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学位論文の要旨（論文の内容の要旨）
Summary of the Dissertation (Summary of Dissertation Contents)

論　文　題　目
Dissertation title

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

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Summary

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.

備考　論文の要旨はＡ４判用紙を使用し，4, 000字以内とする。ただし，英文の場合は1, 500語以内とする。

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