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SUMMARY

Fossil fuel energy supply has remained the share of more than 80% in total primary energy supply for four decades despite the increasing non-fossil energy. This dominated complexion of fossil fuel is projected to continue until 2035. Since fossil fuel is depletable, this will lead to a massive future burden on the natural resources. Furthermore, fossil fuel combustion is the key driver of the surge in global carbon dioxide (CO_2) emissions to reach the level of 32.2 $GtCO_2$ in 2013. As carbon dioxide emissions are the most contributors to climate change, several substitutions of fossil fuel are of major concern to international communities regarding future energy guarantee and environmental and human wellbeing protection.

Biodiesel fuel (BDF) is widely considered to be an alternative energy source which is environmentally friendly and renewable. Over the last decade, the production of biodiesel has increased gradually from just under 7 million liters per day in 2004 to almost 70 million liters per day in 2012. The benefits of biodiesel are well recognized, such as greenhouse gas (GHG) emissions reduction, energy supply diversification and security, energy price stabilization, job creation, rural development, renewability, easy biodegradability, and non-toxic and safer handling than fossil fuels. Several scholars, nevertheless, pointed out that producing and using biodiesel also have some disadvantages such as deforestation and biodiversity loss due to land-use change, food price increase and conflict, net GHGs emission increase, non-climate-related environmental impacts such as soil erosion due to tilling, eutrophication due to fertilizer runoffs, impacts of exposure to pesticides, habitat, and noneconomical fuel source. Of various biodiesel feedstocks and production techniques, returned profits and burden vary case by case. Therefore, to date researchers seldom stated that the application of biodiesel always brings net benefits.

In 2007, Viet Nam introduced a new Energy Development Scheme which planned to

produce and use about 250 thousand metric tons ethanol 5% (E5) and biodiesel 5% (B5) and 1.8 million metric tons E5 and B5 by 2015 and 2025, respectively. Since then, several biodiesel studies and experiments have been conducted. Of which, a highly promising project is 'Multi-beneficial Measures for Mitigation of Climate Change in Vietnam and Indochina Countries by Development of Biomass Energy' funded by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA), as one of the projects of Science and Technology Research Partnership for Sustainable Development (SATREPS) from 2011 to 2016 (hereinafter called Project). In this Project, a scenario was designed to develop a closed-loop system of BDF production and utilization, starting from oil plant cultivation to BDF end-use in cruise ship in Ha Long Bay, Quang Ninh Province, Viet Nam. In the designed system, this Project supposed to solve the environmental problems and enhance the application of biodiesel supporting the economic development in Ha Long Bay. As mentioned before, BDF production and use can generate either benefits or handicaps. Thus, the final goal of this study was to assess and evaluate the sustainability of the whole life cycle of BDF for cruise ship operation in Ha Long Bay.

To reach the goal, an Inclusive Impact Index, so-call Triple I was used for the calculation. This index aims to evaluate and combines the three-dimension sustainability over the whole life cycle of a product system as a single index by integrating the ecological footprint, cost-benefit, ecological risk and human risk assessments. Triple I was applied in several previous sustainable studies in, for example, marine technologies and energy sector. However, the application of Triple I differed case by case and in several cases, a simplified Triple I was used which omitted some parameters of Triple I, ecological risk and human risk, for example. Since Triple I is a single-index quantitative evaluation tool for sustainability assessment throughout the life cycle of a product system, and Life Cycle Sustainability Assessment (LCSA) framework provides a proper pathway for the assessment, it is necessary to connect the two methods to get an all-inclusive result with a systematic approach. Therefore, to contribute to the sustainability assessment of renewable energy for transportation, this study firstly aimed to propose a methodical estimation for Triple I by integrating the framework for LCSA.

This dissertation consists of 8 chapters. The main focus and results of each chapter are as follows:

Chapter 1 provides a general background of this dissertation. Firstly, an overview about biodiesel as an alternative to fossil fuel in transportation is given. Then, the current global trend of inedible vegetable oil-based biodiesel is introduced. In this part, several common inedible vegetable feedstocks for biodiesel production are reviewed and summarized. The aim of this study is clarified.

In Chapter 2, a nationwide potential of biodiesel feedstock production based on data about land use of Vietnam is simulated. Several maps are made for each region of Vietnam with potential oil plants, cultivation areas, and yields. Finally, a whole map of Vietnam with biodiesel production rank is introduced. The map shows that the highest potential of oil plant cultivation belongs to mountainous provinces dwelling near the national border zones with considerable unused marginal lands and high rate of poverty.

Chapter 3 describes the state-of-the-art of the vegetable oil-based biodiesel production focusing on Vernicia montana L. (Trau) and Hibiscus sabdariffa L. (Roselle). This chapter sets out all the stages from cradle-to-grave of biodiesel production system in Ha Long Bay. The whole life cycle of biodiesel production in Ha Long Bay starts with the intercropping of Roselle-Trau in open-pit mines and mining dump sites (raw material acquisition); harvesting,

sun-drying and transportation of oilseeds; extraction of oil and other medicines as co-products; co-solvent transesterification of Roselle-Trau crude oil to obtain biodiesel (methyl ester); distribution and use of biodiesel in cruise ships in Ha Long Bay; and ending with the field application of Roselle leaves and Roselle-Trau de-oiled cake as composts to offset a certain amount of mineral fertilizer use according to their nutrient components.

Chapter 4 devotes to identify the linkage between Triple I and LCSA. By integrating LCSA, a methodical estimation for Triple I is proposed. In this chapter, promising options for the monetary evaluation of environmental impacts and human health impacts, which play as important conversion factors of various assessments under Triple I, are also recognized. Moreover, a more flexible application of Triple I is also propounded which accounts for the payback time of a project considering both environmental and economic burden.

Chapter 5 shows the result of the light-scale Triple I (only ecological footprint and economic issues were under consideration) applied to assess the sustainability of Jatropha curcas and waste cooking oil biodiesel production from gate-to-grave. The result profiles the unsustainability and much sensitive of the B5 system. Therefore, the development of B20 and above is recommended. The study in this chapter lays a foundation for the application of the full-scale Triple I presented in Chapter 7.

Chapter 6 projects the ecological risk of oil spills and leakages from the operation of cruise ships in the Bay. The purpose of this chapter is to provide data about potential ecotoxicity of the discharged fuel. The comparison is made between petrodiesel, neat biodiesel including Roselle biodiesel, Trau biodiesel, and Roselle70-Trau30 mixed biodiesel. ADIOS 2 – a simple oil weathering model and biodegradation and solubility of data of fuels are used for the estimation. It is stated that the cumulative water-accommodated fraction of neat biodiesel is from seven- to twenty-time lower than petrodiesel. There are, nonetheless, not evident enough to confirm the ecotoxicity of all examined fuels. The evaporation components of petrodiesel vapors should be taken into account since more than 70 percent of oil spill volatilized within the first five days.

Chapter 7 estimates the sustainability of Roselle-Trau biodiesel production system throughout its whole life cycle. The full-scale of Triple I is employed to evaluate the entire system under various scenarios. Triple I indicates the sustainability of neat biodiesel (B100) system itself. Unfortunately, other blends are not sustainable. When putting all the blends in the context of alternatives to fossil diesel, the implementation of the B5 system and higher blends providentially confirms their prominent potential as a sustainable energy source. Over whole life cycle stages of biodiesel production and utilization in Ha Long Bay, this system proves a substantial decrease in ecological footprint, which also results in an ecological reserve, comparing to petrodiesel system. Revenue of the biodiesel system is also considerably high due to the contribution of various co-products. Of all processes, nevertheless, the intercropping of Roselle-Trau and the extraction of crude oil from vegetable seeds show the highest burden on ecosystem quality and human health, respectively. Under a thorough consideration about nutrients, a possible solution for the agricultural practices is to replace mineral fertilizers with composts.

Chapter 8 summarizes all the conclusions of the dissertation.

審査結果の要旨

本論文は、ベトナムにおけるバイオディーゼル燃料（BDF）の生産・普及に関するプロジェクトにおいて、サブテーマの一つとして取り上げられている、BDF の生産・普及による環境面と経済面の持続可能性を、ベトナムのハロン湾の観光船をモデルとして評価するというもので、以下の成果が得られている。

(1) ベトナム全土における各省の荒廃地面積のデータベースを作成するとともに、各地の気候や産業を考慮し、北部では広東アブラギリとハイビスカス、中部ではゴム、南部では南洋アブラギリを原料樹種としたときの種子生産量を推定し、各省の BDF 生産ポテンシャルマップを作製した。これにより、ベトナムにおける BDF 生産シナリオの提案が行えるようになった。

(2) 環境面と経済面を統合した評価指標である Triple I（トリプルアイ）の各項の算出方法について、すでに手法が確立されているいくつかのライフサイクル評価手法（LCA、LCC、S-LCA など）との関連付けを行い、総合的かつ系統的に各項を計算する手法を開発するとともに、その評価手法を用いてハロン湾の観光船に BDF を導入した際の有効性と課題（BDF 生産と消費の距離は離れていると不利）を明らかにした。

(3) 環境－経済統合評価に環境リスクの観点を導入する目的で、観光船から燃料漏れが生じた際の海洋生態系へのインパクトについて、軽油と BDF の比較評価を行い、BDF の観光船への利用によるリスク軽減効果を示した。またこのリスク評価を含めた Triple I 評価をハロン湾の観光船を対象に行い、その結果を踏まえ、BDF 生産はハロン湾のあるクアンニン省（炭鉱跡地）で生産し、観光船には B20（BDF20%、軽油 80%）燃料での運用を行うことが望ましいというベトナム政府への提言をまとめた。

以上の研究成果は、ハロン湾における観光船への BDF 利用をモデルとして、環境面と経済面を統合した新しい評価手法により多益性を示すことで、ベトナムにおけるエネルギー政策の決定プロセスにおいて有効な判断材料を提供したという点で非常に有益であるとともに、申請者が自立して研究活動を行うに必要な能力と学識を有することを証したものである。学位論文審査会は、本論文の審査ならびに最終試験の結果から、博士（工学）の学位を授与することを適当と認める。