Prospective life-cycle design of regional resource circulation applying technology assessments supported by CAPE tools

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Abstract

In this study, we examine regional transformation by applying carbon-neutral technologies as a springboard. Unutilized renewable resources can be recovered in some regions, for example as surplus variable renewable energy or as residues from agriculture and forestry. To link such locally available resources with energy systems consisting mainly of fossil resources, technologies for their procurement, transfer, storage, and operation need to be systematically selected and integrated into the system pre-emptively. Simulation-based design support is needed to identify possible solutions, taking into account multiple energy requirements, such as low-carbon resources, high stability, and high economic efficiency. As case studies of such regional transportation, computer-aided process engineering (CAPE) tools are employed in the technology assessments. The candidate solutions for the design of regional energy systems are generated through the characterization of the regional availability of renewable and waste resources. As the technologies utilize such resources, electric vehicles powered by local surplus photovoltaic, biomass conversion through torrefaction, biomass-derived combined heating and power, and thermal energy storage and transport are considered. Some of the options are now demonstrated in Tanegashima, an isolated Japanese island.

**Keywords**: microgrid decarbonization, lignocellulosic biomass, circular economy, pre-emptive life-cycle synthesis.

* 1. Introduction

The design of energy systems has become a global issue and necessitates regionally customized solutions to foster technological and social changes that revitalize local industries and resources. Well-coordinated, multifaceted actions including a shift from fossil to locally available renewable resources and empowering of regions are vital in addressing this challenge. Technology assessments such as life-cycle assessment (LCA), material flow analysis (MFA), and regional input–output analysis (IOA) can visualize the future potential in regions, including the implementation of emerging technologies such as biomass conversions (Corradini et al., 2023). For engaging stakeholders, such a visualized future vision is key information (Kikuchi et al., 2020). When we generate alternative candidates for future regional systems, however, the appropriate combination of applicable technologies in a region must be addressed as the life-cycle design of regional resource circulation. Because various technology options seem to be available in a region, process systems must be devised considering regional characteristics.

In this study, we examine the regional transformation through the application of carbon-neutral technologies as a springboard. Prospective thinking inevitable in such transformation can be supported by CAPE tools developed for process systems synthesis, simulation, assessment, and optimization. This study proposes a prospective life-cycle design through a case study of regional system design and assessment in Tanegashima, a remote island in Japan.

* 1. Materials and method
		1. Prospective life-cycle design of regional resource circulation with CAPE tools

Prospective life-cycle design requires the steps of PSE, e.g., alternative generation, analysis, evaluation and optimization, and sensitivity analysis. Considering regional resource circumstances, adequate alternative candidates must be generated for regional transformations. Figure 1 illustrates a prospective thinking to generate the alternatives of circulating resources preemptively.



Figure 1 Preemptive thinking for alternative generation in prospective life-cycle design toward regional sustainability.

Forward-looking LCA has become an important tool for examining the future applicability of emerging technologies considering the scenarios in line with shared socioeconomic pathways (van der Giesen et al., 2020). Conventional LCA does not consider changes in technology level and social infrastructure such as power mix. Conducting a strategic LCA of emerging technologies and systems for the 30-year time horizon up to the target year, e.g., carbon neutral in 2050, is important. Toward regional real sustainability, carbon neutrality is just one of the issues; it must address ecosystem conservation, implementation of stable food production, intensification of regional industries, construction of reliable transporting infrastructure, and realization of resilient energy systems. For such long-term visions beyond carbon neutral, prospective life-cycle design should be able to synthesize emerging technologies into regional systems. Emerging technologies, as defined by Rotolo et al. (2015), are characterized as innovative, rapid growth, consistent, significant impact, and uncertain, making technology assessment difficult because of the lack of existing data and knowledge. The mechanisms developed in PSE can be applied to such system design problems.

* + 1. Case study in a region: Tanegashima, a remote island in Japan

Well-coordinated, multifaceted actions, including a shift from imported fossil to locally available renewable resources and empowering rural areas, are vital to solving social challenges such as resource security, sustainable food production, and forest management. The co-learning approach to practice multifaceted actions with a case study on Tanegashima, an isolated Japanese island, was applied to move society toward sustainability. (Kikuchi et al., 2020) In these actions, knowledge of the feasible technologies, locally available resources, and socioeconomic aspects of the local community should be shared among the stakeholders to motivate change. In addition to the technoeconomic analysis, several other analyses were conducted to reveal the concerns of respective stakeholders, share the possibilities of technology options, and their socioeconomic implications on local sustainability. Tools such as the LCA, input–output analysis, and choice experiments based on questionnaire surveys on residents' preferences are used for the analyses. The stakeholders were provided with the results. These opportunities gradually converted the concerns of local stakeholders about their future regional energy systems into expectations and yielded constructive alternatives in technology implementation that can use locally available resources. PSE basics were employed in simulating and visualizing possible future visions achieved by feasible technologies and available resources. Several systems design, assessment, and demonstration projects were launched and conducted through preemptive life-cycle management (Research Center for “Co-JUNKAN” Platform towards Beyond “Zero-Carbon,” 2023). Parts of the projects were taken up as case studies of prospective life-cycle design.

* 1. Results and discussion
		1. Demonstration of prospective life-cycle design by technology implementation

Figure 2 schematically shows three demonstration tests conducted in Tanegashima. The following sections describe the background of prospective thinking demonstrations on regional targets.

* + - 1. Regional transportation as a solution to multiple local problems

Problems are progressively emerging in remote island regions, which have difficulties in spreading electrification of transport because of issues such as a declining population, high energy prices, and the limited number of users. The introduction of variable renewable energies has been promoted, but the share of renewable energies in the power supply mix is not increasing because of inadequate microgrid adjustment capacity. Electrification of transport can be a means of stabilizing electricity demand and utilizing local variable renewable energy (Ravi and Aziz, 2022), but the situation is that there are few early adopters. In this study, four electric vehicles and three quick chargers were introduced to Tanegashima Island in 2021 as a social demonstration test (Idemitsu Kosan Co. Ltd., 2022). Because of the small number of users, the environmental impact of infrastructure development in the LCA tended to be high, and depending on the fuel consumption of the internal combustion engines, greenhouse gases may have increased. However, it was possible to achieve electrification of the transport infrastructure in the region through discussions with the public transport sector in the region to provide a first opportunity for electrification initiatives to strengthen the transport infrastructure. In addition, a regional power supply configuration model (Kikuchi et al., 2014) was implemented, although only in small quantities, and simulations found the possibility of regulating variable renewable energy in the region (Igarashi et al., 2022). In this demonstration, the transformation of regional transportation concerns not only vehicles and their infrastructure; it also involves a transformation of lifestyles regarding transportation on the island. Electrification of vehicles can thus serve to help address various local issues.



Figure 2 Demonstration tests conducted in Tanegashima based on prospective life-cycle design (Research Center for “Co-JUNKAN” Platform towards beyond “Zero-Carbon,” 2023)

* + - 1. Green transformation technologies to intensify food production and ecosystem conservation

Various industries of agriculture, forestry, and livestock exist on Tanegashima. Sugarcane is a particularly strong part of regional culture, and the sugarcane industry, which produces raw sugar from local sugarcane, is one of the core industries. Sugarcane bagasse has long been used as fuel in the sugar mill in Tanegashima, and previous studies have shown that there is potential for more bagasse-derived energy than is needed for sugar production as an unutilized resource (Kikuchi et al., 2016). Also, forests in Tanegashima are in an unhealthy state because the trees are aging, even after the harvesting age, and have a small ratio of high-quality timbers suitable for sawmilling, so expanding their energy use could help to simultaneously replace fossil fuels and improve forest health. (Kanematsu et al., 2017) Industrial symbiosis is proving to be a regional innovation for fossil-free resources in agricultural and forestry regions. The combined application of bagasse and woody biomass could become a stable biomass resource in Tanegashima for producing fuels through torrefaction. (Corradini et al., 2022) Additionally, the cultivar breeding of sugarcane can also increase the potential of the sugarcane industry (Ouchida et al., 2023), as confirmed by sophisticated checking of adverse effects on sugar production (e.g., Ohara et al., 2023). Such green transformations (GX) enable the intensification of local agriculture and forestry by replacing fossil fuels.

* + - 1. Energy supply–demand systems addressing local concerns on energy

In addition to higher fuel prices compared to mainland areas, microgrids in remote island regions are subject to risks such as power outages and supply disruptions. The introduction of regional mechanisms such as industrial symbiosis into the energy infrastructure can not only make it more resilient but also can lead to de-fossilization.

In this study, a mobile thermal energy storage system is demonstrated in Tanegashima for industrial use using a zeolite water vapor adsorption and desorption cycle that can utilizes waste heat. A numerical model was developed to predict the performance of the system using a moving bed indirect heat exchange system as the heat-discharging system and a moving bed countercurrent contact system as the heat-charging system, coupled with mass, energy, and momentum conservation equations for obtaining the foreground data for the prospective LCA (Fujii et al., 2022). The results demonstrated that the unused energy derived from regional renewable resources has not been effectively distributed and has the potential to replace fossil fuels. This means that the regionally available resources can be substituted for imported resources.

* + 1. Preemptive approach to regional resource circulation by CAPE tools

Geels and Schot (2007) argue that transitions occur through interactions among niche innovations, sociotechnical regimes, and the sociotechnical landscape. To grow the seeds of niche innovation, niche actors should be involved and motivated by technology assessments (Geels et al. 2017). Also, the social embeddedness of emerging technology options should be addressed through the holistic application of scientific technology assessments into co-learning. The main questions are whether systematic technology assessments could contribute to the bridging of the valley of death between research development and actual implementation, how the settings of assessment, i.e., boundary, indicators, and raw data could be defined through co-learning for mitigating concerns of stakeholders, and how the assessment results can help stakeholders understand the necessity of implementing the technology options.

Unutilized renewable resources can be recovered in some regions, for example as surplus variable renewable energy or as residues from agriculture and forestry. To link such locally available resources with energy systems consisting mainly of fossil resources, technologies for their procurement, transfer, storage, and operation need to be systematically selected and integrated into the system as alternative generation. Simulation-based design support is needed to identify possible solutions, taking into account multiple energy requirements, such as low-carbon resources, high stability, and high economic efficiency. Based on the simulation results, forward-looking assessments should be conducted. When we design an applicable solution for regional systems, specific conditions should be considered for resource demand and supply (e.g., Shimizu et al., 2015). The CAPE tools must be usable for region-specific designs of resource circulation.

* 1. Conclusions

Prospective life-cycle design can be conducted by applying an adequate combination of CAPE tools enabling alternative generation, analysis, evaluation and optimization, and sensitivity analysis. PSE can manage such regional systems development preemptively. The basics of PSE, i.e., mathematical modeling and simulation of changes to understand the impact on mass and heat balances, are essential for appropriate technology and system assessments. The obtained information applying PSE can become the essential information for the social changes that involve various stakeholders. The elaborated interpretation for those who are not experts in PSE is needed to accurately convey the quantitative and qualitative essences clarified by PSE.

Acknowledgments

This work was supported by MEXT/JSPS KAKENHI (JP21H03660, JP23K11521, JP21K12336, JP22K18061, and JP21K17919), JST COI-NEXT JPMJPF2003, JST PRESTO (JPMJPR2278), JST-Mirai Program (JPMJMI19C7), the Environment Research and Technology Development Fund (JPMEERF20213R01) of the Environmental Restoration and Conservation Agency of Japan, and the Nippon Foundation. Activities of the Presidential Endowed Chair for “Platinum Society” at the University of Tokyo are supported by Mitsui Fudosan Corporation, Sekisui House, Ltd., East Japan Railway Company, and Toyota Tsusho Corporation.

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