Development of a Land Use Planning Method for District Heating System Using Waste Heat: A Case Study in Fukushima, Japan

Yi DOU[1], Takuya TOGAWA[2] , Liang DONG[3], Minoru FUJII[2], Tsuyoshi FUJITA[2], Satoshi OHNISHI[2], and Hyeongwoo KIM[3]

[1]Member of JSCE, Center for Social and Environmental Systems Research., National Institute for Environmental Studies (16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan)
E-mail:dou.yi@nies.go.jp
[2]Member of JSCE, Center for Social and Environmental Systems Research., National Institute for Environmental Studies (16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan)
[3]Center for Social and Environmental Systems Research., National Institute for Environmental Studies (16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan)

After the Great East Japan Earthquake in 2011, energy shortage and global climate change has become a dilemma that disturbs world economy and sustainable development. As one solution supported by Industrial and Urban Symbiosis (I-US), District Heating System (DHS) using waste heat has been indicated in many practice that could reduce both the fuel consumption and CO_2 emission by substituting fossil fuel and increasing energy use efficiency. However, geographic proximity and heat load density are two crucial requirements that affects the popularization of DHS. Previous researches usually pay attention to improve conventional district heating technology to adapt with low heat demand areas, not involve the discussion on guiding the land use planning for symbiosis design. Therefore, this study establishes a GIS based planning support tool including system design and simulation for DHS, and quantitatively assessing the impacts of different land use design. Through an application in a typical low density case named Shinchi Town in Fukushima Prefecture, results indicate DHS using waste heat could realize a co-benefit of energy saving and CO_2 reduction in low heat demand cases, if positive guidance to I-US on land use planning is implemented. Furthermore, the analysis framework of this study also helps to quantify the policy implementation.

Key Words : *Industrial-Urban Symbiosis, district heating, waste heat, land use planning, Fukushima*

1. INTRODUCTION

After the Great East Japan Earthquake in 2011, energy shortage and global climate change has become a dilemma. As one feasible solution, the popularization of distributed energy system such as District Heating System (DHS) using waste heat and renewables is of increasing importance[1)]. On the other hand, from the perspective of Industrial Ecology, Industrial and Urban Symbiosis (I-US) has been proposed into practice, which supports a systemic analysis and design process for promoting the utilization of industry-based waste energy in urban areas by process synergy and cooperation between urban and industry[2)]. Such progressions could farthest reduce fossil fuel consumption and CO_2 emission.

Nowadays, the popularization of DHS using unused energy is also a hot topic in Japan. However, two necessary conditions should be satisfied, known as geographic proximity and linear heat load. Because of the longtime separation of urban and industrial planning and incompact land use, popularization of DHS is often doubted and implemented hesitantly. This study proposes a land use planning method for popularizing DHS using waste heat, which aims at complementing this shortage. Furthermore, its effectiveness is quantitatively examined through a case study of typical low heat demand industrial city.

2. POSITIONING

District heating system has been popularized in Europe, America and Northern China for decades. By contrast, individual heating system is dominant in Ja-

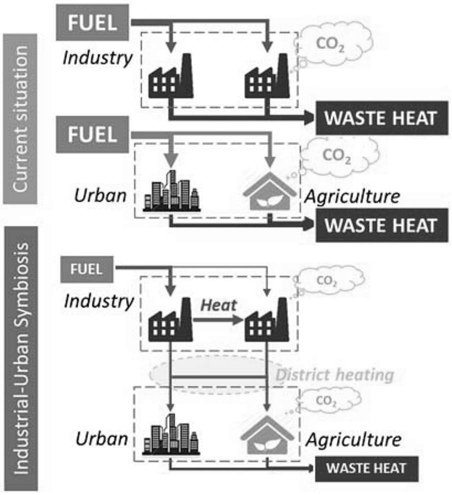

Fig.1 Energy synergy through Industrial-Urban Symbiosis.

pan. Most of previous researches are focusing on enhancing conventional district heating technology to adapt with low heat demand areas. For instance, Low-temperature and Low-energy district heating are considered as the future trend of technology development. The efficiency of DHS is indicated that could be further improved through optimization design like using twin pipelines, "T-connection" network layout and smart control of flow rate by decreasing the heat loss and economic cost[3-4]. However, they cannot fundamentally increase the feasibility of DHS, especially when facing rapidly popularizing low-energy buildings. Therefore, urban planning integrated with DHS is essential, which could bring a great possibility for popularizing DHS.

In recent years, with the development of GIS (Geographic Information System), spatial analysis and planning for DHS is attracting increasing attention in the field. Due to precise spatial inventory survey on heat supply and demand ("Heat Atlas"), indicators like geographic proximity and linear heat load could be visualized. Particularly, combining system optimization and spatial analysis has become a neceaasry process for planning such distributed regional energy sytem[5-6]. However, these researches pay less attention to future land use changes. Therefore, this study exactly purposes to release land use policy as a measure of long term demand side management for project planning. Based on knowledge of I-US and support by GIS spatial analysis, this study develops a planning and modelling method to support the system design and assessment of DHS using waste heat, and quantitatively evaluate the impacts of land use planning on DHS performance.

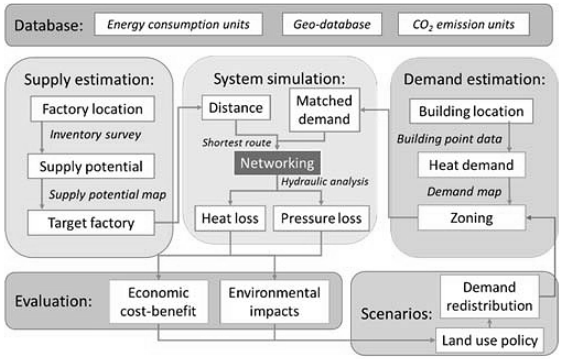

Fig.2 Model framework.

3. METHODOLOGY

(1) Model framework and dataset

The model framework developed in this study is shown in **Fig.2**. Based on the supply and demand distribution, a pipeline network is designed to connect them, and its performance is simulated by hydraulic model and evaluated by cost-benefit analysis. For investigating the effects from land use planning, scenario are set externally by adjusting demand distribution and other parameters in the model. Dataset mainly includes building point data from ZENRIN, geographic data from ArcGIS Data Collection, and other parameters referring from governmental documents and entrusted consulting companies.

(2) Inventory survey of potential heat supply and demand

This study takes thermal power plants and energy intensive factories into the consideration for waste heat supply. Many factors should be considered, including capacity of the facility, detailed technical process, and difficulty of implementation. Generally, this study assumes to recover low temperature heat from exhaust gas and condenser. The potential is estimated due to survey and advice from companies.

Otherwise, the waste heat is thought to be used for civilian purpose including space heating and hot water. A common method is applied to estimate the distribution of heat demand at building level. The formula is as below:

$$Q_d = \sum_{i,j} A_{i,j} \times u_j \qquad (1)$$

where Q_d is the sum of heat demand of buildings, $A_{i,j}$ is the floor area for purpose j in building i, and u_j is the average consumption unit by floor area for purpose j.

(3) Network design and simulation

The process of network design and hydraulic model is summarized into flow chart shown in **Fig.3**. The network design is mainly based on the analysis

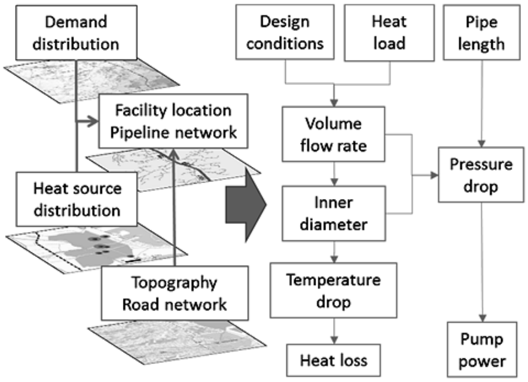

Fig.3 GIS-based network design and hydraulic model.

of geographic distance between heat source and demand distribution, considering the local conditions such as topography and road network. Due to zoning of concentrated heat demand, and following the principle of shortest route supported by GIS network analysis, a hierarchical heating network including trunk and branch pipeline is designed. Accordingly, the heat load and length of each pipeline could be estimated. Then a simplified hydraulic model is developed to calibrate the parameters and simulate the performance of heat distribution. The model includes four steps:

a) Design conditions

In case of low temperature heat recovery, hot water is chosen as heat medium. Mainly accoording to the **Ref.7-8**, supply temperature of medium and temperature difference by user side is set as 80℃ and 20℃. Commonly, single steel tube and glass wool is considered as conduit and heat insulating material. Laying method is assumed to be underground.

b) Pipeline size

Based on the presupposed conditions mentioned above, inputing heat demand Q_d and pipeline length l as two independent variables, the volume flow rate V_v is calculated as follow:

$$V_v = Q_d/(C\rho t \cdot \Delta T) \tag{2}$$

where C is the specific heat capacity of water, ρ is the density of water, t is operation time and ΔT is the temperature difference in user side. Then inner diameter is calculated as follow:

$$d = \sqrt{4V_v/\pi v} \tag{3}$$

where v is the average flow rate set as 2m/s (for avoiding the corrosion inside pipelines).

c) Pressure drop

Caused by the friction between medium and pipeline, there is a pressure drop ΔP in heat transport that needs pumping power to complement. Based on the Darcy–Weisbach Equation, it is calculated like:

$$\Delta P = \lambda \cdot \frac{2l(1+k)}{d} \cdot \frac{v^2}{2}\rho \tag{4}$$

where k is the local resistance ratio, the frictional coefficient λ is given by

$$\lambda = 0.0055 \cdot \left|1 + (20000\frac{\varepsilon}{d} + \frac{10^6}{Re})^{1/3}\right| \tag{5}$$

where ε is the equivalent roughness of pipe wall (set as 0.045mm) and Re is Reynolds number. Then necessary pumping power W' is estimated as follow:

$$W' = \frac{\rho g V_v h}{\eta_P \eta_M} \tag{6}$$

where $h = \Delta P/\rho g$ is the pressure head loss, g is gravitational acceleration, η_P is the efficiency of pump and η_M is the efficiency of motor, set as 0.7 and 0.9 respectively.

d) Temperature drop

As an important indicator, the temperature drop, which means heat loss, ΔT_l is estimated by

$$\Delta T_l = (T_\omega - T_a) \cdot \exp\left(-\frac{1}{CV_w(R_s+R_p)}\right) \tag{7}$$

where T_ω is the supply temperature, T_a is surface temperature (average 13℃ in Fukushima Prefecture), V_w is weight flow rate, R_s is soil heat resistance and R_p is heat resistance of pipeline.

e) Constraint condition

Physically, total heat supply Q_s should be no more than the potential $\widehat{Q_s}$, but equals to the sum of heat demand Q_d and heat loss Q_l as follow:

$$Q_s = Q_d + Q_l,\ Q_s \le \widehat{Q_s} \tag{8}$$

(4) Cost-benefit assessment

Generally, the economic costs of a district heating system consist of heat distribution cost (infrastructure construction), heat transport cost (pumping power), heat production cost, and management and maintenance cost, while the benefit includes the heat sales. This study supports a wider understanding of the system, considering social benefit which is total fuel cost reduction (the value covers the sum of production cost and heat sales), and environmental benefit that is total CO_2 emission reduction. Cost is formulated as follow:

$$C_d = a \cdot \textstyle\sum_n c_n \cdot l_n \tag{9a}$$

$$C_t = (a \cdot c_w + p^e \cdot t) \cdot W' \tag{9b}$$

where C_d and C_t are annualized cost of heat distribution and transportation. c_n and l_n is respecticely the average cost and length of pipe with diameter n. c_w is the average cost of pumping equipment, p^e is the price of electricity and t is operation time. a is the annuity rate and defined as follow:

$$a = \frac{i}{1-(\frac{1}{1+i})^\tau} \tag{10}$$

where i is the interest (set as 1.15%) and τ is durable years (set as 20 years). Then the benefit of fuel cost reduction R_f and CO_2 reduction R_{CO_2} are calculated as below:

$$R_f = \textstyle\sum_i q'_i \cdot p_i \tag{11a}$$

$$R_{CO_2} = \textstyle\sum_i q'_i \cdot \varepsilon_i - W' \cdot t \cdot \varepsilon_e \tag{11b}$$

where q'_i is the fuel substitution of type i, p_i is the price of fuel type i, ε_i is the emission unit of fuel type i, and ε_e is emission unit of electricity.

Due to the data availability, management and maintenance cost is assumed as fixed expenses (SGA) including labor, sales service and general maintenance cost. It is set as 37 million yen/yr according to a similar case in Hitachi Station area of Ibaraki Prefecture.

4. CASE STUDY

This study employs Shinchi Town in Fukushima Prefecture of Japan as a case study area, of which the total land area is 46.35km^2 and about 8 thousand residents are living in. In 2011, the coastal area is destroyed by the Great Eastern Japan Earthquake. Following with revitalization, several large scale projects are just in implementation and planning including a LNG base and huge advanced natural gas thermal power plants. As a future energy base and recognized Environmental Future City, how to efficiently utilize the resources and realize low-carbon development has become an emphasis. These facts support a great flexibility on the discussion of future land use planning.

Learning from the geographical information of Shinchi Town shown in **Fig.4**, it is obvious that buildings distribute dispersedly along the main roads. In the southern coastal part, Shinchi Town shares a large industrial park with Soma City named Soma Central Industrial Park, in which many factories, especially the planned LNG base, are located.

5. SCENARIO SETTING

(1) Distribution of heat sources and demand

The distribution of heat sources and their supply potential are mapped in **Fig.5**. (Note the result of supply potential is still tentative.) Annually, the two thermal power plants in northern industrial park could supply about 60TJ waste heat, while the sum of factories is about 50TJ. On the other hand, the distribution of heat demand is estimated and shown in **Fig.6**. Total civilian heat demand (space heating and hot water) is about 160TJ, of which Shinchi Station area and Komagamine possess a half. Most of the grids have heat demand density below 0.1TJ/ha. Due to the distance analysis based on road network, Shinchi Station area and Komagamine are within the feasible transport distance (6km) of DHS. Since there is no existing infrastructure for DHS, considering limitation of initial investment and project scale, Komagamine (3km) is chosen as target area in this study. However, its annual heat demand is only 24TJ/yr, much lower than supply.

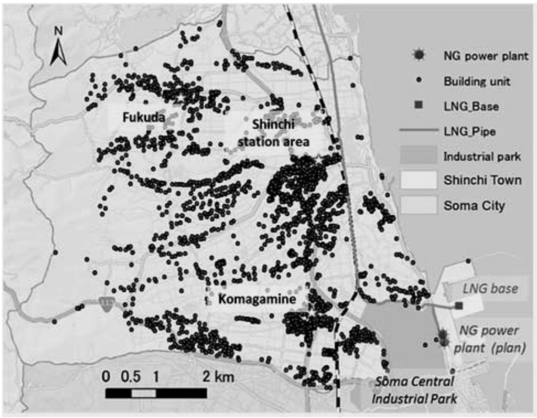

Fig.4 Geographic information of Shinchi Town.

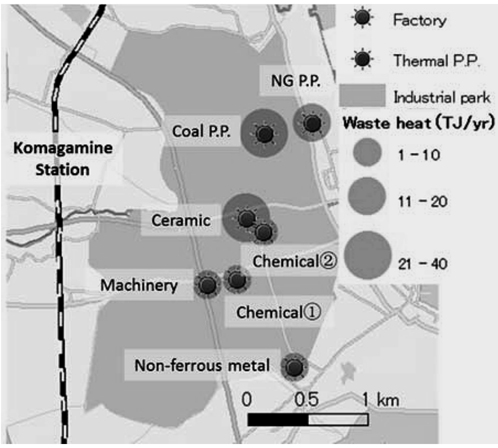

Fig.5 Distribution of waste heat potential.

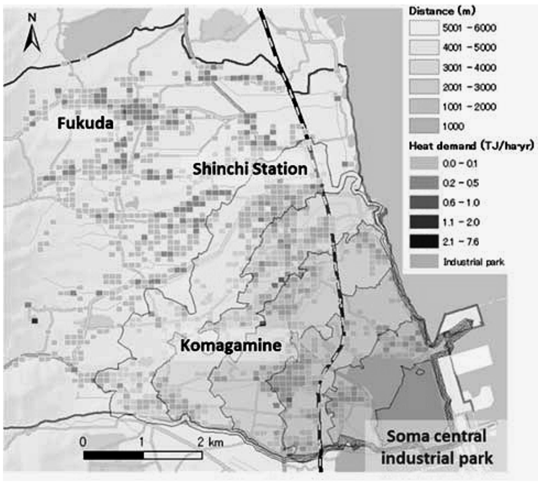

Fig.6 Distribution of heat demand and distance to heat sources.

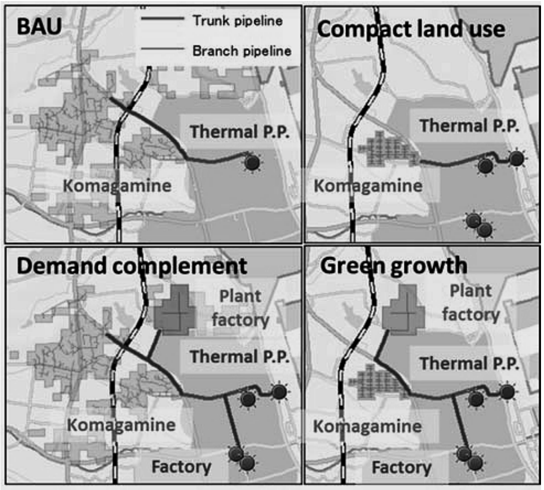

Fig.7 Land use changes in scenario setting.

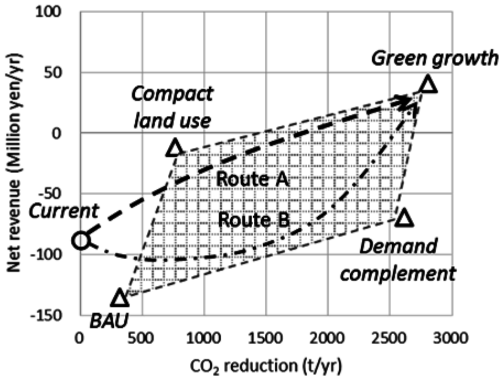

Fig.8 Summary of scenarios results.

(2) Scenario setting

Assuming factors such as population, energy price, technology development not change significantly in short term period, this study specializes land use as an adjustable factor for scenario setting. Against the low heat demand of Komagamine, two approaches are proposed to improve the feasibility of introducing DHS. One is to conplement redundant heat supply by inducing energy intensive factory such as plant factory near the park (named Demand complement), the other one is to guide a compact land use of Komagamine in near future (named Compact land use). Finally the combination of these two approaches is named Green growth. Referring to real case of plant factory in Shinchi and Eco-village Kobunaki Town while satisfying supply-demand matching under seasonal variation of heat demand, main parameters are changed as **Table 1**.

Table 1 Main parameter changes of 4 scenarios.

Scenario	BAU	Demand complement	Compact land use	Green growth
Heat demand	17 TJ	48 TJ	24 TJ	51 TJ
Population density	8 p/ha	8 p/ha	80 p/ha	80 p/ha
Pipeline length	18.0km	19.7km	6.8km	9.2km
Linear heat load density	0.94 TJ/km	2.44 TJ/km	3.53 TJ/km	5.54 TJ/km

6. RESULT AND DISCUSSION

(1) Scenario result

As shown in **Fig.8**, although scenario result reveals the introduction of DHS using waste heat succeeds to reduce CO_2 emission, current disperse land use cannot avoid a great cost on pipeline construction and heat transport. Guiding a compact land use could cut most of cost to make DHS benefitial. In addition, induced plant factory reveals significant effect on CO_2 reduction. The best policy is to combine these two measures so as to enjoy a co-benefit on economy and environment.

(2) Policy path

The 4 scenarios exactly constitute possible future prospection. To reach the best state towards the Green growth, different policy path will lead to different sum of cost and benefit. Giving priority to compact land use (Route A) leads to less total cost but would lengthen the period of policy implementation, by contrast, giving to induce plant factory (Route B) would not avoid excessive cost. Due to the model built in this study, it is possible to catch the difference of policy path quantitatively.

(3) Future uncertainty

As a first step work, the model in this study is static without considering more changeable factors. Several key prospections will be discussed next. Firstly, benefitting from waste heat supply, power plants and factories may expand the capacity of heat exchanger so that total supply would increase. Secondly, economic revitalization would bring more residents that leads to more heat demand. Thirdly, energy price would keep increasing that brings more economic benefit.

7. CONCLUSION

This study develops a planning and modelling method to support system design of DHS using waste heat, and quantitatively evaluate the impacts of land use policy on feasibility. It also employs a typical low heat demand city, Shinchi Town in Fukushima to confirm the effectiveness of model framework. Tentative result reveals a decisive role of land use planning on district heating system. Furthermore, the model could quantitatively analyze the effect of different path of policy implementation so as to be an effective support tool for decision making.

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APPENDIX

Some important parameters in this study are listed in **Table 2**, **Table 3**, **Table 4**.

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Table 2 Energy consumption unit by purposes.

Unit: $MJ/(m^2 \cdot yr)$

Type	Electricity	Cooling	Heating	Hot water
Detached house*	67.12	1.04	61.61	55.06
Collective house*	79.04	1.22	72.55	64.83
Office**	561.60	293.04	129.60	9.36
Shop**	813.60	523.08	146.52	96.12
Hotel**	720.00	418.68	334.80	334.80
Hospital**	612.00	334.80	309.60	334.80
Plant factory***	30.14	0	555.00	0

* Local average value estimated by author; ** National average value (Japan Institute of Energy, 2008); *** Survey value of a local typical plant factory.

Table 3 Cost of pipeline and pump equipment.

Item	Value
Piping cost (trunk)	150000yen/m*
Piping cost (branch)	60000yen/m*
Pumping cost	36800yen/kW*

*Market survey data

Table 4 Fuel price and CO_2 emission unit.

Fuel type	Price	CO_2 emission
System electric power		163.61t/TJ
(household)	24.9yen/kWh	
(business)	15.3yen/kWh	
LPG	7.08yen/MJ	59.03t/TJ
Fuel oil (A)	2.44yen/MJ	69.30t/TJ

Public data from the Tohoku Electric Power, the Oil Information Center, the Agency of Natural Resources and Energy, and the Ministry of Environment, Japan

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