plant size, and improvements in conversion technologies. The sensitive analysis of cost components in ethanol PCs suggested the research orientation in development technologies to reduce rice straw ethanol PC in Vietnam. Additional discussion in this Chapter showed potentials for expected environmental, socio-economic benefits of rice straw ethanol production, as well as concerns related to sustainable production and use of rice straw ethanol; how to promote the development of industrial production of ethanol from rice straw in Vietnam. This study is expected to be a valuable document to assist interested parties and bio-energy policy makers during the initial stage of evaluating the potential for development of the cellulosic ethanol facility in Vietnam. This research methodology can be a fundamental tool for economic analysis of ethanol production from rice straw at any certain time.

## 6.2 General discussion

### 6.2.1 Potentials of environmental, socio-economic benefits related to rice straw ethanol production in Vietnam

Production and use of bioenergy are growing in many parts of the world as many countries seek to diversify their energy sources in a manner that helps promote economic development, energy security and environmental quality (GBEP, 2011). In developing countries, where traditional use of biomass is prevalent, the switching from traditional to modern bioenergy can also reduce disease from indoor air pollution, free women and children from collecting fuel wood and reduce deforestation; including promoting rural economic development, increasing household income through job creation and selling biomass. Furthermore, bioenergy can expand access to modern energy services and bring infrastructure such as roads, telecommunications, schools and health centers to poor rural areas.

In the case of rice straw ethanol production in Vietnam, according to the results of this study, just 5% of total rice straw generation can be economically exploited for ethanol production, thus the remaining available rice straw also should be used for biomass-fired power plant together with rice husks; mushroom cultivation or compost production locally, as the model of biomass town plant has been developed in suburb of Ho Chi Minh city (MAFF, 2013). Utilisation of rice straw for sustainable production of energy and various products lead to creating the new addition value for the areas, increase income for farmers, create more jobs, thus can help formulating a recycling-based society and revitalising rural areas.

In Vietnam, rice is the most important crop in Vietnam. It is planted on about 84 % of agricultural land and mainly concentrated in Mekong River Delta - MRD and Red River Delta - RRD. The MRD is 40,602 $km^2$ (12% of Vietnam‟s area), 64% of this area is used for agricultural-aquatic cultivation. Population is 17 million, 80% of this population is engaged in agriculture production. The RRD has the area of 16,700 $km^2$ (1.67 million ha), nearly 50% of the 802,600 ha of total land is used as agricultural land (Phan and Fujimoto, 2012). Population is 19 million and more than 70% population is engaged in agricultural production and more than 70% of farm households cultivate rice (Vu, 2012). Therefore, tens of millions of farmers will get more income from rice farming by selling rice straw, and collecting of and transporting of rice straw can created many jobs for farmers during leisure time and the unemployed.

The MRD is one of the most vulnerable areas in the world to climate change impacts due to the potential increase in floods, drought, storms and threats to local water sources. This low-lying area is threatened by sea level rise and saline intrusion. The rice – shrimp farming used to be a common practice for decades in the MRD as this area suffers from seawater intrusion caused by tide during dry season. People of the affected area, mostly from coastal area of the MRD practice rice farming in the wet season but they can only fish or practice aquaculture for subsistence in the dry season. Since the booming shrimp demand in the world market in the 1990s, the government has found opportunities to develop intensive shrimp farming by constructing dams to constrain saline water to the lower delta. Farmers observed the high profit from shrimp compared to profit from rice, they decided to convert the paddy fields and mangrove forests to shrimp ponds. The average annual reduction in mangrove forest coverage was 13.1% in the period (1995–2001) (Phan and Jacques, 2007). Intensive shrimp farming in the Mekong Delta develops rapidly caused a danger to the environmental, socio-economic development of the country. Detailed problems associated with intensive shrimp farming include disease, channel contamination and an inability to return to traditional rice farming, disease is the primary immediate cause of shrimp harvest failure and push more farmers to poverty. Reasons contributing to the disease outbreaks include environmental conditions, climatic factors, the intensive use of chemicals and nutrients pollutes the water (Nguyen and Andrew, 2010). Mangrove deforestation pushes more resident areas to the risks of flooding and more agricultural land areas affected by saline intrusion, reduces the habitats of fauna and flora. Concerns regarding sustainability, environmental and social-economic impacts of shrimp farming have been raised in Vietnam by international and national public. The Vietnamese government is now supporting an ongoing national environmental monitoring and early warning system in aquaculture. The multidisciplinary work program of Environmental Security for Poverty Alleviation (ESPA) integrates the fields of science, diplomacy, law, finance and education and is designed to provide policy makers with a methodology to tackle environmental security risks in time, in order to safeguard essential conditions for sustainable development, in which, renewable energy is considered as a potential for alternative economic activities in the MRD (Institute for Environmental Security, 2007). In other words, rice straw utilization for production of ethanol or other value added products can contribute to mitigate the effects of climate change and the sustainable development in the MRD and other rural areas of Vietnam.

### 6.2.2 Concerns related to sustainable production and use of rice straw ethanol

Modern bioenergy presents great potentials for sustainable development and climate change mitigation as mentioned above, but it brings challenges too. If not sustainably produced, bioenergy can place extra pressure on environmental pollution, and biodiversity, scarce water resources and food security. Report published by GBEP, 2011 presented indicators of sustainability regarding the production and use of modern bioenergy, broadly defined. These indicators were developed to provide policy makers and other stakeholders a set of analytical tools that can inform the development of a national bioenergy policies and programs and monitor the impact of these policies and programs. The indicators were intentionally crafted to report on the environmental, social and economic aspects of sustainable development.

One of the most important indicators is lifecycle GHG emissions: Production and use of renewable energy is considered environmental benign as renewable energy is produced from biomass which is renewable and carbon-neutral. However, the production process of any renewable energy from biomass and distribution of this product require energy and thus release significant amounts of GHGs (Greenhouse Gases). Therefore, Life Cycle Assessment - LCA of GHG emission of renewable energy with different boundaries must be conducted to understand environmental benefit. In the case of rice straw ethanol production in Vietnam, rice straw is waste and disposed by burning on fields and ethanol is used by mixing with gasoline in the form of gasohol E5 (a mixture of 5% ethanol and 95% gasoline). The utilization of rice straw as feedstock for ethanol production, the LCA for GHG emission saving from rice straw ethanol production and utilization in the form of E5 compared to using gasoline and deposition of rice straw as burning should be conducted to ensure the environmental benefits of rice straw ethanol practice. The recent study on economic and environmental effects of rice straw ethanol production in Vietnam stated that satisfying economic viability is more difficult than attaining environmental viability. It is anticipated that under advanced and innovative technologies, there is positive contribution to saving GHG emissions from rice straw ethanol production in Vietnam (Kunimitsu and Ueda, 2013). This information held promise of environmental benefits for rice straw ethanol production in Vietnam.

Other indicators belong to environmental pillar such as biological diversity in the landscape, water quality; land use and land-use change related to bioenergy feedstock production, etc. Trend of growing dedicated crop for ethanol production in particular or renewable energy production in general such as switch grass and eucalypts, etc. can cause land use change, reduce biodiversities, and completion of water use with other food crops. Land use change includes conversion of native ecosystems into agricultural use, as well as switching from one crop type to another. However, ethanol production from crop residues such as rice straw can avoid these concerns. But another concern occurs, if rice straw ethanol production is realized, it is anticipated that farmers may collect all rice straw for selling. Therefore, it is necessary to have regulation or guide for farmers in leaving some amount of rice straw on farm. To ensure sustainably agricultural production, 5 - 10 % amount of farm residues should be left on the field to reduce erosion and recycle nutrients back into the soil.

### 6.2.3 How to promote the development of industrial-scale rice straw ethanol production in Vietnam

Current high production cost and lack of market support for green fuels and unenforced-governmental policies has been the main obstacles for the progress of promoting rice straw ethanol production in Vietnam.

Lignocellulosic ethanol PC is sensitive to key parameters such as: composition of feedstock; farm-gate price of the feedstock; size of ethanol plant; the conversion efficiency; level of investment costs. For the case of Vietnam, the larger size of ethanol plant can be built and the lower cost of biomass can greatly reduce the PCs. Although the current estimation of delivered cost of rice straw is considered quite high for mass ethanol production, there are some rooms for reducing feedstock cost that lead to further reduction in PC such as development of new collecting and baling machines, use of waterway for transportation of rice straw bales. In MRD and RRD with available flexible waterway systems, the actual farm"s location, transportation distance and the amount of rice straw collected at once will be considered for waterway or roadway transportation. Thus, the main challenges for competitive PC are the technical challenges and high investment cost.

Technical challenges include improvement of ethanol yield, advanced technologies for lignin utilization, pretreatment step, efficient enzyme and microbial cell factories. Higher performances of advanced and innovative technologies indicate that more research and development efforts should be encouraged with the involvement of public sectors, higher fund for research from government and call for transferring technologies from developed countries. The substantial improvements of conversion technologies in recent years tested in pilot, demonstration plants in Japan and the U.S will pave the way for large -scale production in near future.

The investments for plant construction are extremely huge, in addition, the high interest repayment of capital investment‟s loan (at least 7% per year), so it is difficult for only Vietnam to pay such costs. Investment funds need to be collected from foreign countries through call for investments. The investment costs are expected to be reduced when the cellulosic ethanol production plants are widely installed or combine with the first generation ethanol production. The rice straw ethanol plants can be considerably located with existing cassava ethanol plants to reduce capital costs in some common ethanol processing steps. Unlike other countries, to date, Vietnam has not drawn any subsidies or supporting investment policies for its biofuel projects, and sales of E5 petrol remain low (Vietnam news, 2013). Thus, Feed-in Tariff for bioethanol development such as significant incentives and subsidies from government for capital investments and ethanol cost of ethanol projects should be proposed and enforced for the environmental benefits and the energy security purpose of the projects.

Experiences learned from cassava ethanol production and the low domestic demand of ethanol because of the difficulty in installing gasoline E5 have forced the ethanol production companies to seek foreign markets, however the selling costs are even lower than PCs, resulting in non-feasible operation of ethanol production plants. The optimized combination of market and governmental support for the production and consumption of ethanol will be an important factor in determining the rate of deployment of rice straw ethanol facilities.

### 6.3. Conclusions

Annually, Vietnam has approximately 83 Mt of agricultural residues from food and cash crops, and this huge amount is mainly generated from rice production (apprx. 50 Mt $year^{-1}$). Analysis of current practices, distribution, and composition of these residues, rice straw appears as the most promising feedstock, and practically, 10-25 Mt of rice straw can be available for ethanol production per year.

Rice straw is abundant in Vietnam but mainly concentrated in the Mekong River Delta and the Red River Delta regions on the basis of rice straw quantity and density. Considering both field- and landscape-level factors, the available densities of rice straw for sustainable ethanol production in 6 administrative regions of Vietnam named 1, 2, 3, 4, 5, and 6 were estimated to be 69, 6.8, 14, 3.9, 12, and 108 dry t $km^{-2}$, respectively. The difference in rice straw densities results in different costs of delivered rice straw by region.

The MDR region has appeared as the most intensively agricultural region and may be one of the best locations for setting up the first ethanol plant in Vietnam. Rice straw is provided mainly from the two main harvest seasons of spring and autumn rice. The areas with high densities of rice straw supply are located along the upper and mid-banks of the Hau and

Tien Rivers.

The delivered rice straw cost in Vietnam varied from 20.5 to 65.4 \$ dry $t^{-1}$ with the transportation distances of 0 to 120 km. This lower cost of biomass is a result of high density of available rice straw and low labor cost for its collection and handling. In fact, this cost can be much more reduced via further improvements in technologies of collecting, baling, and storage of rice straw and especially application of waterway for transportation. In the MRD and RRD, the waterway transportation is expected to reduce the assumed transportation cost to one third.

To minimize the overall production costs, it‟s crucial to choose the optimal facility size for minimal production costs. Based on the reasonable approaches, an equation for calculation of the radius of optimal biomass collection area - $R_{opt}$ (imply optimal plant capacity) was developed and applied for calculate the optimal plant size by region. Regions 1 (Red River Delta) and 6 (Mekong River Delta) were found to be the optimal locations for ethanol production, with economical facility sizes of 112.5 and 195 ML $year^{-1}$, respectively.

In the short term, considering to economical production, optimal ethanol plants in the MRD and RRD are expected to be constructed and the amount of ethanol produced from these two regions (502.5 ML $year^{-1}$) is capable to replace 9.8% of the country's gasoline imported in 2009. With current technologies, the PCs for the plants on the scale of 200 ML $year^{-1}$ in Vietnam was 1.19 \$ $L^{-1}$. Different with the case of Japan, enzyme and energy are the two biggest shares of PCs. Investment cost and rice straw cost has been significantly reduced in Vietnam, thanks to high plant capacity and much lower labour cost compared to Japan.

Thus strategies for further reduction of PCs in Vietnam are to develop innovative technologies to reduce energy consumption in pretreatment steps, utilise residue for energy supply within EtOH plants, and increase specific enzyme activity. For the future scenario, considering such improvements technologies, the production costs in Vietnam can be significantly reduced to 0.45 $ $L^{-1}$.

Therefore, rice straw-derived ethanol promises opportunities for Vietnam to reduce dependence on fossil fuels, impact of climate change and contribute to sustainable developments of rural areas. A huge amount of rice straw generated annually and concentrated in the two deltas facilitates building large-scale ethanol plants. In addition, low labour cost and high density of rice straw in the deltas contribute to the low cost of delivered biomass. People livings in the MRD and RRD are considered the most vulnerable to the risks of climate change in Vietnam. The implementation of rice straw ethanol production can be an alternative economic activity in the two deltas. The current PCs are still high (1.19 $ $L^{-1}$), the main hurdles for Vietnam are to develop advanced technologies and calls for investment. The application of new, engineered enzyme systems for cellulose hydrolysis, energetic yeast strains, improved pre-treatment technologies, using by-products will promise significant reduction in PCs (0.45 $ $L^{-1}$) in future. Vietnam possesses good potentials for reducing rice straw ethanol PCs, however the success in rice straw ethanol production strongly depends on substantial supports from both government and public based on environmental concerns as well as desire to reduce oil dependency.

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