博 士 論 文（要約）

Evaluation of energy saving and ecological benefit from low carbon and ecological city transition with the concept of urban-industrial symbiosis

（都市－産業共生の概念を適用した都市システムの低炭素化・生態化がもたらすエネルギー削減と環境便益の評価）

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Summary

As the main living and production places of humans, cities are responsible for more than 60% of global energy consumption and 70% of the world's greenhouse gas (GHG) emissions. Rapid industrialization and urbanization has caused serious problems in terms of overpopulation, energy consumption, and environmental pollution. Urban–industrial symbiosis (UIS) is regarded as a solution that can be used to optimize a regional metabolic network through resources with the aim of reducing resource consumption and emissions, and coordinating the relationship between industries and urban development. UIS further explores synergies in the urban and industrial sectors by using municipal solid waste (MSW) in industry and using industries as providers for living resources such as waste heat and steam.

The development of a feasible analytical approach for evaluating the ecological benefits of UIS systems is necessary. While traditional evaluation of UIS systems has provided critical environmental insight, to date, there have been few studies on the ecological evaluation of UIS. After reviewing the existing UIS studies, three aspects of UIS have been identified that require further research: (1) consideration of multiple waste-to-energy options of MSW treatment in UIS systems, (2) economic feasibilities and geographical effect of the heat transportation of UIS systems, and (3) consideration of the ecological benefits from resource formation and emission dilution processes in the natural environment, as well as indirect carbon emissions.

This doctoral dissertation ultimately aims to promote the transition of low carbon emission cities through UIS and proposes policy suggestions for the application of UIS systems in target areas. This requires evaluation of the energy savings, GHG emissions, and ecological benefits, including feasibility analysis of UIS systems.

To achieve this research target, this dissertation sets out to address the following

four research tasks:

(1) In order to improve energy recovery efficiency from waste treatment, this study puts forward multiple waste-to-energy options and evaluates the cost benefits and GHG emissions reduction effect of UIS systems with different waste treatment options.

(2) In order to analyze the feasibility of UIS systems, this study analyzes the cost benefits of UIS systems (economic feasibility) and the heat loss in the steam transportation process (geographical feasibility).

(3) In order to quantify the direct carbon emissions from the waste management sector and the indirect carbon emissions from other industrial sectors, as well as the reduction of carbon emissions through the recycling of waste, this study employs a hybrid life cycle analysis (LCA) model, and then quantifies the life cycle carbon footprint of the waste management sector in a UIS system.

(4) In order to quantitatively analyze the ecological benefits of resource conservation by UIS, this study establishes an integrated MFA–emergy analysis (EmA) model that is used to analyze the resource saving amounts as energy values and uses the newly designed ecological benefit ratio (EBR) to reflect the ecological benefits.

This thesis is organized as follows:

Chapter 1 introduces the research background of this dissertation. This chapter reviews the evolution of the theory, practice, and analytical methods of UIS, and summarizes the current state of MSW management in Japan and China for the application of UIS. Based on the research gaps and questions addressed, the aims of this thesis are stated and then the thesis framework is introduced.

Chapter 2 describes the research boundaries of the thesis, the conceptualized and determined evaluation framework, and an integrated evaluation model of UIS. This chapter presents a UIS system concept to promote low carbon and ecological city transition. The life cycle carbon footprint used to quantify the energy savings and carbon emission reduction potential, the integrated MFA and emergy model, and the new indicator used to analyze the ecological benefits of UIS are explained. These parameters form the basis for the evaluation of UIS systems in the following Chapters 3–6.

Chapter 3 addresses the aforementioned research task (1), using the Tokyo metropolitan area as a case study, in order to discuss different waste treatment options with the aim of improving the energy saving and cost benefits of a MSW treatment system using the UIS concept. This chapter proposes UIS systems with four different MSW treatment options. These include four different waste-to-energy options and the combination of a waste management system with industrial and district heating systems. Option 1 is a BaU option, which assumes that the MSW treatment system is not different from the current system used and that mixed waste is incinerated. Option 2 is a solution from a new policy perspective, in which MSW is treated in a centralized/consolidated incinerator. Option 3 proposes a solution from a technological perspective, in which MSW is treated with a source separation policy: waste paper and plastic are separated and sent to make refuse paper and plastic fuel (RPF), which can then be used as a substitute for fossil fuels in industry, and food waste is sent for fermentation treatment. The residue of mixed MSW is treated in an incinerator. Option 4 is a UIS system without source separation, combining a waste management system with a living system in a city. As a result, theoretically speaking, the supply of steam from an incinerator to industrial processes has two times the fossil fuel saving potential than electricity production, assuming that the produced steam is fully used. With the most energy-saving waste treatment option evaluated by this study, the highest potential for GHG emission reduction was 5.19×10^5 tonnes CO_{2e}. In this case study on the Tokyo metropolitan area, in practice, if a combined heat and power generation (CHP) system is applied to a waste incinerator with the consideration of the monthly changes in the energy demand of the city, the system would supply a lower energy amount than a waste power generation option. The introduction of a CHP system needs to determine appropriate amounts of electricity and steam production.

Chapter 4 addresses the aforementioned research task (2) and details the feasibility analysis of UIS systems in the city of Shenyang in China. This chapter focuses on the feasibility analysis of a UIS system: steam transportation from a geographical perspective, the cost benefits of the change in the waste treatment method, and pipeline construction from an economic perspective. The results indicate that steam transportation (geographical factor) limits the energy saving effects of a UIS system, and the heat loss of the steam supply was estimated as 1.06×10^5 GJ, which accounts for 12% of the steam produced in the incinerators. The economic factor plays a key role, since the payback time for any investment into waste incinerators that produce steam is up to 11 years. The results suggest that cities in developing countries have great potential to implement UIS, to recover 8.05×10^6 GJ of energy, as well as reducing CO_2 emissions by 1.3%. Since local governments are seeking a MSW treatment method with a larger energy saving, it is better to situate new incinerators near to industrial areas to reduce the heat lost in the steam transportation process.

Chapter 5 addresses the aforementioned research task (3), using the Tokyo metropolitan area as a case study, and details the application of a hybrid LCA model in the evaluation of the life cycle carbon footprint of the waste management sector in order to reflect its carbon emissions contribution. MSW management conditions in the Tokyo metropolitan area are analyzed, and the direct carbon emissions of the waste treatment sector and indirect carbon emissions from other industrial sectors are quantified. Furthermore, recycled carbon emissions were estimated using the LCA and related IPCC parameters. The results show that indirect and direct carbon emissions contributed 6.29×10^4 and 9.15×10^4 tonnes to the life cycle carbon footprint of the waste management sector, respectively. The carbon emissions reduction from waste recycling is enormous, accounting for 1.15×10^6 tonnes CO_2e. From a life cycle perspective, the waste management sector of the Tokyo metropolitan area reduced its emissions by 9.92×10^5 tonnes of equivalent CO_2 in 2011, which accounted for 1.6% of the total carbon emissions in the city.

Chapter 6 addresses the aforementioned research task (4), and details the application of an integrated MFA and EmA model to quantitatively analyze the ecological benefits of resource saving from UIS. The EmA presents an energetic basis for the evaluation of ecosystems, goods, and services. With this new parameter, the results show the resource saving benefits of UIS in a typical industrial city. The results highlight that UIS systems generate significant life cycle environmental benefits in terms of the reduction in upstream resource mining and downstream waste disposal within the regional metabolism. In total, around 14.3 million tonnes of mined ore, 6.9 million tonnes of solid waste, and 2.3 million tonnes of CO_2 emissions were reduced annually. From an ecological perspective, the total emergy input, which reflects the reduction in the ecological burden, was reduced by 1.3×10^{22} sej. The ecological beneficial ratio was 12%, indicating that the city could save 12% of its total emergy consumption in relation to UIS.

Chapter 7 summarizes the main findings of this thesis and proposes policy implications, as well as prospects for future research on UIS studies.