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Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: A case in Fukushima, Japan

Yi Dou[a,b], Takuya Togawa[a], Liang Dong[a,c,d], Minoru Fujii[a,*], Satoshi Ohnishi[a], Hiroki Tanikawa[b], Tsuyoshi Fujita[a]

[a] *Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan*
[b] *Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan*
[c] *School of Geography and Remote Sensing, Nanjing University of Information Science & Technology, Nanjing 210044, China*
[d] *CML, Leiden University, Leiden, The Netherlands*

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ABSTRACT

Energy shortage and global climate change have created a dilemma in Japan, especially after the great earthquake of 2011 in eastern Japan. District Heating System (DHS) using waste heat is highlighted as an attractive solution. However, because of low heat demand in urban areas and the geographic separation of industries, popularizing this solution is considerably difficult in Japan. Previous studies have focused on technical improvements on existing district heating networks, but these studies lack sufficient discussion on an early-stage integrated land-use planning. Supported by technological assessment and emerging concepts of Industrial-Urban Symbiosis (I-US), this study combines the system development of DHS and land use scenarios into a symbiotic design based on inventory survey and geographic database, and conducts a cost-benefit analysis to scientifically and quantitatively evaluate the effects brought from land-use policies. Results from a case study of Shinchi Town in the Fukushima Prefecture indicate DHS using waste heat can realize significant benefits of energy saving and CO_2 reduction, provided positive guidance on land use planning is implemented. Moreover, the model framework of this study also supports a quantitative assessment on policy implementation to help in decision making on urban sustainable energy planning.

1. Introduction

Energy shortage and global climate change have created a dilemma in Japan, especially after the great earthquake of 2011 in eastern Japan. It is accepted worldwide that distributed energy systems such as the District Heating System (DHS), which is connected to reuse waste heat sources and renewables, is an attractive solution and is of increasing importance (Hayashi and Hughes, 2013; Rezaie and Rosen, 2012).

In Europe and North America, long-term practices have indicated that DHS has a higher efficiency energy usage when compared to Individual Heating Systems (IHS). The benefits from the scale effect of heat production through the development of efficient processes and the convenience of accessing local waste heat and renewables are the main reasons for this trend giving rise to what is known as Fourth Generation District Heating (4GDH) (Morandin et al., 2014; Zhao et al., 2014). This future DHS technology is expected to play an important role in a low-carbon sustainable energy system, which involves facing the challenges of combining multi-sources and distributed generation technologies and integrating these with smart energy systems (Ivner and Viklund, 2015; Lund et al., 2014). Nowadays, the trend to improve the District Heating System is spreading all over Europe, such as the Heat Roadmap Europe project and the STRATEGO project (Enhanced Heating and Cooling Plans in EU), through which most of the European cities aim to realize a citywide integrated district heating and cooling system in the near future (Connolly et al., 2014; Persson et al., 2014).

By contrast, there are only few cases of such district heating in Japan, only located in several large cities and that function as a small-scale enterprises. Compared to the popularity of this system in European countries (e.g., 58% in Denmark, 48% in Finland, and 12% in Germany), Japan is very far behind (1.2%) (JES, 2008). The

* Corresponding author.
E-mail address: m-fujii@nies.go.jp (M. Fujii).

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main reasons for this are thought to be not only the relatively warm climate but also the slowdown in urban infrastructure development and building refurbishment. The dispersed market scale and management, competition with high efficiency individual heating, and languishing support policy are also some of the causes (JHSBA, 2011). However, existing DHS in Japan still realizes an average of 20.6% reduction in primary energy consumption compared to individual heating (METI, 2008). However, Japan also generates a large amount of unused heat estimated at approximately 6000 PJ annually from general waste incineration, factories, thermal power plants, sewage systems, oceans, and rivers (Fig. 1). This quantity surpasses the total energy consumption for heating civilian spaces and hot water generation (approximately 5000 PJ) (JES, 2011). Promoting DHS using waste heat countrywide has great potential for energy saving and reduction of CO_2 emission.

As far as the proportion of unused heat is concerned, waste heat from factories and thermal power plants are the major sources of unused heat. Most of these factories and power plants are concentrated in the Tokyo Metropolis area, Aichi and Fukushima Prefecture, and depend on the availability of large energy industry groups. Recently, due to the increasing concerns about climate change and energy saving in Japanese society, district heating has been popularized in many densely populated areas of the Tokyo Metropolis. However, in colder areas such as Fukushima Prefecture, the development of district heating has languished for decades (currently only one project of DHS is located in Fukushima). With the progress in revitalization after the earthquake in eastern Japan, the timing is just right to introduce DHS that helps in utilizing the excessive waste heat. This energy saving would significantly support socioeconomic development and bring about environmental improvement.

Comparing the geographic conditions of Fukushima with Tokyo Metropolis, there are mainly two factors that are responsible for this difference in the popularization of DHS. One is the linear heat load (total heat load divided by pipeline length) and the other is the geographic proximity with waste heat sources. The former usually implies the efficiency of district heating, while the latter implies the cost incurred to access the various heat sources. Because of the low population density and the geographic separation between urban and industrial areas as a result of urban planning, it is necessary to explore a way to circumvent these two problems.

According to previous studies, the mainstream solution for extending DHS is to introduce new technology and system optimization to enhance the district heating network. Researchers are focusing on system design to combine the various resources and cogenerate so as to form a multisource distributed energy system. The *low-temperature* and *low-energy* DHSs are specific for low-density cities. For instance, Fang et al. (2013) discuss the technical feasibility of recovering low temperature waste heat from industry to urban areas through district heating. They identify the process and provide a method to estimate the potential for reuse of industry-based waste heat and evaluate a low-temperature District Heating System in northern China. Their results show that such a system not only improves the thermal energy efficiency of factories but also reduces cost, pollution, CO_2 emission, and water consumption. Moreover, Brand et al. (2012) describe several practical approaches to reduce the supply temperature of DH as much as possible by connecting with local unused heat sources such as latent heat of rivers and underground soil. Similar studies have been conducted worldwide (Broberg et al., 2012; Kapil et al., 2012; Li and Svendsen, 2012; Ostergaard and Lund, 2011; Sun et al., 2014). Other researchers such as Chae et al. (2010), Dalla Rosa and Christensen (2011), Dalla Rosa et al. (2012), and Tol and Svendsen (2012) focus on support-system optimization techniques such as introducing twin pipelines, layout of a *T-connection* network, and smart flow rate control to further improve the efficiency of DHS. These technical improvements are considerably effective in districts where DHS is already popular and serve to further extend its application by increasing the competitiveness of DHS *vis a vis* individual heating. However, without a reform in urban planning, the expected improvement of the system is considerably limited.

By contrast, on the basis of technology assessment, material and energy flow analysis, and the Life Cycle Assessment (LCA) method, the emerging Industrial Symbiosis (IS) breaks the bottleneck of simplex technical path that focuses on optimal technology integration and combination of spatial elements. From the perspective of industrial ecology, IS supports a systemic analysis and design process for promoting the exchange byproducts including material, energy, and water, to enhance the competitive advantage through process synergy and cooperation between industries (Chertow, 2000; Dong et al., 2013; Olsson et al., 2015; Park et al., 2008). Its extended version, known as Industrial-Urban Symbiosis (I-US), focuses on utilizing waste heat starting from municipal solid waste incinerators to industries and recovering low temperature waste heat from industrial process to urban areas (Fig. 2) (Dong et al., 2014; Van Berkel et al., 2009). On the basis of a technical assessment

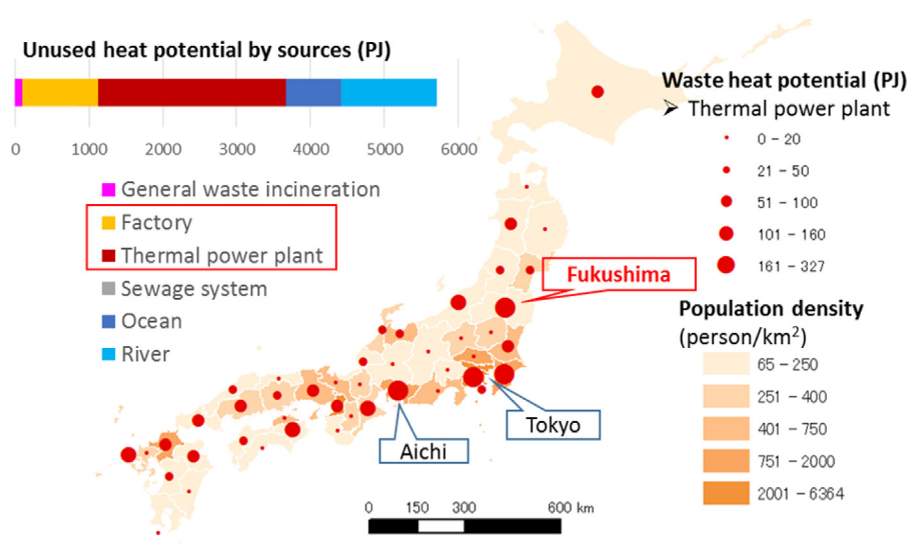

Fig. 1. Annual unused heat potential by sources and distribution of power-plant-based waste heat potential in Japan. Data source: JES (2011).