Spatial Planning and Assessment for District Energy Systems Considering Strategic Urban Renewal

(都市の戦略的更新を考慮した地域エネルギーシステムの空間計画及び評価)

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Summary

Excessive greenhouse gas emissions from human activities are very likely to be the main cause of global climate change, of which approximately 90% is relating to energy utilization. For realizing a carbon-neutral society, not only substantial energy saving is necessary, but also a dramatic shift of fossil fuel usage toward renewable energy usage is dispensable. Distributed energy system, as an important platform to connect to local renewable energy sources, is expected to be popularized in both dense cities and rural areas. Particularly, production and consumption of renewable energies locally within a city can help in forming an economic circle that keeps a necessary local investment and employment. However, the popularization of distributed energy systems is facing various barriers including depopulation, low-intensity land use plan, geographic separation between users and distributed energy sources, as well as other social and financial problems. Previous researches mainly focus on optimization of energy supply system or real-time demand response, that lacks a long-term and cross-sector insight of managing energy demand side through land use measures.

Under this background, this study aims at developing an integrated model framework to simulate the impact from long-term urban renewal on proliferation of distributed energy system, so as to investigate the most effective way of demand side management for a quicker low-carbon energy transition. Being a summary and reference of the study, this thesis is structured as follows:

Chapter 1 and Chapter 2 summarize the research background and related literature review to describe the research problem and needs, as well as the importance and originalities of this study.

Chapter 3 describes the analytic framework and model development in this study, including the

methods for estimating the potential of energy demand and supply, with designing distributed energy systems and evaluating the environmental and socio-economic impacts. On the other hand, urban simulation based on 4-dimension Geographic Information System is conducted with land use and policy scenarios to estimate the future distribution of energy demand. Data sources and main assumptions in this study are also summarized in this chapter.

Based on the model development shown in Chapter 3, two case areas in Japan are selected for case studies, including Soma Region in Fukushima Prefecture and Kitakyushu City in Fukuoka Prefecture. Chapter 4 introduces the case of Soma Region, where the feasibility of introducing district heating system using gas-fired cogeneration around regional stations is discussed. Although results indicate an enhancement on economic feasibility by compact city planning and related policies, the potential of CO_2 emission reductions is limited because of the progressing decarbonization in grid electricity. Therefore, two additional cases are conducted for enhancing the environmental benefit of district heating by utilizing waste heat.

Referring to the case of Soma Region, Chapter 5 provides a more comprehensive case study in Kitakyushu City, where energy saving and demand redistribution during long-term urban renewal is estimated to help distinguish the possible extension of district heating using waste heat and its impacts to local environment and socio-economy. Particularly, changes of material use in building stocks are also studied which are relating to embodied energy in buildings as well as biomass energy from recycled wooden material.

According to the results and discussions in Chapter 4 and Chapter 5, Chapter 6 furthermore discuss the market mechanism, business model and policy packages that can support the implementation of integrated planning.

Finally, Chapter 7 concludes the main findings in this study and future works based on the model development in this study, as well as the model generalization and applications to the other cities in Japan or rest countries.

This study is especially referable for the local municipalities to plan and assess the comprehensive urban design considering the impacts to local environment and energy systems.

Keywords:

District energy system; strategic urban renewal; urban and industrial symbiosis; energy efficiency; Japan

Abbreviations

4d-GIS	4-dimension Geographic Information System
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium Model
CHP	Combined Heat and Power Generation
CLT	Cross-Laminated Timber
CUE	Computable Urban Economic Model
FY	Fiscal Year
GHG	Greenhouse Gas
GRP	Gross Regional Product
LCA	Life-Cycle Assessment
METI	Ministry of Economy, Trade and Industry
MFA	Material Flow Analysis
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MOE	Ministry of Environment
NDC	Nationally Determined Contributions
ZEB/ZEH	Net-Zero Energy Building/House

1. Research background

1.1 Background

1.1.1 Importance of developing district energy technologies

Climate change is currently a key issue in discussions on global scale environmental problems, which is very likely to cause long-term sea-level rise and widespread drought, as well as extreme weather such as short-time rainstorm and frequent typhoon. Excessive anthropogenic emissions of greenhouse gases (GHGs, equivalent to CO_2 emissions below) from human economic activities to the atmosphere are thought as the main cause of global climate change. By 2014, the global carbon emissions from fossil fuels increased to about 10 billion metric tons carbon annually, which is almost 20 times than it in 1900 (Boden et al., 2017a), wherein the emissions from electricity and heat production, industrial process, and buildings take proportion at 25%, 21% and 6% in the total, respectively (IPCC, 2014).

Regarding the global climate change issue, countries of the world continuously conduct international cooperation and inspiration activities that target at promoting an economy-wide decoupling between civilization development and GHG emissions. In the latest achievement at the 21st Conference of the Parties (COP 21) in Paris on 12 December 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a milestone agreement that aims at suppressing the global temperature rise in this century within 2℃ above pre-industrial levels, even pursue more endeavor in CO_2 emission reductions to limit the global temperature rise within 1.5℃. Additionally, each party is required to declare a “nationally determined contributions” (NDCs) which clearly records the country’s targets on CO_2 emission reductions and supporting measures for achieving the targets (UNFCCC, 2018).

Japan is the top six economic entity in annual carbon emissions from fossil fuel combustion and industrial processes, following China, the United States, EU-28, India, and Russian Federation. He possesses 2% of the global population but is emitting 4% of the global CO_2 emissions (Boden et al., 2017b). As shown in Figure 1-1, Japan once met an expected decrease of GHG emissions from 2005 to 2010, but the emissions rebounded from 2011 because of the energy shortage caused by closing all the nuclear power generation after the 3.11 Great East Japan Earthquake (METI, 2015). This fact even rises the anxiety of Japanese society in transiting towards a low-carbon sustainable society in a relatively short time. Since 90% of the GHG emissions are relating to heat and power generation, measures for substituting fossil fuel consumption, energy saving in user side, and efficiency improvement in energy conversion and transition are considered critical to realize a low-carbon energy system.

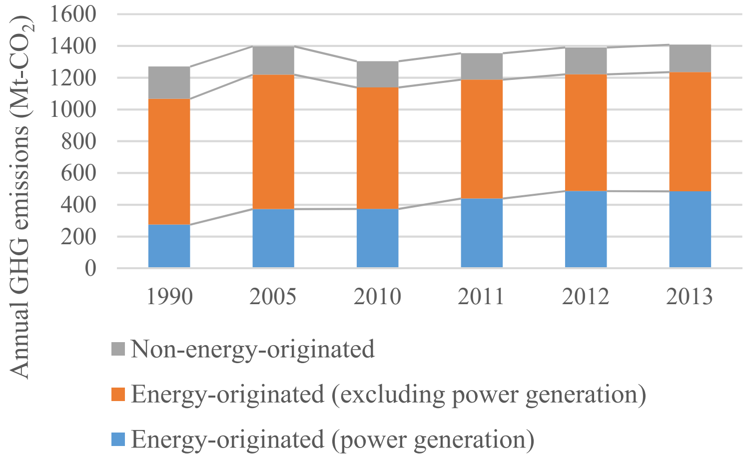


Figure 1-1 GHG emission changes in Japan (1990-2013)

Referring to the sectoral structure of annual CO_2 emissions in Japan (Figure 1-2), a trend disparity between sectors in emissions can be recognized in recent 30 years (NIES, 2017a). Obviously, industrial sector possesses the largest proportion of CO_2 emissions, but it has turned to decrease and the same with transportation sector. Meanwhile, residential and commercial sectors reveal a strong increment which offset the decrement brought from industrial sector in total. In this perspective, industrial sector may still remain a substantial potential in emission reductions, while suppressing the emissions from residential and commercial sectors is also in priority to achieve long-term targets for low-carbon sustainable development.

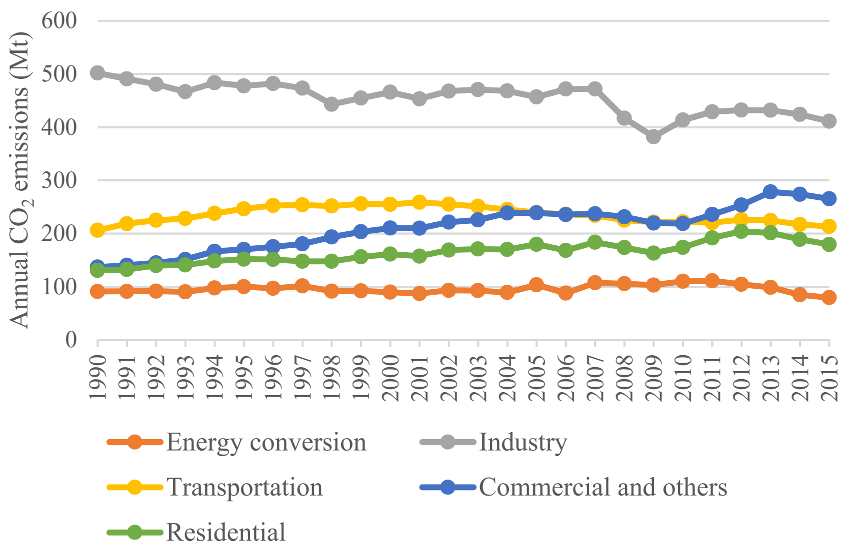


Figure 1-2 CO_2 emissions by sectors in Japan

Receiving the great pressure on global CO_2 emission reduction targets, Japan positively takes the responsibility in promoting country-wide energy saving and emission reductions that has declared an ambitious target in his INDC according to the Paris Agreement (MOEJ, 2015). In the document, Japan targets to reduce 26% of GHG emission reductions by fiscal year (FY) 2030 compared to the level in FY 2013 (Table 1-1). Especially, Japan decides to cut 25.0% energy-originated CO_2 by FY 2030 compared to FY 2013, in which commercial, residential and transport sectors are facing a serious pressure on reducing CO_2 emissions.

Table 1-1 Target of CO_2 emission reduction by 2030 published in Intended Nationally Determined Contribution (INDC) of Japan

Sector	Target in 2030	FY2013 (FY2005)
Total energy-originated CO_2 emissions	927	1235 (1219)
● Industry	401	429 (457)
● Commercial and others	168	279 (239)
● Household	122	201 (180)
● Transportation	163	225 (240)
● Energy conversion	73	101 (104)

From 1990s, Japan established a series of laws, regulations, policies and action plans in promoting energy saving and resource conservation for realizing a low-carbon sustainable society. In the demand side, substantial reductions of energy consumption in industrial process, building energy use, and embodied energy use in building stocks are expected through process improvements and technology innovations. While in the supply side, more unused and renewable energy sources are expected to be connected to current energy system of which the efficiency in energy conversion and transition should be substantially improved. Usually, the former measures are packed into the concept such as Eco-Industry and Eco-City which are implemented through planning or projects in cities and industrial parks, while the latter measures are particularly relying on the popularization of district energy systems. Figure 1-3 shows the primary energy supply structure of 2013 and 2030 in Japan according to the Long-term Energy Supply and Demand Outlook by the Ministry of Economy, Trade and Industry (METI). Although METI reveals more cautious in the target of reducing fossil fuel consumption after the great earthquake in 2011, the proportion of renewable energy still doubles than it in 2013. Although Carbon Capture and Storage (CCS) is thought to be the final and most effective measure against the CO_2 emissions from continuous fossil fuel combustion, distributed energy system as a platform to connect to renewables and waste heat is currently more cost-efficient with higher energy efficiency, which can also connect to natural gas using cogeneration technology in some cases. Therefore, in a long term, distributed energy systems will still keep the environmental and economic competitiveness with concentrated energy systems.

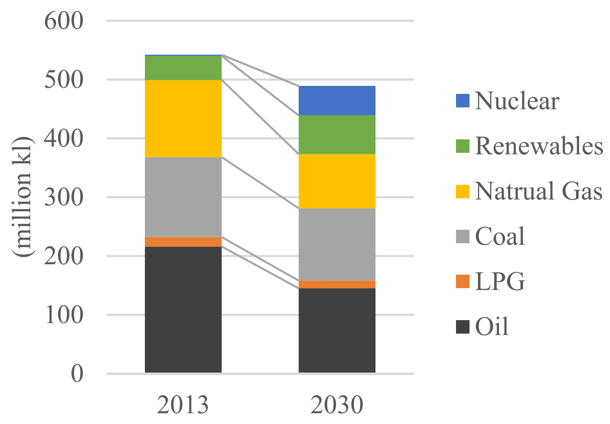


Figure 1-3 Primary energy supply structure of 2013 and 2030 in Japan

Particularly, distributed energy systems are recently proposed as a strong measure to support the revitalization of local cities and villages where depopulation and ageing problem is likely to bring about a long-term economic decline. Figure 1-4 shows a common structure of distributed energy system, which combusts energy resources in boiler and general wastes in incinerator and deploys electricity and heat to surrounding buildings in various purposes through electric wires and pipeline network. The key of distributed energy system to contribute in such issue is to form a local economic circle through utilizing local resources, cycling the local investment in energy infrastructure and create local jobs. This mechanism is also known as “local production and local consumption” in Japanese society. In 2014, the restructured Second Abe Cabinet formally proposed the concept of “local revitalization” which aims at systemically solving the problems such as suppressing the country-wide disparity between mega-city Tokyo and local cities and slowing down the speed of depopulation in local cities. Except for supporting the strategical renewal in city centers, the cabinet also selected out two series of pilot cities to test the city-level reform and redevelopment, known as the “Eco-Model City” and “Future City Initiative”. Until 2018, the 5th Basic Environment Plan of Japan initiated a concept named “Regional Circular Symbiotic Area” to nationally promote city redevelopment to form a wide economic circulation. Distributed energy system is quite expected to contribute to these two national policies.

Figure 1-4 Structure of distributed energy system and expected contributions

Another critical reason to develop district energy system is to make use of the local low-carbon renewables and unused heat which is widely distributing in the nature and industrial process. Although district energy system is usually doubted in long-term necessity because of the popularization of Net Zero-Energy Buildings, the easier access to local low-carbon heat sources such as biomass and waste heat is also a non-substitutable function according to the local situations. Due to the energy flow analysis of Japan, approximately 60% in the primary energy input is reported that has been wasted during energy use without recovery and reuse (IEA, 2012). As shown in Figure 1-5, the potential of unused heat in Japan is estimated at approximately 6,000 PJ annually, which is generated from widely distributed incineration facilities, factories, thermal power plants, sewage facilities, oceans, and rivers. This potential is actually over the total heat consumption for space heating and hot water generation in civilian sector (JES, 2011). Within the potential sources of waste heat, thermal power plants and factories are the top two sources possessing about 60% of the total, meanwhile the technologies for recovering the waste heat have been well developed for popularization. However, being a kind of distributed energy, waste heat potential also reveals a spatial disparity with energy demand distribution. For instance, populated regions like Tokyo Metropolitan Area and Aichi Prefecture have a great amount of waste heat from thermal power plant that is easier to find users, while the other regions, e.g., Fukushima Prefecture, have lower energy demand to match the potential supply of waste heat. Recovering and cascade use of waste heat can not only reduce fossil fuel combustion and emissions, but also help vitalize the local economy and ensure the energy security.

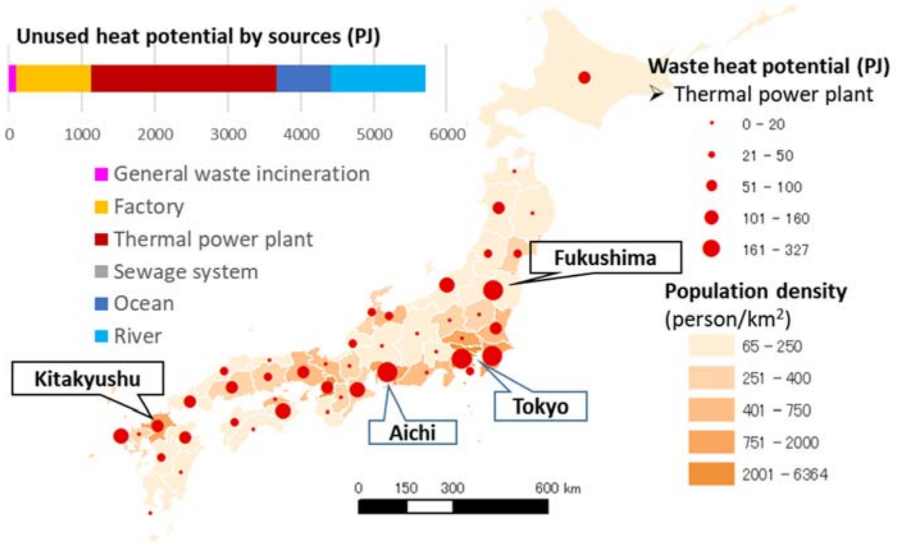


Figure 1-5 Potential of unused heat by sources and its distribution in Japan

1.1.2 Opportunities and challenges in popularizing district energy systems in Japan

Although distributed energy systems have critical importance for low-carbon urban sustainable development in Japan, its popularization is relatively slower than expectation because of various barriers. As a typical example, introduction of district heating system using waste heat and cogeneration technology is quite of importance in Japan which has been officially promoted from 1990s. However, until 2014, the number of cases served by district heating systems is still limited at 141, in which 37 cases are utilizing unused energy and further only 2 cases make use of waste heat from power plants (REF). This indicates only 0.05% of the potential unused energy has been used currently. In addition, due to the same statistical report, the total heat sales have already turned into decline tendency, and most of the existing enterprises are small and weak in surviving from market decline. Overall, the popularity of district heating system in Japan now is still around 1.2%, which is quite far behind it in European countries (e.g., 58% in Denmark, 48% in Finland, and 12% in Germany) (JES, 2008). Especially, the popularity of heat recovery from waste incineration for district heating is quite low, despite 83% of municipal waste is incinerated in Japan. Although around 40% of incinerators have installed power generator to use the waste combustion heat, the overall heat use efficiency is still at 20% level (JESC and JWRF, 2016). Consequently, approximately 40% of generated heat energy is directly wasted without any recovery and reuse (data of the year 2013) (MOEJ, 2014).

This fact is caused by various reasons. In case of district heating system, a comprehensive report by

Japan Heat Supply Business Association provided several factors, such as relatively warmer climate in Japan, decreasing and unconcentrated heat market, slowdown of investment in urban infrastructure, serious competition from high-efficiency individual heating, and languishing support policy from the government side (JHSBA, 2011). Furthermore, another comprehensive survey by Japan Environmental Sanitation Center identified more specific barriers and concerns relating to the popularity of incineration waste heat recovery (JESC and JWRF, 2016). As summarized in the Table 1-2, these barriers and concerns can be categorized into spatial, physical and economic criterion, of which the most important factor is the long distance between waste heat sources (waste incinerator) and users (urban area) that leads to an affordable initial investment on pipelines network. Accordingly, the limited budget and subsidies with undistinguished business model also worsen the overall economic feasibility, let alone the difficulty in matching the operation schedule between suppliers and users. This study would further specify the barriers and opportunities of promoting district heating system as follows.

Table 1-2 Summary of the barriers in promoting waste heat exchange from incinerators in Japan, based on the survey by MOEJ (JESC and JWRF, 2016)

Criterion	**Barriers and concerns**
Spatial planning:	● Far away from urban areas, hard to find proximate large industry
	● Large initial investment in equipment and pipeline
Economic feasibility:	● Facility is aging, the scale is too small for steam supply
	● Only power generation is considered beneficial
	● Inadequate budget, ineffective financial, and subsidy system
Business barriers:	● Hard to satisfy industry requests concerning pressure/temperature
	● Hard to adjust operation schedule for demand side
	● Hard to negotiate with municipal government (target priority)

(1) Technical solutions for dealing with lower energy demand density

Because of stagnant market of district heating, the technologies applied in actual district heating networks in Japan are quite far behind them in European countries. Currently in Europe, not only district heating network has been popularized in main cities for several decades, there is also a trend to upgrade these networks towards the Fourth Generation District Heating (4GDH), which has less heat loss and is easier to connect to low-temperature heat sources such as natural renewable heat and waste heat from factories and incinerators (Morandin et al., 2014; Zhao et al., 2014). In contrast, most of district heating networks in Japan are still at the first and second generation, using steam or high-temperature hot water as heat carrier. Except for the advantages in thermal insulation and connection to low-temperature renewable heat sources, they also have too strict requirement on heat demand to satisfy the conditions of feasibility.

Linear heat density is usually used as a key indicator to evaluate the concentration level of heat load which substantially affects on the feasibility and efficiency of district heating system. Figure 1-6 shows the distribution of current district heating networks in Japan between linear heat density and floor area ratio. Obviously, most of them are locating in high-plot-ratio areas with high linear heat density, such as cold Hokkaido Prefecture and dense Tokyo Metropolitan Area. By contrast, many European district heating networks are locating in regions with linear heat density lower than 10 TJ/km and plot ratio under 80%. Without better thermal insulation and cheaper construction cost of pipelines, as well as more efficient heat exchange rate in user side, the application of district heating will be limited only in dense city center.

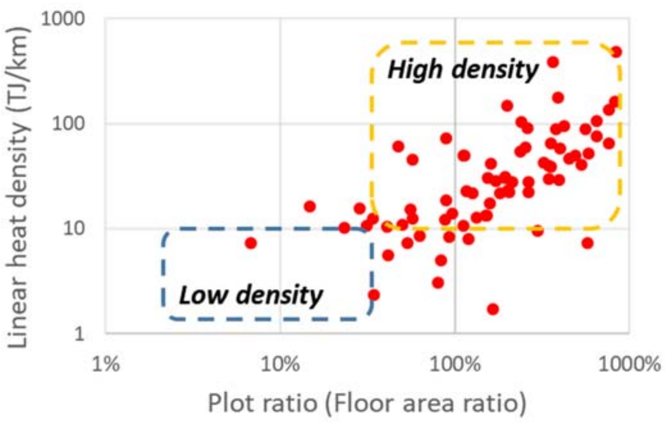


Figure 1-6 Conditions of existing district heating systems in Japan

(2) Geographic proximity to distributed heat sources

Geographic proximity to distributed heat sources is another key factor effecting on the feasibility of district heating. Although unused low-temperature heat from river, sea, underground and subway is thought as ideal sources for district heating, current heat pump technology for temperature upgrade is still not competitive, that connecting to incinerators, industries and biomass resources is critical to improve current district heating system. However, incineration facilities and industries are usually recognized as NIMBY (not-in-my-backyard) facilities to residential zones, meanwhile agricultural and forestry regions are also far away from the cities. Proximity to these energy sources cannot avoid a decrease in land price (Hashimoto et al., 2015). Consequently, a tough conflict happens here that, the larger is the city, the more difficult is it to make use of waste heat and biomass.

However, because municipalities are the main bodies to treat general waste from household, the incineration facilities in Japan distribute more densely in metropolitan area. Particularly in Tokyo Metropolitan Area, more than 150 incinerators are located, of which some are directly located near residential or commercial areas. This indeed helps a lot in recovering incineration waste heat for district heating to nearby industries or residential areas.

(3) Business model design

Generally, power and heat price are the determinant factor for evaluating economic benefit of district heating project. However, there is no fixed method to decide the price, but to refer to the negotiation between supplier and user. Furthermore, in the case of introducing waste heat, how to decide the price of waste heat is also a question, to which the answer should be discussed by stakeholders in advance.

Another important question is the share of initial investment. Facing the large initial investment for infrastructure and equipment, stakeholders should negotiate on the share of initial investment which also leads to the corresponding share of benefits. In European countries, many district heating networks are operated by municipal holding companies (called "Kommunaler Querverbund" in German) that most of the initial investment can be covered by public finance. This will naturally affects on pricing mechanism, e.g., setting heat price equal to average cost of heat supply. However, most of current district heating networks in Japan are operated by small and independent private companies, which brings difficulty in heat pricing (Tabata and Tsai, 2016).

As a whole, connection to district heating system is not a duty in urban planning and building design in Japan, pipeline network for heat transmission was totally ignored during the recent fast urban development in the 20th century, even in the cold Northeastern Japan. By contrast, the pipelines for district heating have been introduced from 1890s in Europe, which is still expanding in most of European countries. These barriers substantially impact on the popularization of district heating that the current distributed energy system is more focusing on power generation rather than combined heat and power generation.

Despite of the technical and business barriers, district heating in Japan also meets various new opportunities and challenges, which may help in improving the situation for popularizing district heating but also increase the long-term uncertainties. These opportunities and challenges are summarized as follows.

(1) Technology innovation

Although the efficiency of individual energy technologies such as boiler and air-conditioner keeps increasing in the future, the efficiency of district heating systems is also considered to rapidly increase because of the introduction of new-generation technologies. Recently, existing district heating systems in Japan reveal an average of 20.6% reduction in primary energy consumption compared to individual heating (METI, 2008). This number will increase if the 4th generation district heating (4GDH) technologies are introduced. The new technologies will allow district heating to connect to low-temperature heat sources using industrial waste heat and biomass, that substantially reduces fossil fuel input and CO_2 emissions. Especially combining the high-efficiency heat pumps using renewable energy, the performance of district heating can be further improved by introducing low-temperature renewable heat, such as solar and river heat even the heat from cooling system of thermal power plants. Meanwhile, demand-side management using Information and Communication Technology (ICT) and Internet of Things (IoT) with high-efficiency energy storage equipment can help in matching the demand variation with supply variation that enables the integration with solar and wind power generation.

(2) Policy supports

Recently, the government carried out various policies to support the development of district energy systems.

a) Feed-in-Tariff (FiT) system

Japan has introduced FiT system from the year 2012, through which the power generated by distributed energy systems will be directly purchased at a certain price. Recently, the government is discussing on specifying an FiT system for heat supply to support combined heat and power generation and usage of waste heat and renewable heat. In fact, this new system has been introduced in Germany and England, known as Renewable Heat Incentive (RHI). As a result of introducing RHI, the usage of waste heat and biomass increased by several times than before in these countries.

b) Liberalization of heat and power market

This is another revolutionary event that deeply impacts on energy systems. Companies owning distributed energy systems can compete with each other in a unified market, where using waste heat and renewables would become a strong advantage. However, because heat is usually used locally, market liberalization may bring merit to combined heat and power generation, while bring demerit to heat-supply-only district heating systems. The difference between heat price and electricity price would lead to totally different application of technologies.

c) Other related policy packages

Except for FiT system and market liberalization, there are also other policy packages relating to popularizing district heating systems. Generally, these include the policies for increasing the usage of renewable energies, promoting the recovery and cascade use of waste heat, popularizing combined heat and power generation, and supporting the introduction of smart grid and district heating/cooling system toward smart cities. Subsidies are available for application to cover part of the costs in infrastructure development and equipment purchase. Especially, to help in identifying the opportunity for waste heat utilization, large facilities including industries, power plants and incinerators will be required by the government to annually report the quantity of heat consumption and waste heat generation in near future.

(3) Long-term changes in demand and supply side

In the long term, both demand and supply side will change a lot. On the one hand, although energy consumption intensity may decrease gradually due to the serious depopulating ageing society and behavior changes toward energy-saving, compact city planning will re-concentrate residents and urban activities back to city center that suppresses the speed of energy demand density around city center. Expect for the Law on Promoting Low-Carbon Cities carried out in 2012, the Ministry of Land, Infrastructure, Transport and Tourism currently has implemented an additional system to guide local municipalities in making master plan for location optimization. As shown in the Figure 1-7, the mechanism considered in this system is to attract critical commercial and public faculties to relocate in city center, which will change the accessibility that attracts residents back to city center with the critical facilities. However, the actual target of the system is trying to maintain the population density in city center that means the energy demand density still has high possibility to decrease gradually in the future.

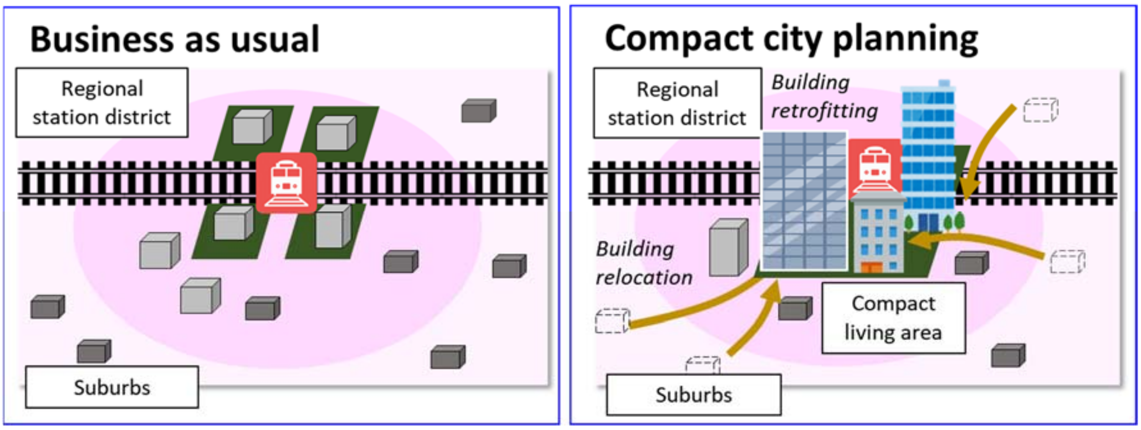


Figure 1-7 Comparison between the current and compact city planning

On the other hand, emerging practice of Industrial Symbiosis and Urban Symbiosis provide a critical solution for integrated design of district energy system. Industrial Symbiosis is firstly defined as a subdiscipline of Industrial Ecology, which provides an inventory analysis to design an exchange network of by-products between industries. The by-products include intermediate products, water, waste, and energy, which can be reused among factories as a substitute raw material and fuel (Chertow, 2000, 2007; Dong et al., 2016; Liu et al., 2017). As an extension from Industrial Symbiosis, Urban Symbiosis aims to recycle municipal waste from cities and reuse them into industrial process, as well as recovery the waste heat from industries for district heating in cities and agriculture. As drawn in Figure 1-8, by-products exchange, waste recycling and cascade energy use would reduce material and energy consumption to the full extent (Dong et al., 2014; Dou et al., 2016b; Fujii et al., 2016; Van Behkel et al., 2009). Such measures are also identified as key methods for forming a circular economy. The most famous typical case is in Kalundborg, Denmark, where a couple of by-product exchange networks have been established and waste heat is exchanged by district heating from industrial park to the residents. District energy system plays as a key platform for exchange power and heat energy, thus the wide spread of Urban and Industrial Symbiosis will surely speed up the development of district energy system in the future.

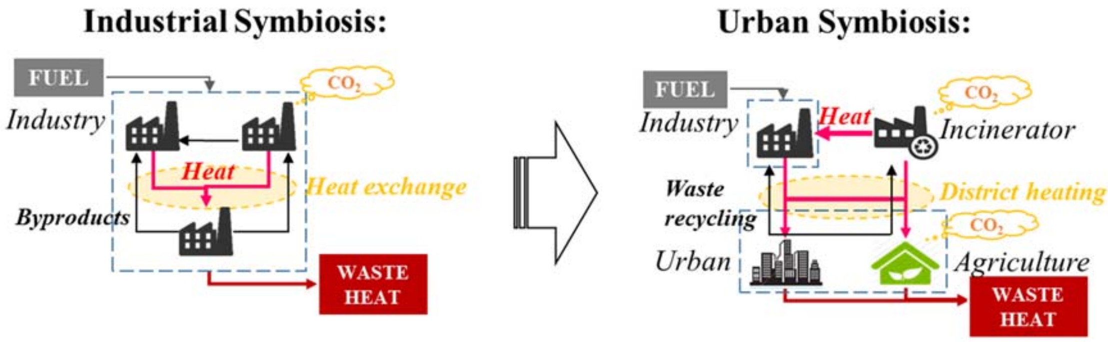


Figure 1-8 Energy synergy in Industrial Symbiosis and Urban Symbiosis

(4) Cities' practice in integrated urban planning for the future

Facing the serious depopulation and ageing problems, local municipalities in Japan begin to rethink and reform the local economy and society through a theme-based co-design between various sectors. From 1990s, the central government and ministries carried out several series of local development policies to encourage cities to renew and reform themselves towards sustainable urban development. Typical series include the Eco-Town Program, Eco-Model City and Future City Initiative (Figure 1-9).

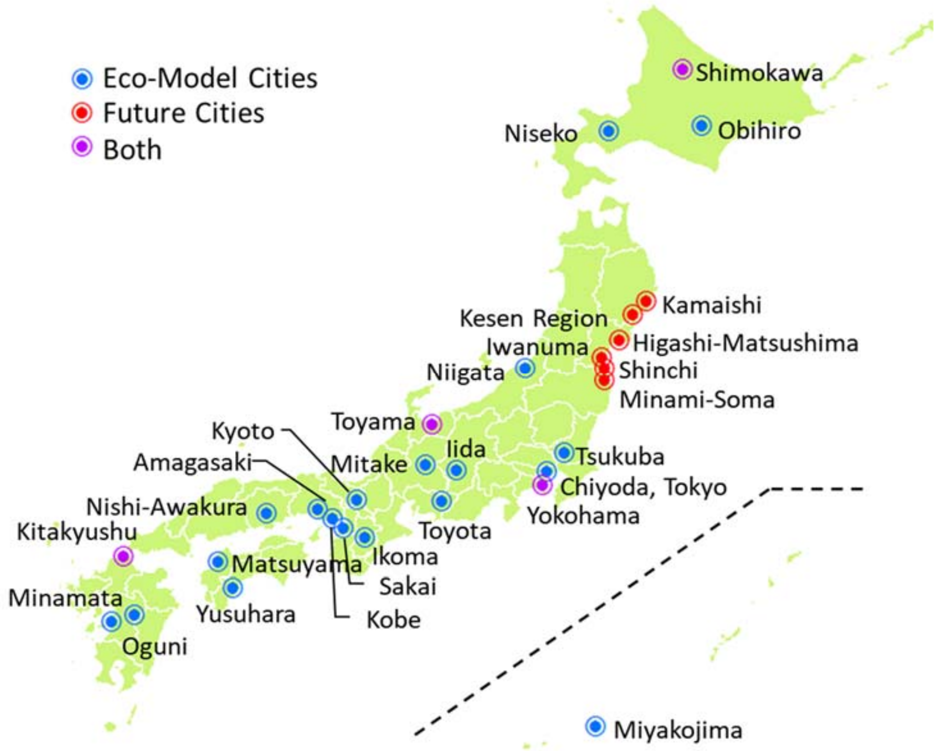


Figure 1-9 Distribution of eco-city series in Japan

Generally, the selected cities should focus on a set of pilot projects focusing on one or several socioeconomic or environmental topics. For example, Shimokawa Town decides to introduce a pilot project using the 4^{th} Generation District Heating technologies and exam the performance on local environment and economy. Shinchi Town and Minami-Soma City carry out Smart Community projects near central rail stations where cogeneration-based district heating system with demand-side control by IoT is proposed. Such practice would provide evaluable experience in integrating district energy systems with urban planning and other sectoral development.

As mentioned above, since the barriers and opportunities bring about large long-term uncertainties in urban energy planning, it is necessary to develop an integrated model framework to design and evaluate urban energy systems considering long-term future changes in urban renewal including city master plan and building retrofitting. The framework should at least be able to answer the two questions as follows:

a) How to rethink and quantitatively evaluate the feasibility of introducing district energy system into low-energy-density cities, considering the impact from compact city plan?
b) How to design the district heating network based on Urban and Industrial Symbiosis and evaluate the impact on system performance?

1.2 Objectives and originalities

To solve the two questions mentioned above, this study aims at developing an integrated model framework to estimate the future energy demand distribution during long-term urban renewal, and evaluate the impact on the feasibility of district energy system under symbiotic design . It is expected to contribute in the research field from the 4 perspectives as below:

- **Model development**. Develop an integrated energy planning model connecting to long-term urban renewal management.
- **Database construction**. Develop a universal database and guideline for municipalities in order to popularize the model application for the whole country.
- **Case study**. Apply the models in actual cities to verify its effectiveness and create policy implications.
- **Policy implications**. Find out typical and innovative policy packages on sustainable urban planning for municipal government.

Accordingly, this study will be belonging to interdisciplinary field that includes population research, land use, industries, economics, architecture, especially focus on energy and environmental studies. Its originalities are summarized as following:

- **4d-GIS Database**: 4-dimension Geographic Information System (4d-GIS) databases for Kitakyushu and Fukushima are established.
- **Design and assessment of urban-industrial symbiotic energy system**: Symbiotic energy system design between industries, incineration facilities, thermal power plant and urban areas.
- **Model innovation for long-term urban energy planning**: An integrated energy planning model connected to urban renewal management and simulation.
- **Case study**: Low-energy-density case in Fukushima to support local revitalization, as well as a case of Kitakyushu City with diverse urban structure.
- **Policy implications**: Comprehensive impact assessment between various policies.

1.3 Dissertation structure

To describe the story and current progressions for achieving the objectives, this thesis is structured into several chapters as Figure 1-10. Chapter 1 briefly describes the research background as well as research objectives and originalities; Chapter 2 summarizes the previous related researches on issues such as material and energy use in buildings, urban renewal, design of district energy system and integrated land use and energy planning, that derives the research gap and contribution of this research; Chapter 3 in detailed describes the analytic framework and model development in this study including the models for urban simulation, energy system design and cost-benefit analysis, as well as data sources and selection of case studies; Based on the model framework, Chapter 4 and Chapter 5 introduce two case studies in Fukushima Prefecture and Kitakyushu City of Japan, which indicate the effectiveness of the model development in this research; Finally, Chapter 6 concludes the main findings and policy implications, as well as future works from this stage.

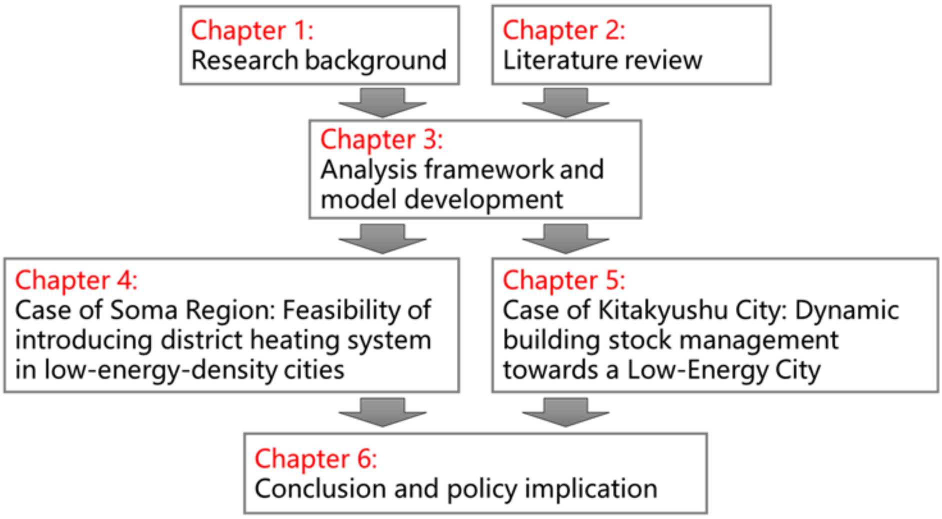


Figure 1-10 Dissertation structure

2. Literature review

The literature review in this chapter follows the story as below. Firstly, the key factors influencing building energy consumption are summarized from related previous studies, so as to find out the ones related to long-term urban renewal (building relocation and retrofitting). Then, the current mainstream methods for estimating future building distribution are reviewed to support the model selection and development in this study. Next, the trend of technology innovations in district energy system is reviewed to provide an overall insight of system design, while the mainstream methods for system optimization are following. Referred to these literature review, the research gap is identified to support the foundation of model development and originality declaration in this study.

2.1 Review on stock and energy management in building sector

2.1.1 Energy consumption in building stocks

As mentioned in Chapter 1, building sector (residential, commercial and others) possesses more than 30% of the total CO_2 emissions in Japan. These emissions are not only from the energy in use during building operation, but also from the material production and embodied energy use from the construction to the demolition. Therefore, it is necessary to conduct a quantitative and systemic approach to estimate the current material and energy use in buildings as well as the future prediction for evaluating the effectiveness of related policies toward low-energy cities.

Energy use in building operation can be simply estimated by multiply the energy use intensity with building floor area. Usually, the energy use intensity is variable due to the type of building and the purpose of energy use. For example, commercial buildings have more intensive energy consumption than residential houses in total by floor area, but lower unit energy consumption for hot water supply. Such datasets are usually available in survey report and statistics provided by the government or consulting company (Perez-Lombard et al., 2008). However, because these data cannot provide real-time information on daily and hourly variation of energy demand, high-resolution monitoring data of target buildings became more popular in energy system optimization based on the development of sensor technologies (Du et al., 2010).

By contrast, the calculation of embodied energy is more complicated that needs the information of material use in buildings as well as life-cycle energy use from material production, building construction and demolition, waste recycling and disposal (Dixit et al., 2010). Estimating material use in buildings is quite similar to the calculation of energy in operation of buildings, that is to multiply the material use intensity with building floor area (Shi et al., 2012). The type of material input and its unit are specific due to the building structure. For example, detached houses in Japan are usually constructed by wooden materials, while collective houses are usually steel-structured or made by reinforced concrete. The datasets of unit material input are available in survey report or statistics provided by the government and consulting companies. Next, Life-Cycle Assessment (LCA) based on Material Flow Analysis (MFA) of building material production is applied to calculate the total energy consumption during material production/recycling and building's lifespan (Dixit et al., 2012). Only if the total energy consumption including energy in use and embodied energy of a building are equal or less than its total energy supply, the building can be called as Net Zero-Energy Building (ZEB) (Chastas et al., 2016; Marszal et al., 2011).

Accordingly, in case of estimating the weight (material input) and energy consumption, especially their distribution in a city, it is possible to firstly estimate each building's material and energy input, then aggregate into the city's map (Tanikawa et al., 2015). Particularly, utilizing the past decades' building distribution data from recorded remote sensing and aerial photograph, a set of GIS-based dataset, named as "4-dimension Geographic Information System (4d-GIS)", would be applicable for tracking the historical changes of the weight and energy consumption in a city, even a country (Marcellus-Zamora et al., 2016; Reyna and Chester, 2015; Tanikawa et al., 2015; Tanikawa et al., 2014).

2.1.2 Energy demand changes during long-term urban renewal

Except for the social and economic changes such as population and economic growth, there are many factors impacting the energy consumption intensity in buildings, including topography and climate, urban planning and microclimate, human lifestyle, proliferation of building and energy use technologies, energy market changes and policy implementation.

As the first and most important influence factor, climate and its long-term changes have high possibility to impact on building energy consumption, especially on heating and cooling demand. For example, heating demand is dominant in cold areas and cooling demand is dominant in warm areas. Accordingly, the future climate changes (global warming) also have high possibility to increase the cooling demand and decrease the heating demand in a city (Wan et al., 2011). Next, microclimate is also an important factor that impacts on the energy consumption of an individual building or mixed buildings in a neighborhood, even extending to district or city-wide according to the urban morphology and neighborhood design (Wong et al., 2011). Measures such as green belt around the urban area, green wall for buildings, mixed shape and height of buildings are indicated useful for reducing building energy consumption (Allegrini et al., 2012; Bouyer et al., 2011; Malys et al., 2014). Furthermore, human lifestyle (behavior) is also a dispensable factor on building energy consumption. The occupants in buildings will always have diverse or similar reaction due to many variables like income, energy price, energy efficiency, event and encouragements, even make changes just according to the sharing information on their real-time energy consumption (Jain et al., 2013a; Jain et al., 2013b; Yu et al., 2011). Fourthly, the diffusion of new energy conversion and management technologies in buildings also contribute a lot to the long-term changes of building energy consumption. Not only the equipment including high-efficiency air-conditioner and heat-pump-based water heater may substantially reduce energy demand, but also control technologies like IoT system for demand-side management can impact on the overall efficiency of building energy system. The trend of technology diffusion depends on both the development progress of technologies and public awareness and acceptance (Andrews and Krogmann, 2009; Kok et al., 2012). Finally, energy policy is indicated as a comprehensive but quite powerful measure, which directly regulates on the energy performance of buildings or indirectly impacts on the influence factors mentioned before. Policies such as making building energy codes, promoting zero-energy buildings, improvements in retrofitted buildings, establishing benchmark and labels for building energy performance, and consumer encouragement for new technology proliferation are thought able to substantially reduce building energy consumption in the future (Nejat et al., 2015). In fact, these five influence factors interact with each other and together determine the changes of building energy consumption in the future.

Although previous researches have provided various modelling methods and detailed assessment on the quantitative changes in building energy consumption, they have not clearly identified the possible spatial changes of building energy consumption, which may deeply impact the proliferation of district energy systems. During the long-term urban renewal, not only buildings will be demolished and relocated, the purpose and structure, even the envelope and built-in technologies of each building will irreversibly change year by year. In another word, this is a dynamic and irreversible process that is hard to repeatedly test and verify the measures for reducing and redistributing building energy demand. From this perspective, simulating the changes of building energy demand distribution can provide a bottom-up approach for a comprehensive assessment on various policies towards low-energy city planning.

As summarized in the Figure 2-1, there are mainly five influencing factors which should be taken into consideration in estimating the distribution of energy demand. First of all, buildings' location may greatly change in the future due to the master plan of the city. Aggregation or decentralization of residential houses, commercial buildings, industrial clusters and public facilities would substantially impact on the accessibility to inner-city renewable resources, the proximity between energy sources and users, and energy demand density for introducing district energy systems. Next, the transfer in building purpose and structure would lead to different energy demand intensity and hourly variation as well as impact on the embodied energy consumption. Furthermore, the speed of urban renewal is also an important factor in diffusing new technologies such as heat insulation, green wall, and IoT system introduction in buildings. Combining these five factors, it is possible to conduct an urban simulation for predicting future building energy demand distribution under the scenarios of urban renewal strategies.

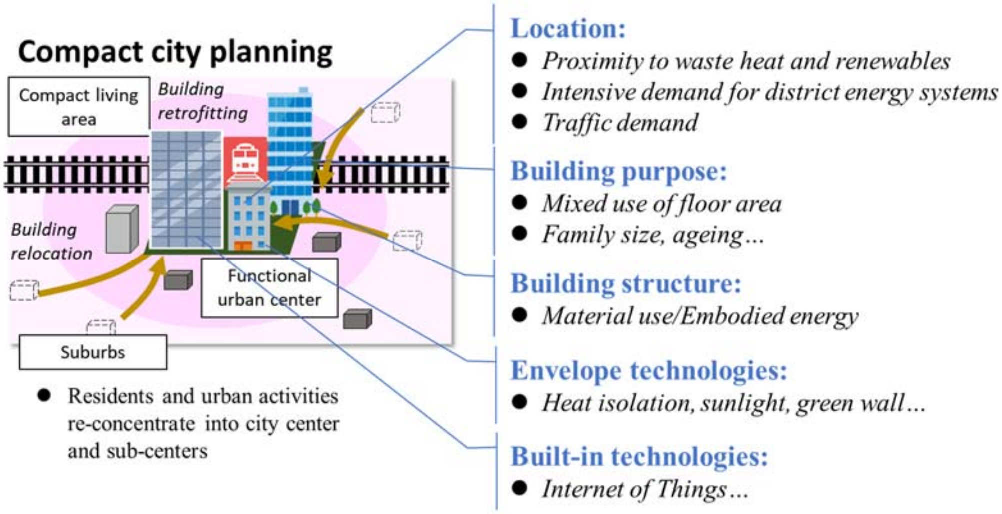


Figure 2-1 Impact from urban renewal on material input and energy use in buildings

What would be the contents of building energy policies during strategic urban renewal? In case of Japan, the main country-side policies have been summarized in the Figure 2-2. Firstly, low-carbon land use planning including compact city and heat-island measures is conducted which would change the distribution of building location, purpose, structure and height. Secondly, the technology diffusion including heat insulation, energy conversion and management system would be supported by regulation and encouragement such as ZEB promotion roadmap. In addition, information sharing and recognition on comprehensive life-cycle impact of buildings would involve the embodied energy consumption that leads to a real zero/minus emission building society.

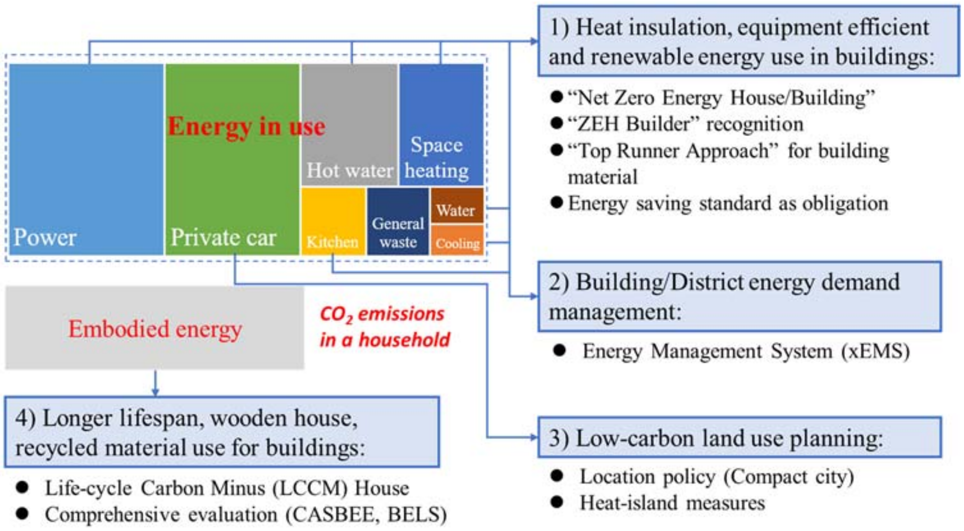


Figure 2-2 Main measures for reducing energy consumption in building sector in Japan

2.1.3 Dynamic urban simulation of strategic urban renewal

Simulation of strategic urban renewal for estimating building energy demand distribution has to be a framework that integrates submodules from various research fields. Currently, although many mature methods, e.g., engineering method, statistic method (regression model, factor decomposition model, data mining, etc.), neural network method, and machine-learning method, have been developed for predicting the energy demand of one building or the whole building sector (Catalina et al., 2013; Fan et al., 2014; Swan and Ugursal, 2009; Wan et al., 2011; Zhao and Magoules, 2012), the real difficulties are from the simulation of land use changes and technology diffusion. However, with the popularization of geographic information system and mass spatial data processing methods, high resolution analysis on land use changes and building distribution has become possible.

In previous researches, the methods for urban land use simulation can be classified into two types as aggregate and disaggregate analysis. Based on location theory, a new subject known as regional science rapidly developed from 1960s, which mainly studies on the issue of location activities and optimization. As the recent progression, new economic geography, founded by Paul Krugman and colleagues, provided a set of methodology for analyzing the aggregation behavior of residents and industries. One of the most frequently applied approaches, which is called spatial econometrics, has high applicability to predict the distribution of population, residential and commercial buildings and other functional facilities (Anselin et al., 2013; Pinkse and Slade, 2010). Generally, spatial econometrics is based on the hypothesis of spatial autocorrelation, which means the spatial elements in a city may have self-correlation effect. Thus, being different from ordinary least square regression, spatial regression models are embedded with a spatial weight matrix so as to accurately reflect the influence from location factors on building distribution. For example, population distribution, civil buildings and land price are found closely correlated to the transportation accessibility to jobs and entertainment and quality of local built environment (Chen et al., 2012; Dou et al., 2016a), in addition the location of industrial clusters is found self-correlated and significantly influenced by local socio-economic characteristics including knowledge and innovation (Aguilar, 2009; Balta-Ozkan et al., 2015). However, this method is strong in empirical studies but not in urban simulation, while it may be doubted in case of a shrinking city with decreasing land price. Furthermore, the higher is the spatial resolution, the more uncertainties appear in the result of model application.

Another well-applied model is called Computable Urban Economic (CUE) model, in which the core part is established upon the interaction between land use and transportation. CUE models generally absorbed the quantified analysis from traditional location preference theory, but mainly established the foundation upon the utility theory from microeconomics and market analysis from macroeconomics. On narrow sense, such CUE models are established upon the base of a partial static economic equilibrium of the land/building market with the equilibrium in urban transportation network (Tsutsumi et al., 2012). After inputting land use and energy policies with other environment changes, equilibrium model can answer how the urban form and building distribution would response to the changes (Anas and Hiramatsu, 2012; Zhang et al., 2016). Following the system equilibrium of integrated land use and transportation analysis, distributed energy system such as solar panel can be a supplement connecting to the building distribution and CO_2 emission accounting in scenarios (Nakamichi et al., 2013; Yamagata and Seya, 2013).

However, conventional CUE models are weak in dynamics of urban changes because of the conditions to apply equilibrium formulations (Simmonds et al., 2013). Grew out from CUE models, discrete and dynamic models such as Cellular Automata (CA), Agent-Based Model (ABM) and Microsimulation were developed to deal with smaller-scale case study and track the location behavior more clearly. The core idea of CA model is to set rules for location or transition behavior of one or various spatial elements. Phase transition of land use, population density, building and infrastructure are usually chosen as the indicator to simulate urban growth, evacuation (Han et al., 2009; Lin et al., 2014; Zheng et al., 2009). By contrast, ABM method emphasizes more on individual behavior based on utility evaluation so that enables more details such as building occupancy, traffic and energy consumption behavior of building occupants (Klein et al., 2012; Langevin et al., 2015; Liao et al., 2012). Similarly, Microsimulation model improved the computability from CA model and ABM so as to extend the application to city-wide energy consumption even connecting to regional Computable General Equilibrium (CGE) models (Ballas et al., 2007; Chingcuanco and Miller, 2012).

Being different from the models based on urban economics mentioned before, the recent emerging studies using 4d-GIS provided an engineering perspective for simulating urban development. Benefiting from the rapid popularization of GIS, many cities have accumulated a set database of building and infrastructure distribution in past several decades. Learnt from the past building distribution, actual lifespan of any specific type of buildings can be estimated for simulating the demolishment and reconstruction of buildings (Komatsu, 1992; Tsutsumi and Komatsu, 2004). Especially in Japan, the actual lifespan of houses is much shorter than designed lifespan, because the price of second-hand detached houses decreases very fast while the old collective houses were usually designed in low quality during the rapid economic growth period (Komatsu, 2006, 2008). Next, the actual lifespan of buildings would be input as a critical parameter into the dynamic simulation of strategic urban renewal. Many previous studies have realized gross simulation of the changes in material and energy consumption during long-term urban renewal (Fishman et al., 2014; Miatto et al., 2017; Shi et al., 2012), even some others established the assessment of material and energy consumption on visualized future building distribution maps, in which each building is manually demolished and redesigned based on its lifespan (Chen et al., 2016; Han et al., 2018; Tanikawa et al., 2010). However, the latter studies are usually conducted at neighborhood scale because of the infinite manual work and too detailed design for each building in such high spatial resolution, thus a more general city-wide simulation based on 4d-GIS database is required.

Comparing to CUE series models, 4d-GIS-based urban simulation is easier for parameter calibration and convenient to input target policy indicators by adjusting parameters, that can be used as a common tool for municipalities to make urban transition roadmap. The Table 2-1 is a brief summary and comparison on the characteristics of each methodology.

Table 2-1 Comparison between the mainstream methods for urban land use simulation

Name	**Spatial econometrics**	**Computable urban economic**	**Cellular Automata, Agent-Based Model, Microsimulation**	**4-Dimension GIS**
Status	Static	Static	Dynamic	Dynamic

Type	Aggregate analysis	Aggregate analysis	Discrete analysis	Engineering analysis
Scale	From city to region, even nation or global scale	City scale	From neighborhood to region scale	From building to nation scale
Merit	Easy to identify the influence factors on spatial aggregation considering spatial autocorrelation	Able to provide reasonable and overall urban simulation based on interaction between land use and transportation	Easy to track the location behavior at smaller scale based on utility and location balance	Support detailed building attribute that is easy to connect to end-use model for energy system design
Demerit	Hard to conduct urban simulation for estimating future building distribution	Hard to apply to dynamic and smaller-scale cases to track the detailed location behavior	Hard to apply to mega-city or larger-scale cases (limited computing ability) considering general market equilibrium	Engineering analysis without consideration of land/building market equilibrium and transportation accessibility

2.2 Design of low-carbon district energy system

2.2.1 Selection of energy supply technologies

There are various energy sources and technologies available for energy supply in current industrialized society. From the form of energy supplier, they can be differentiated into concentrated energy technologies and distributed energy technologies. Also, the technologies can be classified into individual energy system or district energy system, where the former serves one individual building and the latter serves several buildings through an energy delivery network.

Previously, concentrated energy technologies, such as thermal power plant by fossil fuel combustion, will have higher efficiency in scaling up due to the economy of scale. Additionally, combined heat and power generation, also called cogeneration, can double the efficiency of energy conversion while double the revenue by combined heat and power sales. However, because of the introduction of distributed renewable resources, e.g., wind and solar power, distributed energy systems have become the mainstream toward the future low-carbon energy system. Although renewable energies are thought as a critical solution to the concern on energy shortage and global climate change problems, it still requires several decades for popularization because of the expensive installation and operation costs and hourly fluctuating energy supply. Between the fossil fuels and renewables, waste heat, which is recovered from industrial process and thermal process in incinerator and power plant, has been recognized as an important energy source that effects on the overall loss rate in the urban energy system. Part of the waste heat can be reused internally while the excessive waste heat has to be delivered to another user through a pipeline network. From this perspective, district energy system would keep the competitiveness with individual energy system in the long term (Averfalk et al., 2017).

The current trend of developing district heating system can prove this mind (Figure 2-3). As described in the Heat Roadmap Europe, district heating systems can be classified into five generations (Lund et al., 2014; Paiho and Reda, 2016; Persson et al., 2014; Ziemele et al., 2017). The first generation started its diffusion from 1880s, in which heat energy is supplied by simple coal-fired boiler or waste incinerator with heat storage equipment. Then, from 1930s, combined heat and power generation technology using fossil fuels was introduced into district heating system, through which both the revenue and CO_2 emission reductions of district heating are substantially enhanced. In case of 1st and 2nd generation district heating system, only steam or high-pressure hot water can be used as heat carrier with a high heat loss rate. Benefitting from the improvement in heat insulation and high-efficiency exchanger in user side, the temperature of hot water supply decreased under 100℃ so that biomass combustion, solar heat and industrial waste heat became important sources of heat supply. Such system is called the 3rd generation district heating which has started operation from 1980s and is the current mainstream.

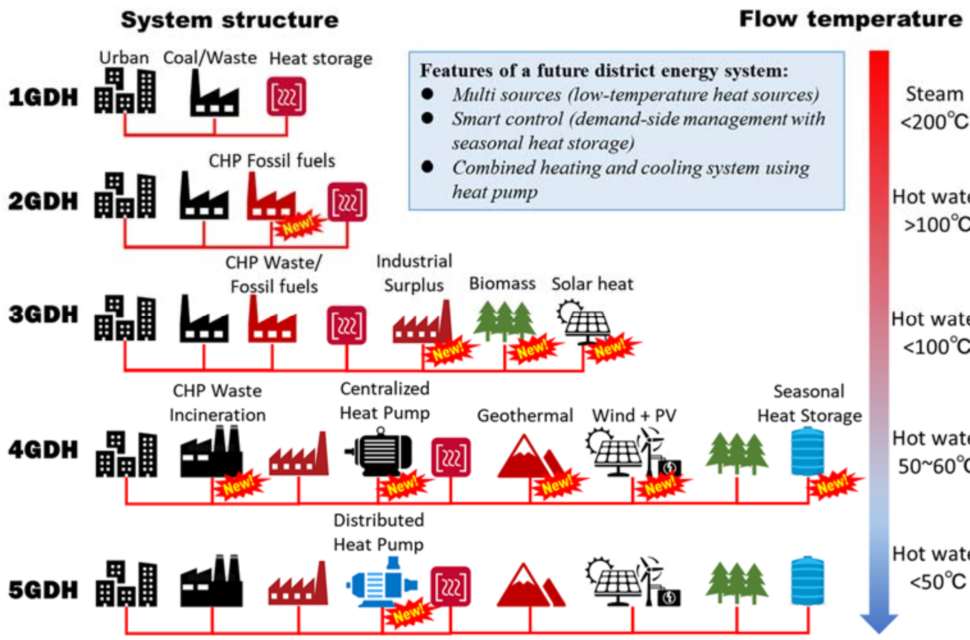


Figure 2-3 Five generation of district heating system

However, in the following 4th generation district heating, because of the further improvements in the overall system design, the requirement on hot water's temperature will further decrease to 50~60℃ level that makes more low-temperature heat sources, e.g., geothermal energy, available to be introduced into the system. Particularly, fossil fuel combustion will be totally substituted by high-efficiency centralized heat pump using low-carbon electric power provided by wind and solar panel (David et al., 2017). With seasonal heat storage, such district heating system could be nearly zero-emission. To some extent, the 5th generation district heating system can be thought as an enhanced 4th generation where the centralized heat pump can be replaced by high-efficiency distributed heat pump, so that each building can install a heat pump using local low-temperature unused heat and renewables with zero CO_2 emissions (Werner, 2017).

2.2.2 Design and optimization of district energy systems

(1) Design condition of district energy systems

One critical difference between individual and district energy systems is the diverse combination between energy sources and users. Usually, one district energy system would connect to several energy sources, such as fossil fuels, biomass, wind power, solar heat, waste heat and unused heat in nature, with multi users such as industrial process, civil buildings and facility agriculture. Quality of energy, which can be evaluated by exergy analysis, is a key indicator for designing an optimal district energy system. For example, an incinerator can supply different qualities of heat to satisfy different requirements on the user side, such as high-pressure, high-temperature steam (300–400°C) directly from the boiler, low-pressure, low-temperature steam (150–170°C) extracted from a turbine, or hot water (~60°C) by heat exchange from condensers and exhaust gases, as shown in Figure 2-4 (Ohnishi et al., 2016b; WSP, 2013). Because biomass and general waste can be combusted together in a boiler, an incinerator is able to adjust its work schedule and stably support heat to match the user's requirement, especially combined with Internet of things technologies (e.g., smart control of heat production by adjusting waste input in an incinerator) (METI, 2016). Although thermal power plants generate greater amounts of waste heat than incinerators, extracting steam during power generation would decrease the power output; meanwhile, the hot water obtained by heat exchange with a condenser has a comparatively low temperature (~40°C) (Holmgren, 2006; Togawa et al., 2014). In addition, industrial process can sometimes supply high-temperature steam and hot water; however, the difficulty of satisfying the supply schedule of users becomes a difficult obstacle for matching negotiation and implementation (Morandin et al., 2014).

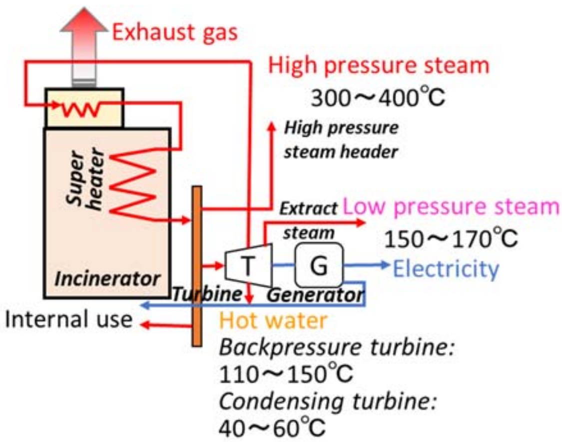


Figure 2-4 Possible heat supply from an incinerator

Another important concern in designing district energy is to decide the energy medium, which can be electricity, heat, Hydrogen and any other medium. Considering the overall efficiency in energy conversion, transmission and storage, direct heat exchange could be more efficient than electricity if the electricity is generated from fossil fuel combustion. In the future, Hydrogen can also be an optional medium, but its efficiency is doubted if the Hydrogen is made from electricity.

(2) Optimization method for district energy system

Optimization is one critical content in researches on district energy system, because the system efficiency is substantially influenced from the combination of technologies and operation schedule responding to demand and supply variation, optimization targets and external conditions. The most applied method is based on linear programming which assume the energy suppliers can real-time adjust their energy output responding to the variation in demand side (Togawa et al., 2017; Togawa et al., 2015). Especially, in case of multi-energy systems, each energy unit, including power station and user, can be both an energy supplier and user at the same time acting as an energy hub. For the best design of such multi-energy systems, complex optimization method with wider consideration in technology selection and evaluation criteria is required (Bazmi and Zahedi, 2011; Mancarella, 2014). Based on such optimization methods, there have been various support tools that can automatically solve the optimization problems in different time resolution and scale, e.g., the software EnergyPRO can solve detailed optimization problem focusing on single energy plant and the optimal design thereof, while the well-known EnergyPLAN can make aggregated optimization focusing on much wider energy systems and cross-sector integration (Allegrini et al., 2015; Connolly et al., 2010).

Of course, technology innovation itself would be the essential solution for system optimization. For example, the mainstream solution for extending district heating system 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 district heating networks 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 district heating 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), 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 district heating system. These technical improvements are considerably effective in districts where district heating system is already popular and serve to further extend its application by increasing the competitiveness of district heating system *vis a vis* individual heating. However, without a reform in urban planning, the expected improvement of the system is considerably limited.

(3) Geographic aspect in designing district energy system

With the development of GIS (Geographic Information System), it becomes much easier to grasp the precise spatial distribution of the heat demand density (Schorah, 2014). Also, the location of local existing and emerging heat sources and sinks can be precisely identified by programming (Finney et al., 2012a; Finney et al., 2012b; Yeo et al., 2013). These maps of heat demand and supply, the Heat Atlas provide very detailed information to help in evaluating the feasibility of introducing district heating system and investigating the most cost-efficient system design. So far, land use has been formally identified to be a crucial factor impacting urban energy planning and this parameter needs to be quantified in the optimization models. Nowadays, the first step in energy planning is to conduct an inventory of regional resources and demand by GIS analysis, and embed the overall geographic information into a linear programming model for technical assessment (Girardin et al., 2010; Nielsen and Moeller, 2013). Consequently, there are several studies being carried out that focus on conducting spatial planning to optimize the civilian utilization of waste heat in the field of energy symbiosis (Togawa et al., 2014). Since GIS is closely related to land use planning, combining technology assessment with symbiosis design and evaluation by GIS spatial analysis will be of increasing importance for promoting waste heat utilization.

2.3 Perspective of integrated energy planning considering urban renewal

2.3.1 Long-term demand-side management

As discussed before, traditional optimization methods for energy system design are usually focusing on supply-side management where the demand side is assumed to be uncontrollable. Against this assumption, recently more and more literatures turn to discuss the method and potential impact of demand side response on maximizing the total revenue of a district energy system. In the short term, application of real-time energy pricing in market and energy management system using IoT technologies has been indicated quite effective in peak shaving (Gottwalt et al., 2011; Paulus and Borggrefe, 2011). Such district energy system with functional demand-side management is usually called as a “smart grid” which is an indispensable component of the so-called “smart community”. On the other hand, because buildings in different purposes lead to different energy consumption intensity and hourly load curve, specified building mix can also effectively stabilize the demand variation that increases the efficiency of district energy system (Best et al., 2015; Fonseca and Schlueter, 2015). With such effective demand-side management measures, the feasibility and performance of district energy systems has been substantially enhanced to compete with individual energy systems.

However, because of the large initial investment for district energy system, the long-term uncertainties in socio-economy, urban planning, technology innovation, changes in energy market and policies still obstruct the popularization of district energy system. Particularly, the promotion of Net and Nearly Zero-Energy Buildings may substantially reduce the energy demand density which can greatly shake the foundation of introducing district energy system (Kylili and Fokaides, 2015; Reiter and Marique, 2012). Therefore, how much and how fast the energy demand can be reduced would be a critical issue in the technical assessment of district energy systems. Long-term demand-side management, which integrates urban design and energy planning would be indispensable in technical assessment of a city's energy planning strategy, as imaged in the Figure 2-5.

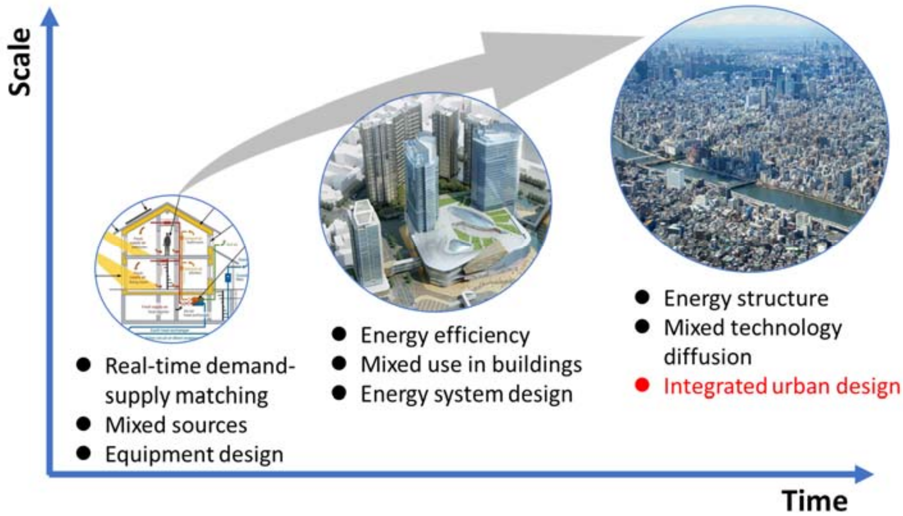


Figure 2-5 Long-term demand-side management as a key content for urban energy transition

2.3.2 Urban and Industrial Symbiosis

As introduced in Section 1.1.2, the emerging concept and practice of "Industrial Symbiosis" and "Urban Symbiosis" have been gradually recognized as a mainstream approach in the term of circular economy which aims to maximize the resources conservation and emission reductions. Essentially, energy issue is not emphasized in industrial symbiosis since utilizing waste heat has been a common issue in factories without complicated design in heat recovery and supply system. However, in the scope of urban symbiosis, sectors including industrial parks, urban area, agriculture and forestry form a wide-scale symbiosis society where the municipal wastes are recycled as fuels in power generation, high-temperature heat extracted from power plant is used in industrial process, and lower-temperature waste heat is recovered for cascade use in district heating for urban area and facility agriculture (Fujii et al., 2016; Geng et al., 2016; Ohnishi et al., 2016a). Urban symbiosis provides a perspective from resource conservation and circular economy on designing district energy system which involves multi energy sources and users.

Using waste heat in district heating is already a common method for resource saving in the world. The most famous practice of industrial symbiosis, located in Kalundborg, Denmark, established a pipeline network to introduce waste heat from industrial park as heat supply to nearby urban area (Domenech and Davies, 2011; Jacobsen, 2006), meanwhile another well-known case, located in Ulsan Eco-Industrial Park of Korea, conducted a set of waste heat exchange pipeline between incineration facilities and various type of industries (Park et al., 2016; Park and Park, 2014). However, waste heat recovery and exchange in these cases is still a part of urban symbiosis, that further consideration regarding land use planning, facility location, combination with waste recycle technology, hierarchical system design for cascade heat use are necessary (Pan et al., 2015; Persson and Munster, 2016). As a trial, this study aims to extend the application of urban and industrial symbiosis concept into a broad district energy synergy between various sectors and provide a manual for designing and evaluating the performance of symbiotic energy system considering possible land use changes.

2.4 Conclusions and positioning of this research

This chapter conducted a comprehensive literature review regarding the estimation of building stock and energy demand distribution based on urban simulation models and optimization method in designing district energy systems. In short-term operation of a district energy system, the previous studies and current mainstream software have been well developed in dealing with real-time and daily variation in demand side. However, still there are several research gaps can be found from the literature review.

- Accumulated GIS dataset of building stock distribution in past decades have not been sufficiently used in urban management. 4d-GIS can be a simple and direct approach to track the changes of building stock distribution in the past and estimate the future changes.
- Energy planning are still not closely integrated with urban planning, where urban land use

simulation is not internalized into optimization model for district energy system.

- Few studies of district energy system focus on low-energy-density cities, where the endowment of renewables and waste heat is substantial.
- The concept of Urban and Industrial Symbiosis has not widely applied in designing district energy system and city-wide urban planning.

In the long term, not only technology innovations but also socio-economy, spatial planning, energy market and policies will impact on the efficiency and proliferation of district energy systems. Accordingly, for successfully transiting the conventional fossil-fuel-based centralized energy system toward a renewables-based distributed energy system, integrated energy planning considering long-term strategic urban renewal at city/region scale would be an indispensable issue in cross-sector urban sustainable management. With the aspect of long-term energy demand side management, this study aims at developing an urban simulation model based on 4d-GIS database for tracking the future changes in building distribution, then evaluate their impacts on promoting district energy system considering possible urban renewal strategies. Thereof, this study would further extend the application of 4d-GIS toward comprehensive urban simulation, as well as provide a novel method and practice of integrating energy system design with urban planning for evidence-based policy making.

3. Analysis framework and model development

3.1 Analytic framework

To investigate the best way of a city to transit towards low-carbon sustainable society through strategic urban renewal which has been a research gap mentioned in Chapter 2, this study aims at integrating urban renewal simulation and energy planning to evaluate the possible impacts from existing or proposed planning and policies on local socio-economy and environment. Accordingly, expected model framework should at least base on the following 3 principles:

a) The model framework should include the considerations on future variations of main macro-level factors, such as regional population and its structure, industrial development, technology innovation of related energy supply and utilization, and market changes in price of energy use, energy resource, labor force, infrastructure costs, and so on.

b) A couple of parallel sub-models should be designed for each sector (urban, industries, forestry and agriculture) to investigate the future changes of energy demand side and supply side, which are flexible and realistic enough to reflect the possible facts, planning and policy implementation in the future.

c) An integrated technical model should be established for designing appropriate urban energy systems and evaluating their impacts to local socio-economy and environment, considering both competition and combination between various technologies according to local energy demand characters.

Under the 3 principles mentioned above, the overall model framework in this study is designed as shown in the Figure 3-1.

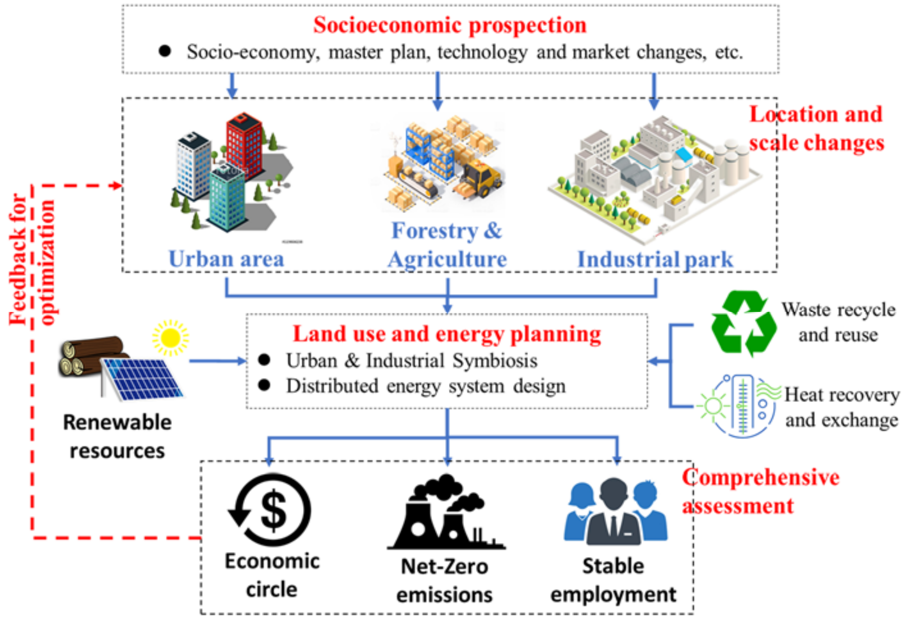


Figure 3-1 Overall model framework design in this study

Firstly, this study tries to collect all the information on future changes of important macro-level factors including socio-economic indicators, master plan, technology development and market changes, and downscale these possible changes into medium-level sectoral planning of urban area, industrial parks, forestry and agriculture. Location and scale of buildings are two main indicators which are directly relating to energy demand and waste heat potential. Secondly, learning from the estimated location and scale changes of building and factories in the future, heat atlas including urban heat demand and waste heat potential are updated and input into an integrated energy planning model, which is specified to assess the feasibility and impacts of introducing symbiotic distributed energy systems. This part mainly focuses on maximum usage of local waste heat and renewables, but not excludes using local fossil energy resources if its economy is confirmed. Finally, a comprehensive assessment model is established for evaluating the possible economic costs and benefits, CO_2 emission reductions, and job creations from the energy projects. Such assessment results will be feedbacks to the previous urban renewal and energy planning process, so as to verify the purposed policy packages and investigate a better cross-sectoral combination of policies.

3.2 Model development

3.2.1 Research scope

Urban system is an extremely complex, interactive and dynamic system, which interlinks various sectors and continuously evolves at any scale and any time. This study is not to establish a total systemic dynamic urban simulation system including all the sectors, but aim at providing a specific perspective of managing long-term demand through purposed strategic urban renewal so as to optimize the overall urban energy planning. Thus, this study set the scope of research based on the following perspective:

(1) Research objective and requirement on model development. This study mainly focuses on bridging the urban planning with energy system design for building energy consumption, thus tentatively transportation sector is out of scope. However, transportation model will be required if considering transportation accessibility in simulating urban migration behavior, or joint energy management as a kind of energy carrier for building energy consumption. This could be another research topic connecting to this study.

(2) Data availability from limited scope of stakeholders. This study requires detailed database of past building distribution as well as parameters of optional technologies. However, only few cities can support detailed series GIS data of building distribution in decades, thus the scope of modelling currently has to be limited in city scale. Therefore, only inner-city migration can be taken into consideration. Furthermore, because most of the data on energy supply technologies are collected from stakeholders in research project, the scope of optional technologies is also limited. This lacked information will not affect the model development and can be further considered in the next stage of research.

In summary, this study at firstly limits the research boundary described as following:

Table 3-1 Research scope

Item	Included	Not included
Energy consumption	Energy in use for building operation	Transportation and embodied energy
Migration	Inner-city migration	Inter-city migration
Urban renewal	Land use intensity, building relocation and scale change, building envelop and material use, and energy use equipment in building	Climate change, behavior change and technology preference of residents
System optimization	Decade-level long-term energy demand and supply management,	Hourly demand variation and supply matching with a high time resolution

	annual energy demand and supply considering their seasonal variation are adopted	optimization model for equipment selection and operation scheduling.
Optional technologies	Large boiler, cogeneration in district heating, heat pump and boiler for individual heating, etc.	Fuel cells and heat pump for combined heating and cooling.

- The energy consumption changes relating to compact city planning accounted in this study is only the energy in use for building operation, which excludes the energy consumption for transportation and embodied energy in buildings' life cycle. The same is true for the emission accounting. Furthermore, cost and benefit analysis in this study also only considers direct accounting of initial investment, operation & maintenance cost, and sales revenue of an energy system.
- Population and its structure are considered as overall variables at city level, while complicated population movement corresponding to transportation accessibility and land price is simplified. In fact, the implementation of compact city planning in this study is assumed to be moderate and gradual, of which the main purpose is to maintain a certain population density and land price in planned compact living area.
- The contents of urban renewal in this study include land use intensity, building relocation and scale change, building envelop and material use, and energy use equipment in building. The other factors influencing energy demand, such as climate change, behavior change and technology preference of residents, are excluded.
- Strictly speaking, design of an energy system should consider hourly demand variation and supply matching with a high time resolution optimization model for equipment selection and operation scheduling. Because this study focuses on decade-level long-term energy demand and supply management, annual energy demand and supply considering their seasonal variation are adopted as the main indicators for energy system design.
- Optional energy technologies in this study include the mainstream, e.g., district heating, combined heat and power generation (CHP), heat pump, boiler and recent individual heating equipment, while energy sources mainly include fossil fuels, industrial waste heat, solar energy and grid electricity.

3.2.2 Material and energy consumption in building stocks

3.2.2.1 Material use in building stocks

Material use in buildings is a basic and the most important indicator for evaluating resource and energy demand of a city from stock management perspective. Part of a city's energy input is used not only during producing building materials and construction process, but also during building demolition, material recycling and final waste disposal. To realize a life-cycle carbon minus (LCCM) building, material input and lifespan performance is indispensable in the final evaluation system. Although strictly speaking each building has different material input intensity due to its unique structure and design, there are some official statistical datasets published in Japan and are available in estimating the weight of buildings. Because floor area is the core indicator in urban simulation conducted in this study, the weight of material use in buildings is generally calculated as the Equation 3-1:

$$W_{i,j} = \sum_k FA_{i,j} \cdot w_{j,k} \cdot \lambda_k^w \tag{3-1}$$

where $W_{i,j}$ is the weight of building *i* due to its structure j, while $FA_{i,j}$ is its total floor area which is multiplied with material use intensity $w_{j,k}$ (k is the type of material). Density coefficient of material type k (written as λ_k) is used for unifying the unit of different type material into unit ton. The units of material use due to building structure are summarized in the Table 3-2.

Table 3-2 Unit of material use due to building structure (per 10 m^2 floor area)

Type of material	Unit	Wooden	Steel-framed reinforced concrete	Reinforce d concrete	Steel structure	Wooden (CLT)*
Cement	**t**	0.94	2.38	3.1	1.64	0.94
Ready-mixed concrete	**m3**	2.24	6.88	8.82	4.24	2.24
Aggregate/Stone	**m3**	4.67	10.74	11.37	7.64	4.67
Timber	**m3**	1.96	0.12	0.3	0.14	4
Steel	**t**	0.16	1.81	1.36	1.53	0.16

Units are extracted from the Annual Field Survey on Construction Material and Manpower Requirement (MLIT, 2015).

*Units for wooden buildings using Cross-Laminated Timber (CLT) are estimation value according to the reference.

Additionally, λ_k is referred to the specific weight summarized in the Table 3-3 according to physics and various reports from material production companies, so that the unit can be unified into ton:

Table 3-3 Specific weight of materials

Type of material	Ordinary Portland cement (t/m^3)	Ready-mixed concrete (t/m^3)	Aggregate/Stone (t/m^3)	Timber (t/m^3)	Timber (CLT) (t/m^3)
Specific weight	3.15	2.3	2.6	0.6	0.5

3.2.2.2 Energy demand in building stocks

Most of energy consumption in buildings is relating to building operation. The most accurate method is to monitor the real-time energy consumption in buildings and summarize one year's consumption. However, due to limited samples of monitoring points, this is still impossible for estimating the energy demand distribution in a city. This study adopts the mainstream method of estimating energy demand in operating buildings by unit energy demand per floor area. Generally, the formula is defined as the following Equation 3-2:

$$Q_{i,j}^{d} = \sum_{k}(FA_{i,j} - FA'_{i,j}) \cdot u_{j,k} \cdot \lambda_{k}^{d} \tag{3-2}$$

where $Q_{i,j}^{d}$ is the annual energy demand of building *i* of building type *j*, while $FA_{i,j}$ is its total floor area and $FA'_{i,j}$ is unused floor area in the building. $u_{j,k}$ is the average energy demand per floor area due to building type *j* for purpose *k*. In addition, λ_{k}^{d} is the regional coefficient to adjust average energy demand with regional climate. The unit energy demand in building operation by purposes herein is summarized in the Table 3-4.

Table 3-4 Unit energy demand in building operation by purposes

Type	Unit	Electricity	Cooling	Heating	Hot water
Residential house*	MJ/m^2	75.6	33.5	83.9	125.6
Office*	MJ/m^2	561.6	293.0	129.6	9.4
Shop*	MJ/m^2	813.6	523.0	146.5	96.1
Hotel*	MJ/m^2	720.0	418.7	334.8	334.8
Hospital*	MJ/m^2	612.0	334.8	309.6	334.8
Plant factory**	MJ/m^2	30.1	0	555.0	0

* National average value estimated by JIE (2008); ** Survey value of a local typical plant factory (Togawa et al., 2014).

Furthermore, the regional coefficient for adjusting unit energy demand in building operation is shown in the Table 3-5. Currently, only the coefficient for space cooling and space heating are available.

Table 3-5 Regional coefficient of energy consumption in building operation

<table>
<tr><th>Region</th><th>Space cooling</th><th>Space heating</th></tr>
<tr><td>Hokkaido</td><td>0.5</td><td>2.4</td></tr>
<tr><td>Tohoku</td><td>0.7</td><td rowspan="2">1.4</td></tr>
<tr><td>Hokuriku</td><td>0.9</td></tr>
<tr><td>Kanto</td><td>1</td><td>1</td></tr>
<tr><td>Tokai</td><td rowspan="4">1.1</td><td rowspan="4">0.9</td></tr>
<tr><td>Kinki</td></tr>
<tr><td>Chugoku</td></tr>
<tr><td>Shikoku</td></tr>
<tr><td>Kyushu</td><td>1.2</td><td>0.7</td></tr>
<tr><td>Okinawa</td><td>1.5</td><td>0.07</td></tr>
</table>

In fact, these units can be further refined considering more detailed building attributes and future changes, such as the difference between detached house and collective house and the difference caused by household size. According to the reference, the changes in unit annual energy demand of one household are summarized in the Table 3-6.

Table 3-6 Unit annual energy demand by living form and household size

Region	Unit annual energy demand (GJ/household)	Household size (person)					
		1	2	3	4	5	6
Tohoku	Detached house	50	79	91	99	109	122
	Collective house	17	30	38	42	46	47

3.2.3 Energy use and waste heat potential in industries

3.2.3.1 Energy use in industries

The procedures for estimating heat demand and waste heat supply are as follows. Firstly, $Y_{i,t}$, defined as the shipment value of industry *i* in year *t* is estimated as below:

$$Y_{i,t} = S_{i,t} \cdot y_{i,t} \cdot \lambda \quad (3\text{-}4)$$

where $S_{i,t}$ is the area of industry i in year t, $y_{i,t}$ is the unit shipment value per area of industry i in year t, and λ is a parameter for adjusting with local statistics. For example, compared to the actual shipment value provided by regional statistics, λ can be set at 0.2 in Soma Region of Fukushima Prefecture.

Then, assuming that annual heat demand and employment are proportional to annual shipment value, heat demand of industry i in year t, written as $Q_{i,t}$, and the number of employees $N_{i,t}$ are defined by multiplying shipment value with units as follows:

$$Q_{i,t} = Y_{i,t} \cdot q_{i,t} \quad (3\text{-}5)$$

$$N_{i,t} = Y_{i,t} \cdot n_{i,t} \quad (3\text{-}6)$$

where $q_{i,t}$ is the estimated unit heat demand of industry i in year t, and $n_{i,t}$ is the estimated unit employment of industry i in year t. Here, the national average value of $q_{i,t}$ and $n_{i,t}$ are calculated referring to the national census (METI, 2009-2014). Because the industries usually have comprehensive usage including direct heat input and indirect heat generated during fuel combustion or electricity consumption with various purposes, simply the heat demand defined in this study is only the direct heat consumption known from the census, excluding the part of heat use for power generation and heat sales to the others.

However, the real difficulty is to estimate the changes of units which are determined by technology innovation and diffusion. As a trial, we apply a simple regression analysis to track the changes of units in the past years for speculating the tendency in the future. Hypothesis is carried out that the units (land use, heat demand, and employees) are proportional to the shipment value of industries (exclude the economy of scale) and follow a converging trend in the future. Accordingly, logarithmic approximation is adopted like following the formula:

$$u_t = \alpha \cdot ln(t - t_0) + \beta \quad (3\text{-}8)$$

where u_t is the estimated unit in year t, t_0 is the initial year of dataset, and α, β are parameters. The results of unit heat consumption, land use, and employees are summarized in the **Figure 3-2(a)**, **Figure 3-2(b)**, and **Figure 3-2(c)**, and the parameters are represented in the **Table 3-7**. Apparently, the conversional industries such as chemical reveal a decreasing heat demand intensity, while new ones such as manufacture of information and communications equipment as well as food and beverage industries reveal an increasing heat demand intensity. Land use and employment per shipment value reveal stable in the future.

Table 3-7 Parameter list of regression analysis on units.

Industry type	Unit heat demand per shipment value (GJ/million JPY)		Unit land use per shipment value (m^2/million JPY)		Unit employment per shipment value (person/billion JPY)	
Parameter	α	β	α	β	α	β
Food	0.7	2	0.11	4.71	0.5	41.2
Beverages	0.6	2.1	0.04	3.42	-0.08	7.3
Chemical	-0.6	7.1	0.13	6.25	-0.1	12.5
Ceramic	1.3	2.2	-0.1	17.78	0.2	29.7
Non-ferrous	0.2	1.8	0.002	6.9	-0.4	15.2
Fabricated metal	0.2	0.2	0.27	8.13	0.5	35.5
Electric equipment	0.04	0.1	0.03	3.79	0.1	28.2
Info. equipment	0.2	-0.06	0.33	1.3	1.5	15.6
Electronic device	0.2	0.3	0.63	2.92	1.7	25
Transport equipment	0.03	0.07	0.07	3.2	-0.06	16.4

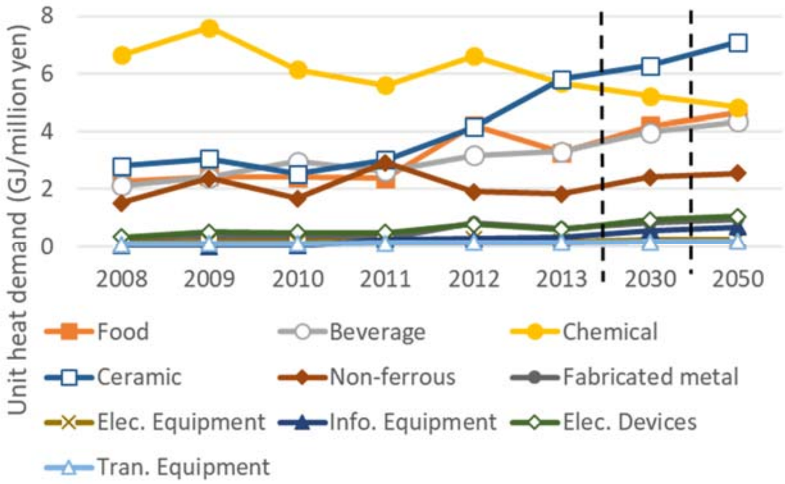


Figure 3-2(a) Changes of heat demand per shipment value.

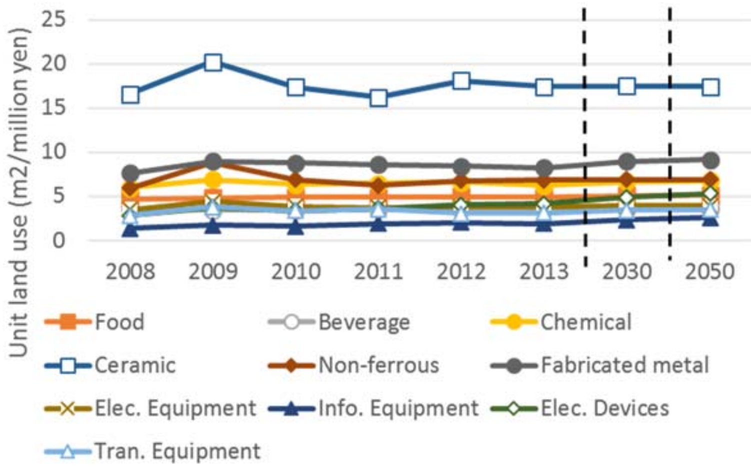


Figure 3-2(b) Changes of land use per shipment value.

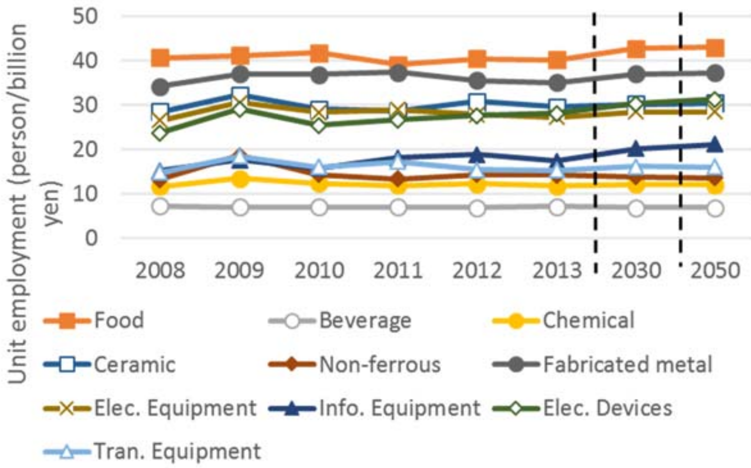


Figure 3-2(c) Changes of employment per shipment value.

Notably, for setting scenarios for environment-oriented policy and employ-oriented policy in Chapter 4, we compare the intensity of heat consumption and employment of different industries by 2050, and find out a trade-off between heat demand density and employment intensity in industries, that high heat demand industries like beverage and chemical have less employment while the other ones like manufacture of information and electric equipment have more employment but less heat demand (**Figure 3-3**).

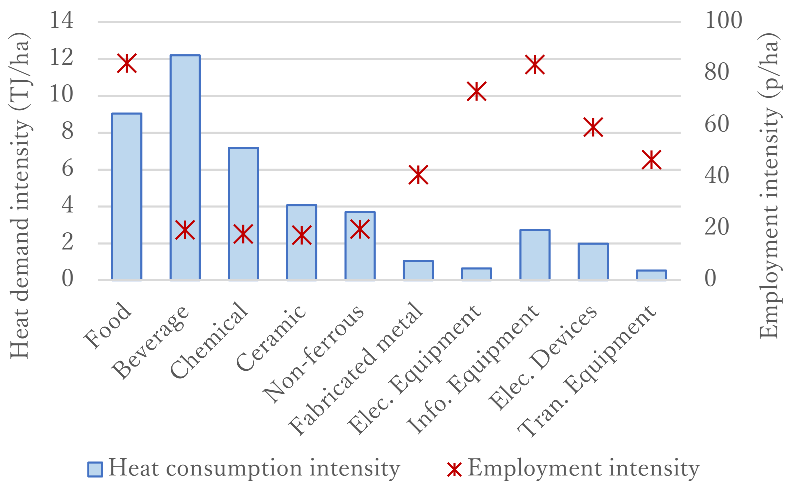


Figure 3-3 Comparison of heat consumption and employment intensity (per area) by 2050.

3.2.3.2 Waste heat potential in industries

According to a previous general survey on waste heat generation in current industries (JES, 2011), waste heat potential can be calculated from the total energy consumption. The proportion of waste heat potential from total energy consumption is varied by industrial types. Using the total energy consumption data from the census (METI, 2009-2014), we apply the following formula to estimate waste heat potential:

$$W_i = E_i \cdot \omega_i \cdot \eta \tag{3-7}$$

where W_i is the waste heat potential of industry i, E_i is the total energy consumption of industry i, ω_i is the specific waste heat generation ratio of industry i, and η is heat recovery rate of heat exchanger. Here, $E_i = Q_i/\delta_i$, where the proportion of heat consumption in total energy consumption δ_i is also calculated referring to the census (METI, 2009-2014). The value of δ_i is estimated at 13.2% for chemical industries, 6.71% for ceramic, and 17.9% for non-ferrous metal manufactures, respectively.

The survey (JES, 2011) supports parameters for 6 main industries which have high potential of waste heat, including pulp and paper, chemical, petrochemical, ceramic, iron-steel, and non-ferrous metal manufactures. Notably, chemical factories can probably support steam while the others cannot and have to recover heat from exhaust gas. Thus, η is set at 100% for chemical and 17% for the others. Additionally, the value of ω_i is estimated at 19.6% (steam) for chemical, 26.8% (exhaust gas, >200℃) for ceramic, and 17.7% (exhaust gas, >200℃) for non-ferrous metal manufactures. Note that a precise survey on industrial process in each factory should be conducted for accurate estimation of waste heat generation.

3.2.4 4d-GIS method and dynamic urban renewal simulation

3.2.4.1 Estimation of actual building lifespan based on 4d-GIS

Usually, it is said that stronger building structure leads to longer lifespan of the buildings. However, because of the impacts from migration, land use change, urban renewal plan, disaster and other unexpectable factors, buildings cannot totally fit their designed lifespan that are demolished earlier or kept in use later. 4d-GIS database would help us in identifying the actual lifespan of any categorized building stocks.

Preparation of the 4d-GIS database and estimation of the buildings' lifespan are the basic components of the analytic framework in this study. Here the concept "lifespan" means the actual value observed in previous building distribution changes. As mentioned before, a completed building distribution GIS database of Kitakyushu City has been established, but it shows a difficulty in case of Fukushima Prefecture because of data lack. Therefore, a hybrid method is developed to combine the current building distribution GIS database with statistical data of building age distribution changes from the city yearbooks. According to the changes of observed number of buildings in different age, the buildings' lifespan can be assumed to follow a certain survival curve, e.g. Weibull distribution, of which the parameters can be calibrated by cumulative hazard function. The detailed calculation process can be found in Reference (Komatsu, 1992). For instance, a Weibull distribution equation of the building survival rate can be written as:

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t}{\theta}\right)^{m}} \tag{3-10}$$

where t is the building age and m and θ are parameters.

3.2.4.2 Dynamic urban renewal simulation

After the estimation of actual building lifespan, related information would be embedded into dynamic urban renewal simulation. In fact, the most important role of estimating building lifespan is to determine the pace of urban renewal and identify the characteristics at neighborhood design.

a) Simulation of strategic urban renewal

As a first stage, this study focuses on integrating future land use scenarios into energy planning. Accordingly, both land use models and energy planning models should be taken into consideration, where land use changes should drive energy planning changes (a causal relationship).

As demonstrated in Figure 3-5, this study develops a land use scenario model based on urban renewal strategies. The strategies are established according to the master plan of municipalities; however, the progression speed and anticipated effects of the strategies correspond to realities such as population changes and building stock lifespan. Starting from the initial distribution of the building floor area, building survival rate is estimated by using the 4d-GIS analysis to determine the extent of building retrofitting, which is reduced by the ratio of depopulation. The spatially-adapted cohort analysis is applied for population and building simulation. In this part of the study, the aim was to simulate the future distribution of building stock and input the results into a technical assessment for energy planning.

Next, a technical assessment of energy planning is conducted where the feasible area for introducing district energy system is adopted as the key indicator for determining the supply quantity of district heating systems. As described in Section 3.2.6 (cost-benefit analysis), the feasibility of introducing district energy system relies on piping cost, equipment installation cost, labor salary, operation and maintenance cost, heat loss, duality (system and pipeline's lifespan), fuel purchase cost, and the price of heat and electricity sales. Within a unit supply area and assuming energy price does not change, plot ratio of the area will be the key factor which determines both energy supply quantity and investment intensity of equipment and infrastructure. Based on a simple relationship, i.e., that compact land use will lead to a higher plot ratio and increase heat demand intensity, the minimum plot ratio required for the introduction of district heating systems are estimated and the service area is identified from the distribution of building floor area. Accordingly, the district heating performance, such as CO_2 emissions reduction, economic costs and benefits, and employment, can be evaluated.

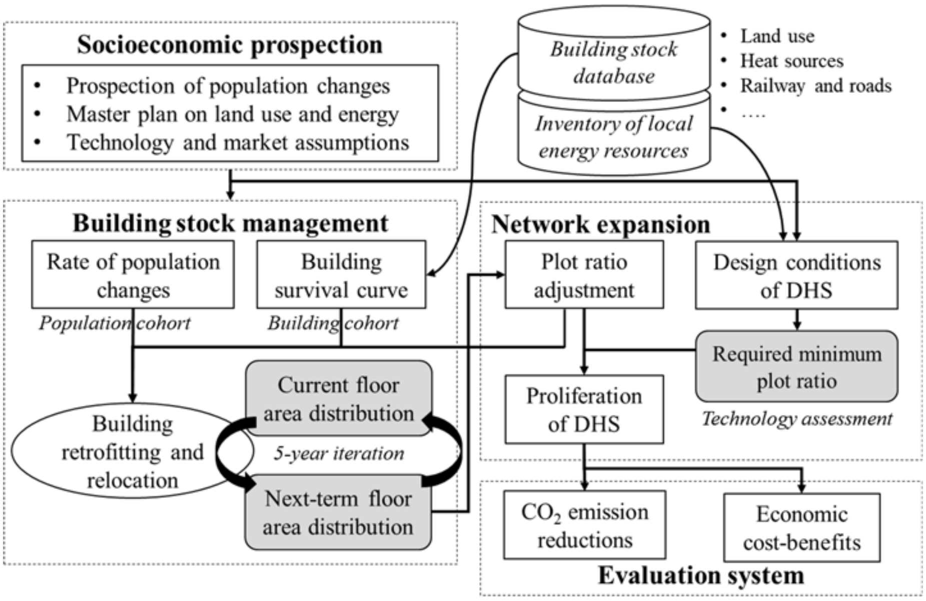


Figure 3-5 Framework of integrated energy planning considering urban renewal

In summary, the main assumptions in this study are as follows:

(1) Migration mechanism. When a building reaches the end of its lifespan, the owners (if they are still alive) can either rebuild the building in the same location or at another location, otherwise the building will be demolished immediately. To simplify the calculation, the inter-regional and the inter-municipal migration are not considered in this study.

(2) Location policy. Only two location activities of the building owners are allowed: ① to follow compact city plan (concentrate nearby regional rail stations) or ② to locate in the same place. To simplify the model, this study also assumes that the proportions of these two actions are fixed at a certain rate in the future.

(3) Duty for connection. If an area is feasible and reserved to introduce district heating network, all the buildings will be connected to the network and served by district heating. In addition, district heating service is assumed to be profit, meaning that annualized costs should be no more than annual profit.

(4) Spatial resolution. The structure, height, and scale of each building will lead to different heat demand densities which makes the model too complicated, thus this study roughly aggregates the floor area of all types of building stock into 100-meter meshes which meets the scale of existing district heating projects in Japan.

(5) Solution to unoccupied houses. When depopulation goes faster than building abandonment,

unoccupied houses appear and will not generate energy consumption. This study assumes that the unoccupied houses occurred in a period will be immediately filled by immigrants, which are in proportion to the quantity of building retrofitting in other areas (such as the effect of compensation for migrating to reuse unoccupied houses).

b) Simulation of land use changes in industrial park:

As the first stage, a concise framework composed by several parts is developed as shown in Figure 3-6. The analysis procedures consist of four steps:

Step 1: Review of regional plans. Being the basis of scenarios setting, the information of future socio-economic prospection and technology tendency are collected for reference.

Step 2: Heat demand analysis. Due to the data availability, national average value of energy consumption, land use, and employment per shipment value, and their tendency are estimated from the Census of Manufacturers and the Survey on Energy Consumption (METI, 2009-2014). According to current site area of factories in case area, heat demand and its tendency are estimated as a baseline;

Step 3: Heat exchange design and evaluation. Based on the design of heat exchange, waste heat potential of target industries is calculated from their annual fuel consumption, and the economic cost-benefits and CO_2 emission reduction are evaluated by heat demand-supply matching;

Step 4: Scenarios setting. According to regional industrial location policies and the prospection of future economic growth, scenarios are set to reflect the location changes under different visions.

The information of industrial location and related geographic database are from the website of local government and the National Land Numerical Information download service. The method for classifying industries is on the basis of Japan Standard Industrial Classification defined by the Ministry of Internal Affairs and Communications in 2013.

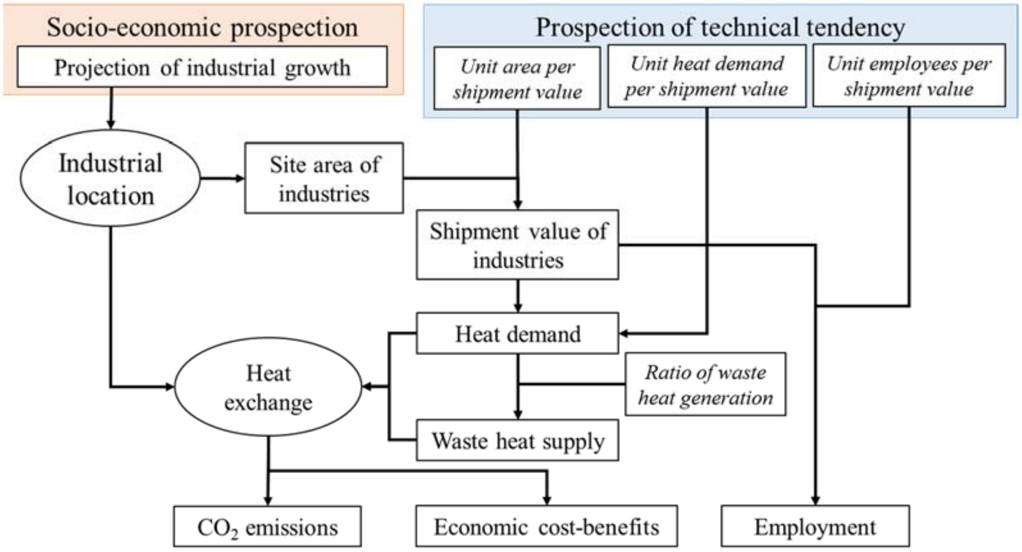


Figure 3-6 Comparison of heat consumption and employment intensity (per area) by 2050.

3.2.4.3 Mechanism of migration and building relocation

This section will provide more details regarding how to determine the quantity of reallocated migration and building floor area mentioned in the section above. Figure 3-7 summarizes the calculation flow of next-term floor area distribution based on the mechanism of compact city planning. Firstly, rebuilding activity only happens when demolition rate is over depopulation rate in a mesh area, otherwise unoccupied floor area will appear. The unoccupied part will be immediately filled in by the migrants from other meshes proportionally, otherwise the oldest houses in the region will be demolished equally to confirm the market clearing. Then, if vacancy does not happen in the mesh, the floor area which needs to be supplemented will be estimated after deducting the part for depopulation and vacancy in other meshes. If the mesh is identified for concentrated living according to the city's master plan, abandoned floor area will all be immediately rebuilt in the same location, otherwise part of them will be relocated in other meshes which are identified for concentrated living. Whereupon, floor area will be added for the latter to reach required plot ratio for introducing district heating network. The method for determining the minimum plot ratio is described later.

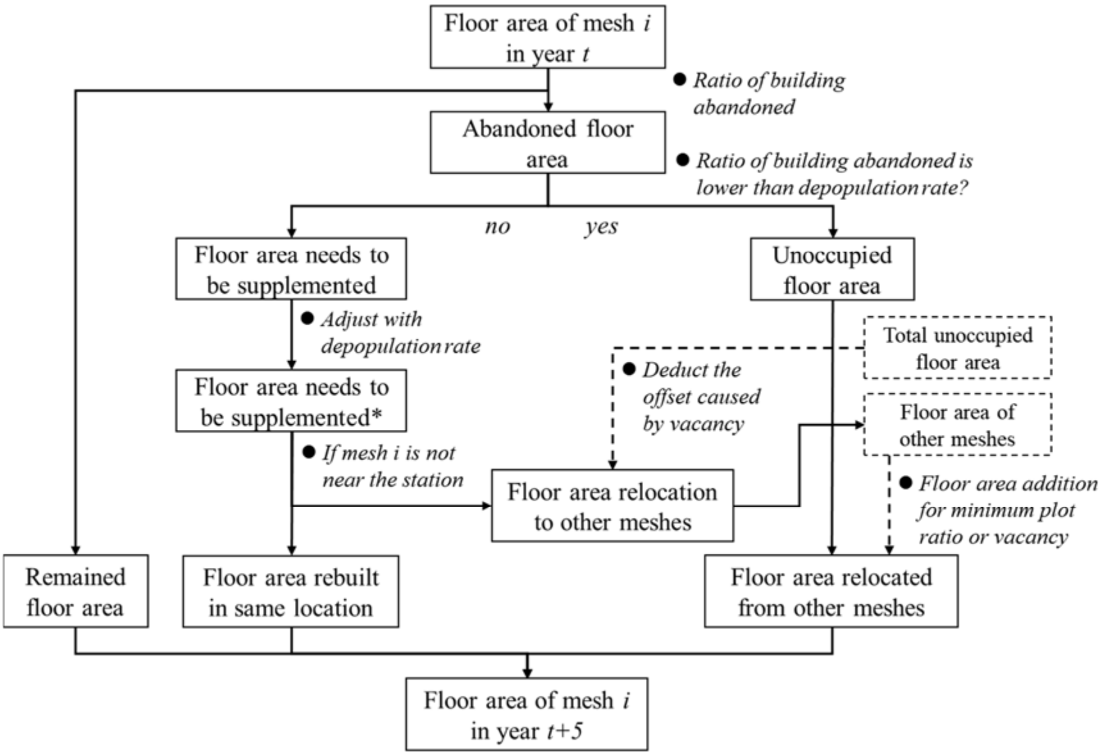


Figure 3-7 Calculation flow of next-term floor area distribution

Accordingly, the rule for allocating the next-term building floor area is simply defined as:

$$a_{i,t+5} = \sum_{y} a_{i,t,y} - (1-\mu) \cdot \sum\nolimits_{y} \left(a_{i,t,y} \cdot \sigma_{y,t}\right) - \mu \cdot \frac{\sum_{y}\left(a_{i,t,y} \cdot \sigma_{y,t}\right)}{\sum_{i,y}\left(a_{i,t,y} \cdot \sigma_{y,t}\right)} \left(\sum_{i,y} a_{i,t,y} \cdot \lambda \right)$$

$$+\theta \cdot (\bar{\rho} - \rho_i) \cdot A_i, \tag{3-10}$$

where $a_{i,t,y}$ is the floor area at age y of mesh i in the year t, σ_y is the 5-year demolition rate of the floor area at age y, λ is the overall rate of depopulation, ρ_i is the plot ratio of mesh i, $\bar{\rho}$ is the target plot ratio, μ is the overall retaining rate of the floor area, and A_i is the area of mesh i. As it is assumed that the proportion of relocated floor area remains the same, $\mu = 54\%$ if mesh i is in the suburbs and $\mu = 100\%$ if mesh i is in the regional station districts. Furthermore, $\theta = 0$ if the mesh is not required to reach the target plot ratio and $\theta = 1$ if the mesh is required to reach the target plot ratio. For example, the depopulation rate in Fukushima during each 5-year period from 2015 to 2040 are 2.04%, 4.98%, 5.38%, 5.80% and 6.39%, respectively (IPSS, 2018).

3.2.5 Energy supply and design of district energy system

3.2.5.1 Principles in designing energy systems

Generally, during designing an energy system, the characteristics in demand-side and supply-side, the optimal technology combination for energy conversion and transmission, as well as appropriate operation schedule for matching the demand and supply variation should be comprehensively considered. First of all, the principles for optimal design of district energy system in this study are summarized as below.

(1) Cascading use of heat energy

As shown in the Figure 3-8, heat energy can be used in different way due to the quality of energy, which is usually defined by the temperature or the pressure of medium such as hot/cool water or steam. The quality can be also measured by the concept of exergy, which measures the work capacity of an energy material. Fossil fuels and Hydrogen have a higher quality of energy, because the combustion can generate steam with very high temperature and pressure that is suitable for large-scale power generation. However, the demand side may not require high temperature or pressure steam, where a loss of energy will happen if we directly input high-quality energy into the processing. Therefore, a general approach is to cascade use the energy, e.g., firstly combusting the fossil fuel for power generation but extracting a part of steam with relatively lower temperature and pressure for industrial use, then recovering the further lower-quality waste heat as hot water or steam for utilization in district heating of urban areas. Mixed combustion of high-quality fossil fuel with lower-quality municipal wastes for power generation and industrial processing also helps in matching the requirement of energy quality, where actually the municipal wastes are upgraded used for higher quality requirement. Based on this principle, it is possible to establish a specific board heat exchange network to connect various heat sources including artificial or natural resources with high or low energy quality to various energy users who require different quality of energy.

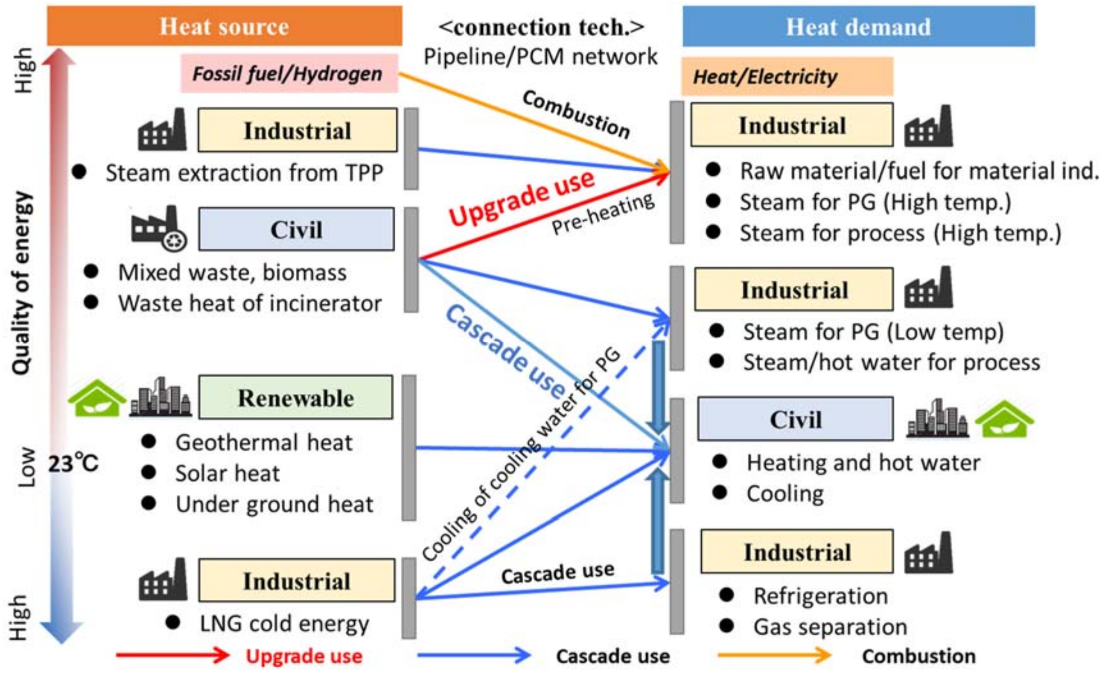


Figure 3-8 Cascade and upgrade use of heat energy

(2) Hierarchical structure of district heat distribution

Point-to-point heat transmission system can be simple in case of building a pipeline between the supplier and user. By contrast, a network of multi heat sources and users should be hierarchical due to their geographic distribution and the condition of energy quality, as shown in the Figure 3-9. Corresponding to the distance from the heat sources and concentration boundary of heat demand, the supply area is rezoned and controlled using substations. The flow rate, which relates to the rate of heat transport, is adapted in real-time to the variations in heat demand by the substations. However, the details in designing the subsystem and real-time operation optimization is tentatively omitted, since this study is mainly focusing on long-term energy plan and assessment.

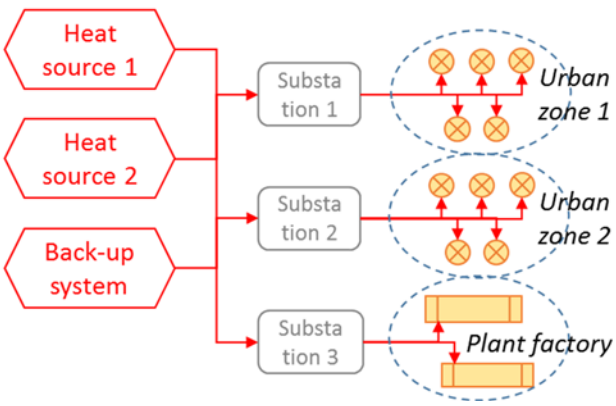


Figure 3-9 The structure of a district heating network connecting multi sources and users

(3) Technologies and energy flow in a heat exchange system

Heat use is usually based on a process of energy conversion where heat energy is in fact exchanged between source and user. The Figure 3-10 provides a theoretical structure of technology combination for a broad heat exchange network involving thermal power generation, waste incineration, industrial processing and district heating. Various technologies are available, such as boiler which directly combusts fossil fuel into high-temperature-and-pressure gas, turbine with power generator which transfers the kinetic energy of high-pressure gas into electric power. Industrial process, heat exchanger, and heat pump are also included. To well design the system structure and energy flow, it is necessary to analyze the performance and conditions of each technology and find out the possibility of forming an energy synergy.

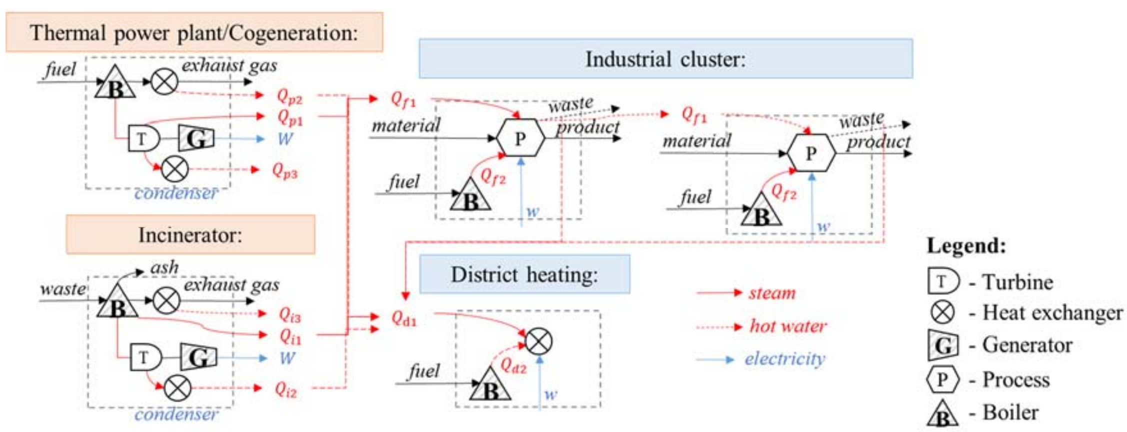


Figure 3-10 Theoretical structure of technologies in a broad heat exchange network

Based on the principles mentioned above, this study aims at reforming the conventional energy supply system (Figure 3-11(a)) into a symbiotic structure where fuel input, final waste heat and CO_2 exhaust are minimized through maximizing the waste recycling and heat recovery (Figure 3-11(b)). Notably, steam is usually used as heat exchange medium between industries while hot water is generally used for district heating network. The methods of designing the pipeline network and hydraulic calculation for feasibility study are provided in the next section.

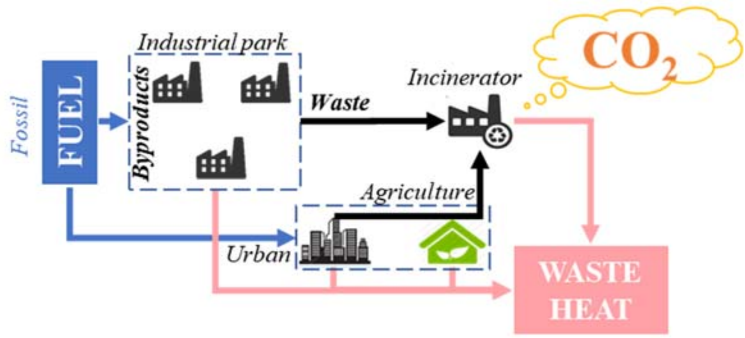


Figure 3-11(a) Conventional heating system

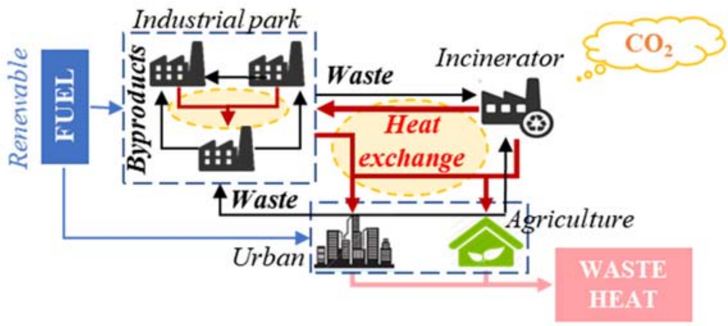


Figure 3-11(b) Symbiotic heating system

3.2.5.2 Design of pipeline network for heat transmission

Design of pipeline network involves many factors, such as pipeline allocation, material, diameter, heat insulator, input temperature and pressure. These factors together impact on the temperature and pressure decrease of heat medium due to transmission distance, what is the key indicator to evaluate physical and economic feasibility of an individual heat transmission route. This study applies two kinds of calculation methods due to the requirement on spatial resolution.

(1) Shortest route analysis

In very detailed scale, the allocation of pipeline network to each user is expected to be confirmed. Because the pipelines for district heating system are usually allocated along the roads or riverbanks in urban area, a simple method to design the pipeline system is using shortest route analysis by the network analysis tool provided in ArcGIS software. Firstly, the segment from supplier/substation to each user is drawn automatically. Then, strange places where the route can be improved are artificially checked and revised. Finally, repetitive parts between any two routes are merged into one segment. The following Figure 3-12 is a sample of using this method. Although the result is not the optimal one, but the total length of pipeline is near or a little over the optimal one that is suitable for estimating the construction and maintenance cost of pipeline systems. Note the actual length of pipeline may be shorter than estimated, because part of them can go cross the ground.

Figure 3-12 Design of pipeline network by shortest route analysis

(2) Pipeline length estimated from the plot ratio

In case of estimating the pipeline length in a mesh area, the correlation between plot ratio and pipeline length is usually applied. As discussed in the references (Nielsen and Moller, 2013; Persson and Werner, 2011), effective width is generally used to estimate the length of pipeline in an area based on the plot ratio, which is defined as

$$\varpi = \frac{A_i}{l_i} = \alpha e^{\beta(a_i/A_i)} \tag{3-11}$$

where l_i is the estimated pipeline length in mesh i, A_i is the land area of mesh i, a_i is the building floor area in mesh i, and α and β are parameters. From the manual of district heating projects in Japan (JHSBA, 2016), those projects selling heat to both residential houses and commercial buildings are screened out and $\alpha = 133.7$ and $\beta = -0.613$ are estimated by regression. These results are relatively high compared with the reference value obtained for Sweden.

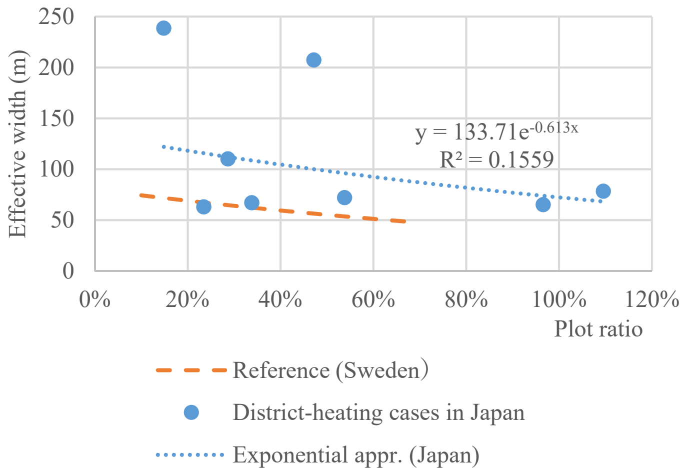


Figure 3-13 Correlation between effective width and plot ratio

In case of a broad heat exchange network, there are many possible heat exchange routes between multi suppliers and users. This study develops an integrated process to automatically search the opportunities of heat exchange combining GIS network analysis with feasibility assessment and market mechanism simulation. As shown in Figure 3-14, the model framework and assessment process mainly consists of four parts. First, according to the survey on the distribution of potential heat supply and demand, the network distance between each supplier and user is estimated by GIS network analysis and recorded into a so-called origin–destination matrix (OD Matrix). Then, for each route between a heat supplier and user, a hydraulic model for steam transport is applied to estimate the temperature drop and the pressure drop; the results are used to judge the physical status of steam or hot water. Because steam will generally condense into hot water when its pressure decreases under saturated vapor pressure, all of the routes that cannot be confirmed to supply steam are directly ignored. This step is designed to select candidate routes that are physically feasible. Then, a cost–benefit analysis is applied to these candidate routes to evaluate their cost-efficiency on CO_2 emissions reduction. Finally, a decision-making process based on a market mechanism is proposed to determine the best order of implementation and to update the changes to the heat atlas carried into the next cycle. The next sections will provide the details of hydraulic calculation and cost-benefit analysis.

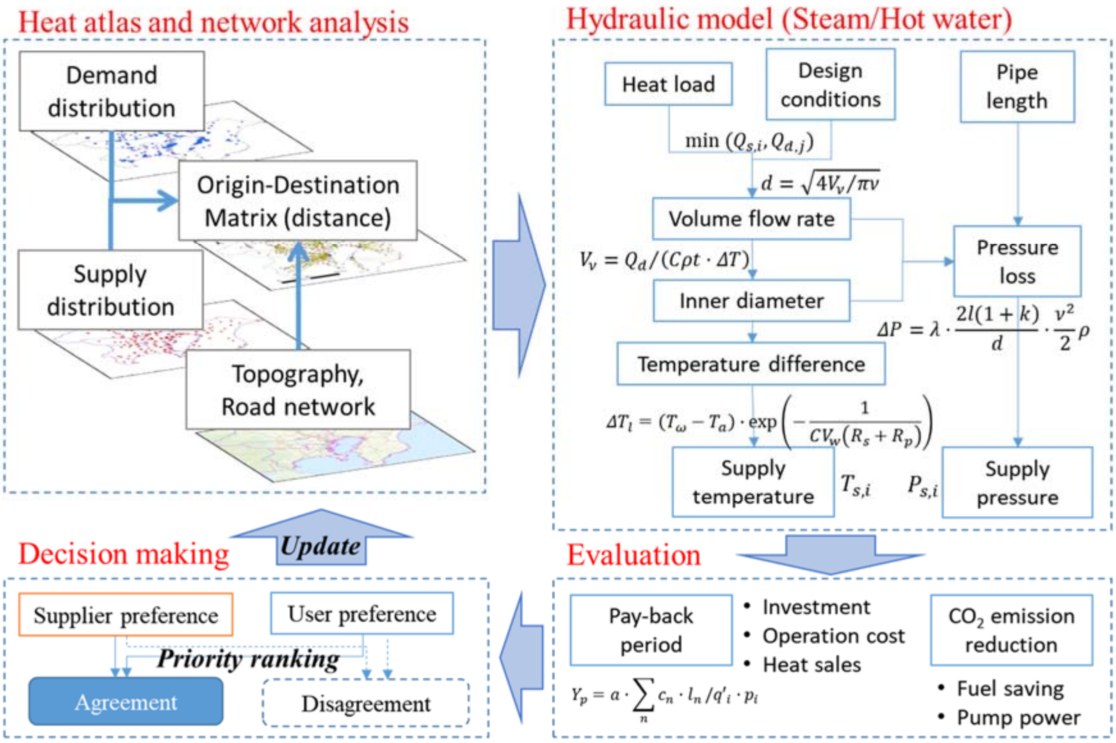


Figure 3-14 Process of designing a broad heat exchange network

3.2.5.3 Hydraulic calculation for heat transmission

This study assumes steam as the medium for high-temperature heat transmission while water as the medium for lower-temperature heat transmission. In case of hot water supply, the calculation is as follows:

a) Design conditions

Generally, hot water is chosen as the heating medium for low-temperature heat transmission, such as civil district heating. Usually, in Japan, the supply temperature of the heating medium and the temperature difference on the user side are set as 80 and 20 °C, respectively (DHCJP, 2014). Commonly, a single steel tube and glass wool are chosen as conduit and heat insulating material respectively, and the pipeline is assumed to be laid underground for protecting urban landscape. Then due to the peak season demand in winter, we calculate appropriate diameter of pipeline and return the result of required pumping power for heat transportation.

b) Pipeline diameter

On the basis of the abovementioned assumptions, the relation between the peak season heat demand Q_d of each pipeline segment, the volume flow rate V_v is written as follows

$$V_v = Q_d/(C\rho t \cdot \Delta T) \tag{3-12}$$

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 on the user side. Then inner diameter is calculated as follows:

$$d = \sqrt{4V_v/\pi v} \tag{3-13}$$

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

c) Pressure drops

Due to the friction between water and the pipeline, there is a pressure drop ΔP in heat transport that needs a certain pumping power to complement this resistance. On the basis of the Darcy–Weisbach equation, the pressure drop is calculated pipeline with length l of a pipeline segment as

$$\Delta P = \lambda \cdot \frac{2l(1+k)}{d} \cdot \frac{v^2}{2}\rho \tag{3-14}$$

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

$$\lambda = 0.0055 \cdot \left|1 + (20000\frac{\varepsilon}{d} + \frac{10^6}{Re})^{1/3}\right| \tag{3-15}$$

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

$$W' = \frac{\rho g V_v h}{\eta_P \eta_M} \tag{3-16}$$

where $h = \Delta P/\rho g$ is the pressure-head loss, g is gravitational acceleration, η_P is the efficiency of the pump, and η_M is the efficiency of the motor. According to Wei (2003), η_P and η_M is set as 0.7 and 0.9, respectively.

d) Temperature drop

The temperature drop, which leads to the heat loss, ΔT_l is an important indicator and is estimated as follows:

$$\Delta T_l = (T_\omega - T_a) \cdot \exp\left(-\frac{1}{CV_w(R_s+R_p)}\right) \tag{3-17}$$

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

e) Constraint condition

Physically, the actual heat supply quantity Q_s should be not greater than the potential of waste heat supply marked as $\widehat{Q_s}$, but is equal to the sum of the heat demand Q_d and the heat loss Q_l as follows,

$$Q_s = Q_d + Q_l,\ Q_s \le \widehat{Q_s}. \tag{3-18}$$

In case of steam transmission, there are some differences in hydraulic calculation comparing to the case of hot water supply, particularly in the constraint conditions.

a) Design conditions

In case of extracting steam from the incinerators, the supply side are usually assumed to extract steam at 400°C and 4 MPa, which would be directly consumed in factories (MOEJ, 2015). The operation time is also simply set as the incinerators running year-round; real-time variations are currently not taken into account. Meanwhile, the user side is thought to only utilize the latent heat of condensation for production processes, which means a heat exchange project would be accepted if the steam conditions can be maintained until the steam is received in factories. Of course, different processes in factories would require different qualities of steam, and higher-quality steam would sell at a higher price. In this study, the factories are assumed to accept any quality of steam. Therefore, two important indicators, including the temperature drop and the pressure drop, are mainly incorporated into the calculation to judge the status change of steam. On the basis of the handbook (DHCJP, 2014), we develop the hydraulic model for steam transport as follows.

b) Pipeline diameter

The formula in case of steam supply is similar with the case of hot water supply but note that steam is a kind of gas that the parameters are different. Pipeline diameter is the key factor for estimating the unit cost of a pipeline and the status change of steam during transport. Initially, the volume flow rate V_v is calculated as

$$V_v = Q_d/(\rho_s \cdot \Delta h) \tag{3-19}$$

where Q_d is heat demand, ρ_s is the density of steam, and Δh is the latent heat of vaporization. The ρ_s can be calculated by the equation of state of an ideal gas, whereas Δh is the difference in the specific enthalpy between saturated steam and saturated water at a certain pressure and temperature. The inner diameter d is then determined as

$$d = \sqrt{4V_v/\pi v} \tag{3-20}$$

where v is the average flow rate, which is set as 20 m/s to avoid corrosion inside the pipelines. Actually, a slower flow rate may lead to a larger pipeline diameter but slow the pressure drop to let steam transport further.

c) Pressure drops

The pressure drops ΔP of steam during transport can be calculated by the Darcy–Weisbach equation. Although steam can be transported without pumping, it will stop moving if its pressure decreases to less than atmospheric pressure. Its relationship with pipeline length l is represented as

$$\Delta P = \lambda \cdot \frac{l(1+k)}{d} \cdot \frac{v^2}{2} \rho_s \tag{3-21}$$

where k is the local resistance ratio (set as 0.4) and the frictional coefficient λ is defined as

$$\lambda = 0.0055 \cdot \left| 1 + (20000 \frac{\varepsilon}{d} + \frac{10^6}{Re})^{1/3} \right| \tag{3-22}$$

where ε is the equivalent roughness of the pipe wall (set as 0.045 mm) and Re is the Reynolds number.

d) Temperature drop

In this study, we considered calcium silicate heat insulating material for heat insulation. The thickness of the insulator is set as 50 mm, and its thermal conductivity follows the equation 0.0407 + 1.28×10^{-4} T ($0 < T \leq 300$) or $0.0555 + 2.05 \times 10^{-5}T + 1.93 \times 10^{-7}T^2$ ($300 < T \leq 800$°C) (T is the temperature of steam). Then, the temperature drop ΔT_l is evaluated as below:

$$\Delta T_l = (T_\omega - T_a) \cdot \exp\left(-\frac{1}{CV_w(R_s+R_p)}\right) \tag{3-23}$$

where T_ω is the supply temperature, T_a is the temperature of the soil surface (e.g., averaging 16.3°C in Tokyo City), V_w is the weight flow rate of steam, R_s is the soil heat resistance, and R_p is the heat resistance of the pipeline. The formulas for heat resistance are omitted.

e) Constraints in steam transmission

A feasible steam supply should satisfy two conditions: the pressure should be constantly positive to keep steam moving toward the user side, and the temperature should always be higher than that of saturated steam to maintain the gas' gaseous status. In the calculation results in this study, we observed that the speed of the pressure drop is much faster than that of the temperature drop, so that the pressure drop corresponding to transport distance is the key factor to determine feasibility, whereas the temperature at the end of the pipeline is always higher than necessary.

Finally, considering that the heat demand is intimately related to the outside temperature, we have divided one year into two periods to identify the seasonal variations in demand and supply: from May to October and from November to the following April. The ratios of the heat load between the former and the latter are, respectively, 35% and 65% for civilian sector and 0% and 100% for greenhouse type plant factory (the data on the demand variation is available from JIE (2008)). Consequently, the pipeline network is designed to accommodate the peak period demand and assumed to be appropriate for the whole year.

3.2.6 Cost-benefit analysis and feasibility condition

3.2.6.1 Cost-benefit analysis

Cost-benefit analysis is one of the core sub-models in this study. The items considered in the analysis are listed as the Table 3-8. Furthermore, the key variables impacting on the items are also identified, so as to evaluate the impact from land use, energy market and technology innovations.

Table 3-8 List of the items in cost-benefit analysis and key related variables.

Economic cost:	**Key variables:**
Annualized pipeline and equipment investment cost	Plot ratio, duality in law
Annual labor payment and maintenance cost	Supply area
Cost of fuel purchase or power supply loss from turbine	Fuel price
Energy loss in transmission	Physical/Fixed value
Economic benefit:	**Key variables:**
Heat and electricity sales	Energy price
Environmental cost:	**Key variables:**
Emissions from fuel combustion	Emission factor
Emissions from pumping if purchase electricity from outside	Emission factor
Environmental benefit:	**Key variables:**
Avoided emissions from individual heating and reduced power supply	Emission factor

(1) Overall economic and environmental costs and benefits

According to the literature (Nielsen and Moeller, 2013; Persson and Werner, 2011), generally the economic costs should include heat distribution cost C_d (infrastructure construction), heat transport cost C_t (pumping power), heat production cost C_p, and management and maintenance cost C_m. The benefits include revenues from heat sales (subsidies are not considered for the moment). This study adopts a more comprehensive understanding on the socioeconomic benefits targeted toward a total reduction in fuel cost (covering production cost and heat sale revenue), and includes environmental benefits, i.e., total CO_2 emission reduction. The cost is formulated as

$$C = C_d + C_t + C_m \tag{3-24}$$

$$C_d = a \cdot \sum_n c_n \cdot l_n \text{ and} \tag{3-25}$$

$$C_t = (a \cdot c_w + p^e \cdot t) \cdot W' \tag{3-26}$$

where c_n and l_n are the average cost and length of pipe with diameter *n*, respectively. c_w is the average cost of the pumping equipment, p^e is the price of electricity, and *t* is the operation time. a is the annuity rate that is defined as

$$a = \frac{i}{1 - \left(\frac{1}{1+i}\right)^{\tau}}, \tag{3 – 27}$$

where *i* is the interest (set as 1.15%) and τ is durability in number of years (set as 20 years, as the same as operation period). It follows that the benefit of fuel cost reduction R_f and CO_2 reduction R_{CO_2} are calculated as below:

$$R_f = \sum_i q'_i \cdot p_i \tag{3-28}$$

$$R_{CO_2} = \sum_i q'_i \cdot \varepsilon_i - W' \cdot t \cdot \varepsilon_e \tag{3-29}$$

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. Management and maintenance costs are considerably flexible among companies, this study assumes that this is a fixed amount including labor, sales service, and general maintenance costs. This value is set to be 37 million JPY annually in view of results from a similar case in Hitachi Station area of Ibaraki Prefecture, which uses industrial waste heat to supply the railway station area.

Regarding the assessment of the environmental impact, this consists of the CO_2 emission from the construction of infrastructure and the electricity consumption of the water pump, from which the advantages due to reduction in emission due to fuel substitution are subtracted. Referring to Togawa et al. (2009), the CO_2 emission unit of pipeline construction is 78 kg/m by LCA and since this value is considerably small when compared to the emission arising from the pumping during its operation period of decades, this is omitted for the current calculation. However, in the future, we expect to conduct a LCA evaluation on the entire project to evaluate the actual environmental impacts. According to the report of Tohoku Electric Power Company, the emission unit of grid electricity and fuel oil consumption in 2013 are 163.61 and 67.78 t/TJ, respectively.

(2) Economic and environmental costs and benefits

Estimation of revenue loss from decreased efficiency of power generation during steam extract is based on the reference[27], in which firstly the electricity loss E_{ls} is calculated as below:

$$E_{ls} = (x(T_0) - x(T_s)) \cdot \frac{Q_s}{1-x(T_s)} \tag{3-30}$$

where Q_s is the quantity of steam extracted from the turbine, and T_0, T_s are the temperature of exhausted gas (35℃=308 K) and extracted steam (400℃=673 K), respectively. Set the temperature of steam generated in the boiler T_b at 839 K (566℃), $x(T_s)$ is defined as follows:

$$x(T_s) = 1 - \frac{T_s \cdot ln(T_b/T_s)}{T_b - T_s} \tag{3-31}$$

Thus, the revenue loss caused by extracting steam C_e could be estimated as below:

$$C_e = E_{ls} \cdot p_e \tag{3-32}$$

where p_e is the average price of electricity, approximate to 15 JPY/kWh for industrial use due to Tohoku Electric Power Company. Finally, the annual net revenue of heat exchange is calculated as the difference between the three items: ($R_f - C_p - C_e$).

(3) Detailed calculation in economic and environmental costs and benefits

The economic costs considered in this study include gas purchase cost, annualized pipeline and equipment investment, annual labor payments, and maintenance costs. The gas purchase cost for mesh i, $C_{\mathrm{g},i}$, is calculated as

$$C_{\mathrm{g},i} = p_\mathrm{g} \cdot q_{\mathrm{g},i} = p_\mathrm{g} \cdot \frac{q_{\mathrm{h},i}}{(1-\zeta) \cdot \eta \cdot \nu}, \tag{3-33}$$

where p_g is the price of natural gas, $q_{\mathrm{g},i}$ is the gas consumption in mesh i, $q_{\mathrm{h},i}$ is the heat demand in mesh i, ζ is the heat loss rate, η is the heat recovery rate for district heating, and ν is the heat value for natural gas.

The annualized pipeline investment (distribution cost) in mesh i is defined as

$$C_{\mathrm{d},i} = c_\mathrm{d} l_i a = c_\mathrm{d} \cdot \frac{A_i}{\varpi} \cdot \frac{\lambda}{1-[1/(1+\lambda)]^\tau}, \tag{3-34}$$

where $C_{\mathrm{d},i}$ is the annualized pipeline investment (distribution cost), c_d is the average pipeline installation cost, a is annuity, λ is long-term interest, and τ is the duality of a cogeneration system in law.

Similarly, the annualized equipment investment cost in mesh i ($C_{\mathrm{e},i}$) is defined as

$$C_{\mathrm{e},i} = c_\mathrm{e} \cdot P_\mathrm{e} \cdot a = c_\mathrm{e} \cdot \frac{q_{h,i} \cdot \epsilon}{(1-\zeta) \cdot \eta \cdot t} \cdot \frac{\lambda}{1-[1/(1+\lambda)]^\tau}, \tag{3-35}$$

where c_e is the purchase price of gas engine per kW, P_e is the required power output of a gas engine, ϵ is the proportion of total annual heat demand in winter (half a year, as in a previous study in Shinchi

Town), and $t = 4380$ h is the operation time over half a year.

The annual labor payment $C_{\mathrm{l},i}$ and maintenance cost $C_{\mathrm{m},i}$ are simply defined as

$$C_{\mathrm{l},i} = c_{\mathrm{l}} A_i n_{\mathrm{l}}, \tag{3-36}$$

$$C_{\mathrm{m},i} = C_{\mathrm{g},i} + C_{\mathrm{d},i}, \tag{3-37}$$

where c_{l} is the average annual salary per employee and n_{l} is the average number of employees per service area. Here, the maintenance cost is considered to be the same as the sum of annualized pipeline and equipment investment cost according to the database provided by the Agency for Natural Resources and Energy.

By contrast, the economic benefits considered in this study include heat-sales revenue $R_{\mathrm{h},i}$ and power-sales revenue $R_{\mathrm{e},i}$, defined as

$$R_{\mathrm{h},i} = p_{\mathrm{h}} q_{\mathrm{h},i}, \tag{3-38}$$

$$R_{\mathrm{e},i} = p_{\mathrm{e}} \frac{q_{\mathrm{h},i} \cdot \mu}{(1-\zeta) \cdot \eta} (1 - \delta - \kappa), \tag{3-39}$$

where p_{h} is the price of heat sales, p_{e} is the price of electricity sales, μ is the power generation efficiency of a gas engine, δ is the proportion of power generated for pumping hot water, and κ is the proportion of power generated by operating other equipment in heat and power stations.

Furthermore, assuming that the current heat consumption for space heating and hot water are supported by air conditioners and gas boilers, respectively, the CO_2 emissions in the current situation, $E_{\mathrm{BAU},i}$, are calculated as

$$E_{\mathrm{BAU},i} = q_{\mathrm{h},i} \frac{\gamma}{\psi} \varepsilon_{\mathrm{e}} + q_{\mathrm{h},i} \frac{1-\gamma}{\varsigma} \varepsilon_{\mathrm{LPG}}, \tag{3-40}$$

where γ is the proportion of heat consumption for space heating, ψ is the COP (coefficient of performance) of the air conditioner, ς is the efficiency of the gas boiler, ε_{e} and $\varepsilon_{\mathrm{LPG}}$ are the emissions factors for grid electricity and LPG (liquid propane gas), respectively. Accordingly, the CO_2 emission reduction obtained by introducing district heating can be calculated as the sum of substituted CO_2 emissions in the current situation and that of substituted power generation after subtracting the increasing CO_2 emissions from gas consumption for cogeneration, as shown in Eq. (11).

$$\Delta E_i = E_{\mathrm{BAU},i} - \frac{q_{h,i}}{(1-\zeta)\eta} \varepsilon_{\mathrm{NG}} + \frac{q_{\mathrm{h},i}\mu}{(1-\zeta) \cdot \eta} (1 - \delta - \kappa) \varepsilon_{\mathrm{e}}, \tag{3-41}$$

3.2.6.2 Feasibility condition

Because plot ratio is considered as the key indicator for the feasibility of introducing district heating, there would be a minimum plot ratio under which the annual costs of introducing district heating is larger than annual revenue. To find out the minimum plot ratio of a mesh for introducing district heating, firstly it is necessary to assume a minimum heat price to balance annual costs and revenue. Using the formulas mentioned above, the changes of minimum heat price in different plot ratios can be calibrated. Figure 3-15 is a sensitivity test on the feasibility of introducing district energy system considering the changes of the key variables. The parameter setting for several scenarios are listed in the Table 3-9. For example, in the baseline scenario, the average piping cost is set as 200000 JPY/m. Then, corresponding to the average heat price set in the case region, the minimum plot ratio can be calibrated. Learning from the statistical yearbook of district heating projects in Japan, the average heat price in existing district heating projects is around 4.4 JPY/MJ, for which the required minimum plot ratio should be 70% (JHSBA, 2016). If the average piping cost is too high, a heat price of 4.4 JPY/MJ may not be able to balance costs and benefits. Because the parameters such as the average cost of piping is variable in cases, the minimum plot ratio required should be variable.

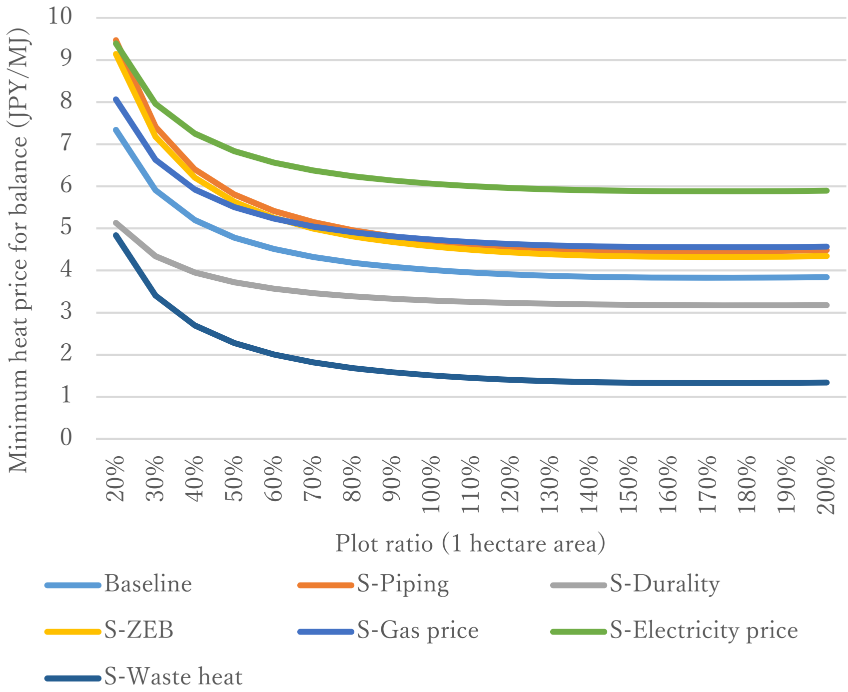


Figure 3-15 Economic balance of extending a district heating network

Table 3-9 List of the items in cost-benefit analysis and key related variables.

Scenario	System type	Piping cost JPY/m	Duality Years	Heat demand unit MJ/m^2	Fuel price JPY/m^3	Power sales price JPY/kWh
Baseline		200000	17	140	57.67	17.5

S-Piping	Gas-fired cogeneration	300000	17	140	57.67	17.5
S-Lifespan		200000	40	140	57.67	17.5
S-Heat insulation		200000	17	70	57.67	17.5
S-Gas price		200000	17	140	69.20	17.5
S-Electricity price		200000	17	140	57.67	10.0
S-Waste heat	Waste heat	200000	17	140	1 JPY/MJ	17.5

By contrast, a sensitivity analysis on key variables is conducted which indicated the complexity in discussing the feasibility of introducing district energy system. Learnt from the scenario S-Piping, S-Lifespan, S-Heat insulation and S-Gas price, result shows either of the changes such as increasing piping cost from 200000 JPY/m to 300000 JPY/m, reducing half of current heat demand density, and increasing 20% of gas purchase price will slightly increase the level of balanced heat sales price by about 0.8 JPY/MJ, while extending the infrastructure lifespan from 17 years to 40 years will slightly decrease the level of balanced heat sales price by about 0.8 JPY/MJ. However, the price of power sales is quite sensitive to the required minimum heat sales price. For example, if the generated electricity is not directly sold to the users but sold to the grid, the current price in market trading is only about 10 JPY/kWh. This will increase the level of balanced heat sales price by 2 JPY/MJ. Considering the average heating cost in case of kerosene-fired heater is around 2.7 JPY/MJ, one solution to keep the competitiveness is to use waste heat (generally purchased at price 1 JPY/MJ), which can reduce the balanced heat price to about 1.2 JPY/MJ. Although higher plot ratio can help in reducing the required minimum heat price, it is more sensitive in the range below 100%.

3.2.6.3 Competition between individual heating and district heating

In fact, incineration facilities can also choose other options, such as directly using steam for power generation; thus, the competition between steam and potential electricity sales should be evaluated. Setting the efficiency of power generation η at 19.8% (currently the highest efficiency achieved in Japan) (JEFMA, 2016) and the FiT price for incineration power generation ${p^e}_i$ at 17 JPY/kWh (the actual value in fiscal year 2016), the benefit multiple of steam supply over power generation $P_f/P_{f,e}$ is approximately 2.35, as calculated according to Equation 3-42. Additionally, the multiple of CO_2 emission reduction effect is determined through Equation 3-43 to be approximately 2.12, setting the emission factor of system electric power ε_i^e at 163.61 g CO_2/MJ. These facts indicate that the steam supply to industries from the incinerator would be competitive with power generation in CO_2 emission reduction effect, but not economically competitive if the annualized costs increase above 58% (1-$P_{f,e}/P_f$). In this study, the baseline for comparison is the assumption that no waste heat is recovered in the incinerator.

$$P_f/P_{f,e} = (q'_i \cdot p_i)/(q'_i \cdot \eta \cdot p^e{}_i) = 2.35 \quad (3\text{-}42)$$

$$R_{CO2}/R_{CO2,e} = (q'_i \cdot \varepsilon_i)/(q'_i \cdot \eta \cdot \varepsilon_i^e) = 2.12 \quad (3\text{-}43)$$

3.3 Data acquisition and parameter setting

To realize the analytic framework shown above, a 4d-GIS database is proposed to be developed that is joined with other datasets for geographic analysis and technical assessment of district heating systems. The most critical aspect of this approach is to collect yearly maps of building distribution. In this study, polygon data of building distribution were adopted, as provided by ZENRIN Co., Ltd., which were collected between 2010 and 2015. These polygon data are first aggregated into 100-meter meshes. Population changes were estimated based on prefecture-level simulation results from the National Institute of Population and Social Security Research. The geographic information is supported by the ArcGIS data (2016) provided by ESRI Co., Ltd. and the database published on the National Land Numerical Information Download Service. Furthermore, the survey data from the report of "FY2017 CO_2 Technology Assessment Promotion Commissioned Program" by the Ministry of Environment of Japan (NIES, 2017b) were also referred to for assessment of district heating technologies. Other references are individually cited in the remainder of this section.

The main parameters adopted in this study are summarized in the Table 3-10.

Table 3-10 Main parameters adopted in this study

Name	Item	Value	Unit	Reference
Average pipeline installation cost in station district Shinchi, Kashima, Odaka	c_d	200000	JPY/m	Reported value**
Average pipeline installation cost in station district Soma, Haranomachi	c_d	500000	JPY/m	Reported value**
Long-term interest	λ	0.0115	-	Typical value*
Legal duality of cogeneration system	τ	17	years	Typical value*
Proportion of heat demand in winter (half a year)	ϵ	0.77	-	Referential value***
Purchase price of gas engine	c_e	200000	JPY/kW	Reported value**
Average annual salary per employee	c_l	10	million JPY	Reported value**

Average number of employees by service area	n_l	3	person/km^2	Reported value**
Heat recovery rate for district heating	η	0.43	-	Reported value**
Power generation efficiency of gas engine	μ	0.45	-	Reported value**
Heat loss rate during transmission	ζ	0.1	-	Referential value***
Proportion of power for pumping hot water	δ	0.1	-	Reported value**
Proportion of power for operating other equipment	κ	0.05	-	Reported value**
Proportion of heat demand for space heating	γ	0.54	-	Referential value***
COP of air conditioner	ψ	3.5	-	Typical value*
Conversion efficiency of gas boiler	ς	0.9	-	Typical value*
Heat value of natural gas	ν	41.1	MJ/Nm^3	Typical value*
Price of natural gas	p_{g}	57.67	JPY/m^3	Reported value**
Price of grid electricity	p_{e}	17.5	JPY/kWh	Reported value**
Emissions factor of grid electricity	ε_{e}	163.61	t CO_2/TJ	Typical value*
Emissions factor of LPG	$\varepsilon_{\mathrm{LPG}}$	59.17	t CO_2/TJ	Typical value*
Emissions factor of natural gas	$\varepsilon_{\mathrm{NG}}$	50.00	t CO_2/TJ	Typical value*

*Typical value in physics or published in calculation guidelines (MOEJ, 2016; NIES, 2017b)

**Reported value from governmental documents or consulting reports (NIES, 2017b)

***Referential value from reference (Dou et al., 2018).

3.4 Case selection

As mentioned before, case studies at city scale usually require a high-resolution geographic database of which the data are provided by local stakeholders or collected by local survey. This study is also conducted through the collaborative projects with local government and companies. These collaborative projects cover various themes in several regions, such as establishing smart communities and spreading innovative technologies in Fukushima Coastal Area (including Soma Region), proposing stock-based low-carbon urban plan in Kitakyushu City, and investigating the feasibility of developing a board waste heat exchange network in Tokyo Metropolitan Area (Figure 3-16). Therein, the cases in Soma Region and Kitakyushu City are requiring an integrated energy system design toward low-carbon economy considering possible land use changes. Particularly, due to the local recovery from tsunami disaster in Fukushima Coastal Area, an epoch-making urban transition through new urban design is required that supports a capacity of implementing this study in actual case studies. Therefore, the following two chapters would like to introduce the application of the models in Soma Region and Kitakyushu City and verify the model performance.

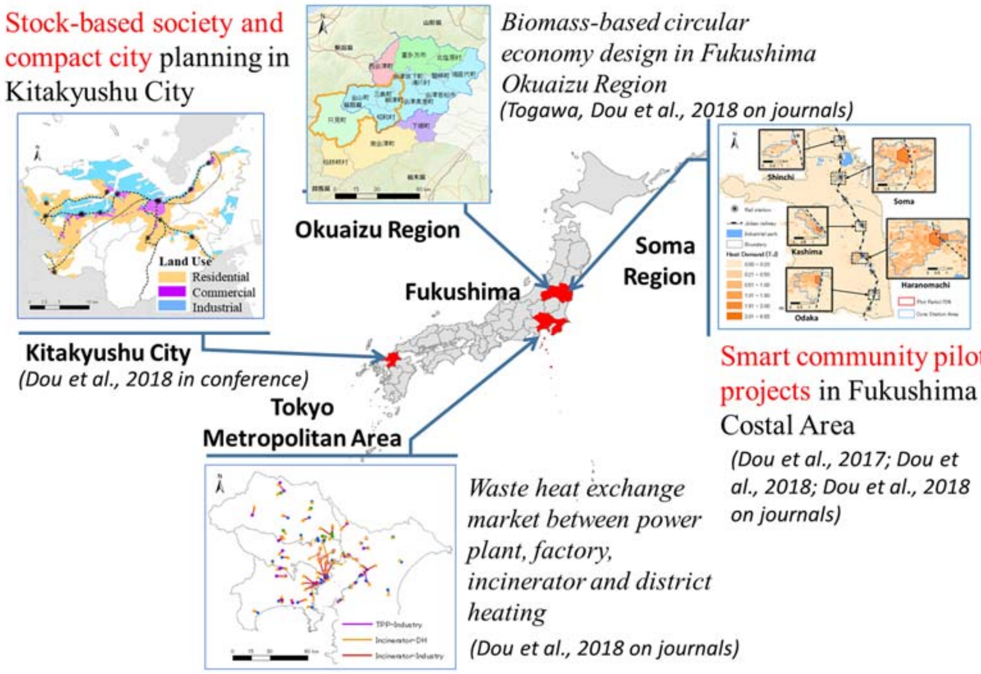


Figure 3-16 Location and main theme of recent collaborative research projects

Another reason of selecting both Soma Region and Kitakyushu City is that they have similar policy target, different geographic characters and supplementary data availability for answering the research questions in this study. As summarized in the Table 3-11, although both Soma Region and Kitakyushu City expect to make the city more compact, because the former has much lower density and is just in the progression of local revitalization from earthquake disaster, the target of local plan is to redevelop the recognized core areas where regional railway stations are located so as to rebuild shopping quarters. In these areas, population density will increase which provides an opportunity to introduce district energy system. By contrast, Kitakyushu City has mixed urban structure with complete GIS database for tracking the past changes of building distribution, this could help in investigating the impact from various factors in urban renewal on energy demand distribution.

Table 3-11 Characteristics of the selected case areas and their position in this study

Case area	Soma Region	Kitakyushu City
Geographic character	The most are low-density area	Mixed with low-density and high-density area
Basic urban planning	Recovery and Redevelopment	Facility Location Optimization Plan

	Plan, Master Plan	
Development method	Core area development (Station district)	Land use adjustment and facility location encouragement
Target of local plan	Redevelop the core areas for local economic recovery	Attract migration and facilities to areas along with public traffic line
Expected result	Population density will increase in core areas	Population density will maintain in attractive area for residence
Data availability	Hybrid 4d-GIS database (Recent GIS data with statistics of past building distribution changes)	Complete 4d-GIS database to track the past changes of building distribution
Answer to the research questions in this study	Discuss the feasibility of introducing district energy system in low-energy-density cities	Investigate the impact from various factors in urban renewal on energy demand distribution

3.5 Summary

This chapter described the theory, hypotheses and model framework considered in this study, as well as the method of database construction and reasons in case selection.

Firstly, the method for calculating material and energy consumption of building stocks is developed based on the distribution of building floor area and database of consumption unit per floor area. All the buildings are classified into 6 purposes including detached house, collective house, office, shop, hospital and hotel, and further distinguished into 3 type of building structure including wooden, steel-structured, reinforced concrete as well as added classification of high-rise buildings and lower-rise buildings. For industrial sector, energy consumption is estimated by average unit with a local adjustment parameter, while waste heat potential is estimated by survey data according to the kind of industries and specified processing.

Then, a dynamic simulation of strategic urban renewal is structured where the location and scale changes of buildings in urban area and industrial parks are predicted due to proposed scenario of resident migration. The key indicator for the simulation is the actual lifespan of different kind of buildings, which is estimated from historical distribution changes of building stocks provided by 4d-GIS database. Detailed algorithm for redistribution of building floor area is developed based on the definition of compact city planning method in the Facility Location Optimization Plan.

Next, the principle and design method of district heating system are introduced. Particularly, this study emphasizes on maximum waste heat utilization by cascade use and symbiotic system design between industrial, agricultural and urban sectors. For allocating the pipeline network, this study applies network analysis by ArcGIS tools to draw a realistic network in case of local resolution, while in case of mesh-based simulation, plot ratio is used to estimate the total length of pipeline work in the mesh. According to the pipeline allocation, hydraulic calculation is adopted to estimate temperature and pressure drops for feasibility judgement.

Finally, cost-benefit analysis is identified to assess the feasibility and performance of proposed energy systems. The costs mainly include costs for installing equipment and pipelines, operation and maintenance, labor forces and interest for investment. Particularly, costs for back-up system, pumping cost for maintaining the water pressure, and power generation decrement during steam extraction are also included. By contrast, the benefits of energy projects are defined as the revenue from heat and power sales.

Being critical supports to the models developed in this study, a 4d-GIS database of building distribution changes in past decades as well as an inventory survey on proposed energy supply technologies has been conducted in advance. Considering the reality and possibility in discussing integrated land use and energy planning, Soma Region and Kitakyushu City are chosen as case areas in this study.

4. Case of Soma Region: Feasibility of introducing district heating system in low-energy-density cities

4.1 Case introduction

4.1.1 Geographic characters of case area

The name "Fukushima" has been well known in the world because of the Great Earthquake of Eastern Japan happened in 2011, especially the accident of Fukushima Daichi Nuclear Power Plant. As shown in the Figure 4-1, Fukushima Prefecture is in the northeastern part of Japan facing the pacific sea. By 2018, there are 1.86 million people living at Fukushima Prefecture with about 14 thousand km^2 land area. Usually, the prefecture is divided into 3 parts named Aizu Region, Nakadori Region and Hamadori Region from west to east, respectively, because of the separation by Ou Mountains and Abukuma Highland. More than half of the population are living in Nakadori Region, while another 25% are living in Hamadori Region. The case area in this study, named Soma Region, is locating at so-called Soso Region, which takes the northern half of Hamadori Region.

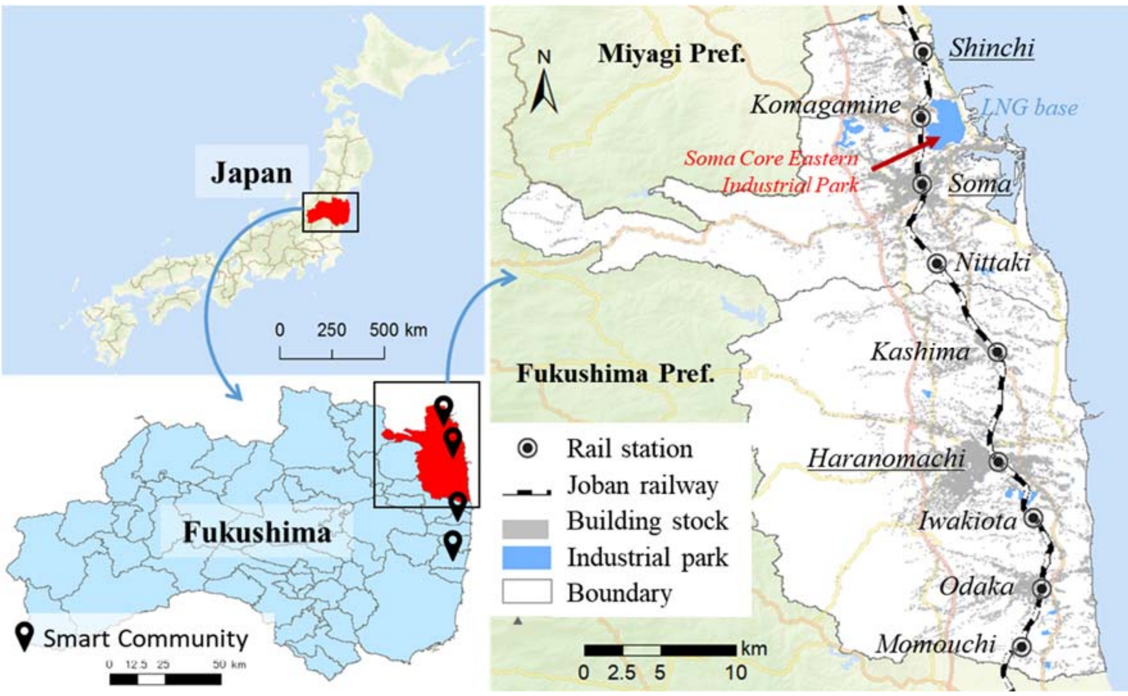


Figure 4-1 Location information of Fukushima Prefecture and Soma Region

The Soma Region includes three municipalities: Shinchi Town, Soma City, and Minamisoma City (from north to south). According to the 2016 Statistical Yearbook of Fukushima, the Soma Region has a total land area of 640 km^2 with a population of around 103 thousand. It had a gross regional product (GRP) of around 506 billion JPY in 2013, of which manufacturing accounted for 17%. Soma City possesses most of the manufacturing production in the region, benefitting from the location of a large-scale industrial park (Soma Core Eastern Industrial Park). In 2014, the shipment value of Soma City reached 175.8 billion JPY, while for Minamisoma City and Shinchi Town the values were 72.4 billion JPY and 10.5 billion JPY, respectively. Currently, a large-scale LNG (liquefied natural gas) base, which is expected to supply cheap gas energy for new industries and therefore aid job creation, is under construction in the industrial park. Effectively exploiting the advantages offered by this location for industrial development is currently of significant interest in relation to revitalization.

By contrast, Minamisoma City has a greater population than do Soma City and Shinchi Town. Generally, residents distribute along the Joban railway line, especially centering around Soma station, Haranomachi station, and Odaka station. With the construction of the LNG base, the introduction of a district heating network using gas-fired cogeneration was proposed by the authors of the present paper. As such, a pilot project has been launched in the newly developed residential district near Shinchi station. In this project, an automatic demand response (ADR) using tablets to visualize household energy consumption is in use (Togawa et al., 2015). Compared with Shinchi station, the introduction of such technologies to the Soma and Haranomachi station districts should be more feasible. This is one of the main practical applications of this study.

Table 4-1 Geographical characteristics of Soma Region

Name	Area (km^2)	Population (person)	Population density ($person \cdot km^{-2}$)	Name of main regional rail stations	Area of identified concentrated living area (km^2)
Shinchi Town	46.53	8218	176.6	Shinchi	0.73
Soma City	197.79	38556	194.9	Soma	2.02
Minamisoma City	398.58	57797	145.0	Kashima	0.86
				Haranomachi	4.11
				Odaka	1.26
Total of Fukushima Prefecture	13783.74	1914039	138.9	—	—

4.1.2 Future prospection of case area

The Soma Region was seriously affected by the Great Eastern Japan Earthquake in 2011. As such, during the process of revitalization, local municipalities have shown a strong desire to introduce smart district energy systems using local natural gas resources as well as to conduct a corresponding brand new urban redevelopment plan to coordinate with the district energy systems.

Furthermore, Fukushima Prefecture is now suffering from serious depopulation and an ageing population, while Soma Region is no exception. According to predictions by the National Institute of Population and Social Security Research, the population of Fukushima will decrease by 1% annually from 2 million in 2010 to 1.5 million in 2040 (IPSS, 2018). However, if planned economic growth is realized in Soma Region, there is a possibility of net immigration and maintenance of the regional population. By applying a snapshot model, the authors predict potential economic growth based on the prefectural Basic Plan for Promoting Industrial and Commercial Revitalization (Figure 4-2) (Dou et al., 2017; Gomi et al., 2015). Currently, the national and prefectural governments are implementing the so-called Innovation Coast Initiative to accelerate the revitalization of the coastal region by ① encouraging new industries including those providing renewable energy, ICT, IoT, artificial intelligence, and medical instruments and ②demonstrating the application of such industries in local smart community projects. By popularizing mega-solar panels, offshore wind power, and biomass-fired and geothermal power generation, Fukushima is targeting at a 100% renewable-energy-based society by FY 2040.

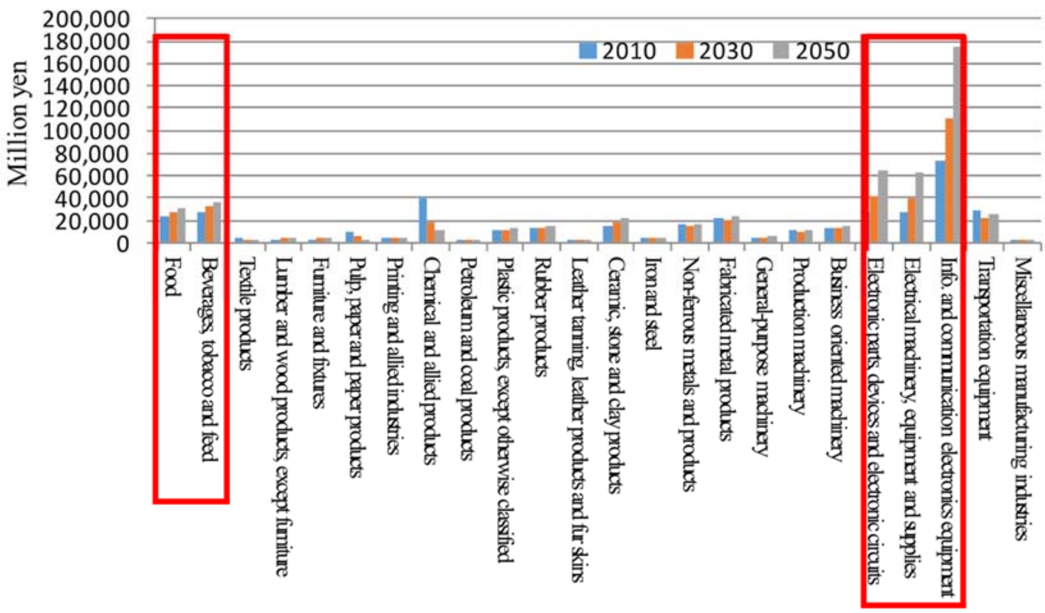


Figure 4-2 Predicted added value by industries in Fukushima Prefecture

On the other hand, Soma Region is also promoting compact land use. Although the three municipalities in Soma Region have not yet declared their own Plans for Promoting Optimal Location (as advocated by the Ministry of Land, Infrastructure, Transport and Tourism of Japan), they have proposed similar Development Plans for Revitalization to promote compact land use. Shinchi, Soma, Kashima, Haranomachi, and Odaka station districts have been chosen as target areas for population concentration. The mechanism of the Location Optimization Plan is to induce the relocation of residents and urban services to target areas through the relocation of critical public facilities including regional hospitals, sports centers, shopping centers, schools, and entertainment. Economic incentives such as location subsidies are given to those critical facilities that follow the guidance of the master plan. In Shinchi Town, households that relocate to the station district are also eligible for location subsidies. In addition, both Shinchi Town and Minamisoma City have been selected as "Future Cities" under an initiative of the Cabinet Office so that their endeavors in promoting compact land use and distributed energy systems using local resources will be used for demonstration purposes to other municipalities across the country.

4.1.3 Proposed energy system

The authors' research group has led one of the smart community projects located in Shinchi Town, which is now in its implementation stage. Based on gas-fired cogeneration using nearby industrial LNG resources combined with solar and wind power networks, energy monitoring and demand response devices have been introduced in smart buildings near Shinchi Station, where compact and mixed land use design is used to provide an optimal matching of energy supply and demand (Figure 4-3) (Togawa et al., 2015; Togawa et al., 2014). As an extension of these attempts, this study aims to consider the feasibility of popularizing such smart community plans across the whole prefecture. As the energy platform for smart communities, the feasibility of introducing district heating is the most important issue.

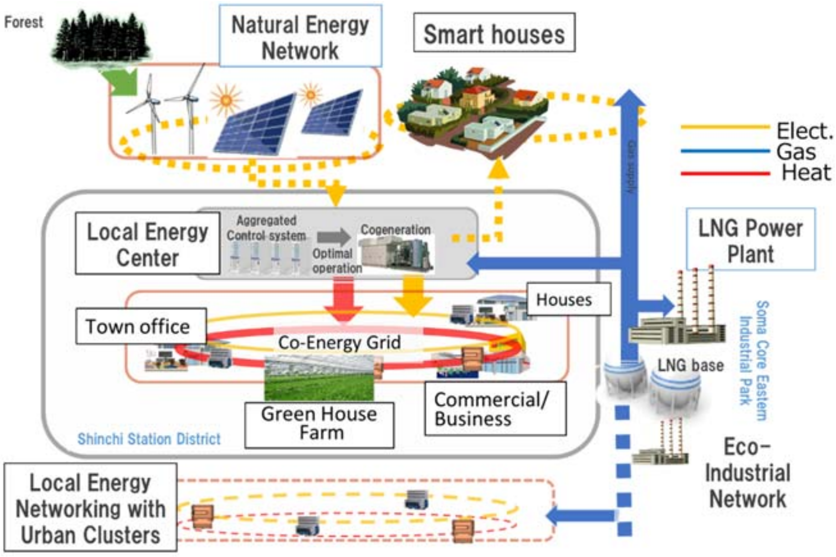


Figure 4-3 System design for an energy-autonomous compact town in Shinchi Town

4.2 Feasibility of introducing district energy system in Soma Region

4.2.1 Scenarios setting

As summarized in the model developed above, the factors which may have an impact on the proliferation of district heating network are categorized as: population change, which determines the total quantity change of building floor area; compact city planning, which arranges the next term building distribution to concentrate into identified station districts; lifespan of buildings, which affects the speed of building retrofitting; heat demand intensity, which represents the unit energy consumption by floor area; supply technology innovation, which occurs in near future that enhances the efficiency of district heating; and changes of units for project evaluation in near future that impacts on the competitiveness of district heating to individual heating technologies. These 6 factors are separated or combined into 8 scenarios as summarized in Table 4-2.

Table 4-2 Scenario setting and related parameter changes

Scenario	Description
BAU-BL	Baseline in business-as-usual. Buildings are renewed in the same location without considering other policies.
BAU-ALL	Business-as-usual. Buildings are renewed in the same location considering all the policies below.
CLU-BL	Baseline in compact land use without considering other policies.
CLU-LL	Compact land use; existing buildings are renewed for 10-year extended use, while new buildings have 30 years longer lifespan than current.
CLU-HI	Compact land use; 50% in 2020, 75% in 2025 and 100% of new buildings after 2030 will improve heat isolation that decreases space heating demand by 40%, and 10% of existing building during each 5 year will improve heat isolation that decreases space heating demand by 30%.
CLU-SI	Compact land use; co-grooves are introduced during new buildings that reduces piping cost from 200000 JPY/m to 150000 JPY/m or from 500000 JPY/m to 300000 JPY/m; lifespan of cogeneration system extends to 30 years; heat loss rate decreases from 10% to 5%.
CLU-UC	Compact land use; annually, the price of electricity, city gas, natural gas and heat increases by 2%, 2.3%, 2.2%, 2%, respectively; emission factor of grid electricity decreases 1.8% annually; COP of air-conditioner gradually increases from 3.13 to 7 by 2040 while the efficiency of water-heating boiler gradually increases from 90% to 95% (Hoshino et al., 2015).
CLU-ALL	Compact land use considering all the policies above.

The effect of compact city planning on district heating network expansion can be evaluated by comparing Business as Usual (BAU-BL) and Compact Land Use (CLU)-BL. Then, to track the joint impact of the other 4 factors on compact city planning, 4 scenarios (CLU-LL, CLU-HI, CLU-SI, CLU-UC) are set separately, by assuming that only one of them will happen in the future, while the other 2 scenarios (BAU-ALL, CLU-ALL) by assuming that none of them or all of them will happen.

However, one problem in this case is that Fukushima Prefecture does not have completed GIS dataset of past building distribution. Currently, building distribution GIS database of Fukushima

Prefecture for the year of 2010 and 2015 were collected, which are input into a hybrid method combining with the statistical data of building age distribution changes from the city yearbooks (Figure 4-4).

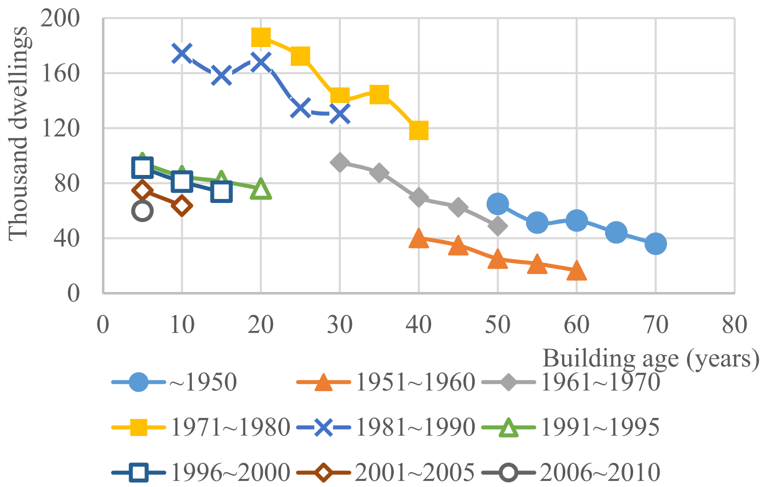


Figure 4-4 Changes of the discovery rate by building vintage

According to the changes of observed number of buildings in different age, it is assumed that the buildings' lifespan follows a Weibull distribution of which the parameters are calibrated by cumulative hazard function. The detailed calculation process can be found in the reference (Komatsu, 1992). In this case, the Weibull distribution equation of the building survival rate is estimated as

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t}{\theta}\right)^{m}} \tag{4-1}$$

which are estimated to be 1.772 and 51.868 in case of Fukushima Prefecture, respectively. Due to this result, the survival and abandonment rates during 5-year periods are estimated, as depicted in Figure 4-5; these rates are applied to all buildings in the case area of Fukushima Prefecture. On average, the lifespan of the buildings is around 40 years.

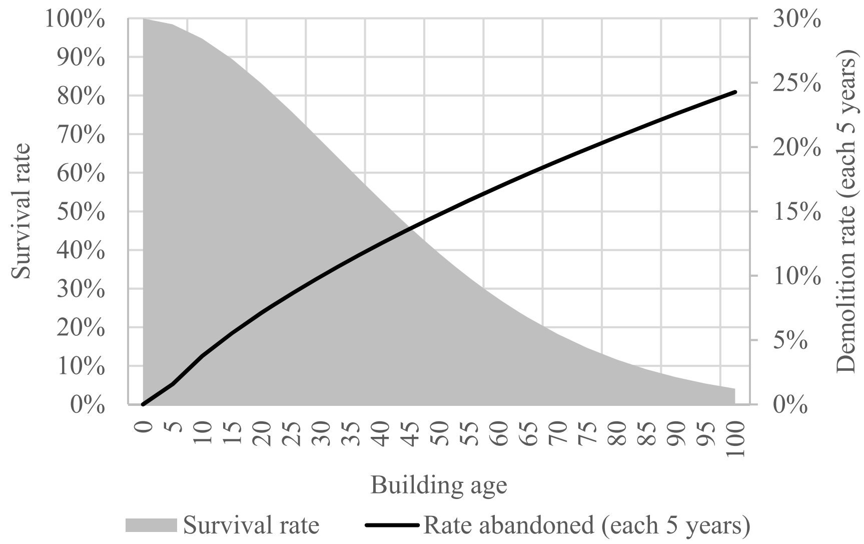


Figure 4-5 Survival rate versus building age (all buildings in Fukushima Prefecture)

Next, the building floor is aggregated into 100-meshes and the average building age for each mesh is estimated through detecting previous demolition activity from GIS database. In detail, by comparing the polygon data of building distribution in 2010 and 2015 using the select-by-location tool in ArcGIS desktop, which helps to automatically identify shape changes in the features between two layers), the changes of building location are classified into three categories: newly built, which appeared for the first time in 2015; demolished, which disappeared from 2010; and no change, which maintained the same location and shape during the time period. Due to this operation, the demolition rate for each mesh during the most recent 5 years is calculated and input into the estimated survival rate curve to determine its most likely building age. In this case, the rate of demolished buildings is found to be 18.1% over the 5-year period, whereas the rate of building renewal is slightly lower at 17.4%. For the demolished buildings, 54.4% were rebuilt in the same mesh area, meaning that the rest were removed or relocated. Notably, in calculating the plot ratio of each mesh, the area covered by river and water, as well as the part for railway, road and other surface infrastructure construction were excluded.

4.2.2 Potential network expansion of district heating

Using the method mentioned in Chapter 3, the heat demand (including space heating and hot water demands) is estimated as shown in the Figure 4-6. The annual total heat demand of Soma Region is estimated at 3100 TJ. Following the distribution of building stocks, the heat demand distribution is relatively concentrated around Soma station and Haranomachi station. Most of the rest areas have a heat demand of lower than 0.04 TJ/km^2, a level at which it becomes infeasible to introduce a district heating network in Japan.

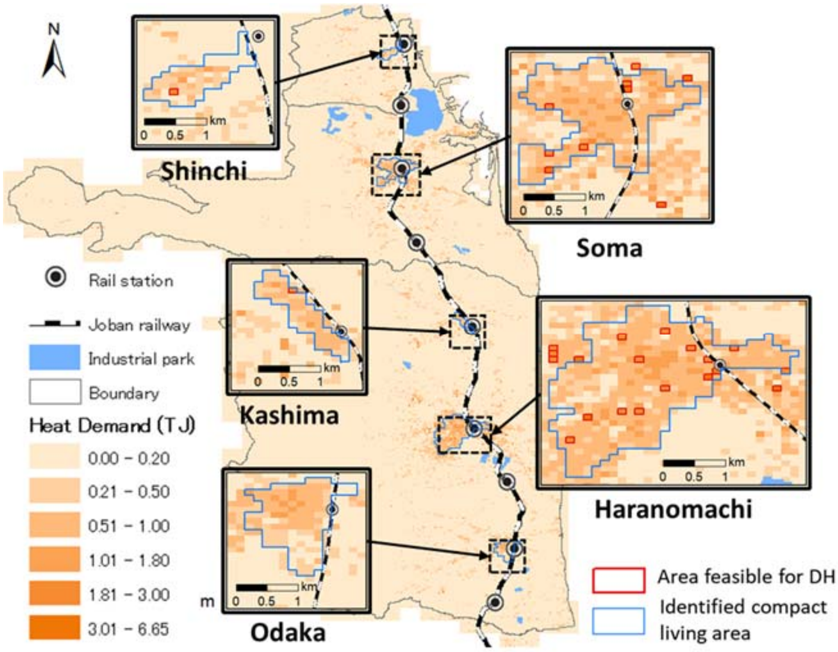


Figure 4-6 Current heat demand distribution in Soma Region (100-meter mesh)

The changes of regional total heat demand in scenarios are exhibited in Figure 4-7. Because population decrease is the only factor affecting the heat demand density in scenarios BAU-BL, CLU-BL, CLU-LL, CLU-SI, and CLU-UC, the total heat demand in such scenarios reveals the same decrease with depopulation rate from 3074.6 TJ in 2015 to 2387.5 TJ by 2040. In comparison, the heat isolation improvement in existing and new buildings is found to further reduce the heat demand to 2167.3 TJ by 2040 (CLU-HI). The contribution ratio of depopulation and heat isolation improvement are 75.7% and 24.3%, respectively. In addition, the policy of extending buildings' lifespan is found to slightly decrease the heat demand reduction to 2190.0 TJ by 2040. In summary, the cities in depopulation trend should be likely to turn into low-energy cities in the near future.

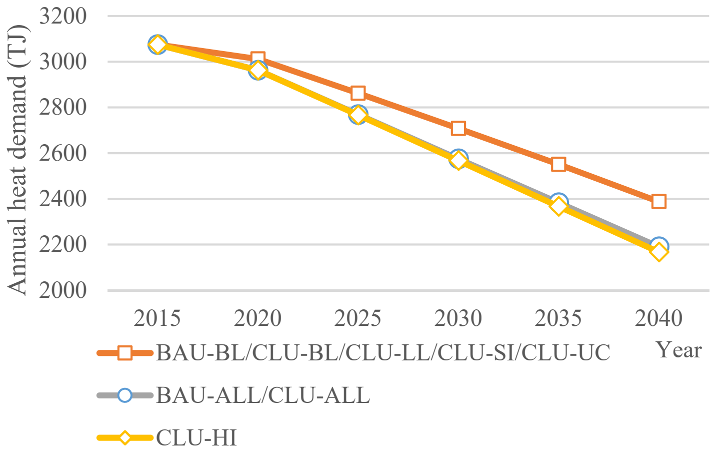


Figure 4-7 Changes of annual heat demand in case region

Under the background of a quick reduction of heat demand in Soma Region, the feasibility of introducing gas-fired cogeneration-based district heating system was discussed considering compact land use planning and other policy implementation, as well as market trend. The results indicate that the feasibility of expanding district heating network can be confirmed through transiting the cities into a compact shape, but the actual performance on economic growth and environmental improvement is substantially affected by the trade-off between various policies and future market trend. Figure 4-8(a)(b) shows the pattern how district heating network is expanding from regional station to surrounding living area under compact land use planning. For simplicity, the maps of network expansion results in each scenario are omitted.

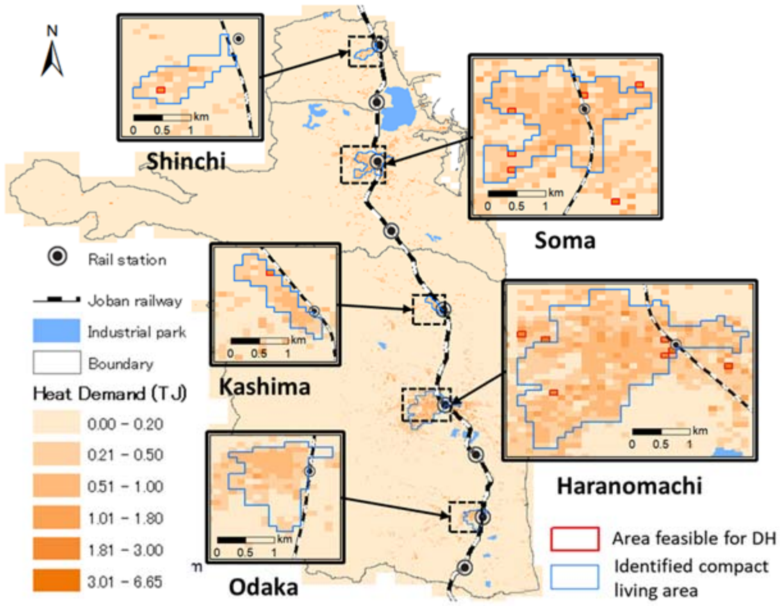


Figure 4-8(a) Expansion of district heating network by 2040 (Business as usual)

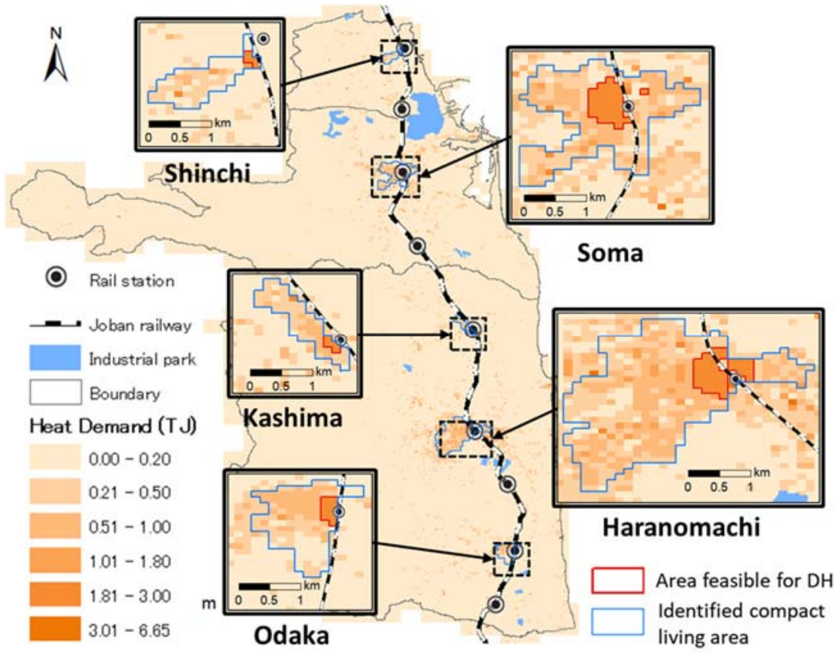


Figure 4-8(b) Expansion of district heating network by 2040 (Compact land use)

Figure 4-9 shows the changes of land area in service of district heating network in scenarios. Compared to current dispersed land use pattern (BAU-BL/BAU-ALL), district heating network is indeed expanding in identified compact living areas, but still quite limited if the other improvements are left out (CLU-BL). Next, the 4 separated scenarios clearly reveal the trade-off effect between the policies and market trend. In CLU-LL, because a large number of unoccupied houses appear after indistinguishably extending buildings' lifespan, the space for adjusting land use becomes extremely limited which almost stops the expansion of district heating network. Similarly, heat isolation improvement decreases the speed of network expansion but still remains the feasibility (CLU-HI). However, this situation is substantially reversed after taking the other 2 positive factors into consideration. Caused by technical and market changes, the average piping cost is reduced while the revenue of selling electricity and heat increases a lot, and the potential of network expansion can reach 92 hectares in CLU-SI and 122 hectares in CLU-UC by 2040. Although in CLU-UC, the fuel price keeps increasing in the same path with the energy price, the doubled increment in revenue by combining heat and power generation completely covers the negative impact. Notably, the positive impact of assessment unit changes (market trend, CLU-UC) appears slower than supply side innovation (CLU-SI) but has a much larger positive effect in the long term. As a whole, these 2 positive factors totally offset the negative impacts from the former 2 factors, which confirm an expectable network expansion to 82 hectares by 2040 (CLU-ALL).

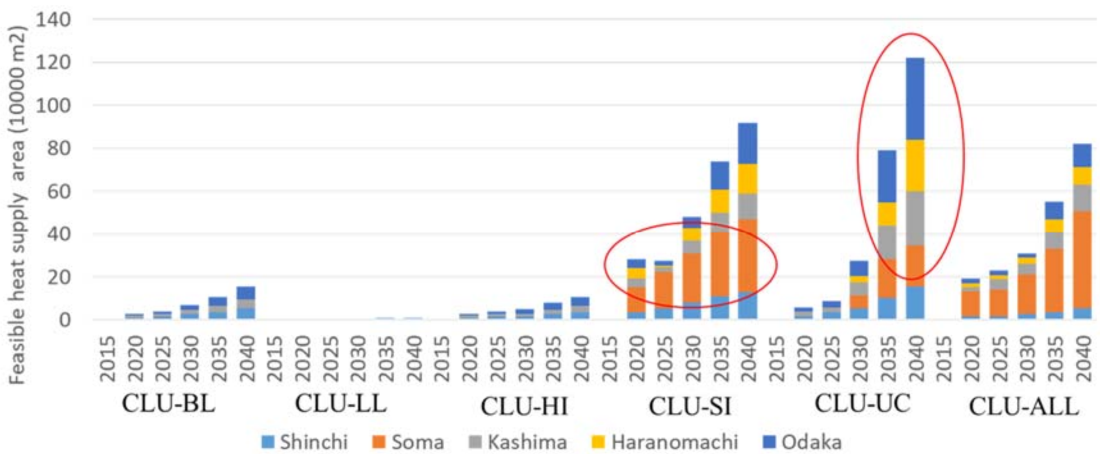


Figure 4-9 Changes of land area in service of district heating network in scenarios

Interestingly, a regional disparity of network expansion in different station districts is indicated. Because Soma City has relatively lower plot ratio near station but similar population scale, it is more sensitive to cost decrease in piping construction rather than price increase in electricity and heat. Therefore, Soma City shows a larger land area for introducing district heating in CLU-SI, meanwhile Minamisoma City shows a larger potential in CLU-UC which is more sensitive to electricity and heat price increment. However, extension of buildings' lifespan causes more unoccupied houses in Minamisoma City, so that in the CLU-ALL scenario, the available land area for district heating is much lower than that in Soma City.

4.2.3 Economic and environmental performance of district heating system

This section compares the impact of introducing district heating on heating cost and CO_2 emissions. Here heating cost means the heat purchase cost in the user side. As indicated in Figure 4-10(a), the annual heating cost is obviously polarized where BAU-ALL, CLU-UC, and CLU-ALL present a fast increment in heating cost. The rapidly increasing fuel and electricity price for performance assessment assumed in these scenarios should be the dominant reason, otherwise the heating cost should decrease with depopulation trend. Compared to baseline in compact city planning (CLU-BL) in 2040, extension of building lifespan slightly increases the heating cost by 0.1 billion JPY, the heat isolation improvement decreases the heating cost by 0.07 billion JPY, and the innovation in district heating decreases the heating cost by 0.5 billion JPY. However, the maximum heating cost reduction by district heating also appears in scenarios in which fuel and energy price changes are considered (CLU-UC), followed by the district heating system improvement (CLU-SI) (Figure 4-10(b)). Even assuming that all the assumptions will happen in the future, the cost saving by district heating still remains rapidly increasing to 500 million JPY by 2040.

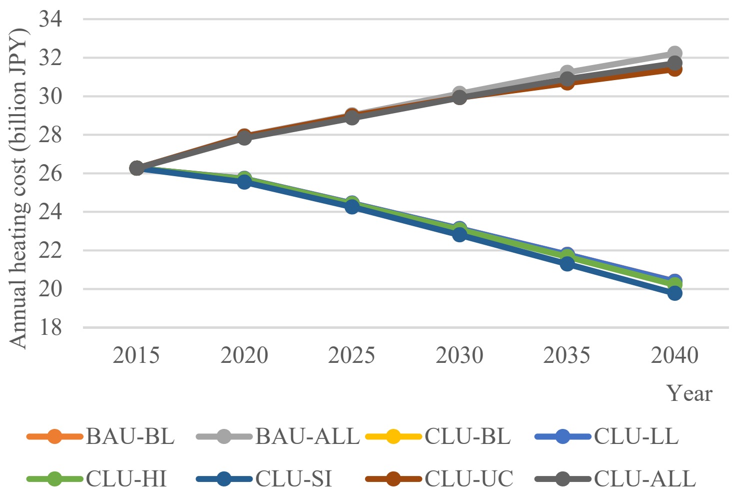


Figure 4-10(a) Changes of annual heating cost in scenarios

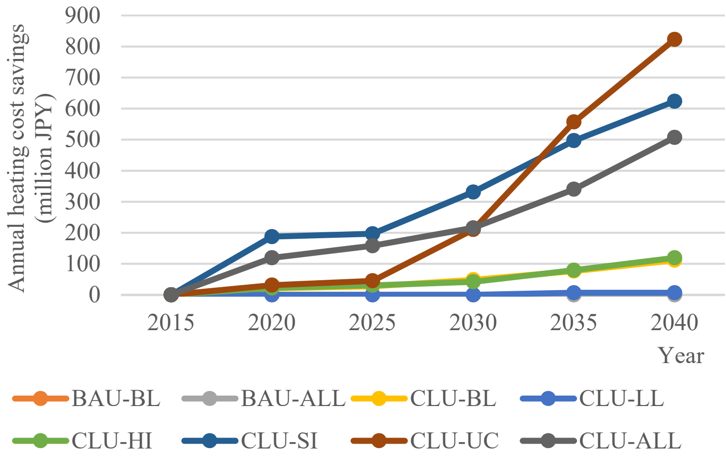


Figure 4-10(b) Changes of heating cost saving by district heating in scenarios

By contrast, CO_2 emission reductions by district heating reveal an opposite trend with heating cost saving. Because of decarbonization in the power generation sector, the annual CO_2 emissions from heating decreases from 179.7 kt to around 86 kt (BAU-ALL, CLU-UC, and CLU-ALL) (Figure 4-11(a)). Compared to the level of CLU-BL in 2040, extension of building lifespan slightly increases the annual emission by 2.3 kt-CO_2, the heat isolation improvement decreases it by 1.7 kt-CO_2, and the innovation in district heating decreases the it by 11.0 kt-CO_2. As shown in Figure 4-11(b), despite the fact that the supply side innovation (CLU-SI) brings an expected increment on emission reductions by district heating, the final result considering all the possible changes in the future reveals that the proposed district heating system (gas-fired cogeneration) is quite limited in CO_2 emission reductions. Although the economic efficiency of the proposed system is confirmed to strongly increase, it will lose environmental importance unless low-carbon heat sources, such as waste heat and renewables, are introduced.

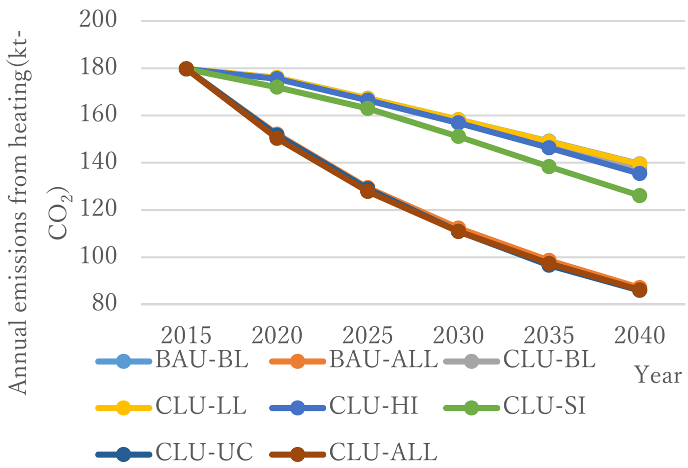


Figure 4-11(a) Changes of annual emissions from heating in scenarios

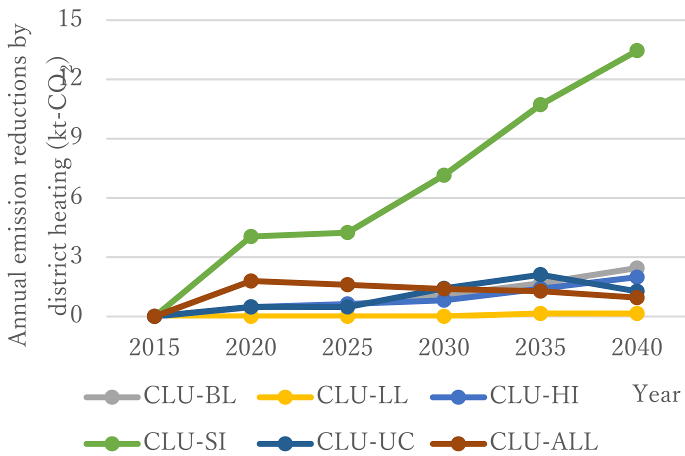


Figure 4-11(b) Changes of annual emission reductions by district heating in scenarios

4.2.4 Impacts from the policies and future changes

Learning from the results above, further discussions on the impacts from policies and future changes are summarized as below.

(1) Lifespan extension of building stocks

Indistinctively extending lifespan of buildings will bring an indispensable barrier for promoting compact city planning in a depopulation region. In the case area, a 5-year demolition rate of buildings is estimated around 8% meanwhile the depopulation rate is around 5%, which means a potential of guiding the citizens to concentrate on regional station districts. However, a longer lifespan decreases the demolition rate even being lower than the depopulation rate, which brings a plenty of occupied houses. In addition, it also slows down the path of diffusing new technologies in new buildings and district heating, which reveals a negative effect on reducing regional energy in use. This policy can be improved by combining with compact city plan that discriminately implements in identified compact living area and the rest area of the city. The prediction on location and quantity of unoccupied houses is critical for delicacy stock management. Notably, embodied energy of buildings is not within the scope of this study which also brings a critical perspective on reducing energy consumption (Cabeza et al., 2013; Dziugaite-Tumeniene and Jankauskas, 2011).

(2) Enhanced heat isolation in buildings

Enhancing heat isolation in buildings is usually considered as an important measure to lower the use of air conditioner and save money. However, space heating only takes a relatively small proportion of the total heat consumption, while the technology also requires a certain time for popularization. In the case, yearly increasing low-energy buildings are indicated to have a certain negative effect on expanding district heating network, but not a determinant barrier if joining the other positive effects. However, the increasing investment intensity of district heating caused by enhanced heat isolation may further weaken the citizens' willingness toward introducing district heating technology.

(3) Innovation in district heating technologies

Technology innovation in district heating is indicated as a key factor for enhancing the competitiveness of district heating system, since the feasibility is quite sensitive to the costs for pipeline construction if given a certain heat price and plot ratio. Promoting co-groove construction in city center as well as extending the lifespan of pipelines and required pay-back period can substantially improve the economic feasibility of district heating. However, generally the investment intensity still remains high because district heating projects will always prefer taking place in areas with higher heat demand density where a denser pipeline network is also needed. In this regard, network expansion of district heating will be mainly limited by available budget.

(4) Changes in project assessment factors

Predicted increment on fuel price is a negative factor to district heating projects, meanwhile increasing price of electricity and heat is indicated to substantially improve the economic competitiveness of district heating with air-conditioner and boiler. However, decarbonization in the power generation sector obviously decreases the low-carbon effect of district heating, which reveals an opposite trend with increasing cost-saving effect. Transiting natural gas into or combining it with other low-carbon heat sources, such as natural energy source and waste heat, is critical to keep the advantage of the district heating system. Otherwise, the economic advantage may also be weakened if the electricity price is effectively suppressed by cheaper production cost of renewable energy. This part should be carefully assessed in the prediction of future energy market changes.

4.2.5 Sensitivity analysis

Although the scenarios analysis on individual impact from each factor has identified some sensitivity concerns, the actual necessity for sensitivity test is from the two assumptions: 60% of residents wish to rebuild houses in the same place (learnt from 4d-GIS database), and 100% of buildings in target area wish to connect to district energy system. Therefore, two scenarios listed as below have been further discussed.

- CLU-ALL(Original): The same definition as above (60% residents rebuild houses in the same place, 100% of buildings wish to connect to district energy system).
- CLU-ALL(100%Migrate): The wish of residents to live in the same place reaches 100%.
- CLU-ALL(60%Access): Only 60% of heat demand really connects to DES.

Results indicate significant difference between the scenarios, as shown in the Figure 4-12. Increment of the residents' wish to migrate is possible to bring 20 hectares wider feasible area for introducing district energy system, but if access rate decreases to 60%, more than half of the feasible areas in CLU-ALL(Original) will become infeasible. Thus, the result is quite sensitive to the access rate which may be a significant risky parameter in the model.

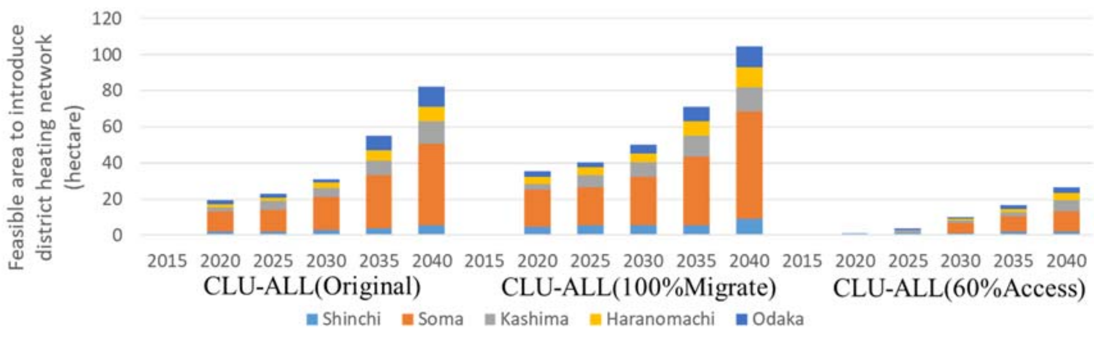


Figure 4-12 Feasible area for introducing district heating network in added scenarios

The annual CO_2 emission reductions and heating cost savings in two scenarios are also summarized in the Figure 4-13(a)(b). In general, the proposed changes in these two factors are likely to bring a ± 50% bias in the simulation. This bias could be suppressed if conducting specific survey for parameter calibration in advance.

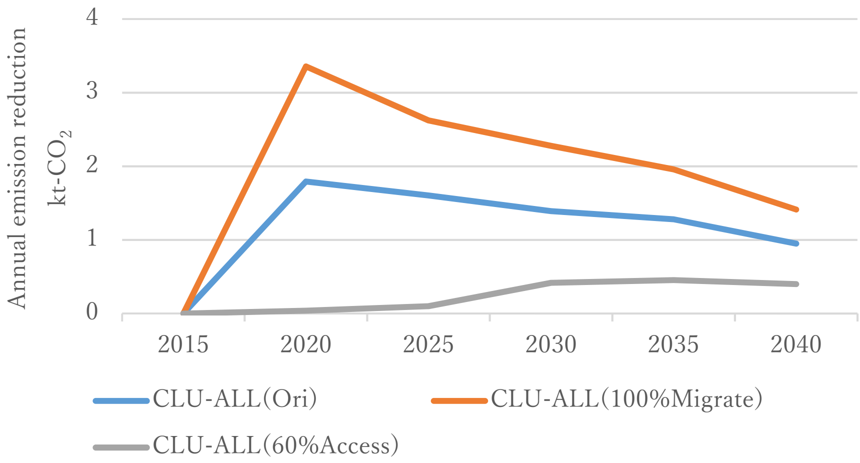


Figure 4-13(a) Annual emission reduction in additional scenarios

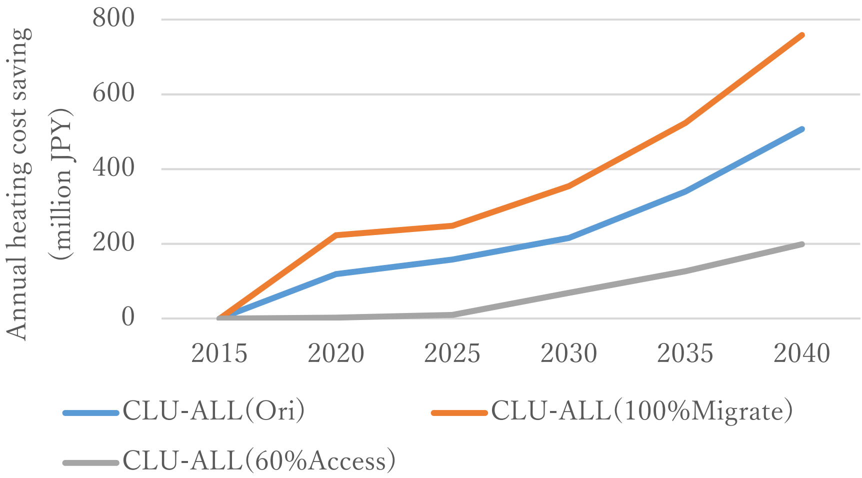


Figure 4-13(b) Annual heating cost savings in additional scenarios

4.3 Enhanced district heating network using industrial waste heat

As a main result in Section 4.2, district heating using gas-fired cogeneration would keep a long-term economic benefit but lose its competitiveness in CO_2 emission reductions due to the decarbonization in power generation sector. Considering the progression of district heating technologies mentioned in Section 2, its competitiveness can be enhanced through utilizing waste heat, renewables or introducing high-efficiency heat pumps. Particularly, the large Soma Core Eastern Industrial Park may contain a corresponding large amount of waste heat which is possible to be recovered for district heating.

4.3.1 Heat demand and waste heat survey

The area of Soma Core Eastern Industrial Park is shared by Shinchi Town and Soma City. Shinchi Town is selected as a future hub of energy resources and as a pilot area of the "Environmental Future City" national project of Japan. Its total land area is only 46.35 km^2 with a population of 8000 as determined in 2014. In the same year, Shinchi Town achieved a GDP of 46.18 billion JPY, for which the primary, secondary, and tertiary industry contributed 1.4%, 26.8%, and 71.8%, respectively (PBS, 2015). Most of the land in the western area is mountainous being covered by forest, while the eastern part is made up of mainly agricultural land. Residential buildings are located dispersedly along the main national and local roads. Three areas where residences were concentrated could be identified from the map, namely Shinchi Station area, Komagamine area and Fukuda area. Shinchi Station area is the town center and is the transit point for the Joban Rail. In the vast farmland area, cultivation of plants (principally greenhouse type allowing irradiation by sunlight) is rapidly becoming popular.

Based on the GIS database of building distribution, heat demand for each building is estimated from the floor area and unit energy consumption by the method mentioned in Section 3. As shown in Figure 4-14, the total annual civilian heat demand for space heating and hot water is about 160 TJ, concentrated mainly in two areas, named Shinchi Station area and Komagamine where possess a half as 80 TJ. By spatially joining them into 100-meter grids, we mapped the heat demand distribution. Learning from the distance analysis along the road network, since there is no existing infrastructure for district heating system and considering the limitation of initial investment and the scale of the project, Komagamine area (within 3 km to heat sources) is chosen as the target area herein. However, the annual heat demand covered in this area is merely 24 TJ, which is much lower than supply potential.

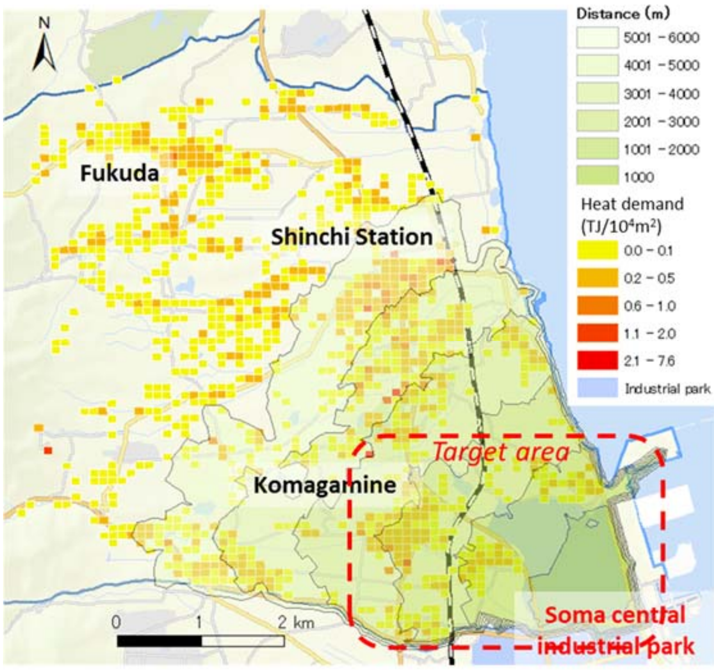


Figure 4-14 Heat demand distribution and distance to waste heat sources

During the 2011 earthquake, the coastal area of Shinchi Town was destroyed and had hundreds of victims. In view of a long-term reconstruction, several large-scale projects are just in planning and implementation stages, including a large-scale LNG base and an advanced natural gas thermal power plant, which are located in the industrial park. Benefitting from the industrial development plan, Shinchi Town aims to attract a population of about 2000 by 2050. To combine the benefits of economic growth and environmental improvement, in addition to improving the regional attractiveness for living, will be a long-term issue for local governments.

Quality and available quantity of waste heat from the sources is a key factor for energy symbiosis network design (Morandin et al., 2014). Through a series of surveys and negotiations with local government and companies, waste heat potential from main industries are estimated according to the method mentioned in Section 3. The results of the heat source survey in Soma Central Industrial Park are mapped in Figure 4-15. Currently, the available sources include two large scale thermal power plants and several factories.

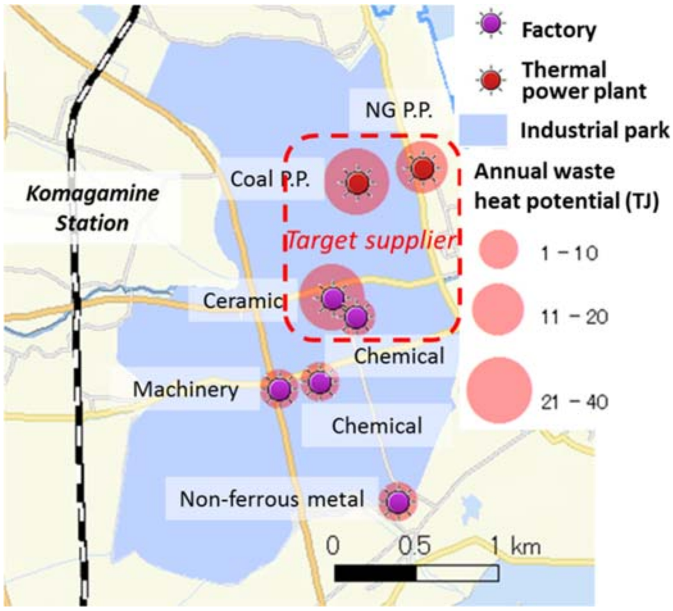


Figure 4-15 Location of waste heat sources and the potential

With respect to the quality, industrial waste heat has a higher quality for district heating because this value can be adjusted to match the requirement without using technologies such as heat pumps. In another parallel study, we at first designed a network of Industrial Symbiosis which extracts steam from the turbine of the thermal power plant (more than 200℃) to provide heat for a factory process. In the second stage, for cascading using the waste heat, we propose to recover the waste heat from the exhaust gas in the power plant's chimney and from the industrial processes of factories. The former can provide heat to raise temperatures of water up to 100℃, while the latter exhaust gas up to more than 200℃ (JES, 2011; Togawa et al., 2014). Both these temperature values are above the temperature requirement of district heating (averagely 80℃) (JIE, 2008).

In parallel, we also surveyed the available quantity of waste heat that can be provided by target companies. Although both the thermal power plants can be at 1000-MW level for recovering waste heat from the exhausted gas, considering the difficulty in introducing a heat exchanger in the existing system and the possible impacts on surrounding environment, at the current stage, the companies agree that with a very conservative supply quantity, the coal-based thermal power plant can supply 40 TJ, while the one based on natural gas can supply 20 TJ annually. However, taking the results from a survey on the energy input for production, we also estimated the waste heat potential from factories by a method taken from JES (2011). The result shows that the ceramic factory has the largest potential of 32 TJ, while the others have less than 10 TJ annually. Since the large suppliers are concentrated in the center of the industrial park currently, we propose to utilize the waste heat from the two power plants; the ceramic factory and the nearby chemical factory. With the progress of this project, in the future, there is a possibility to encourage factories to increase the waste heat supply once the benefits are actually realized through the implementation of the project.

4.3.2 Scenarios setting

Although the survey shows that a large amount of waste heat is available for urban area use by symbiosis design, most of the area in Komagamine has a heat demand density even lower than 50 TJ/km^2 (generally 420 TJ/km^2 is thought as the minimum heat density required by district heating system in Japan), the feasibility of introducing district heating system is doubtful in the current situation. Two approaches can be considered to improve the feasibility: one is to increase the waste heat usage by guiding energy intense factories or agricultural units such as plant factory to locate near the park, and the other is to promote a compact land use in the residential areas to reduce pipeline costs. Both are currently available in Shinchi Town, since the greenhouse type plant factory is a regular feature in Northeastern Japan and compact urban development has already become a national policy due to the Low-carbon Urban Development Law of Japan passed in 2012.

To assess the impacts of introducing district heating system using waste heat by different land use policies, four scenarios are set to reflect the four extreme situations. The contents of the four scenarios are summarized as below:

Table 4-3 Scenarios setting

Scenario	Content
Business as usual (BAU)	Directly introduce district heating system using waste heat into Komagamine, and no specific land use policy is implemented;
Green agriculture	Directly introduce district heating system using waste heat into Komagamine, with guidance to locate newly built plant factories near the industrial park to use the redundant supply;
Compact land use	Promote compact land use in Komagamine while introducing district heating system using waste heat from industries;
Green development	Promote compact land use in Komagamine while introducing district heating system using waste heat from industries, and guide the location of newly built plant factory to use the redundant supply.

To ensure that all these scenarios are realistic, the heat consumption unit of the plant factory is set with reference to a local plant factory in Shinchi Town and the compact land use indicator is set with reference to a similar project in Kobunaki Eco-Town of Shiga Prefecture. Moreover, several assumptions are made for achieving a variable control:

- Total population and floor area in the location of case study, energy consumption intensity and the energy price are assumed to not change significantly in the short term;
- All the users in case area prefer to connect to the district heating system network rather than individual heating, because of the attractive price of heat purchase;
- No epoch-making technology revolution in individual or district heating during the time period of this study. COP (Coefficient of Performance, defined as the ratio of energy for heating or cooling divided by work required) of the air conditioner is set as 7.0, efficiency of water heater and fuel oil boiler are set as 0.95 and 0.9, respectively (CRDS, 2013). These parameters are set higher than current values considering the general availability of high efficiency technology in near future.

Since geographic proximity is a crucial factor for I-US design, we try the best to localize the demand site close to the industrial park. As far as residential areas are concerned, we have proposed to limit the location of the households into the area between the entrance to the industrial park and Komagamine Station, by increasing population density from current 800 to 8000 person/km^2 (Kobunaki Eco-Town level); for the plant factory, we propose to utilized the farmland north of the industrial park, which has at least more than 0.5 km^2 available area. The image of the spatial layout for each scenario is mapped in Figure 4-16.

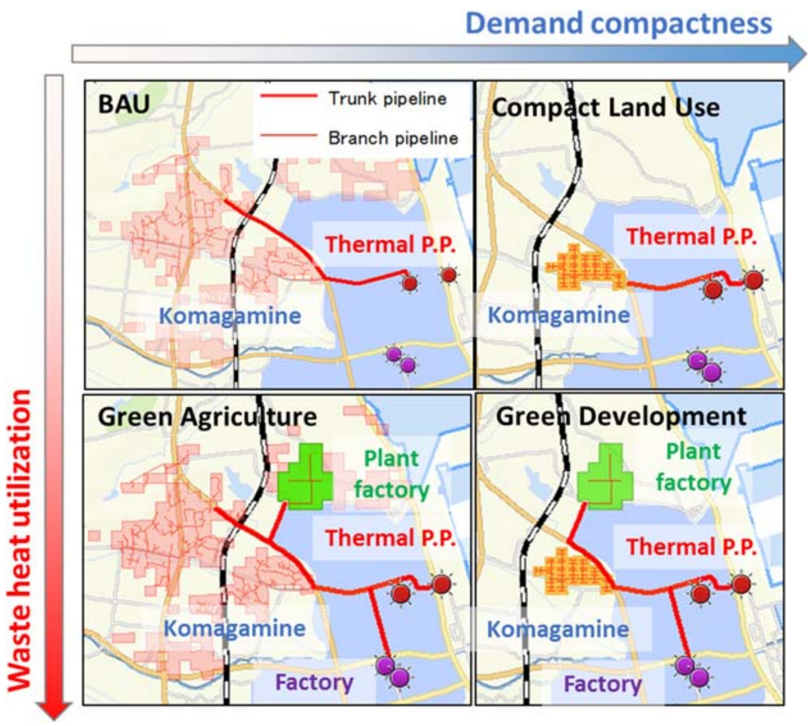


Figure 4-16 Land use design of scenarios

In the BAU and Green Agriculture scenarios, the pipeline network is designed along the road branch by the shortest route analysis, while in Compact Land Use and Green Development scenarios the pipeline is designed following feasible and efficient *T-connection* pattern (Dalla Rosa et al., 2012). Due to the different land use patterns in these scenarios, there is a baseline for each scenario that shows the total energy demand, CO_2 emission and fuel cost before the introduction of district heating. The main parameter differences are summarized in Table 4-4.

Table 4-4 Comparison of main parameters between scenarios

Indicator	BAU	Green Agriculture	Compact Land Use	Green Development
Land area* (km^2)	1.11(0)	1.16(0.05)	0.20(0)	0.24(0.04)
Annual energy demand* (TJ)	47(0)	79(32)	62(0)	91(28)
of which heat demand* (TJ)	17(0)	47(30)	23(0)	51(27)
Annual CO_2 emission* (t)	4453(0)	7035(2581)	5864(0)	8180(2316)
Annual fuel cost in case of individual heating* (million JPY)	222(0)	314(92)	295(0)	378(82)

Pipeline length** (km)	17.9(15.9)	19.7(15.9)	6.8(6.0)	9.2(6.0)

*data in parenthesis is the quotient of the plant factory;

**data in parenthesis is the quotient of branch line

4.3.3 Economic and environmental assessment

On the basis of the scenario setting, the performance of district heating system is evaluated and the results are summarized in Table 4-5. When environmental performance is considered, all the scenarios seem to reduce CO_2 emission in the future. Green Development realizes the largest reduction of approximately 2800 t CO_2 emission annually which is 35% of the total baseline emission, while the least reduction is for the BAU scenario that achieves a 300-t CO_2 reduction which is 7% of the total in the baseline scenario (current individual heating). Approximately 2600 t of extended CO_2 emission reduction comes from the location of the plant factory. However, when economic performances are considered, only Green Development realizes an annual net revenue of 40 million JPY. Although the close location of the plant factory brings approximately 50 million JPY of additional income from sales, the policy of promoting compact land use reduces much more cost (approximately 110 million JPY per year) by reducing the investment in infrastructure and equipment. Since compact land use and proximate location of plant factory are not in conflict, to realize a co-benefit of economy and environment, the best policy is to combine these two aspects for maximizing the advantage of district heating system using waste heat.

Table 4-5 Result of scenario analysis

Scenario	BAU	Green agriculture	Compact land use	Green development
Annual usage of waste heat (TJ)	24	56	27	56
Overall rate of heat loss	29%	14%	13%	8%
Annual operation time (h)	8760	8760	8760	8760
Annual net revenue (million JPY)	−135	−69	−12	41
Annual CO_2 reduction (t)	313	2620	761	2814
Pay-back period (year)*	-	-	-	12

*Investment on facilities and pipelines divided by annual cash flow (without subsidies);

“-”: over the preset operation period (20 years).

Since the four scenarios represent four extreme situations, theoretically, the actual future of policy implementation should be within the limits between four scenarios (Figure 4-17). Moreover, although Green Growth is the best choice, the way this policy is implemented will impact the cost and benefit of the project. For a cursory analysis, we assume that the priorities of the land use policy can be described by the following two possibilities:

- Pathway A: The budget is insufficient so that the promotion of compact land use is given the priority, following which district heating system is introduced gradually to adapt to the increasing heat demand density;
- Pathway B: Budget is sufficient to speed up the substitution of individual heating by district heating.

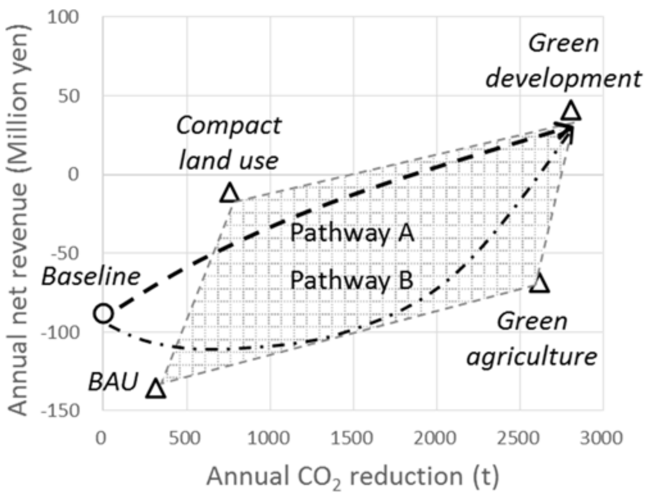


Figure 4-17 Result of scenarios and policy pathway

Clearly, since there is a trade-off between economic and environmental benefits, in the case of an insufficient budget, it is better to first relocate residents so as to concentrate the households near the industry before beginning the construction of district heating network. This option leads to lower total cost but also to less reduction in CO_2 emission. In contrast, in case of an unlimited budget, e.g. the availability of external funding for environmental improvement, introducing district heating system at early stage is definitely more efficient and will lead to more reduction in CO_2 emission. Although the two different pathways will lead to the same result, that is, towards Green Growth during the time period of policy implementation, the accumulated economic cost and CO_2 reduction is quite different for the two cases. In the case shown in Figure 4-17, roughly, the pathway B reduces approximately 10000 t CO_2 more than pathway A, but it increases the total cost by 500 million. In the sense of a carbon market, the average price of reducing CO_2 in this case is approximately 50000 JPY/t. This aspect could be further discussed in business models and financial systems such as introducing CDM (Clean Development Mechanism), PPP (Public-Private-Partnership) for the project (Wand et al., 2016).

As a first step trial, this study constructs a static model and assumes that all the factors remain invariant except for land use. In fact, according to the local master plan of Shinchi Town and market trends, several critical factors including waste heat supply are very likely to change in the future. According to the survey and negotiation to the companies, it reveals that the companies of thermal power plants will try to recover more waste heat, if economic benefit is actually realized by current practice. Otherwise, as mentioned in Section 4.3.1, Shinchi Town carried out a master plan to increase population to 10,000 persons in 2015 which means a 2,000 increment from 2014 level. Shinchi Station area and Komagamine area, where are recognized as two pilot redevelopment area, are expected to accommodate the increasing population. Finally, energy price is also a variable which is predicted to increase a lot in the future. To test the sensitivity of results, we further add three external scenarios defined as follows.

- Aiming at achieving more economic benefit, thermal power plants decide to increase the heat supply by 30% through expanding the capacity of heat exchangers;
- In the future, large scale LNG base construction and industrial development attracts approximately 1000 migrants to "Eco-Village" Komagamine;
- Due to the carbon tax and global fossil fuel price increase, energy price in Japan continues to increase and reaches two times the current value.

The impacts of these three assumptions are summarized in Figure 4-18. Clearly, the more the heat supply increases, the larger could be the scale of plant factory. In contrast, limited by the maximum supply quantity, increasing the heat demand in urban areas offsets the attractiveness of the plant factory, but improves the economic balance. Predictably, the energy price could increase a lot in the future that would significantly increase the economic benefit of energy saving. Consequently, even in a low heat demand density area, as a long-term vision, introducing district heating system could be a priority selection if we follow the global trend and implement the relevant land use policies. This should lend a strong support to making district heating system more popular.

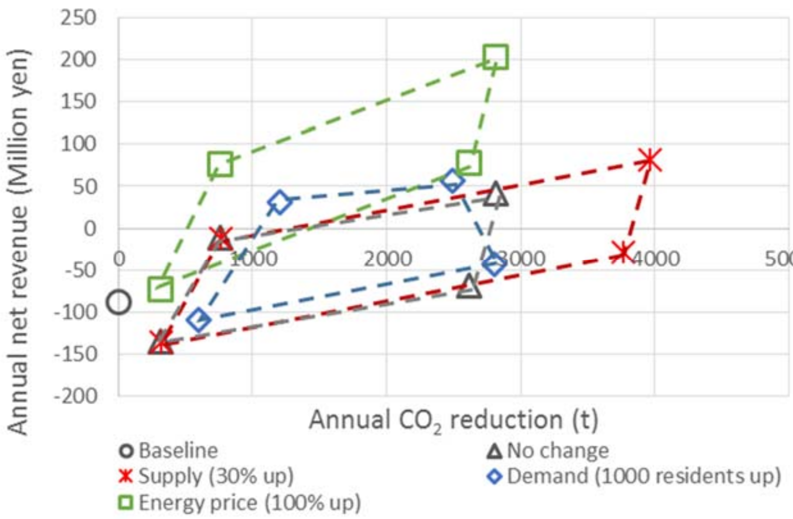


Figure 4-18 Sensitivity analysis considering socio-economic and market changes

4.4 Cascade use of waste heat in industrial park

4.4.1 Waste heat potential and heat exchange network design

Soma City is the manufacture center in this region. According to the Census of Manufacturers, the shipment value in Soma City reached 175.8 billion JPY in 2014, while it is 72.4 billion JPY in Minamisoma City, and 10.5 billion JPY in Shinchi Town. In Soma City, the top productive industries are the manufacture of transportation equipment with shipment value of 129 billion JPY, followed by the manufacture of non-ferrous metals and products (12 billion JPY), the manufacture of chemical and allied products (9 billion JPY), and the manufacture of fabricated metal products (9 billion JPY).

As shown in the Figure 4-19, there are several industrial parks located in the region along the national road and near the interchanges of expressway. Within them, Soma Core Eastern Park and Soma Core Western Park are two largest parks which occupy 4.86 km^2 and 1.05 km^2 area in Soma City, respectively. The eastern park is the largest one which is neighboring to a planned large LNG base. In a detailed map of this industrial park (Figure 4-20), except for a large coal fired thermal power plant in the north, 51.5 ha land is used for non-ferrous metal manufacture, 35.2 ha land is used for chemical industry, 10.7 ha land is for ceramic industry, and the rest 10.6 ha is for manufactures of fabricated metal, production and transportation equipment.

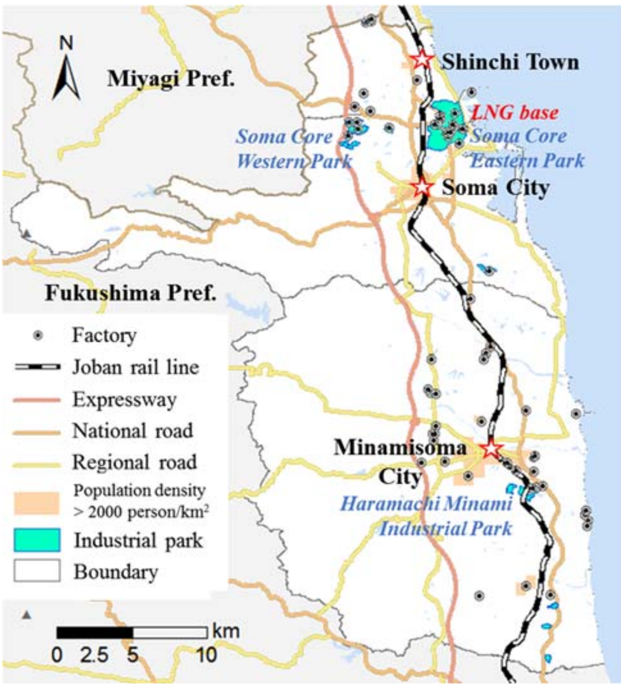


Figure 4-19 Location of main industrial parks in Soma Region

Benefitting from the proximity between planned large LNG base and industries, the utilization of waste heat becomes a hot issue. Especially, a 1200 MW scale gas fired thermal power plant is planned which can potentially extract approximate 100 GJ/h steam, compared to the case of SteamNet in Kawasaki. Accordingly, we propose a heat exchange network between the power plant and factories as shown in Figure 4-20. The configuration of heat exchange network is designed according to the location of factories through network analysis tool supported by Geographic Information System (GIS). In addition, the same scale coal fired thermal power plant in the north is currently not in supplier list, because of the difficulty to install heat exchanger in existing facility. In the rest of this paper, we focus on this industrial park and discuss the possible location changes by scenario analysis.

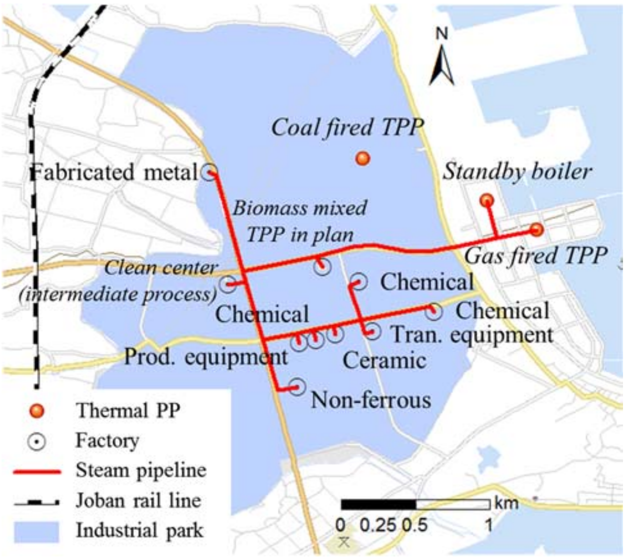


Figure 4-20 Distribution of power plants, factories and assumed heat exchange network in Soma Core Eastern Industrial Park

For guiding a comprehensive revitalization, Fukushima Prefecture has carried out a Basic Plan for Promoting Industrial and Commercial Revitalization in 2013 and is now in revising. In the plan, the Shinchi-Soma region is expected to enhance the leading role of the manufacture of information and communications equipment, transportation equipment and semiconductor related industries. Beyond this, industries related to renewable energy, aerospace, and medical appliances are also welcomed. According to recent Innovation Coast Initiative, this region would become a test area for emerging robot industry in the future. These regional plans would be a basic reference for setting future scenarios.

4.4.2 Scenarios setting

In this study, industrial location changes include two situations: One situation is in the future a new industry can be induced into industrial park, or an existing industry can withdraw from its current location. Another situation is the adjustment of site area between existing industries. The policies of scenario setting in this study are summarized in the **Table 4-6**. 3 typical scenarios are taken into consideration. Firstly, BAU (Business as usual) means current industries will keep location in the industrial park, but follow the changes on unit heat consumption, employment, and productivity. In this scenario, because chemical factory can probably directly extract steam to proximate factories (who use lower temperature and pressure steam), it plays a critical role in heat exchange for cascading use between industries. Then the insufficient part for satisfying all the heat demand is totally supplied from steam extract in the thermal power plant. Additionally, the waste heat of exhaust gas from non-ferrous and ceramic factories can be also used for district heating to nearby plant factory and urban area. The discussion on district heating is excluded in this study. Therefore, the site area allocation and heat supply flow are summarized in Figure 4-22(a).

Table 4-6 Scenario setting and description.

Scenario	Description
BAU	Industries keep current location until 2050
LC1	Low heat demand industries with low growth rate withdraw from current location, while top heat demand industries with availability of heat recovery for district heating are induced
LC2	Low growth rate industries withdraw from current location, while top growth rate industries with intensive employments are induced

For setting scenarios for environment-oriented policy and employ-oriented policy, we compare the intensity of heat consumption and employment of different industries by 2050 and find out the trade-off between heat demand density and employment intensity in industries, that high heat demand industries like beverage and chemical have less employment while the other ones like manufacture of information and electric equipment have more employment but less heat demand (Figure 4-19). Referring to the projection of added value changes of industries in Fukushima Prefecture by Snapshot model (Section 4.1.2), the effect of inducing the manufacture of information equipment, electric machinery, and electronic devices has been reflected as a rapid growth rate, while chemical industry is predicted to decline gradually in the future.

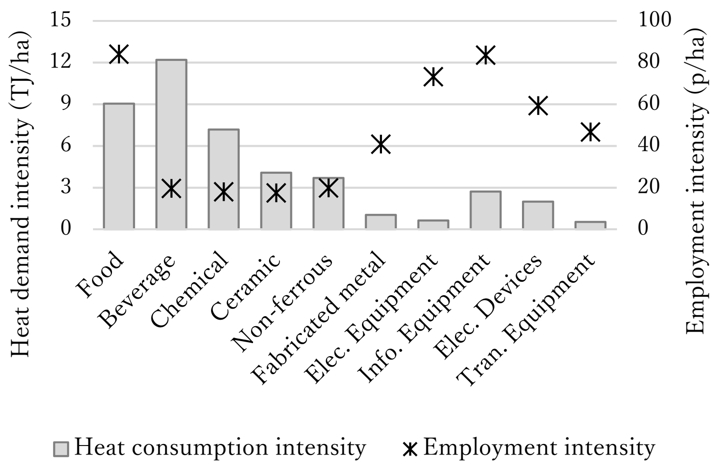


Figure 4-21 Comparison of heat consumption and employment intensity (per area) by 2050.

Assuming that only the industries with positive growth can be induced into the industrial park, we define the detailed location changes into two extreme scenarios, written as LC1 and LC2. In LC1, CO_2 emission reduction target is in priority, thus, the location of the critical chemical factory is confirmed but its scale is hard to be enlarged because of the decline of shipment value. The factories with low heat demand are assumed to be substituted by high heat demand industries, e.g., food and beverage. The site area for induced industries are allocated referring to the proportion of added value at prefecture level. By contrast, LC2 emphasizes on job creation target that high employment intensity industries, e.g., information equipment, electric machinery, and electronic devices, are induced to substitute low employment intensity chemical factory. The site area allocation of factories and heat supply pattern in these two scenarios are represented in Figure 4-22(b) and Figure 4-22(c), respectively. Note that the scenarios in this study also follows several quantitative constraints: 1) Total site area is constant. In present, there is an unoccupied land which keeps unoccupied in BAU scenario but is used in LC1 and LC2 scenario. 2) The increment of shipment value of the induced industries follows their scale in the outlook of regional industrial growth. It means the induced industries have equal chances to occupy unused site areas. The site area is calculated as the shipment value divided by unit shipment value per hectare.

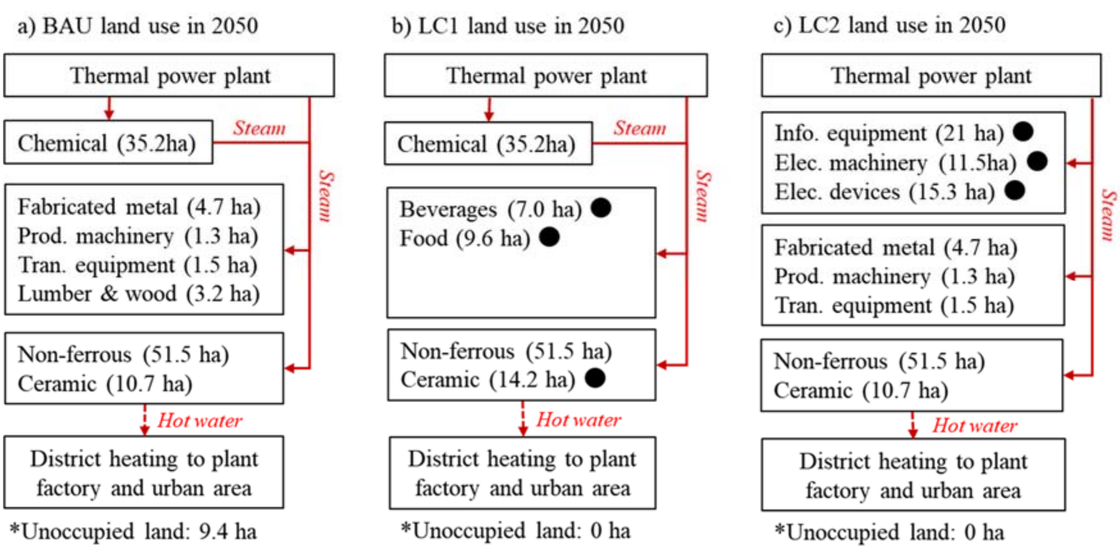


Figure 4-22 Site area assignments in scenarios (Changed item is marked by ●).

4.4.3 Economic and environmental benefits

Scenario results indicate that different policies of location changes in case area indeed bring diverse impacts on environment and local society. Figure 4-21(a) shows the structure of waste heat supply and CO_2 emission reduction by scenarios. In BAU, the total heat demand in case park increases a little from 104 TJ/year to 110 TJ/year. Within the supply of waste heat, the quantity exchanged from chemical factories to the other factories are around 60 TJ, while the rest half of heat demand are covered by steam extracted from thermal power plant. Additionally, 30–40 TJ/year low temperature heat can be recovered for district heating to nearby plant factories and urban area. Consequently, in industrial sector 5200 t CO_2/year emission reduction can be achieved. Because of the decreasing unit heat consumption of chemical factory, the scale of heat exchange between industries becomes smaller, but as a whole, heat balance and low-carbon effect do not change a lot.

By contrast, learning from LC1 scenario, induced food and beverage factories are estimated to bring 46 TJ/year more heat demand, but is almost covered by increasing extracted steam because of the difficulty to enlarge the chemical factory. The excess heat for district heating would increase to 43.8 TJ/year, and net CO_2 emission reduction reaches 6080 t CO_2/year. Oppositely, the results of LC2 scenario indicate that inducing employment intensive factories can decrease a part of total heat demand to 93 TJ/year, but affected by the withdraw of chemical factory, all the heat demand have to be covered by extract heat from thermal power plant, which greatly lower the CO_2 emission reduction effect to 1682 t CO_2/year. From the perspective of low-carbon development, LC1 is the most expected vision in the case area.

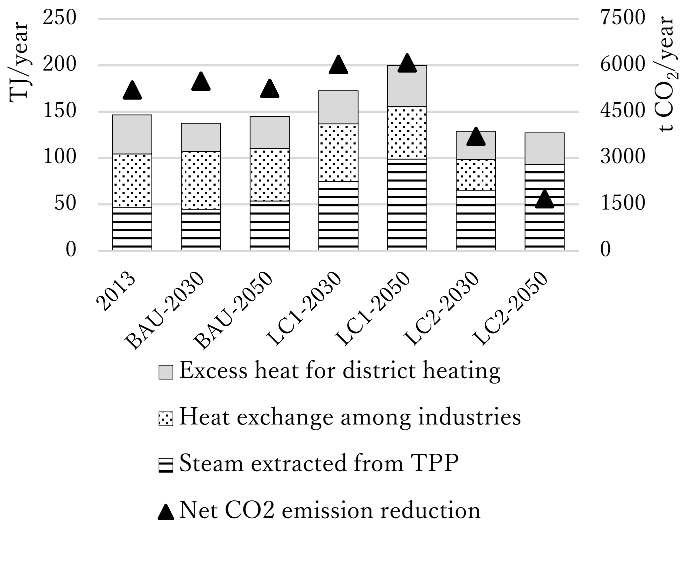


Figure 4-23(a) Heat balance and CO_2 emission reduction by scenarios

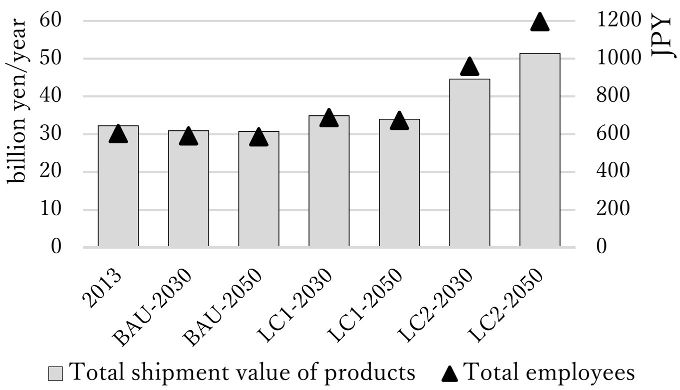


Figure 4-23(b) Shipment value of products and employees by scenarios

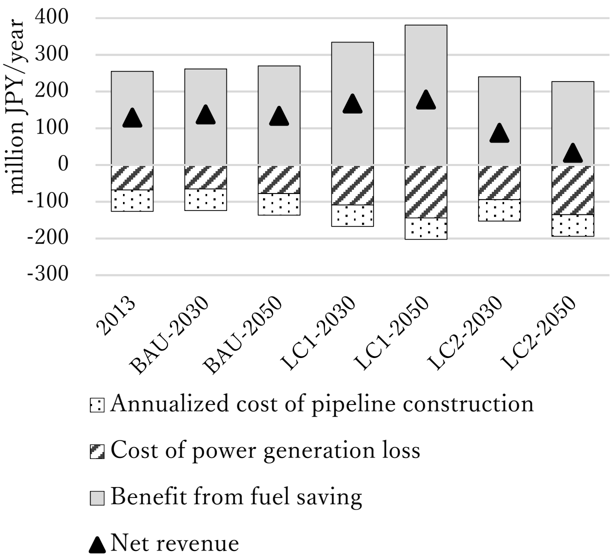


Figure 4-23(c) Economic costs and benefits by scenarios.

Opposite conclusion comes from the perspective of economic growth and job creation. As shown in Figure 4-23(b), in BAU scenario, both shipment value and employment of industries reveal stable until 2050 because the intensity of industries does not change a lot in the future. In the LC1 scenario, induced food and beverage factories bring about 200 jobs that increases the total employees a little from 600 to 670 people. By contrast, in the LC2 scenario, since the withdrew chemical industry reserves a large site area for induced manufactures of information equipment and electric devices, 700 jobs are created that increases the total to 1200 persons. Similarly, the total shipment value in LC2 scenario also doubles compared to BAU scenario.

From the perspective of project feasibility as well as resource conservation and recycling, the more the waste heat is used, the more feasible and efficient a heat exchange network would be. As summarized in Figure 4-23(c), originally the annualized pipeline construction cost is 59 million JPY/year, and approximate 130 million JPY/year of net revenue could be realized. Since the steam from chemical factory is limited, increased heat demand in LC1 scenario leads to more steam extracted from thermal power plant. Even though, the net revenue of heat exchange increases to 178 million JPY/year. By contrast, because of the lacked role like chemical factory in cascading heat use, although the total usage of waste heat does not change a lot, increased usage of steam from thermal power plant offsets the revenue so much, that the net revenue decreases to 33 million JPY. In this sense, whether to keep chemical factory stay or not is the most important decision for realizing a heat exchange network in the case. The pay-back years of heat exchange network are 9 years in BAU, 7 years in LC1, and 35 years in LC2. Obviously, heat exchange will be not feasible in LC2 scenario.

The scenario results indicate that location policy for industries in a region can surely bring about quite different impacts to the socio-economy and the environment. Here, we temporarily ignore the location competition and leakage effect between regions. However, the positive policy for industrial location mentioned in this study does not mean to impose restrictions on individual location behavior of companies. The essential mechanism is to provide a well-founded vision at early stage of industrial development reflecting both public expectation on job creation and environmental improvement. Such a vision can guide the related industries to judge the costs and benefits in location decisions. Once the benefits from proposed symbiosis, including location subsidies, and social responsibility are recognized, the environmental value would be finally internalized into economic accounting, so that companies would judge if accept the vision and follow the inducement. Beyond this, for adjusting the costs and benefits and avoiding unordered location competition and leakage between regions, a board industrial plan is required which can also help in optimizing the industrial location for maximizing the overall effects.

4.5 Summary

This chapter introduced the case study of Soma Region in Fukushima Prefecture, which is now a hot-spot of local revitalization after the great earthquake in 2011. In the region, the coastal area was destroyed by great tsunami that needs an innovative design of local social and economic recovery, especially to make use of local resources like renewables as well as the cheap natural gas from the newly built LNG base in Soma Core Eastern Industrial Park. As a pilot project of symbiotic energy planning, a district heating system using gas-fired cogeneration with automatic demand response has been proposed and begun its construction near Shinchi Station, where a new town is now under development. Since smart communities are expected to be introduced in Soma Region due to the plan of "Future City Initiative" carried out by the cabinet office, such a symbiotic district heating system can be an option for contributing to the smart community projects. Under this circumstance, this chapter discussed the feasibility of popularizing the model district heating system from Shinchi Town to the whole Soma Region in a long term, particularly considering possible changes in urban renewal, technology innovation, energy market, and units of energy consumption and emission intensity.

Results indicate that, under positive implementation of compact living plan during urban renewal considering future changes in building envelop technology, energy market and decarbonization in energy sector, the feasible area for district heating using gas-fired cogeneration in Soma Region is possible to reach 82 hectares by 2040. However, although its total revenue may increase to 500 million JPY by 2040, CO2 emission reduction keeps decreasing to less than 1000 t-CO_2 comparing to household air-conditioner and gas-fired boiler. This is mainly because of the fast decarbonization in energy sector where more and more renewable energy is introduced. On the other hand, the minimum plot ratio is indicated flexible due to the local geographic characters. In lower-density city such as Soma City, with the progression of co-groove diffusion and energy price up, the required plot ratio can gradually decrease from 80% to 50%, while it of central railway station in Minamisoma City still remains high as 100% level because of more expensive piping cost in dense area. In addition, scenario analysis also revealed the synergy and trade-off between various factors. For example, longer building lifespan and improved heat insulation are found to play negatively on proliferating district energy system, but at the same time, the positive impact from potential energy price increase and co-groove construction in urban renewal could double than the negative impact.

Two additional cases are proposed to enhance the economic and environmental advantages of district heating including waste heat usage from industries to urban area and cascade heat use between industries. Results reveal that conduction of a heat exchange between industries in Soma Core Easter Industrial Park as well as extraction of industrial waste heat to nearby residential area can bring maximum 10 kt CO_2 reduction in case of compact living and positive industrial location attraction. The heat price even can decrease to be lower than 3 JPY/MJ, which is competitive to the boiler combusting heavy oil. Particularly, because of the diversity in Soma Core Eastern Industrial Park, waste heat itself are enabled to be cascade utilized between industries.

Finally, in sensitivity test, additional scenario are added to test the two assumptions, i.e., migration strength and network access rate which are assumed to be 60% and 100%. Results reveal ±50% bias may happen if all migrates wish to move or only 60% heat demand is connected. With detailed survey and continuous calibration for these two parameters, the modelling results can be more accurate and referable for decision making.

As a whole, the case study in Soma Region confirmed the classification and transition of district heating technologies by generations. Although gas-fired cogeneration can maintain a high economic benefit by combined heat and power supply, its eco-performance would be weaker than waste heat usage and heat pump using decarbonized electricity. Furthermore, in low-energy-density areas, feasibility of introducing district heating network may not be ensured if policies for compact urban planning are lacked. Therefore, for proliferating district heating network continuously in future cities, not only a continuous transition of system design and energy sources is necessary, but also correlated master plan and stock management policies are required.

5. Case of Kitakyushu City: Dynamic building stock management towards a Low-Energy City

5.1 Case introduction

5.1.1 Case area

5.1.1.1 Geographic information

Kitakyushu City is a regional core city locating in Fukuoka Prefecture, one of the two cities designated by cabinet order in Kyushu Island. It is a typical industrial city where large and heavy industries, including iron and steel, chemical, ceramic, and electrical machinery, are located (Figure 5-1). Kitakyushu City has 491.95 km^2 land area, where around 950 thousand people are living in (estimated number in the year 2018) (BoS, 2018). There are 7 districts distinguished under the city government, of which the urban structure reveals a zonal distribution. Industrial zone distributes in northern coastal area and along the western canal, while the residential zone distributes cling to the industrial zone and extends along the corridor of rail roads. By contrast, commercial facilities are especially concentrating in the city center, where Kokura Rail Station is located available for both local railway and high-speed railway. Beyond the central station Kokura, other regional stations such as Kurosaki and Tobata also attract a certain amount of commercial buildings that become the subcenters for districts.

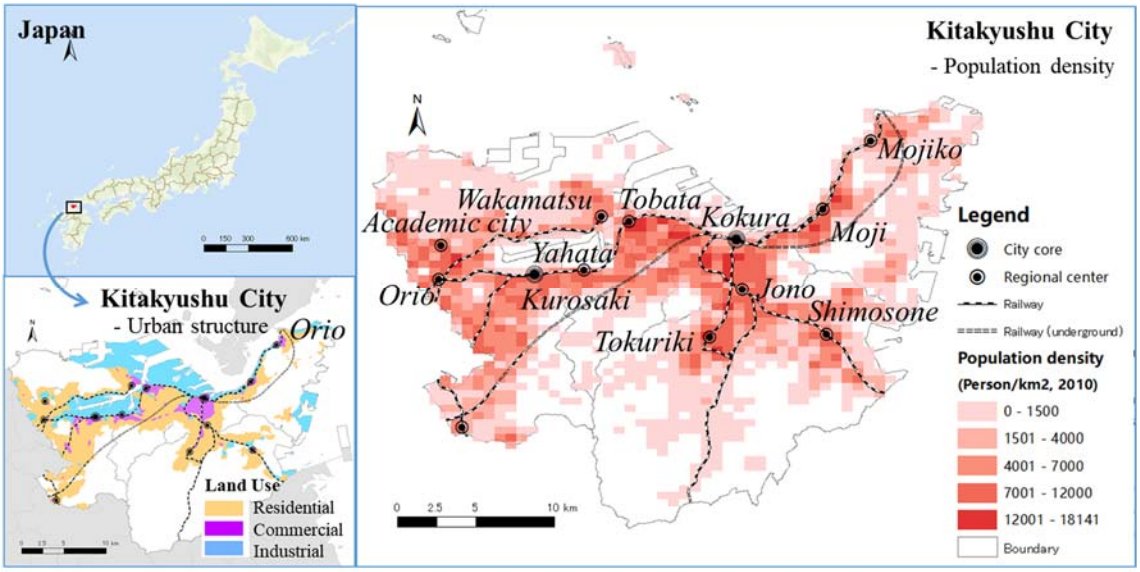


Figure 5-1 Geographic information of Kitakyushu City. Data source: MILT (2018) and ESRI

(2017).

As a consequence of the complex zonal urban structure, the distribution of population density in Kitakyushu City shows a large spatial disparity. According to the 500-meter regional statistical mesh data provided by ESRI Japan which is edited from the national census in 2010, population density in the city center (Kokura Station) could achieve 18000 person/km^2 but decreases a lot in other regional station areas. Because of the extrusion from the hills and river valley, residents can only live along the local railways and bus routes that the population density rapidly decreases to lower than 1500 person/km^2 from the station.

Kitakyushu City is also a typical shrinking city, where population keeps fast decreasing but elder people possess more proportion in total population. From 1990 to 2015, the total population decreased from 1026 thousand to 961 thousand, while the proportion of elder people (age > 65) increased from 12.7% to 29.3%. This situation will further worsen in the future due to the prediction by IPSS (2018). The population is estimated to be lower than 800 thousand by 2045 while the ageing ratio increases to 37.8% (Figure 5-2).

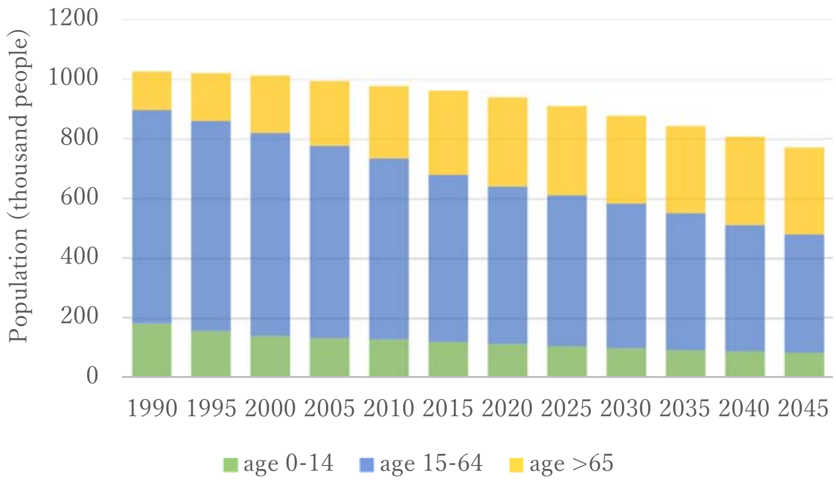


Figure 5-2 Population structure of Kitakyushu City and future prospection

On the other hand, because of the location advantages of industries, Kitakyushu City is always attracting large industries even during the several times industrial revolutions in the 20th century. Since the well-known Yahata Iron Factory began its operation from 1901, Kitakyushu City became the core of so-called Kitakyushu Industrial Zone. From 1990s, advanced industries such as automobile-related industries and semiconductor industry began concentrating in Kitakyushu coastal industrial parks, followed by recycling industries, new energy industries, robot-related industries and medical equipment industries. In 1997, Hibikinada Industrial Park of Kitakyushu City is selected as a pilot area of the National Eco-Town Projects supported by the Ministry of Environment and the Ministry of Economy, Trade and Industry. By 2015, the total GDP of Kitakyushu City reached 3687 billion JPY, in which about 800 billion JPY are contributed by manufacture production. Primary metal industries, especially iron and steel, contributed almost the half, followed by chemical, fabricated metal and ceramic industries. Partially impacted from the depopulation and ageing problems, economic growth in Kitakyushu City remains a relatively stable performance recently.

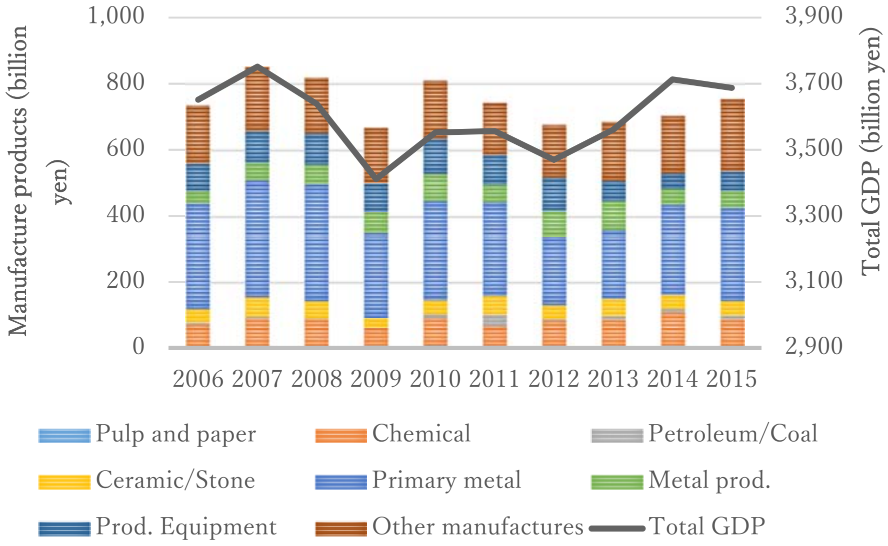


Figure 5-3 Economic growth of Kitakyushu City and the structural changes

5.1.1.2 Historical changes of building stocks

Based on the datasets of building stock distribution in Kitakyushu provided by ZENRIN Corporation, a completed 4d-GIS database was established containing 4 years' building distribution (1985, 1995, 2005, 2015). According to the methodology mentioned in the Chapter 3, the distribution of building floor area due to buildings' purposes and attributes can be clearly identified, such as the sample of FY 2015 shown in the Figure 5-4. Obviously, most of the existing buildings are built during the period from 1970s to 1990s, when the economy rapidly grew, and population continuously migrated into the city. From the perspective of buildings' purposes and attributes, lower wooden detached houses possess the main in the total. By contrast, the proportion of lower-concrete-structure collective houses and non-residential buildings kept decreasing, while they are gradually substituted by lower-steel-structured collective houses and non-residential buildings. From 1970, the continuous migration began raising the skyline of city, thus more and more higher-concrete-structured collective houses and non-residential buildings appeared that became the major of annual building construction. However, all these trends immediately stopped from 2005, since the whole city has enrolled into the period of depopulation and ageing.

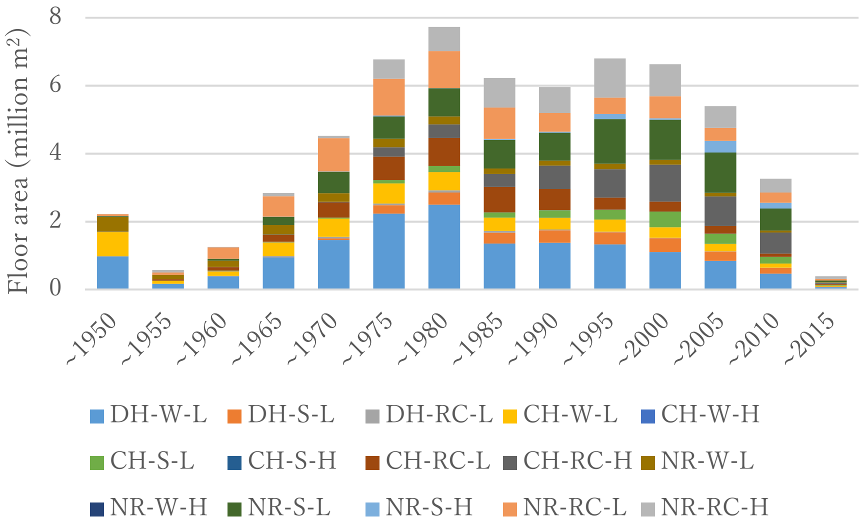


Figure 5-4 Current distribution of building floor area due to buildings' purposes and attributes

(DH=Detached House, CH=Collective House, NR=Non-Residential Building, W=Wooden, S=Steel Structured, RC=Reinforced Concrete, L=Number of Floors Lower than 6, H=Number of Floors Higher than 6)

The current building stock distribution by building purposes is shown in the Figure 5-5.

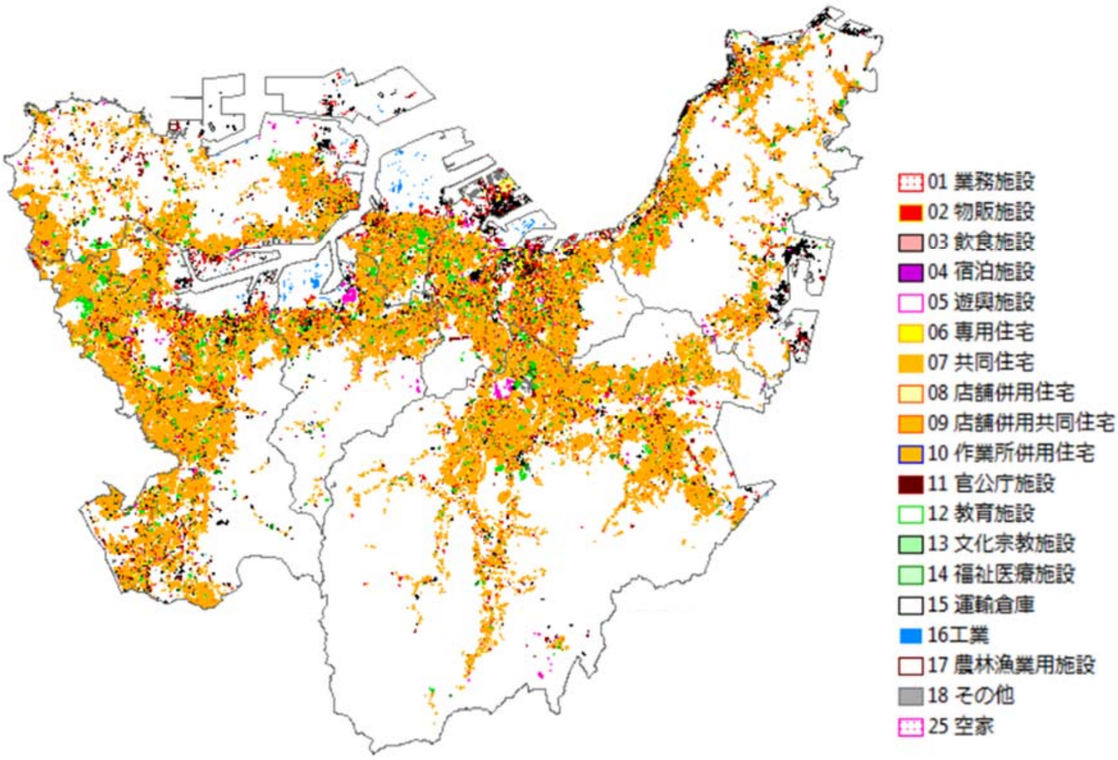


Figure 5-5 Building distribution changes in Kitakyushu City

5.1.1.3 Urban Facility Location Plan

Serious depopulation and ageing problem will reduce the tax income and bring about inefficiency in utilizing infrastructure and public facilities. Currently, the best solution to this problem is thought to be compact city planning (also known as “smart shrink”), which aims at keeping a certain intensity of land use in urban area. In 2011, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) issued a set of law and guidance on promoting low-carbon city development, in which compact city planning is positioning as a key method for urban transition. Although many municipalities followed the guidance in making their local master plan, the approach for policy implementation has not been clearly identified. In view of providing a practical system to guide the implementation toward compact city, the MLIT designed a so-called “Urban Facility Location Plan” to promote the “compact city plus network” concept from 2014. In this system, two types of zones, called attraction zone of urban functions and attraction zone of residence, are distinguished to attract the location of critical urban facilities and residence. Notably, this approach is not emphasizing on controlling the land use but to guide a concentrated/optimized distribution of building stock.

Following the guidance provided by the MLIT, Kitakyushu City carried out his local urban facility location plan in 2017. As drawn in the Figure 5-6, the city identified several key rail stations, in which Kokura is defined as the city center, Kurosaki is defined as subcenter and the others are defined as regional central stations. Based on the definition summarized in the Table 5-1, attraction zones for urban function are designated around the city center, subcenter and regional central stations, while the attraction zones for residence are designated along the local railway and trunk bus lines. In the future, the city purposes to promote high-quality redevelopment in the former zones to attract commercial, medical and education facilities back to the stations, while to remain a minimum residential density in the latter zones. Note this figure is edited by the author due to the definition in Kitakyushu City's plan that may be a little different from the official figure.

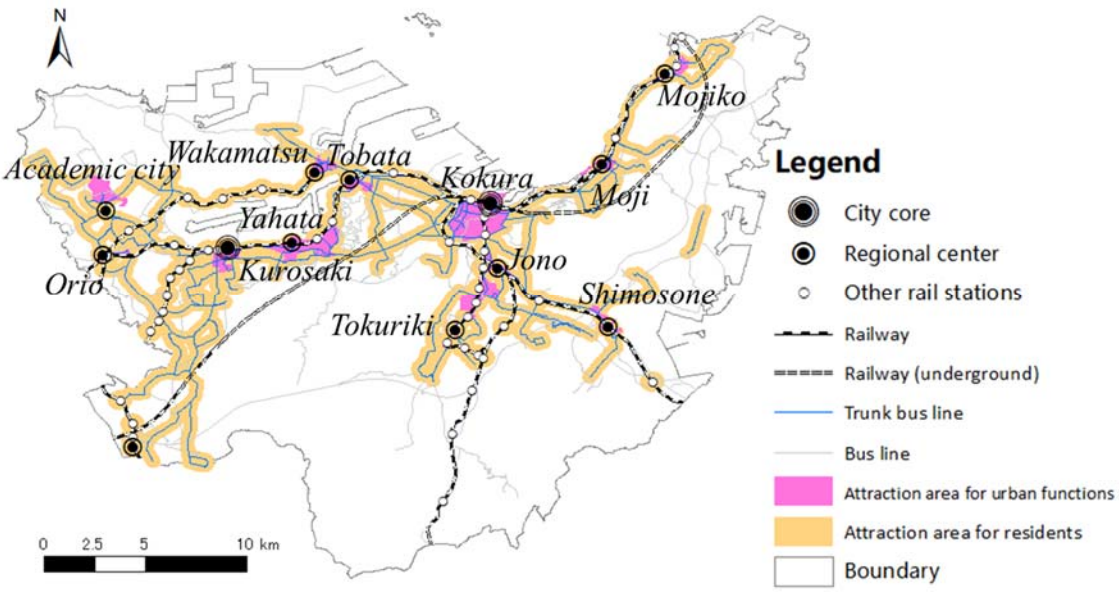


Figure 5-6 Urban Facility Location Plan of Kitakyushu City

The following Table 5-1 is an excerpt from the Urban Facility Location Plan of Kitakyushu City published in 2017.

Table 5-1 Definition of attraction zone for urban functions and residence

Attraction zone for urban functions:
Definition: ● Specified areas where concentrate regional critical urban facilities that supports the citizens' life through continuously maintaining and inducing advanced urban functions.
Zoning method: ● Select out base sites from a set of city center, subcenter and regional central areas according to the master plan.

Attraction zone for residence:
Definition: ● Specified areas including the attraction zone for urban functions where aims at inducing advanced urban function, traffic zones with high accessibility to public transportation, and high-quality residential areas where favorable living environment is continuously maintained with high-efficiency use of public facilities and infrastructure.
Zoning method: ● Covering the attraction zone for urban functions; ● Accessibility to public transportation: within 500 m distance to the railway station, and 300 m distance to the trunk bus routes; ● Including the other areas where favorable living environment has been formed and preserved.

Beyond the possible land use changes lead by the urban facility location plan, there are also various critical factors would change in the future.

(1) Extension of buildings' lifespan. In 2017, the Kitakyushu city government issued a Plan for Extending the Lifespan of City-owned Buildings, which aims at a longer utilization of these public facilities with better maintenance. In case of the city-owned buildings built in 1970s, extend the durable time to 60 years; in case of the city-owned buildings built after 1990s, extend the durable time to 80 years. Although private buildings are not involved in this plan, there is a country-wide trend of increasing the durable time of building stocks through retrofitting and rebuilding.

(2) Decreased density of residence. Being a shrinking city, the overall residential density cannot escape from a decreasing trend. Since the residents have freedom to design the architectural form if satisfying the requirement on plot ratio and other regulations, more and more residents would prefer living into detached houses during the trend of land price decrement. In Kitakyushu City, many collective houses have been observed that were demolished and rebuilt into detached houses.

(3) Proliferation of Cross-Laminated Timber (CLT). In European and American countries, CLT is recognized as a key technology to extend the usage of wooden material in medium-and-high-rise building stocks. Japan also declared to popularize the production and usage of CLT and has already established a specific roadmap for systemic preparation. In Kitakyushu, CLT is expected to be firstly utilized in medium-height buildings.

(4) Proliferation of Net-Zero Energy Building (ZEB). Promotion of ZEB has been identified as a

key measure to realize a low-energy society in Japan. Except for installing high-efficiency energy supply equipment using renewables, heat insulation of building stocks would be substantially improved by upgraded envelop technologies so as to reduce heat consumption to the full extent. In fact, this is a negative factor on the performance of district heating system.

5.1.2 Scenarios setting

With consideration of the possible changes brought about from socio-economy, technology innovation and related policies, scenarios including individual evaluation on one policy and comprehensive evaluation are established. The Table 5-2 describes the mark and content for each individual scenario, these

Table 5-2 Scenarios setting

Factor	Mark	Content
Depopulation	BL	Population keep decreasing; all demolished buildings are rebuilt in the same location as needed.
Compact land use	CLU	Population keep decreasing; part of demolished buildings is re-allocated into the attraction zone for urban functions and residence.
Longer building lifespan	LL	The lifespan of existing building stock is extended for more 10 years utilization after they meet the lifespan; by contrast, all the newly built buildings have 70 years' lifespan.
Low-density residence	DH	All the lower collective houses will be demolished into detached houses when they meet the lifespan.
Proliferation of CLT	WU	All the newly-built lower collective houses and non-residential buildings are made from CLT material.
Proliferation of ZEB	HI	Heat insulation in existing and newly built buildings is gradually improved due to the roadmap of popularizing ZEB.

5.1.3 Parameter settings

According to the 4d-GIS database, public statistics and reports, parameters are set as the follows.

(1) Socioeconomic changes in the future

The socioeconomic factors considered in the model mainly include the rate of population changes assumed to impact on the total floor area of non-residential buildings, the rate of household number changes assumed to impact on the total number of houses, and the average family size (unit: person/household) assumed to impact on the unit energy consumption by floor area. These parameters are summarized in the Table 5-3.

Table 5-3 Main indicators of socioeconomic changes

Year	2015	2020	2025	2030	2035	2040	2045
Total population*	961286	938897	909840	877426	842929	807022	771168
Depopulation rate	-	-2.3%	-3.1%	-3.6%	-3.9%	-4.3%	-4.4%
Household number*	423474	422927	415452	404344	392060	378927	364652
Decrease rate of household number	-	-0.1%	-0.8%	-1.2%	-1.4%	-1.6%	-1.8%
Average family size**	2.27	2.22	2.19	2.17	2.15	2.13***	2.11***

*Predicted value by IPSS (2018).

**Average value of Fukuoka Prefecture.

***Trend value added by the author due to the time series data.

(2) Lifespan of building stocks

Learnt from the past changes of building floor area by building vintage, survival curves of buildings due to the purpose and structure are estimated using the logit distribution. The equation is defined as following:

$$R = \frac{1}{1 + \exp(at + b)} \qquad (5-1)$$

where *R* is the survival rate in building age *t*, *a* and *b* are parameters. The two parameters are calibrated as listed the Table 5-4. In addition, to simulate the policy of extending building operation for 10 more years and lengthen the half-life period over 70 years, parameter *a* is accordingly adjusted while *b* keeps the same.

Table 5-4 Parameter setting for calculating building survival rate

Scenario	Current		Extended use for 10 years		Half-life period > 70 years	
Type	***a***	***b***	***a***	***b***	***a***	***b***
DH-RC	0.047	-2.955	0.041	-2.955	0.042	-2.955
CH-RC	0.074	-4.046	0.062	-4.046	0.058	-4.046
NR-RC	0.063	-3.021	0.053	-3.021	0.043	-3.021
DH-S	0.044	-3.657	0.038	-3.657	0.044	-3.657
CH-S	0.061	-3.165	0.047	-3.165	0.045	-3.165
NR-S	0.074	-2.365	0.055	-2.365	0.034	-2.365

DH-W	0.056	-3.872	0.049	-3.872	0.056	-3.872
CH-W	0.053	-3.093	0.045	-3.093	0.045	-3.093
NR-W	0.058	-1.704	0.043	-1.704	0.025	-1.704

Note: For the meaning of abbreviations, please refer to the Figure 5-6.

As shown in the Figure 5-7, there is a large disparity on survival curve between different kind of buildings. The steel-structured detached houses reveal the longest half-life time at 80 years, while wooden and steel-structured non-residential buildings have shortest half-life time at 30 years. The other kind of buildings have medium half-life time ranging from 45 to 70 years. Generally, detached houses have longer lifespan because they are private properties and receive less impact from land use adjustment, while collective houses have strengthened structure but usually locate in dense urban area that is more frequent to be impacted by land use adjustment. By contrast, non-residential buildings usually are constructed in durable concrete structure, but the most of them are located near city center or district center where land use design is frequently changed. Interestingly, this order of actual lifespan is just opposite to the order of designed lifespan for different kind of buildings.

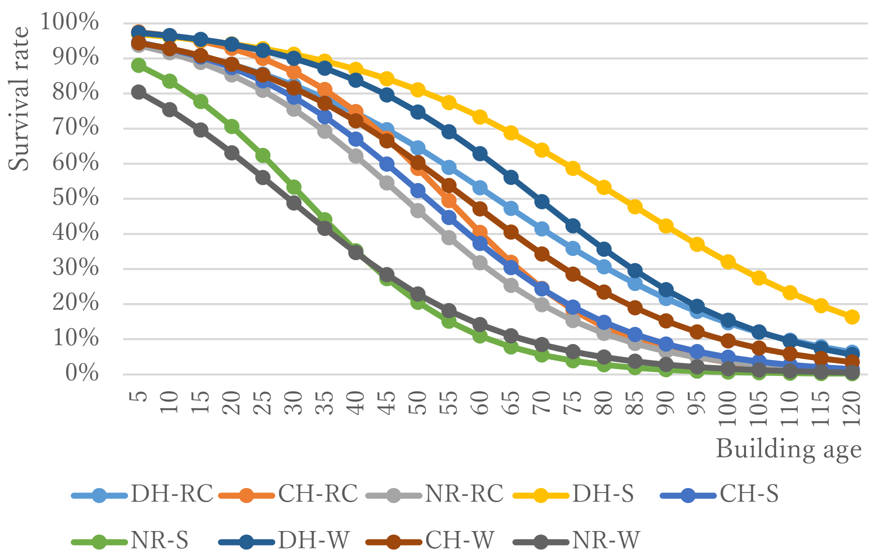


Figure 5-7 Survival curve of buildings due to purposes and structure

(3) Characteristics of neighborhood design

For defining the components of various kind of buildings at neighborhood scale, current characteristics of neighborhood design is referred using building distribution map, based on several hypotheses as follows.

a) The higher is the plot ratio in an area, the more capacity can contain the floor area of non-residential buildings. The Figure 5-8(a) clearly reveals a perfect relationship between the capacity and plot ratio, of which the differential coefficient is a minus quadratic function. It means, the attractiveness of non-residential buildings will increase before plot ratio reaches 200% because of the agglomeration of residents, but decrease later because of crowed infrastructure, market competition and high land price.

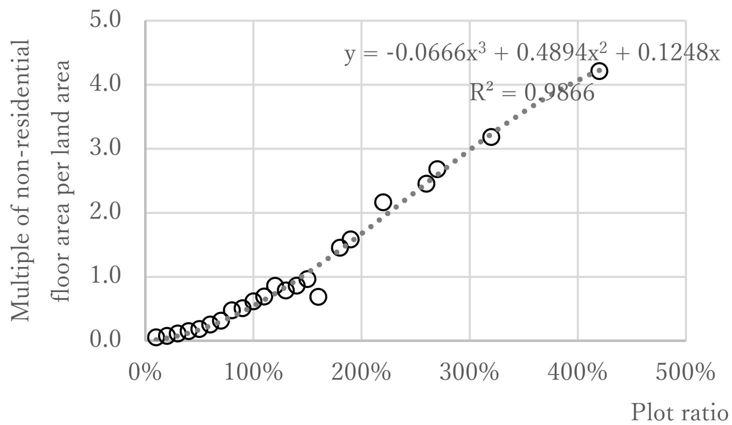


Figure 5-8(a) Non-residential floor area capacity due to plot ratio

b) The height of non-residential buildings is proportional to the plot ratio. This is to define the components of low-rise and high-rise buildings in a mesh area. The Figure 5-8(b) clearly proves this relationship and shows that essentially, non-residential buildings are likely to be higher to support an intensive commercial land use.

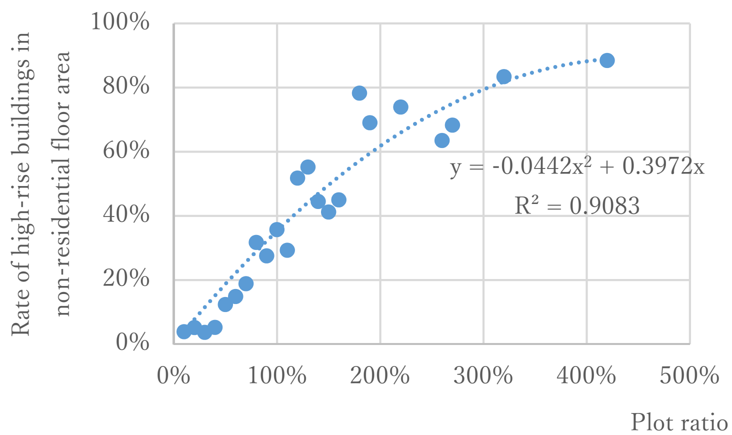


Figure 5-8(b) Proportion of high-rise non-residential floor area due to plot ratio

c) Synergy and trade-off happen between residential and non-residential building location due to the plot ratio. Usually, the plot ratio of residential area is limited within 200%, while commercial area can have plot ratio over 200%. At first, migration into an unoccupied area will attract commercial and business service, which in return attract more migration from the outside. However, too crowded commercial and official buildings also cramp the space for residence that leads to a trade-off. As expected, the Figure 5-8(c) well interpreted this correlation.

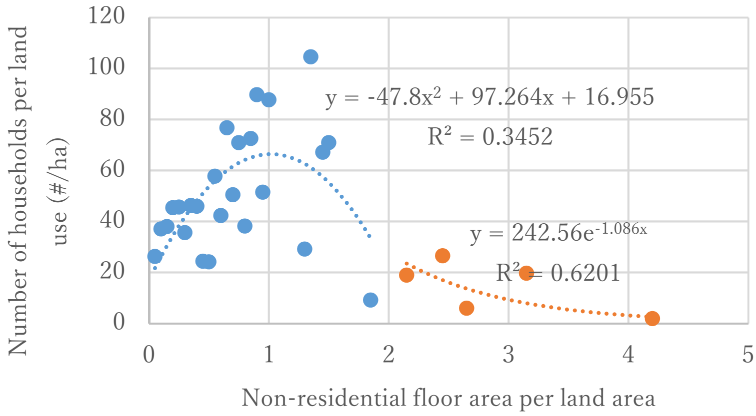


Figure 5-8(c) Correlation between residential buildings and non-residential buildings (blue points: plot ratio <= 200%; orange points: plot ratio >200%)

d) The proportion of collective houses, especially high-rise collective houses, is in direct proportion to the plot ratio. Both the two hypotheses are confirmed in the Figure 5-8(d). Since two-floor apartment and tenement house are two popular architectural forms in Japan, the proportion of collective houses starts from 40%, even in the place where the plot ratio is quite low.

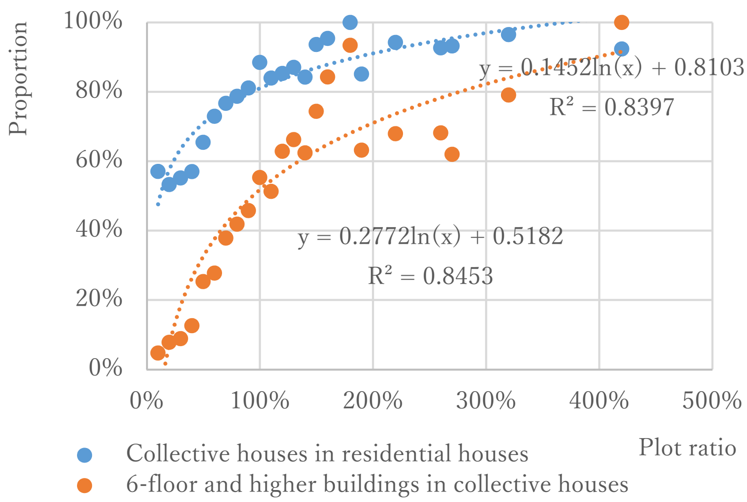


Figure 5-8(d) Proportion of collective houses in residential houses due to plot ratio

(4) Characteristics of building structure

After defining the neighborhood design, finally the structure of each newly built building should be identified. Due to a statistics of current building distribution, the possibility of building structure due to the height of building are estimated as shown in the Figure 5-9. As expected, the most of detached houses are made from woods, while the most of high-rise collective houses and non-residential buildings are made from reinforced concrete. Steel-structured buildings often appear as lower collective houses and non-residential buildings.

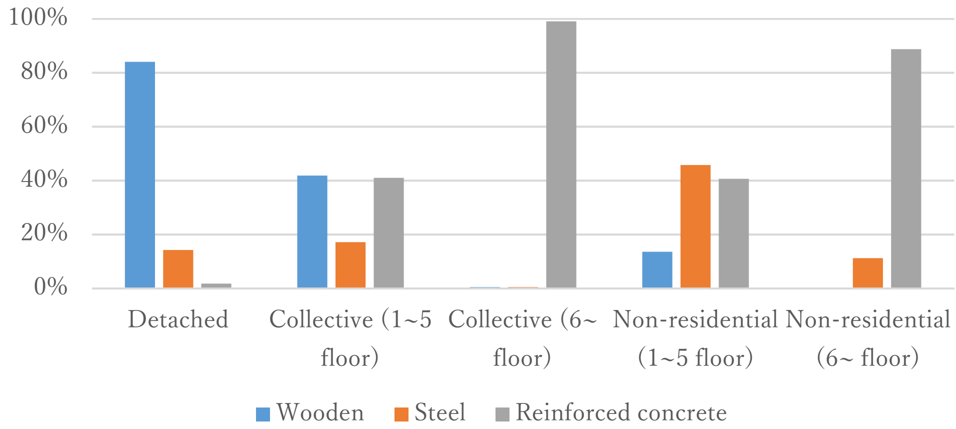


Figure 5-9 Building structure changes due to the height of building

5.2 Long-term demand changes during urban renewal

5.2.1 Distribution changes in building location and structure

The results of estimated future building floor area distribution by scenarios are summarized in the Figure 5-10. Generally, the total building floor area decreases in all scenarios because of the decrement of total population. However, the proportion by different type of buildings reveals a large variation. Comparing the current situation with BAU-BL in which no policies are carried out, the total floor area decreases but the part of wooden detached houses remains stable. This pattern is also similar in scenario CLU-BL and CLU-LL. By contrast, the trend of demolishing collective houses into detached houses is found greatly increase the floor area of detached houses while the total floor area is decreasing. In addition, promoting the usage of CLT in lower collective houses and non-residential buildings is indicated having a large potential in increasing the proportion of floor area, but the total floor area does not change a lot. Furthermore, comparing the scenario BAU-ALL and CLU-ALL, both the total floor area and the proportion are quite similar, which indicate that compact urban planning proposed in the Facility Location Optimization Plan actually would not impact a lot in the quantity of building floor area and building structure.

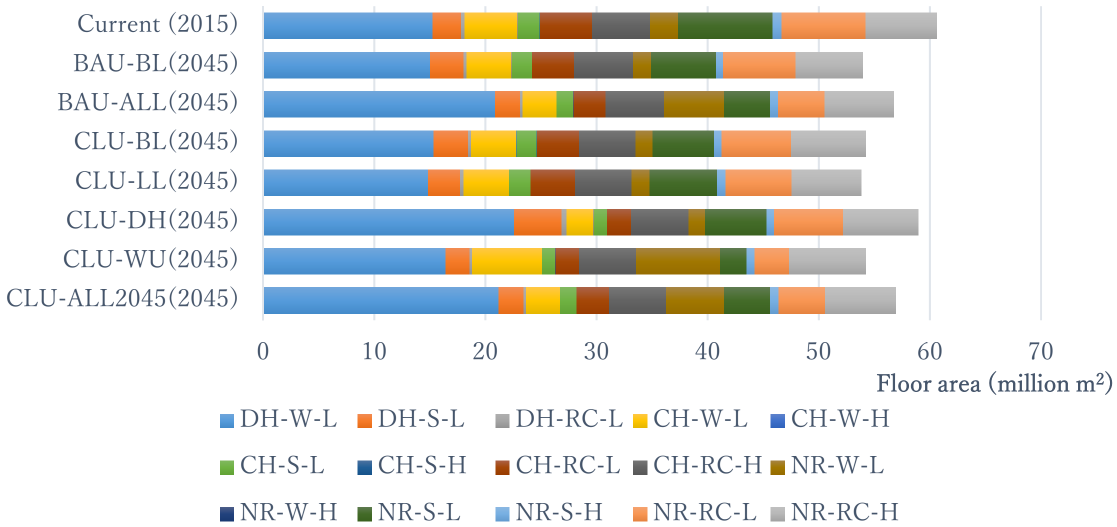


Figure 5-10 Building structure changes due to the height of building

Although the total building floor area and its proportion by building category are quite similar between the scenario BAU-ALL and CLU-ALL, the spatial distribution of buildings are quite different. Firstly, the difference of plot ratio distribution between the two scenarios by 2045 is shown in the Figure 5-11(a). Obviously, large difference of plot ratio happens in the areas which are identified as attractive zone for residence and urban function in the master plan. Comparing to the scenario BAU-ALL, citizens are indeed migrating from the suburbs to the areas near central and regional rail stations, especially the stations such as Kokura, Yahata, Moji and Mojiko. In these station districts, compact land use planning seems able to increase the plot ratio by around 15% than BAU scenario.

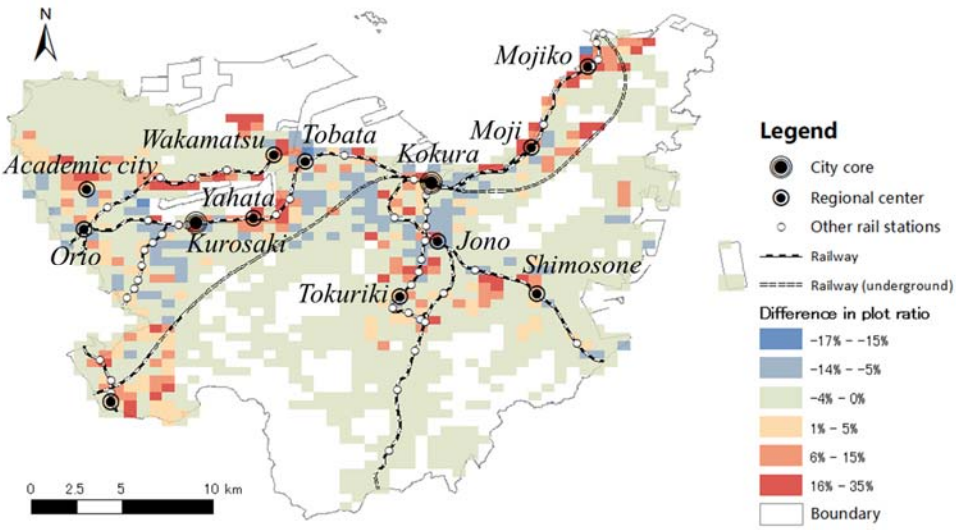


Figure 5-11(a) Difference of plot ratio distribution by 2045 between BAU-ALL and CLU-ALL

Focusing on the relocation of high-rise buildings including collective houses and non-residential building, compact land use in scenario CLU-ALL also shows a clustering effect than the scenario BAU-ALL. As shown in the Figure 5-11(b), central station Kokura and regional stations such as Yahata, Academic City and Tokuriki have relative high potential to attract more high-rise buildings.

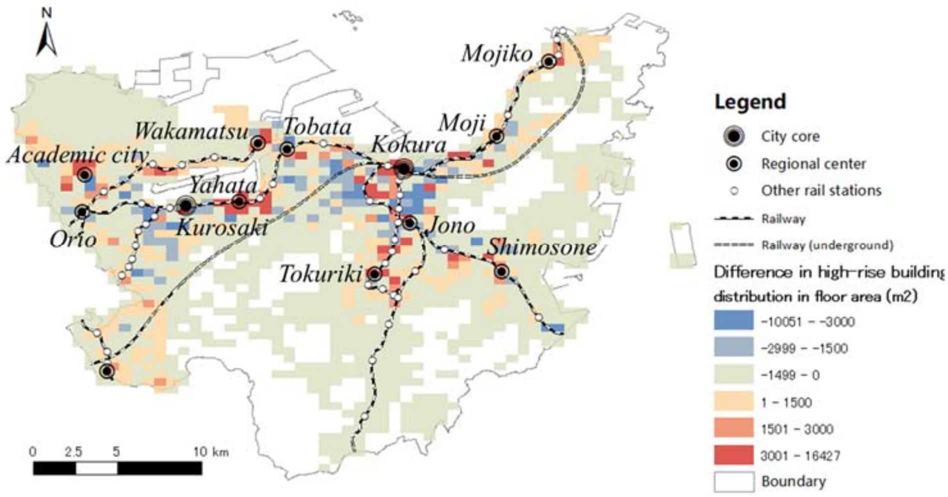


Figure 5-11(b) Difference of high-rise buildings' floor area distribution by 2045 between BAU-ALL and CLU-ALL

In addition, the distribution of wooden houses by 2045 also reveals a large difference between compact city scenario and business as usual, as shown in the Figure 5-11(c). Because the higher is the plot ratio of an area, the lower proportion detached houses would take, the attracted migrates build detached houses in identified compact residential zone but somehow keep a distance to the station districts. The districts nearby station Mojiko and Academic City reveal high potential for detached houses because of their relatively lower initial plot ratio.

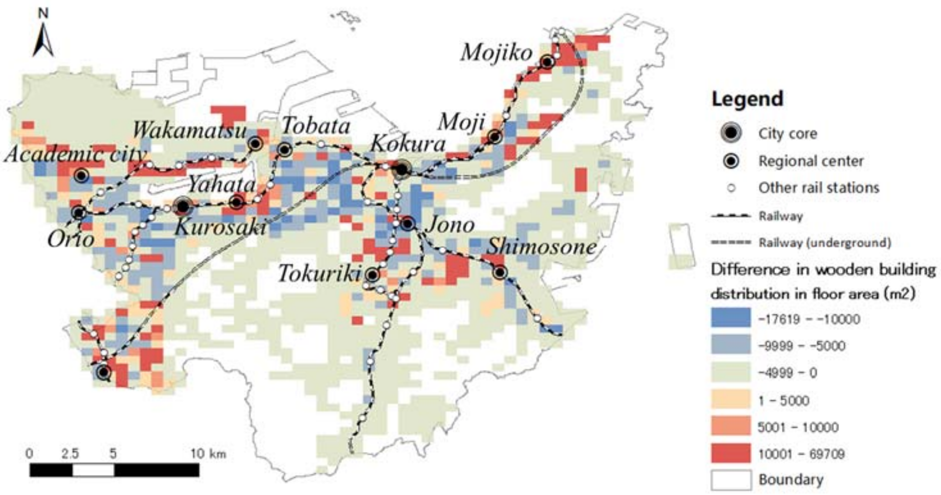


Figure 5-11(c) Difference of wooden houses' floor area distribution by 2045 between BAU-ALL and CLU-ALL

5.2.2 Changes of material and energy consumption by scenarios

Based on the building distribution and structure changes mentioned above, material and energy consumption can be estimated as follows.

As shown in the Table 5-7, generally the accumulation of building stock demolished is much larger than the quantity newly built during the period 2015-2045, but the accumulated quantity and speed are quite different between scenarios. From the sight of total quantity, scenario BAU-BL, CLU-BL, CLU-DH and CLU-HI have similar value, while BAU-ALL, CLU-LL and CLU-ALL have much less value in comparison. This indicated that the critical factor influencing the path of building retrofitting is the measure on buildings' lifespan extension, not the compact city planning proposed in the Facility Location Optimization Plan. However, even in the scenarios which have the similar accumulated stock retrofitting quantity, the proportion by material type are quite different. For example, the wooden material input in CLU-DH is higher than it in CLU-BL, but at the same time the material input of cement and concrete is also higher than it in CLU-BL. This indicates although the preference of transferring collective houses into detached houses can increase the wooden material use, somehow the other material input may also increase because of higher material input intensity per person in detached houses. The really effective measure is to promote CLT usage in low-and-medium-height buildings, which is estimated to substantially reduce the material input of cement and concrete in comparing scenario CLU-BL with CLU-WU. By contrast, the proportion in BAU-BL and CLU-BL are not obviously different that indicates compact city planning in this shrinking city will not change the building structure a lot.

Table 5-7 Accumulated building stock newly built and demolished during 2015-2045

Newly built	BAU-BL	BAU-ALL	CLU-BL	CLU-LL	CLU-DH	CLU-WU	CLU-HI	CLU-ALL
Cement	1658	825	1658	999	1714	1217	1658	830
Concrete	14234	6724	14223	8557	14455	10000	14223	6755
Stone	21168	11436	21203	12793	22645	16642	21203	11508
Wood	2047	3086	2106	1332	3198	4184	2106	3117
Steel	329	100	327	195	324	154	327	100
Total	39436	22171	39516	23875	42336	32197	39516	22309
Demolished	**BAU-BL**	**BAU-ALL**	**CLU-BL**	**CLU-LL**	**CLU-DH**	**CLU-WU**	**CLU-HI**	**CLU-ALL**
Cement	2053	1425	2053	1430	2051	2034	2053	1425
Concrete	17578	12170	17575	12245	17555	17344	17575	12171
Stone	26405	18384	26399	18377	26400	26334	26399	18383
Wood	2520	2001	2522	1823	2551	2970	2522	1998
Steel	420	280	420	287	419	399	420	280
Total	48977	34260	48968	34163	48975	49081	48968	34258

Unit: thousand m^3

From the perspective of net accumulated material input, some different results can be concluded as shown in the Figure 5-12. Although extending the lifespan of buildings can slow down the path of building retrofitting, the net material input is not quite different to the other scenarios. Generally, the net accumulated material input and its proportion are quite similar between the scenario BAU-BL, CLU-BL, CLU-LL, CLU-HI that reveals both compact city planning and building lifespan extension are not main factors influencing the changes in building structure. Meanwhile, promoting CLT usage in buildings reveals to be a powerful measure to reduce the material input of cement and concrete.

Oppositely, the current trend of changing collective houses into detached houses is unexpected that may increase the material input of cement and concrete. As compared the scenario CLU-ALL with CLU-BL, the total effect of combining all the policies is estimated to lead to about 50% more reductions in net material input.

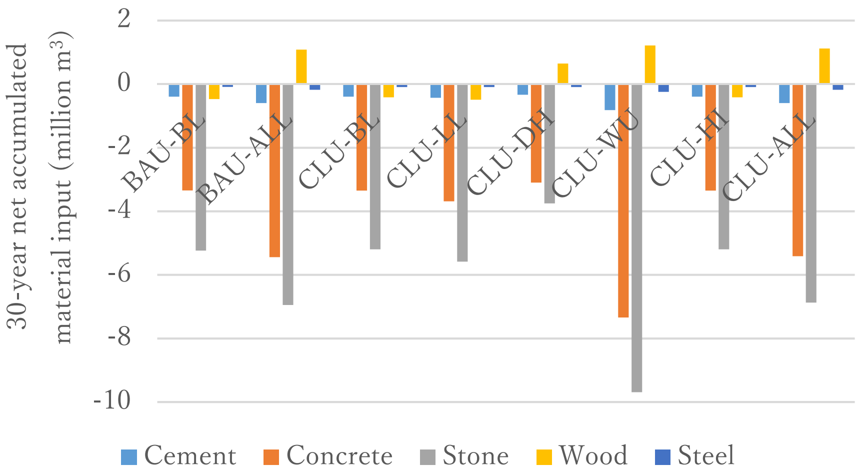


Figure 5-12 Net accumulated material input during 2015-2045

On the other hand, the changes in building location and structure also lead to the changes of head demand distribution. In the sight of the trend in total energy demand, all scenarios reveal rapid decreasing total energy demand because of the unavoidable depopulation in Kitakyushu City. However, the level of decrement is different between scenarios, as shown in the Figure 5-13. In scenario BAU-BL, where no policies are carried out except the trend of depopulation, the total energy demand decreases from 26.5 PJ to 22.4 PJ, similar to the results in CLU-BL, CLU-LL, CLU-WU. This indicates the location changes by compact city planning, building lifespan extension and structure changes to wooden collective buildings using CLT are not main factors influencing the total energy demand. By contrast, heat insulation improvement through the popularization of ZEB/ZEH reveals a deep impact in energy demand reductions in scenario CLU-HI, but the impact would be offset by extended building lifespan and other polices as the results of BAU-ALL and CLU-ALL. Only one exception, the trend of changing collective houses into detached houses leads to more energy demand, but this increment may be also offset by more introduction of solar panel which needs added discussion in the design of energy supply system.

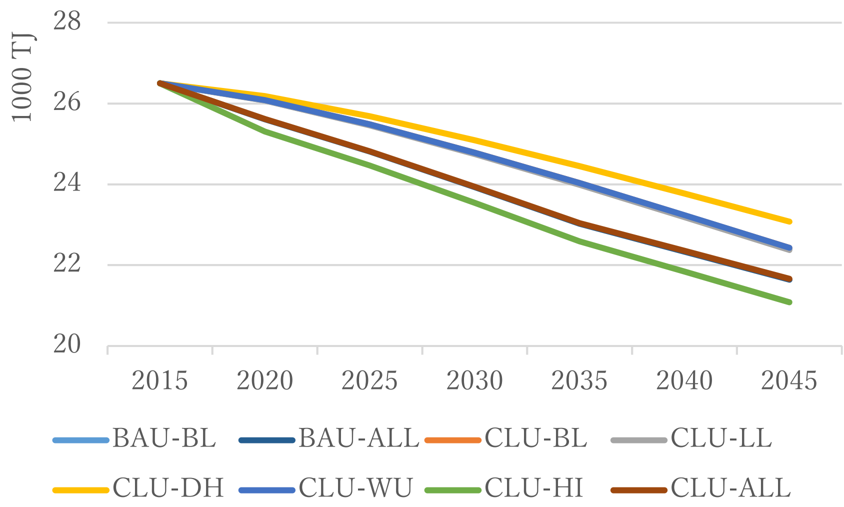


Figure 5-13 Trend of total energy demand in building operation

Although the total energy demand is near between the scenario BAU-ALL and CLU-ALL, the distribution of energy demand reveals quite different, as shown in the Figure 5-14(a)(b). The former map shows the changes in heat demand distribution of scenario BAU-ALL between the year 2015 and 2045. Most of the mesh areas in the city show a decrement of heat demand, especially the meshes with high population density and a little faraway from regional stations. However, many meshes in suburb and rural region reveal increasing heat demand, because of the higher energy demand intensity during the transition from collective houses to detached houses. Obviously, without compact urban planning, the economic declines in city center and subcenters cannot be avoided that leads to lower and more dispersed energy demand distribution.

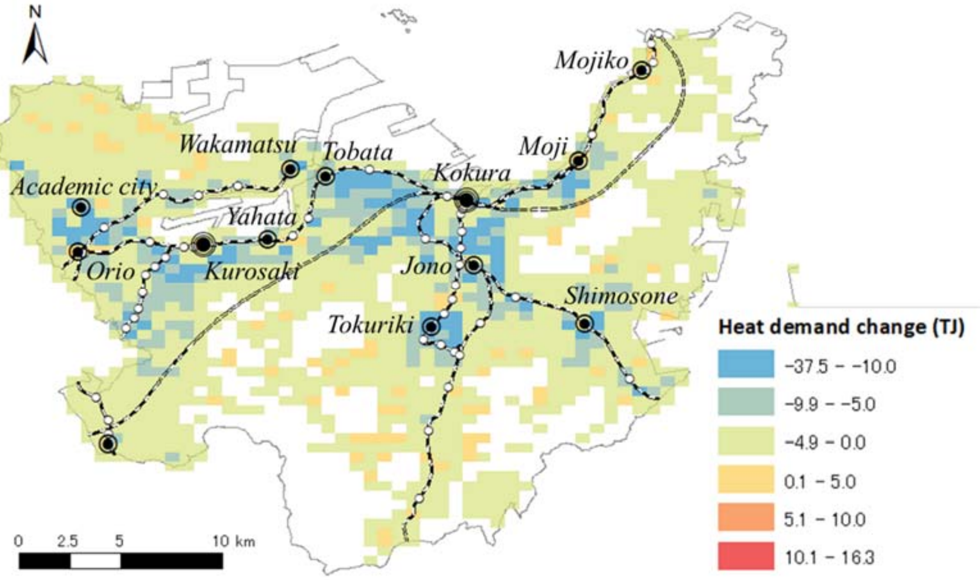


Figure 5-14(a) Distribution change of heat demand in scenario BAU-ALL (2015-2045)

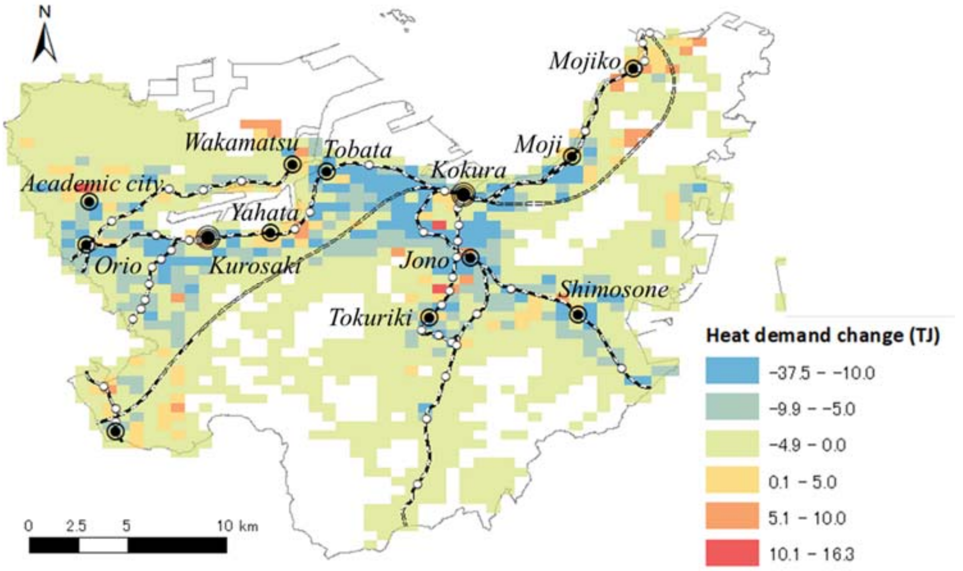


Figure 5-14(b) Distribution change of heat demand in scenario CLU-ALL (2015-2045)

By contrast, the latter map shows a different trend in scenario CLU-ALL. Although many collective houses are demolished into detached houses in suburb and rural region, half of the residents migrate to the city center and subcenters that can maintain or enhance the population density in such areas. However, the meshes, which currently have high population density but are not identified as target areas for concentrated living, still cannot avoid a rapid decrement in population density and energy demand density.

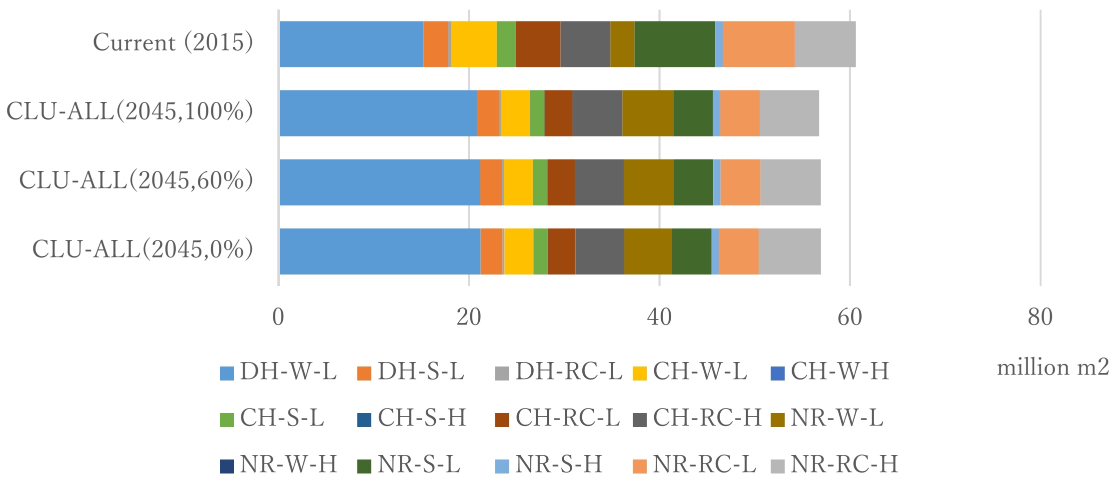
5.2.3 Sensitivity analysis

Because the main research target is the case of Kitakyushu City is focusing on impact from urban renewal on energy demand with high-resolution simulation, the only concerned assumption is how much rate of residents wish to migrate to other place while their houses meet the lifespan. Thus, two scenarios using different migration rate are added in discussion.

- CLU-ALL(100%): 100% of residents continue living in the same place.
- CLU-ALL(60%): 60% of residents continue living in the same place (the same as Section 5.1.2).
- CLU-ALL(0%): All of residents migrate to the attractive area for residents while their houses meet the lifespan.

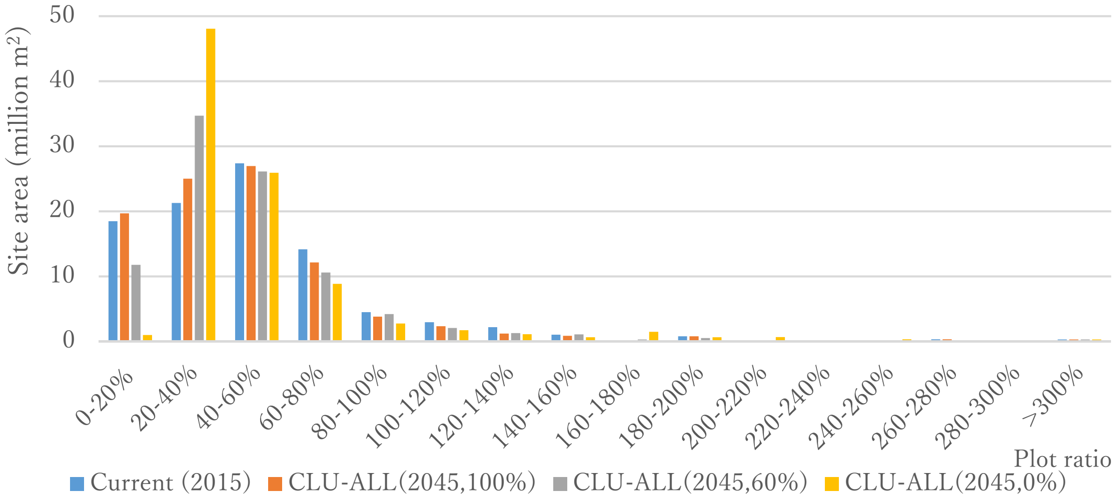
Result as shown in the Figure 5-15 reveals an interesting phenomenon: the distribution of building floor area in the future does not change a lot between 3 scenarios. This is because the defined attractive area for residents may be too wide to accept the migrate, where detached houses have sufficient site place to locate. In this perspective, migration rate may not be a sensitive parameter in predicting the component of building type in the future.

Figure 5-15 Distribution change of heat demand in scenario CLU-ALL (2015-2045)



The difference in the component of site area by plot ratio in added scenarios within attractive area for residence can prove this reason. Even though the migration rate changes from 0% to 100%, the actual changes are mainly happening in attractive areas of which the plot ratio is lower than 40%. In these areas, detached houses are easy to locate, even some of them are coming from the higher-plot-ratio attractive areas. In conclusion, the assumption on migration rate is indicated sensitive to part of the areas of which the plot ratio is lower than 40%.

Figure 5-16 Component of site area by plot ratio in added scenarios within attractive area for residence.



5.2.4 Proposal: Symbiotic energy planning considering strategic urban renewal

Based on the estimated future distribution of energy demand, it is possible to conduct a comprehensive long-term energy planning for realizing a deep decarbonization in energy sector. However, this requires much more information regarding the optional individual and district energy technologies as well as more complex spatial analysis and energy flow optimization for multi-generation system design. Thus, this section only provides a long-term energy vision, as shown in the Figure 5-17.

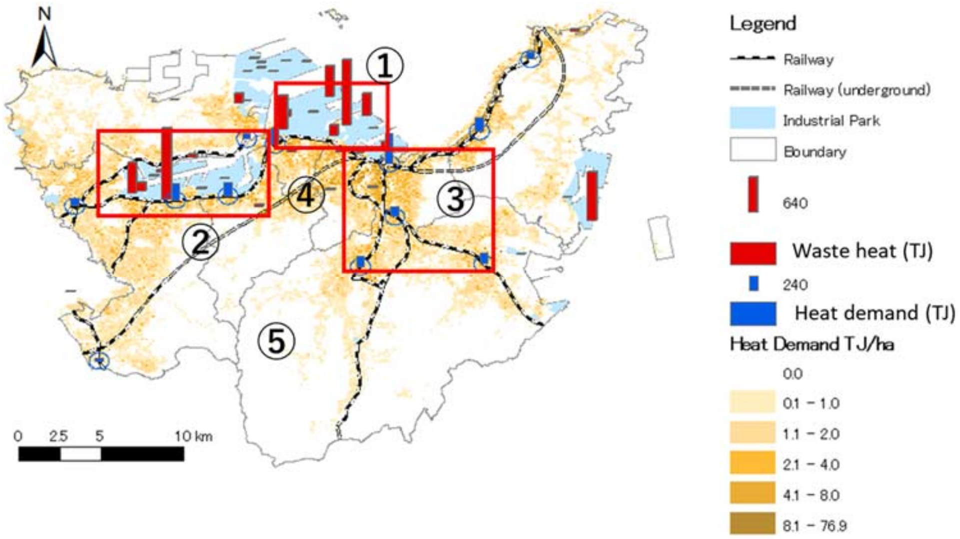


Figure 5-17 Proposal of long-term energy vision for Kitakyushu City

According to the local characteristics, the city can be differentiated into 5 zones with specially selected energy systems as follows.

- Zone type ①: Apply a broad heat exchange network between large industries in Hibikinada industrial park;
- Zone type ②: Introduce district heating and cooling systems using industrial waste heat to nearby station districts;
- Zone type ③: Introduce district heating and cooling systems using heat pump or biomass cogeneration in station districts with higher population density but faraway from waste heat sources;
- Zone type ④: Efficient heat pump using geothermal and other renewal heat can be an option for suburb and rural low-density areas, combining with solar power systems;
- Zone type ⑤: Speed up the migration from the rural shrinking areas to nearby station districts.

5.3 Summary

This chapter conducted a case of Kitakyushu City of Fukuoka Prefecture in Japan and discussed the possible impacts on stock material input and heat demand distribution from strategic urban renewal in quite detailed resolution. A complete 4d-GIS database of building distribution for past four decades are established, in which the buildings are differentiated into 3 purposes (detached houses, collective houses and non-residential houses), 3 type of building structure (wooden, steel-structured and reinforced concrete) and 2 elevation levels (low-rise and high-rise building). According to the lifespan for each type of buildings estimated by accumulative hazard method, a simulation of urban renewal based on the latest Facility Location Optimization Plan of Kitakyushu City was progressed to reflect the corresponding changes in stock material consumption and energy demand distribution.

Results indicate the proposed compact urban planning may not have obvious impact on the total net stock material input and total energy demand but restructure the distribution of energy demand through migration from suburbs to city centers and subcenters. As a result, the total building floor area decreases to 57 million m^2 by 2045 due to the decreasing population, and the proportion of detached houses is likely to increase and over 1/3. Although compact city plan itself reveals not significant to affect total material and energy consumption during urban renewal, it is indicated to effectively slow down the density decrement in city center within 20%, as well as bring maximum 35% density increase in some nearby areas. However, only maintaining the population density is not enough to keep a certain energy density, even in some regional station districts energy consumption may face a 30% decrement by 2045.

Being similar with the case of Soma Region, synergy and trade-off between various policies are tested which indicate that, increased detached houses have negative impact on material and energy consumption reduction, but the positive impact from promoting CLT and heat insulation (ZEH) doubles than the negative, respectively. Toward a real low-energy city, it is necessary to clearly consider the multiply effect and trade-off between the policies. On the other hand, sensitivity analysis on migration strength shows, migration rate, which represents the wish of residents to move to attractive area, has small impact on the total and component of future building floor area, but it may largely affect on the floor area distribution in attractive areas of which plot ratio is lower than 40%.

Based on the changes in energy demand distribution, this chapter proposed a possible long-term energy plan combining different technologies according to local characteristics, e.g., heat exchange network can be established in Hibikinada Industrial Park, while district heating and cooling system can be introduced in station districts at the fringe between urban area and industrial park. In other station districts which has concentrated heat demand but far away from industrial waste heat, district heating and cooling system using heat pump or biomass can be a competitive option. In other vast suburb and rural region, tentatively individual power system such as solar panel is expected to be introduced during the progress of building retrofitting.

6. Conclusion and next frontiers

6.1 Main findings

This study developed an integrated energy planning model considering long-term strategic urban renewal which substantially impacts on future energy demand distribution that leads to different scenarios of proliferating district energy systems. Particularly, emerging measures and practice on compact city planning, cascade energy use and energy symbiosis design are taken into consideration, which are thought to lead the systemic revolution in cities towards future ultra-low-carbon societies. Two case areas, Soma Region in Fukushima Prefecture and Kitakyushu City in Fukuoka Prefecture of Japan, were chosen for model application and verification. Results not only revealed the performance of model development in this study, but also indicated the necessity and effectiveness to integrate urban renewal strategy with energy planning so as to enhance the overall efficiency of urban energy supply system.

Firstly, from the perspective of technology assessment, this study identified plot ratio as a basic and critical local geographic character to bridge the urban planning with feasibility study of district energy system. The integrated model indicated that, there is a minimum heat price with related minimum plot ratio that are required for introducing district energy system. In case of district energy system based on gas-fired cogeneration, the minimum heat price is found hard to be lower than 3 JPY/MJ (due to the situation, the required heat price may over 8 JPY/MJ), but using waste heat for district heating it may decrease to be lower than 2 JPY/MJ where the related required plot ratio can decrease towards 50%.

Secondly, from the perspective of stock management in urban renewal, this study discussed the possible impact from compact urban planning on the future population and building distribution, particularly in a high resolution using 4d-GIS database, considering the integrated effect of various policies. Both in Soma Region and Kitakyushu City, compact city plan has potential to maintain, even increase population density around central and regional railway stations. However, in depopulation background, current compact city plan in Kitakyushu City reveals insignificantly impacting on building type changes to avoid the transition to detached houses. In Kitakyushu, policies on promoting CLT and better insulation in buildings can cover the rebound effect from detached houses in material and energy consumption, but the decrement in energy demand may over the increment caused by compact city plan.

Thirdly, from the perspective of proliferating district energy system during urban renewal, this study discussed the feasibility of introducing district energy system in low-energy-density cities and quantitatively identify the impact from various factors not only in urban renewal and energy system, but also in technology innovation and external environment. In detailed, it is indicated that district energy system is feasible to be introduced into low-density cities if the minimum plot ratio was satisfied. However, the threshold value of plot ratio is different according to city's local characters and always changing with the progression of urban renewal and technology diffusion. Therefore, although plot ratio is important for connecting to district energy network, the critical factor for keeping feasibility is still the system transition to renewables and waste heat.

Furthermore, learnt from the sensitivity analysis and case application result, this study helped categorize and quantify the impact from various factors, i.e. opportunities including technology innovation, co-groove diffusion, energy price increment, and accessibility to waste heat, barriers including lifespan extension and heat insulation of buildings, and risks including access rate of district energy network and migration strength. Combining the opportunities, smartly escaping from the barriers and risks should be an important issue for developing district energy network.

As a pilot research, this study especially contributes to the following academic fields.

- Contributions to the research field of energy planning. This study developed an integrated energy planning and assessment model to identify the detailed content and mechanism of long-term demand side management, which is now recognized as an indispensable content for low-carbon energy transition in future cities.
- Contributions to the field of urban planning. Integrated planning has been identified as the main direction of current planning system reform in cities, where cross-sector co-design and cooperation are required. This study provided a perspective and quantified evidence that help in the decision making of integrating urban energy and land use planning.
- Contributions to the practice of district energy system. This study proved the proposal of five-generation district heating system, and further proposed a planning and assessment method to embed urban and industrial symbiosis to enhance the performance of district energy system. In addition, the perspective from urban planning also helped in extending the scope of feasibility study. Through the cooperative projects with the stakeholders in the two case regions, the opportunities of project implementation identified in this study are possible to be really

implemented.

6.2 Policy implications

Being a disciplinary research, this study realized a connection between energy planning and long-term urban renewal and applied a set of framed models in case studies of Soma Region and Kitakyushu City. Learning from the application results, several cross-sectoral policies are proposed for supporting the decision making during urban long-term renewal management and energy planning.

(1) Appropriate geographic delineation of compact living area

In case of Soma Region, because only regional core station districts are recognized as target compact living areas, the target area itself is compact in area so that it is easier to maintain and even increase the plot ratio, especially considering the background of refugees returning and city center redevelopment. However, in Kitakyushu City, target compact living area along trunk bus route seems to be vast for decreasing population that the rapid increment of detached houses may become a problem. According to population changes, dynamic management of the geographic boundary for compact living is important to avoid virtual urban sprawling in depopulation condition.

(2) Linked management between urban planning and district energy system

Through the integration between energy planning and urban renewal, this study indicated the effectiveness of long-term renewal management in promoting district energy systems. One important and possible measure for district-energy-oriented urban renewal strategy could be setting target of minimum plot ratio in zones based on local characteristics of resource endowment.

Usually, maximum plot ratio regulation was usually in urban planning system to regulate the development intensity of identified zones. During the past rapid economic growth period, such regulation had been successful in avoiding the excessive concentration of migration from the suburbs to the city center and kept an ordered urban sprawl and appreciated city view. However, currently the local cities have already turned into a shrinking progress that depopulation and inoccupancy in buildings seriously spread from city center to the suburbs. Therefore, setting target minimum plot ratio also becomes a key performance indicator for urban management sector. Here, the minimum plot ratio not a mandatory indicator for land developer but a target of building stock management which is flexible due to the progress of district energy system. Also, this can be a reference indicator for the management of unoccupied houses in city center and station districts.

(3) Pricing initiative from district energy system transition

In this study, access rate of district energy system is a quite risky factor impacting the feasibility study of introducing district energy system. However, this study also identified the pricing mechanism of heat sales that, not only fuel purchase cost, but also technology innovation and urban renewal management such as plot ratio management and co-groove diffusion can be positive factors for reducing heat sales price. In this perspective, district energy companies should make long-term plan in decreasing heat price through system innovation and connection to renewables and waste heat sources to keep the competitiveness and avoid the risk from decreasing network access rate.

(4) Co-design of energy system and policies in urban planning

The case studies have indicated the substantial cost saving and CO_2 emission reduction through energy symbiosis between multi sectors. In fact, because of the increasing price of energy and pressure of taking measures in dealing with climate change, companies have recognized the great risk in long-term energy supply and the importance of energy transition to renewables and unused heat. Symbiosis mechanism will gradually influence to the large industries of which energy purchase cost takes a high proportion in total costs. Recent cases in Nordic countries have indicated that, combining energy symbiosis with material supply chain design in the circle of biomass economy can help in attracting related factories to realize a win-win benefit by strengthening the whole circular value chain.

On the other hand, in the energy symbiosis proposed in this study, municipal and agriculture wastes can be used in industries, while industrial waste heat can be recovered for district heating in urban area and facility agriculture. Fringe areas between urban, industries and agriculture are possible to be a new hot-spot area for symbiotic urban redevelopment, where new business such as city sightseeing agricultural park, farm-fresh local supermarket, technology incubation center could locate to promote "local consumption of local production" (including local energy). If no conflict to the master plan toward a compact city, such urban fringe area can be also an optional place for developing new town to help shorten the commuting distance between jobs and houses. In this case, a cross-sector co-design among the city, industries, agriculture and forestry is indispensable.

(5) Funding initiative from energy company to public finance

For attracting migration to the city center and filling in the unoccupied houses, local government usually takes a part of government budget as subsidies for relocation and house retrofitting. The efficiency of these subsidies is often doubted and hard to be quantified. In fact, this cost can not only be recovered from maintaining commercial sales in city center, but also be value added by creating local energy companies, and returned into government budget through tax income. This study could provide a tool to quantify the multiplier during this funding circle.

6.3 Uncertainties

Uncertainty is thought as a critical concern in any simulation on future changes. Although this study tried the best to take all possible changes of related factors into consideration, still there are many factors excluded from the current model framework.

(1) Emergence in technology innovation

Technical assessment and comparison between technologies is a quite difficult task because of too many influence factors and their complicated interaction. As a trend, centralized heat pump has high possibility to substitute boiler and cogeneration because of its higher annual performance in total energy efficiency, but it may also be substituted by distributed heat pump if no pipeline network was existing and grid electricity was decarbonized enough. Moreover, the information of emerging optional technologies, such as Hydrogen-related technologies and thermoelectric materials, are still insufficient to be taken into future simulation.

(2) Complexity in location preference

In this study, the relocation of buildings and industries in scenarios is assumed following the guide of master plan. However, the actual location behavior is much more complex, even either of current urban economic models can provide accurate prediction. For example, in Tokyo Metropolitan Area residents are found returning from the suburbs to city center faster than expected without any location subsidy and encouragement. It is hard to judge if local cities can enjoy the same trend of migration. By contrast, environmental concerns are also initially not coinciding with the industry-side target of optimal location, unless it has been embedded in its decision mechanism. In this sense, the scenarios and cost-benefit analysis conducted in this study is not aiming to accurately predict the location impulsion of factories, but to make quantitative assessment on the basis if location behavior follow the guide of master plan. Then the results could provide some evidence for industries which may be taken into account for future location decisions.

(3) Behavior change and public acceptance

This study simply assumed all the buildings in target area are able to connect to district heating network. In fact, it is not a duty in Japan so that recently very few residents turn to connect to district heating because of the higher price than kerosene stove. However, central air-conditioning systems are now gradually popularizing in newly built detached houses and collective houses, which make them easier to connect to district heating network. In addition, people will feel more comfortable with floor heating rather than small air-conditioner and Kotatsu (a table with an electric heater attached to the underside of the table), so that increases the heat consumption intensity in space heating.

(4) Energy market changes

In the long term, energy market is also a complicated variable factor, of which energy price and structure will change. Although the price of fossil fuels is thought likely to increase while it of renewables will decrease gradually in the future, new energy resources such as shale gas and combustible ice may be dark horses to break the equilibrium between fossil energy and renewables. In another word, although environmentalists tried to internalize the externality of environmental impacts into energy market, at bottom energy suppliers are paying more attention on the short-term profit of energy sales.

Although this study faces many uncertainties mentioned above, it has provided enough information as evidence for energy policy making from urban planning perspective, also a preliminary process and manual for technical assessment. Thus, the model development can be further extended and include more submodules according to the needs.

6.4 Next frontiers

This study provided basic perspective and idea for model development that still needs further improvements as summarized below.

(1) Additional assessment considering more emerging technologies

As mentioned before, the district energy system proposed in the cases is firstly based on gas-fired cogeneration using local natural gas resources, then transit to cascade use of waste heat between various sectors. Such proposal is generally belonging to the 3rd generation district heating technology according to the current classification in academy. With the more usage of renewables in power generation sector and cost down of heat pump technology, gas-fired cogeneration in district heating may be substituted by centralized heat pumps in later decades. Furthermore, transition toward all-electric houses may quicken the popularization of roof-top solar panel with individual heat pump, which would compete with district heating more seriously. However, efficient seasonal heat/power storage and Phase-Change Material (PCM) for heat transmission can make a concrete reason in proliferating district heating system, especially in case of promoting Hydrogen economy. In addition, industrial waste heat would also exist for a long term to support the competitiveness of district heating. All these energy technology visions should be evaluated combining with urban planning scenarios to realize a long-term optimization for urban energy systems.

(2) Optimization model considering technology selection with geographic aspects

Long-term demand-side management during urban renewal proposed in this study is actually an optimization approach for urban energy planning from the perspective of land use planning. However, the parameters used in the assessment model are just typical value based on previous studies. Project-level energy system optimization methods, such as linear programming, are expected to be embedded as supplement to this study. Downscaling the results from long-term scale to short-term scale would support more details in optimal technology selection and total investment reduction during the transition toward real low-carbon urban energy systems.

(3) Integration with computable urban economic models

Urban simulation based on 4d-GIS database is indicated as an easy and effective tool to track the influence from proposed urban renewal strategies on material and energy consumption in the future. However, although this method is quite useful for local municipalities in determining the target indicator of stock management and energy policies, it is difficult to define and quantify the economic encouragements for policy implementation because of the lack of urban economic and market mechanism. In fact, the very detailed and historical dataset through 4d-GIS could be a powerful support to establish reasonable urban economic models. Through the combination between 4d-GIS and computable urban economic models, not only policy targets but also economic incentives can be identified and quantified for a comprehensive urban planning towards low-carbon sustainable urban development.

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