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Comparison of the Potential for Ethanol Production from Rice Straw in Vietnam and Japan via Techno-economic Evaluation

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Abstract – *This study aimed to compare rice straw ethanol production costs in two countries based on recent production technologies developed in Japan and predict the potential for economical ethanol production in the future. Analysis of cost component distribution and sensitivity showed a trend towards reduced ethanol production cost (PC) in each country. The PCs in the current scenario were 2.28 $/L and 1.45 $/L at a scale of 15 ML/year in Japan and Vietnam, respectively. In Vietnam, the potential for bigger ethanol plants combined with lower feedstock cost can eliminate the majority of investment costs and reduce PC to 1.19 $/L at a scale of 200 ML/year. In Vietnam, enzyme and energy costs are the two biggest cost components of PC. In Japan, the biggest component is the feedstock cost, so increasing ethanol yield is essential to the reduction of PC. In a future scenario, with improvements in production technologies and enzyme activities, the present PC for a scale of 15 ML/year can be reduced to 1.54 $/L and 0.88 $/L in Japan and Vietnam, respectively. In Vietnam specifically, the PC is sharply reduced to 0.45 $/L at a scale of 200 ML/year. This study reveals the high potential for economical production of ethanol from rice straw in Vietnam in the future, and the contrasting difficulties in Japan.*

Keywords – Ethanol, feedstock, production cost, rice straw, techno-economic evaluation.

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 [1]. 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 [2], [3].

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 [4], [5]. Rice straw is the major agricultural residue in Japan (approximately 10 Mt/year) and Vietnam (approximately 50 Mt/year); in both countries ethanol production from this biomass source has been promoted [6], [7]. 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 with low rice straw costs (including transportation fees) [7].

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 [2], [8], [9]. 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 will 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 ethanol production from rice straw and has developed 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

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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 [6].

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. Vietnam has both a lower cost of rice straw and the potential to build a higher capacity ethanol plant when compared with Japan [7], [10]. This study compares 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 model a 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.

2. MATERIALS AND METHODS

A process for ethanol production from rice straw was designed, as shown in Figure 1, by considering the economic efficiency and environmental sustainability of lignocellulosic ethanol production technologies that have been researched and developed in Japan. A diagram of all equipment in the plant for energy consumption calculation is shown in Figure 2 [11]-[14].

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 C5 and C6 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 Figures 1 and 2).

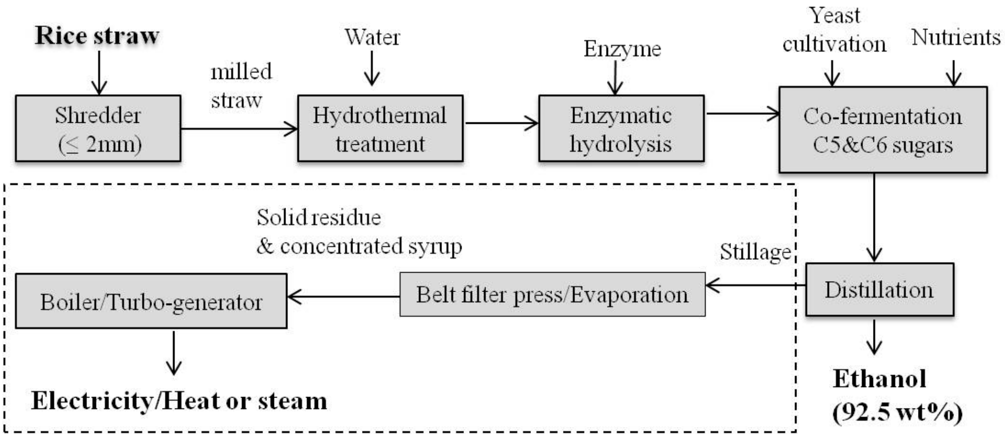

Fig. 1. Process flow diagram of bio-ethanol production.

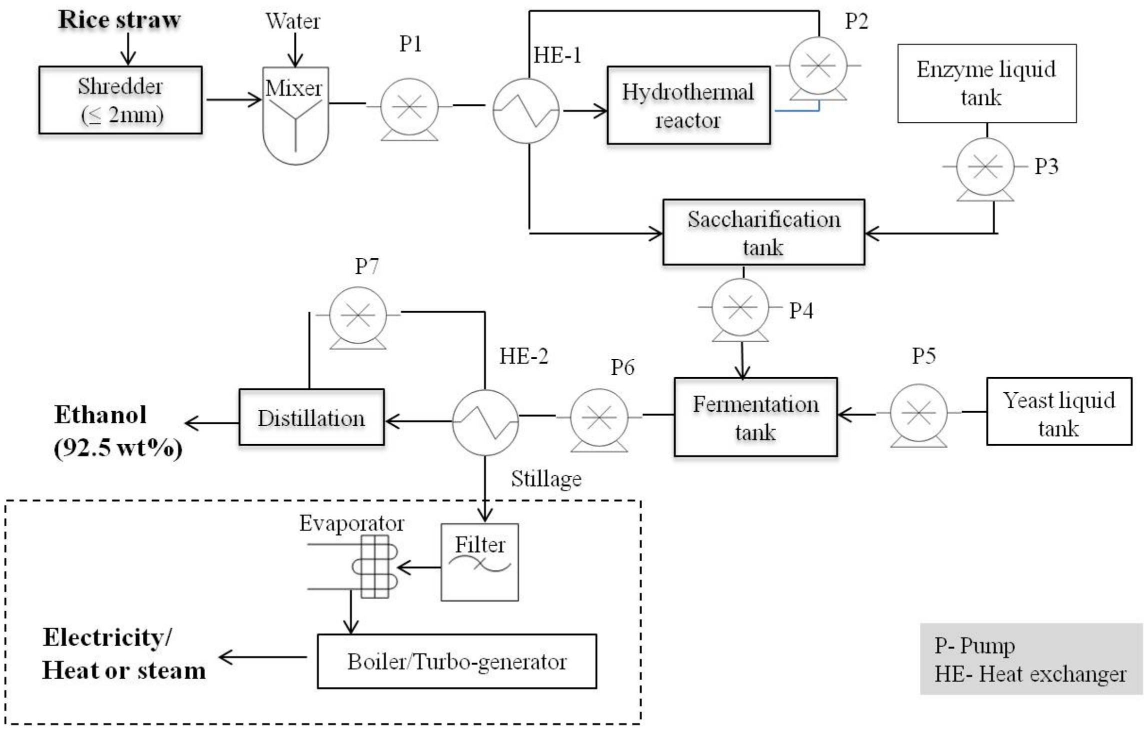

Fig. 2. Equipment diagram of the bio-ethanol plant.

2.1 Specific Conditions for Mass and Energy Balances

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 [15].

Plant size: based on previous studies [6], [7] 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 the Biomass Technology Research Center, AIST, Japan were applied for setting the process conditions of the base case to estimate current ethanol production cost [12], [13]. The process conditions for the future case were set based on ethanol production cost reduction targets [12], [16]-[17]. The detailed conditions of the process are shown in Table 1. The process flow, mass and energy balances were used to calculate operating costs.

2.2 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 a previous study [7]: $Y = 20.695X^{0.49}$ where "Y" is the total capital investment (millions of US $); "X" is plant size (in megalitres (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 [8].
- Maintenance cost per year: 3% of total capital investment (TCI).
- Plant life: 20 years, with a straight-line depreciation cost per year = TCI/20.
- Labour cost: In Japan, the following equation was applied: $A = 1.17 \quad (B/20)^{0.27}$ where "A" is labour cost and "B" is plant size (ML/year) [9], [18]. 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 or 194.8 US$/dry ton for a plant size of 15 ML/year. In Vietnam, prices were set as 26, 28.5, 34, 36, 40, and 44 US $/dry ton for plant sizes of 15, 50, 100, 150, 200, and 250 ML/year, respectively [7].
- Other material and energy costs (Table 2) were from vendor quotes or published documents. All costs were updated to 2012 with an exchange rate of 1 US $ = 77 JPN = 21,000 VND.

Table 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 % fraction converted to product after hydrolysis: Glucan to glucose: 86% (glucose yield) Xylan to xylose: 66% (xylose yield)	2 –fold increasing in specific enzyme activity, (10 FPU/g-dry rice straw). Glucose yield: 95% Xylose yield: 75%
Co-fermentation C5 and C6 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. Fermentation rate: Glucose to ethanol: 90% Xylose to ethanol: 90%	-
Distillation	Ethanol distillation yield 99% Product: ethanol 92.5 wt%	-
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%)

Table 2. Other costs of materials and energy.

List of material or energy	Price	References
KH_2PO_4 (\$/kg)	9.35	[19]
$(NH_4)_2SO_4$ (\$/kg)	0.61	[19]
$MgSO_4.7H_2O$ (\$/kg)	0.84	[19]
Heavy oil ($/GJ)	19.67	[20], [21]
Electricity ($/kWh)	0.16 (0.06)	[22], [23]
Running water (\$/m^3)	0.26	[24]
Yeast-on site production ($/ton)	15.97	[25]
Enzyme-on site production ($/kg)	3.9	[9]

In brackets: price in Vietnam.

3. RESULTS AND DISCUSSION

3.1 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 3. The distribution of cost components are shown as percentages of total cost in Figure 4.

As mentioned in previous studies, the production cost strongly depends on raw material (feedstock) and plant size [6], [16]. In Japan, with its target to produce ethanol from rice straw at a plant size of 15 ML/year [6], the estimated PC was 2.28 $/L. In Vietnam, with the same plant size, the estimated PC was 1.45 $/L 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 [7]. A scale of 200 ML/year has been proposed as the optimal plant size in Vietnam, with an estimated PC of just 1.19 $/L. 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 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 [26], so the current PC must 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 [6], [8], [11].

As shown in Figure 4, 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 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 must 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.

For process designs that utilise hydrothermal pre-treatment and enzymatic hydrolysis, energy and enzyme costs are large components of PC [18], [27]. 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 [6].

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.

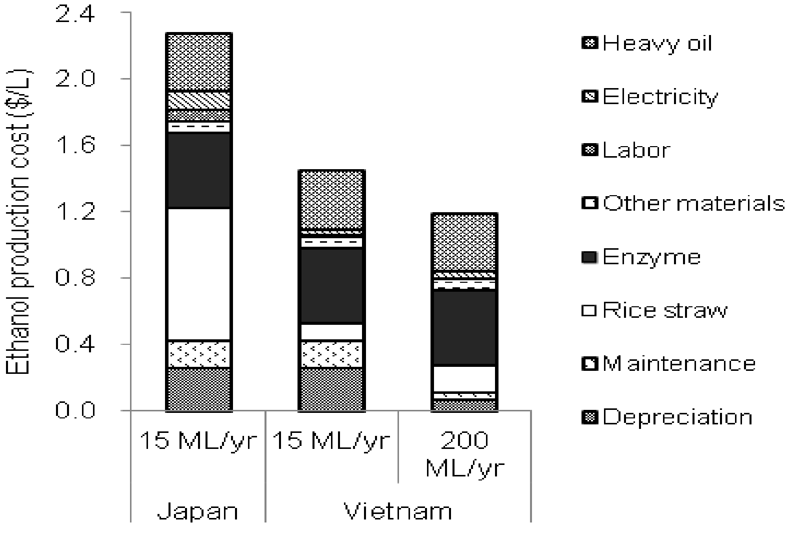

Fig. 3. Estimated ethanol production cost under the current scenario.

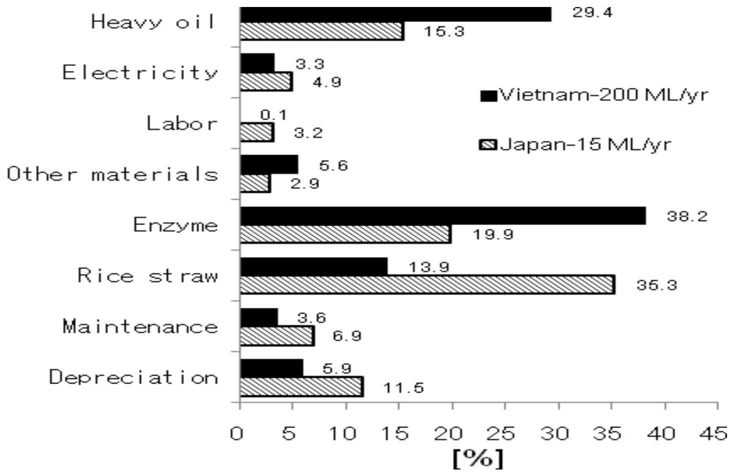

Fig. 4. Production cost contribution chart.

3.2 *Sensitivity Analysis*

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

- *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 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).

For the base case, rice straw composition was applied from a nominal variety [15]. 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 [5], [28]. Thus, ethanol yield could be increased to 287.5 L/dry t. Improvement in sugar yields through the saccharification step will substantially increase ethanol yield (Table 3).

Table 3. Rice straw composition and ethanol yield.

Theoretical yield of fermented sugars (mg/g dry rice straw)	Saccharification yield	Fermentation yield	Ethanol yield (L/ton dry rice straw)
Glucose: 382.2 Xylose: 154.5	Glu - 83%, Xyl - 66%	90%	241.7 (base case)
	Glu - 95%, Xyl - 75%	90%	276.1
Glucose: 432.2 Xylose: 212	Glu - 83%, Xyl - 66%	90%	287.5
	Glu - 95%, Xyl - 75%	90%	328.3

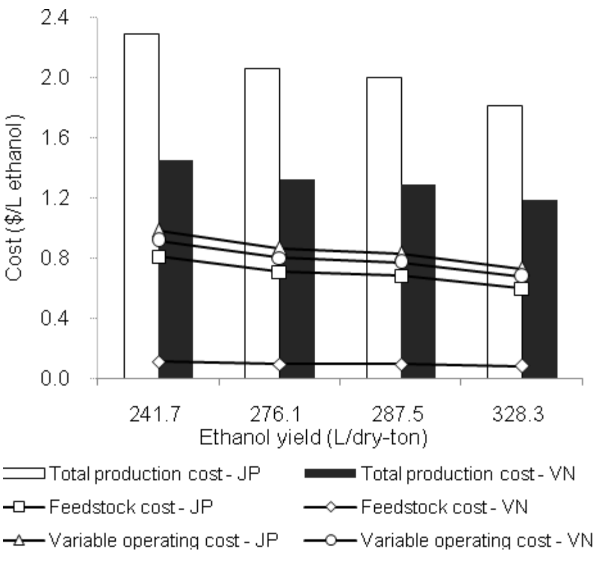

Fig. 5. Impact of ethanol yield on ethanol production cost.

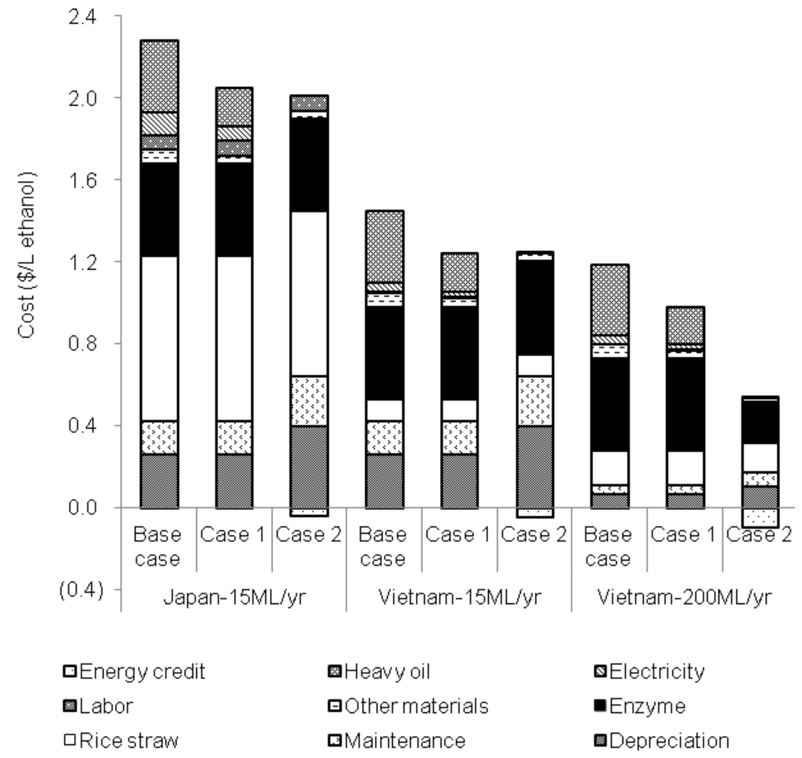

Fig. 6. Changes in ethanol production costs with respect to increasing solid concentration for hydrothermal treatment.

As shown in Figure 5, 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 was more substantially decreased when compared with Vietnam. Thus, when the feedstock is a large component of the PC, improvements in feedstock composition and conversion yields are important factors in reducing PC.

- *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 will decrease in the pre-treatment and distillation steps as the ethanol concentration in the fermenter increases [11]. Additionally, as residue concentrations in the stillage increase, the residues will be 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). The impact of solid concentration for pre-treatment on the PC and cost components is shown in Figure 6. 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 that 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 15 ML/year, the PC was reduced by 14.4% and 16.9% for cases 1 and 2, respectively. With a plant size of 200 ML/year, 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.

- *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 [7]. The potential for further PC reduction based on plant capacity is shown in Figure 7. 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 7. When plant sizes increase, feedstock costs increase and non-feedstock costs decrease, especially investment costs [7], [16]. The nature of this trade-off is demonstrated in the figure. The production cost under the current scenario was substantially reduced when the plant size was increased from 15 to 150 ML/year, but slightly reduced when the plant size increased from 150 to 200 ML/year, and starts increasing when the plant size exceeds 200 ML/year. These data confirm the optimal plant size for Vietnam, as shown in a previous study, is 200 ML/year [7]. However, if rice straw is not as available as assumed, the optimal plant size could be in the range of 150-200 ML/year.

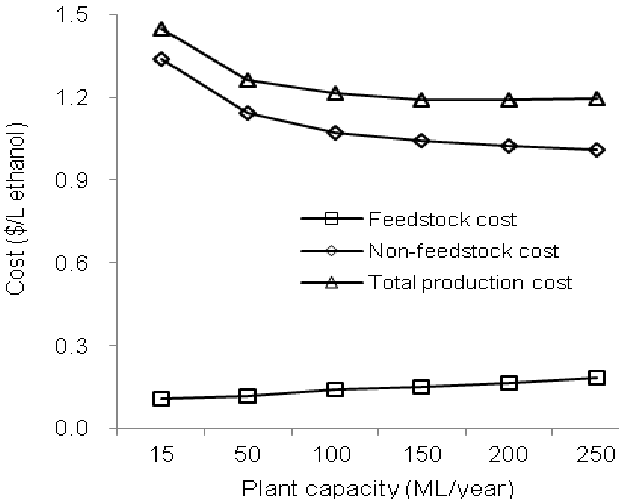

Fig. 7. Impact of plant size on ethanol production cost in Vietnam.

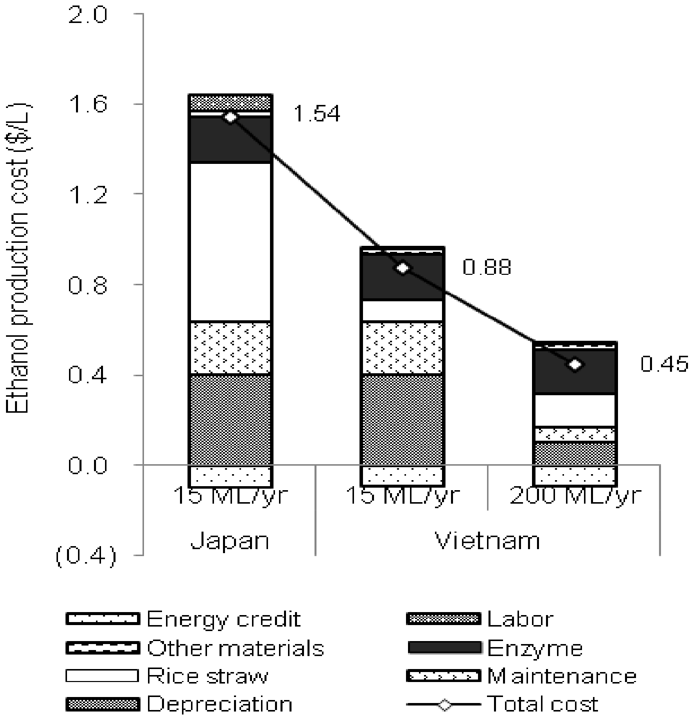

Fig. 8. Future ethanol production costs in Vietnam and Japan.

3.3 *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 8.

In Japan, the current production cost can be reduced to 1.54 $/L in the future scenario, but this cost is still higher than the recent target for production of cellulosic ethanol with a cost of 100 yen/L or 1.30 $/L [18]. The analytical results in this study are consistent with previous studies that conducted techno-economic analysis of rice straw ethanol production in Japan, [9],

[6]. 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 and 0.45 $/L for plant sizes of 15 ML/year and 200 ML/year, 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 $/L of gasoline equivalent [LGE] in some probable scenarios [8]. 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.

4. CONCLUSIONS

With current technologies applied to the designed production process, the PCs for the plants on the scale of 15 ML/year in Japan and Vietnam are 2.28 $/L and 1.45 $/L, 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) are 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 is 1.19 $/L.

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 and 0.88 $/L, respectively, for a plant size of 15 ML/year. The ethanol production cost can reach 0.45 $/L for a plant size of 200 ML/year 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.

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