Energy System Analysis

TOHOKU UNIVERSITY

Design and analysis of district heating system utilizing excess heat in Japan

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1. Introduction
2. Methods
3. Results and discussion
4. Conclusions

Outline

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2. Methods
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Rebunto Is.
Kunashiri Is.
Etorofu Is.
Shikotan Is.
HABOMAI ISLANDS
Sapporo
Okushirito Is.
Aomori
Akita
Morioka
ORTH KOREA
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OKI ISLANDS
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Nishinoshima Is.
OGASAWARA
Chichijima Is.
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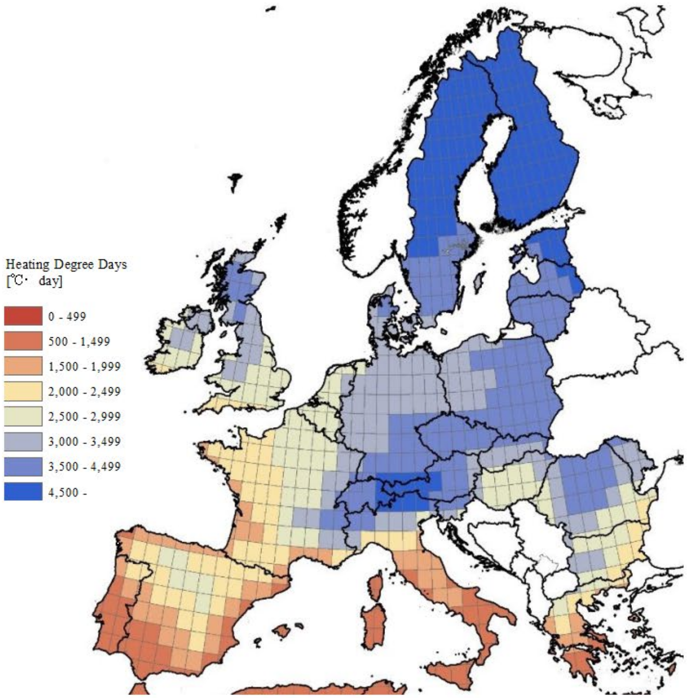
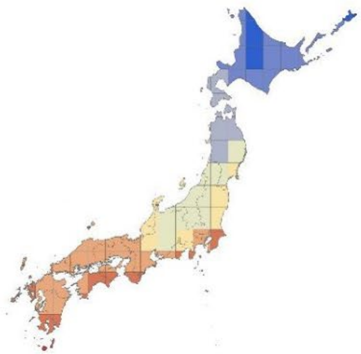
Naha

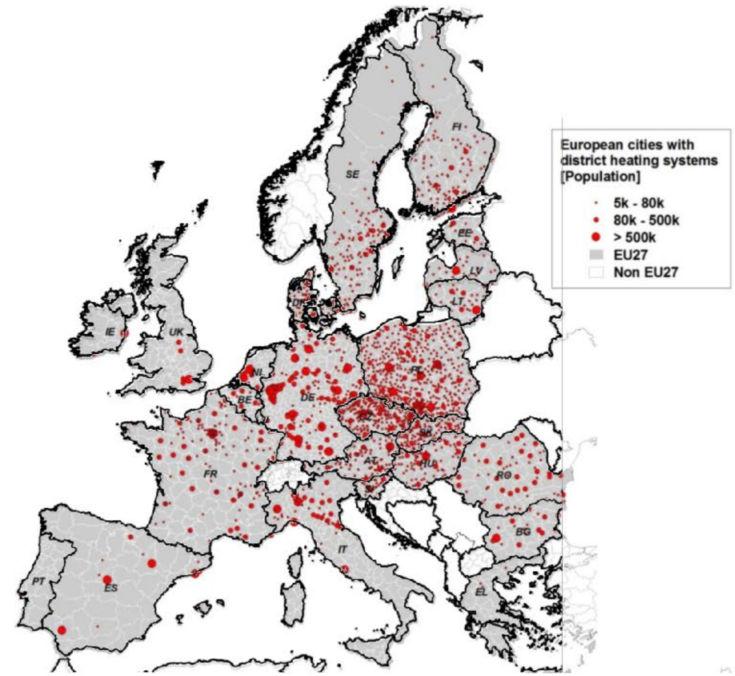
Gas pipeline in East Asia

Interactive World LNG Map © 2017 Petroleum Economist

Heating degree days and DHS



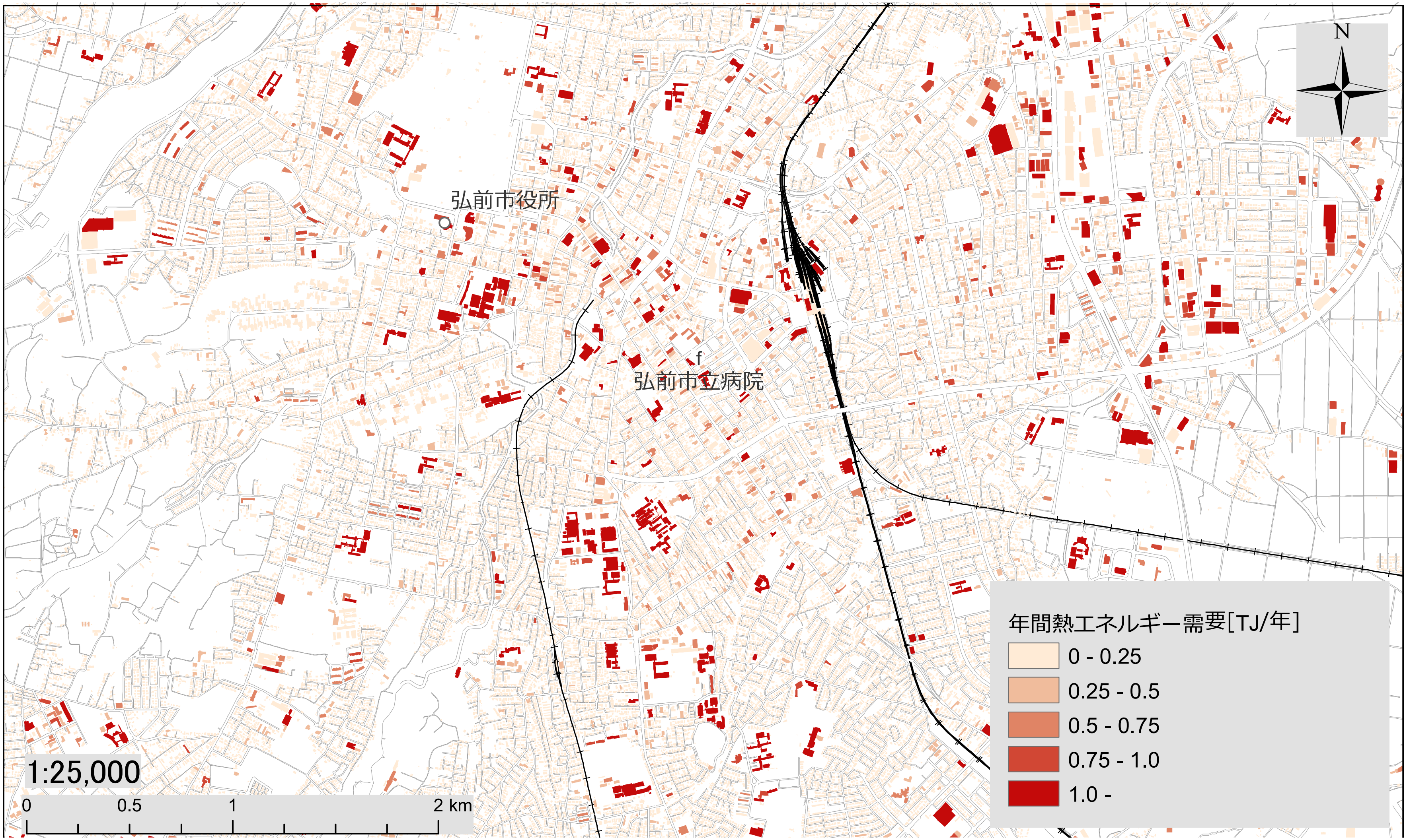


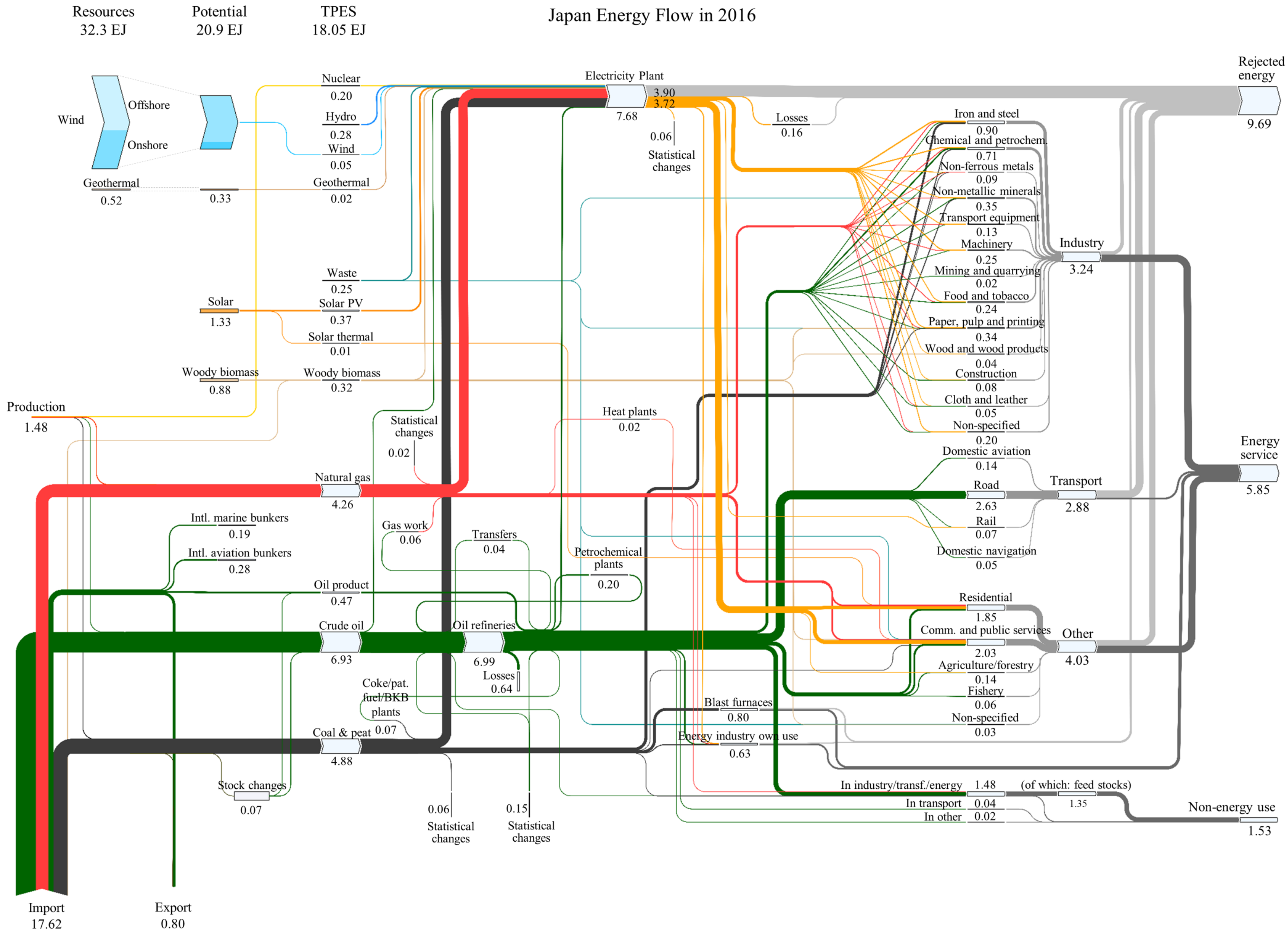


Ref. : Climate: monthly and annual average heating degree days below 18℃ GIS data at one-degree resolution of the World from NASA/SSE, OpenIE
Heat Roadmap Europe 2 Maps, Halmstad & Aalborg Universities, 2013

Above 2500 °C-day
10 prefectures in North Japan

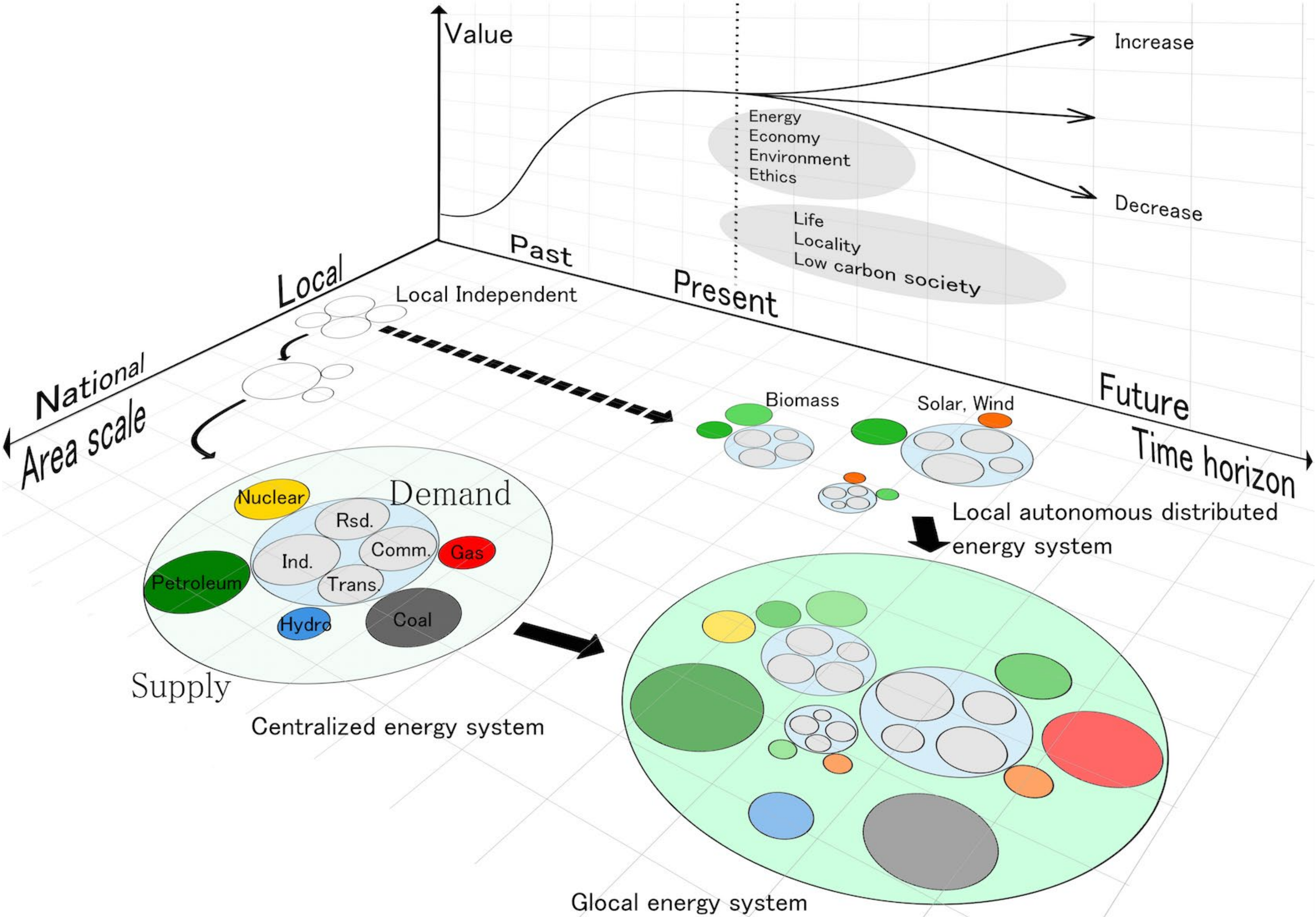
Heat density map in Hirosaki city





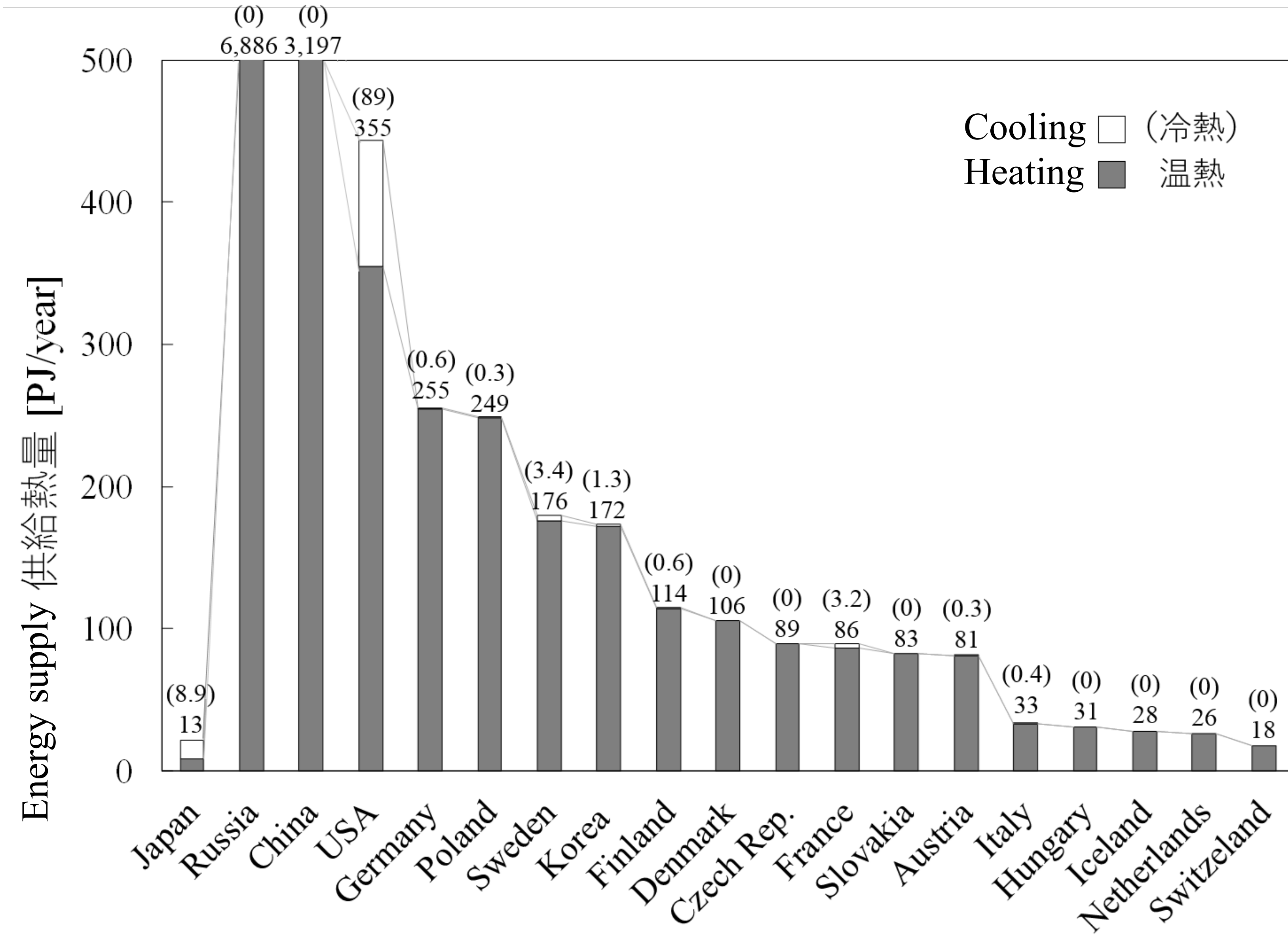
Reference : Japan Agency for Natural Resources and Energy, Energy balance table, FY 2016
Kondo, Energy and energy utilization efficiencies in the Japanese residential/commercial sectors, 2009 etc.

Sep. 18, 2018 H.Onodera@Nakata Lab.



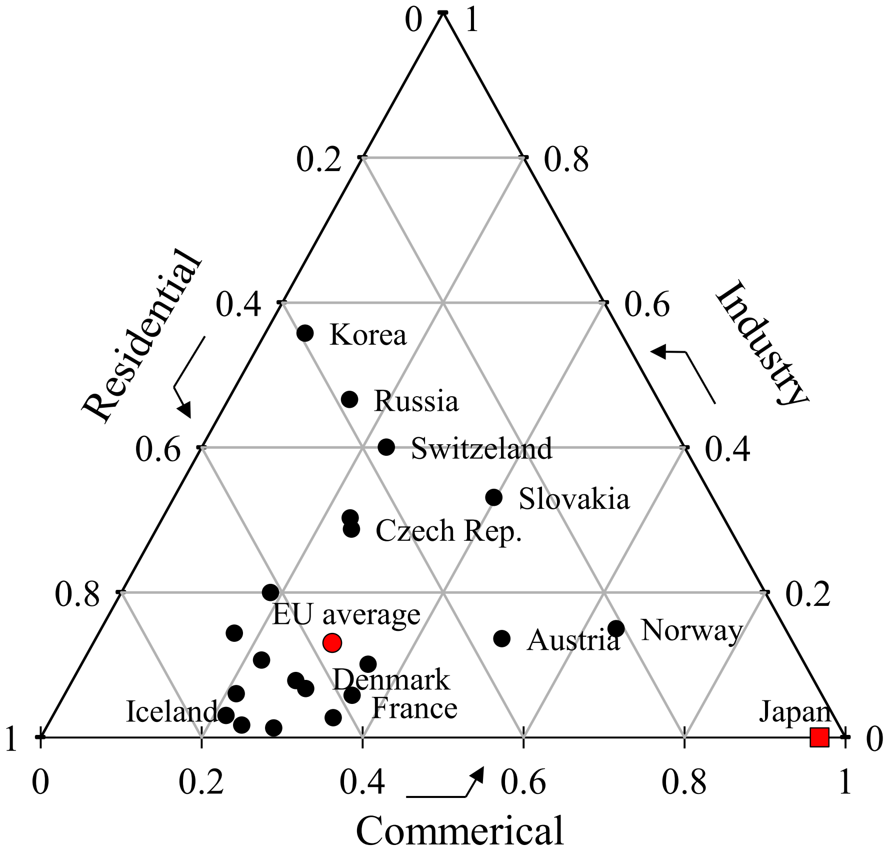
May. 21, 2013 K.Aikawa@Nakata lab.

DHS by countries

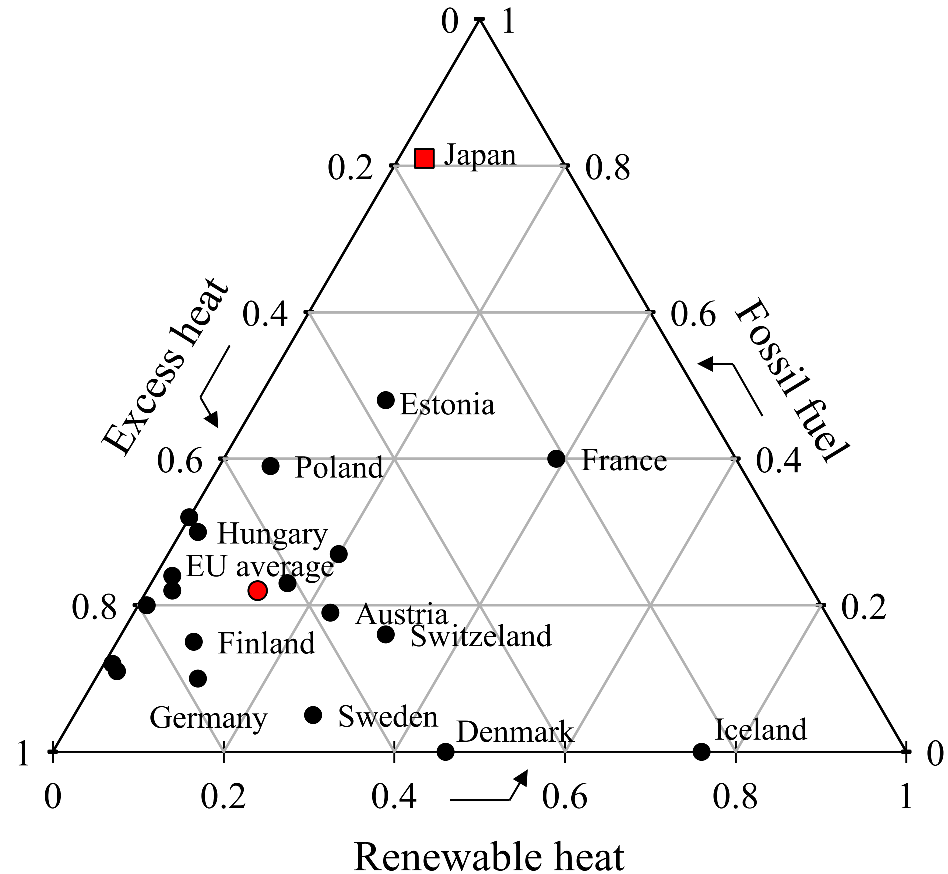


参考 EUROHEAT & POWER, 2015 Country by country – Statistics overview (2013 data)
熱供給事業便覧 平成28年度版,（社）日本熱供給事業協会, 2017 等

Demand sector and heat resource composition



(a) User composition



(b) Heat resource composition

Ref. EUROHEAT & POWER, *2015 Country by country – Statistics overview (2013 data),* 2015.
Japanese district heating association, *Handbook of district heating projects*, 2017. et al.

Objective

- Find out the potential of installing district heating system (DHS) utilizing excess heat in North Japan
- Evaluate the designed DHS performance

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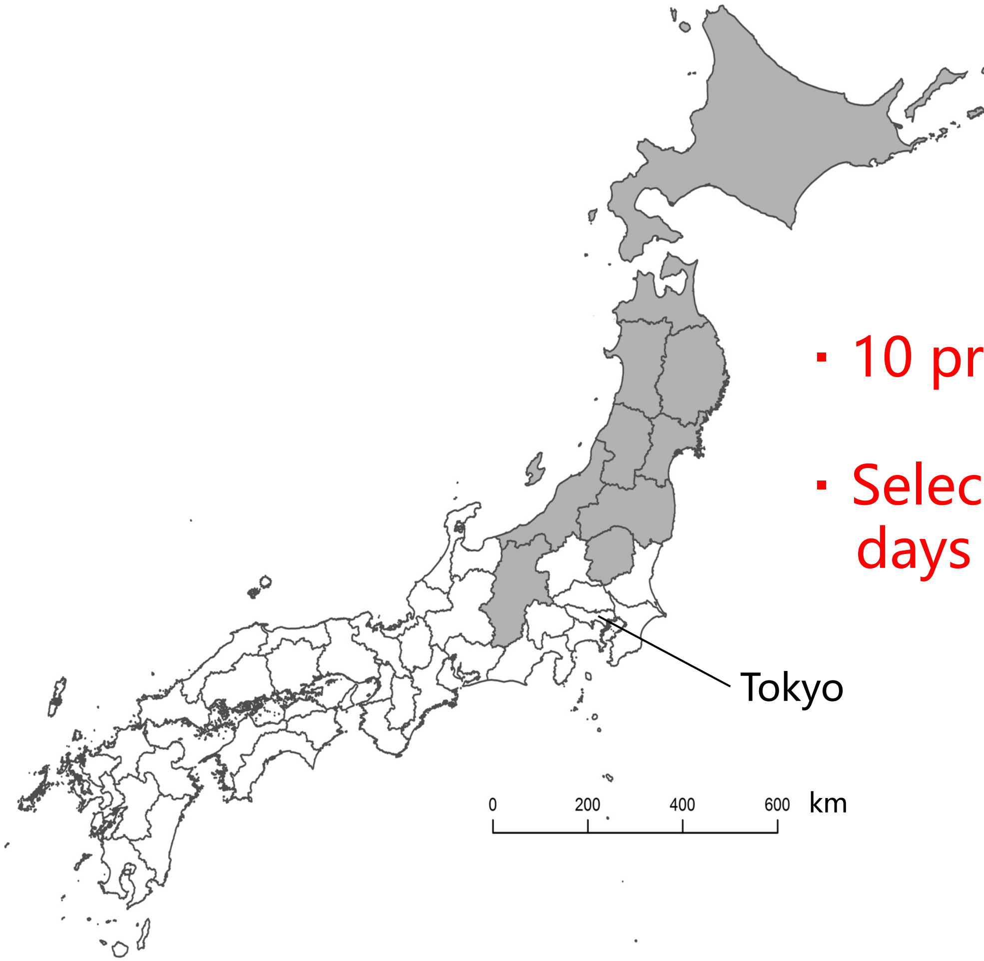
Target area



- 10 prefectures in North Japan.
- Selected prefectures’ heating degree days are larger than 2,500°C day.

Methodology

1. Excess heat potential analysis — Resource side
2. Heat demand estimation — Demand side
3. System components allocation — Allocation
4. System performance evaluation — Evaluation

Available excess heat

Waste incineration plants, WIP

$$EX_{\mathrm{WIP},i} = \frac{LHV_{\mathrm{WIP},i} \times m_{\mathrm{WIP},i} \times \eta_{\mathrm{WIP}}}{1000} \quad (1)$$

EX_{WIP}	: Excess heat from waste incineration plants	[TJ/year]
LHV_{WIP}	: Lower heating value	[MJ/t]
m_{WIP}	: Disposal amount of municipal solid waste	[t/year]
η_{WIP}	: Excess heat available rate (= 65%)	[-]
i	: Waste incineration plants	

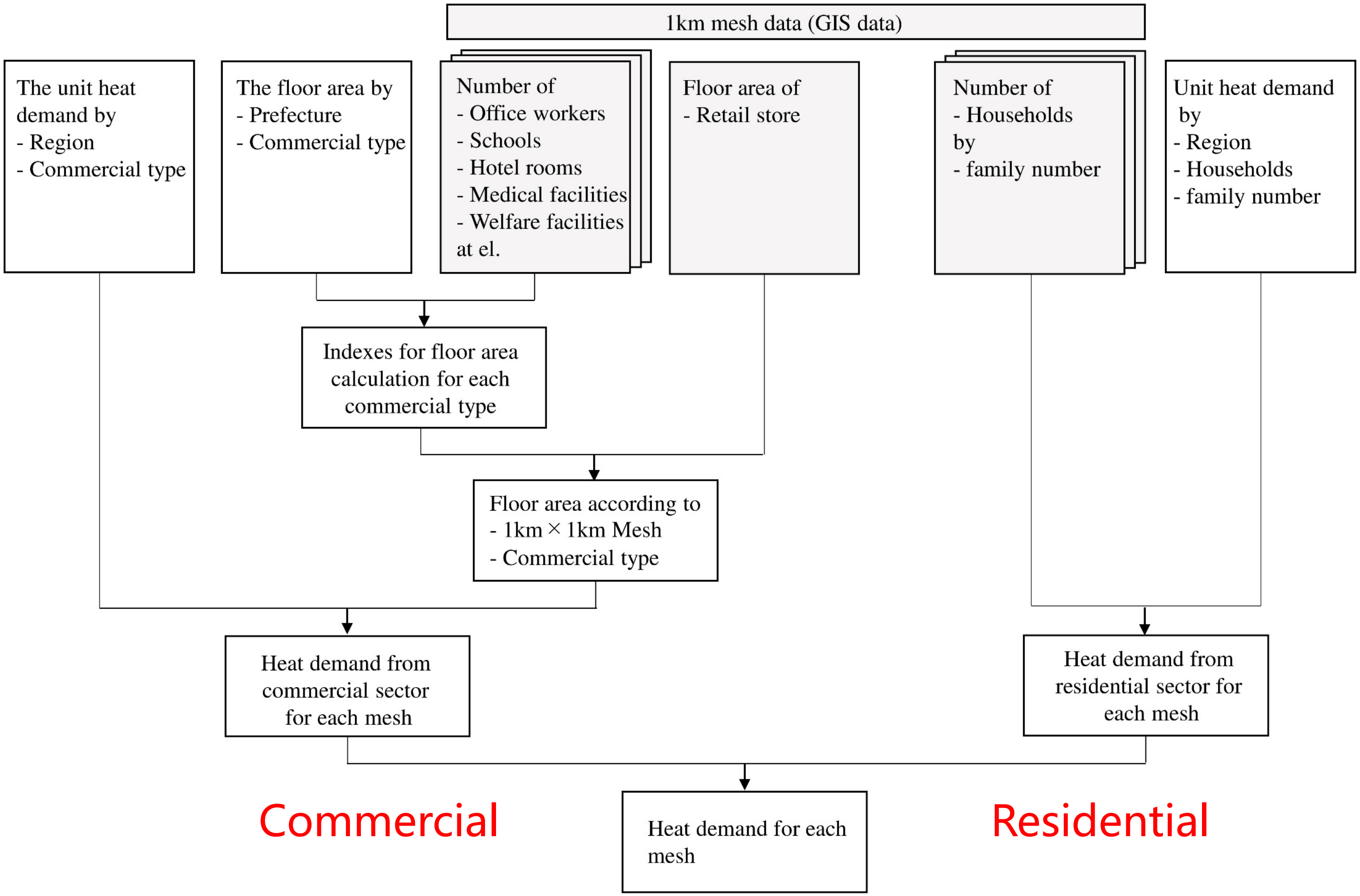
Thermal power plants, TPP

$$EX_{\mathrm{TPG},j} = \frac{Cap_{j} \times \eta_{\mathrm{TPG}} \times 8760 \times 3.6}{1000} \quad (2)$$

EX_{TPG}	: Excess heat from thermal power generation	[TJ/year]
Cap_{TPG}	: Plant capacity	[MW]
η_{WIP}	: Excess heat available rate (= 50%)	[-]
j	: Thermal power plants	

Ref. Ministry of Environment, *Research of municipal solid waste disposal situation*, 2017.
Ministry of Land, Information, Transport and Tourism of Japan, *Geographic and quantitative data of waste incineration plants*, 2014.
U. Persson and S. Werner, District heating in sequential energy supply *Appl. Energy*, Vol. 95, pp. 123–131, 2012
Ministry of Land, Information, Transport and Tourism of Japan, *Geographic and quantitative data of thermal power plants*, 2014.

Process of heat demand estimation by 1km mesh



Heat demand estimation

Commercial sector

$$Q_{\mathrm{com},mesh} = \sum_{type} q_{\mathrm{com},type,mesh} \times Area_{type,mesh} \qquad (3)$$

Q_{com}	: Annual heat demand of commercial sector	[TJ/km^2/year]
q_{com}	: Heat demand unit	[TJ/year/m^2]
Area	: floor area	[m^2/km^2]
type	: commercial type	

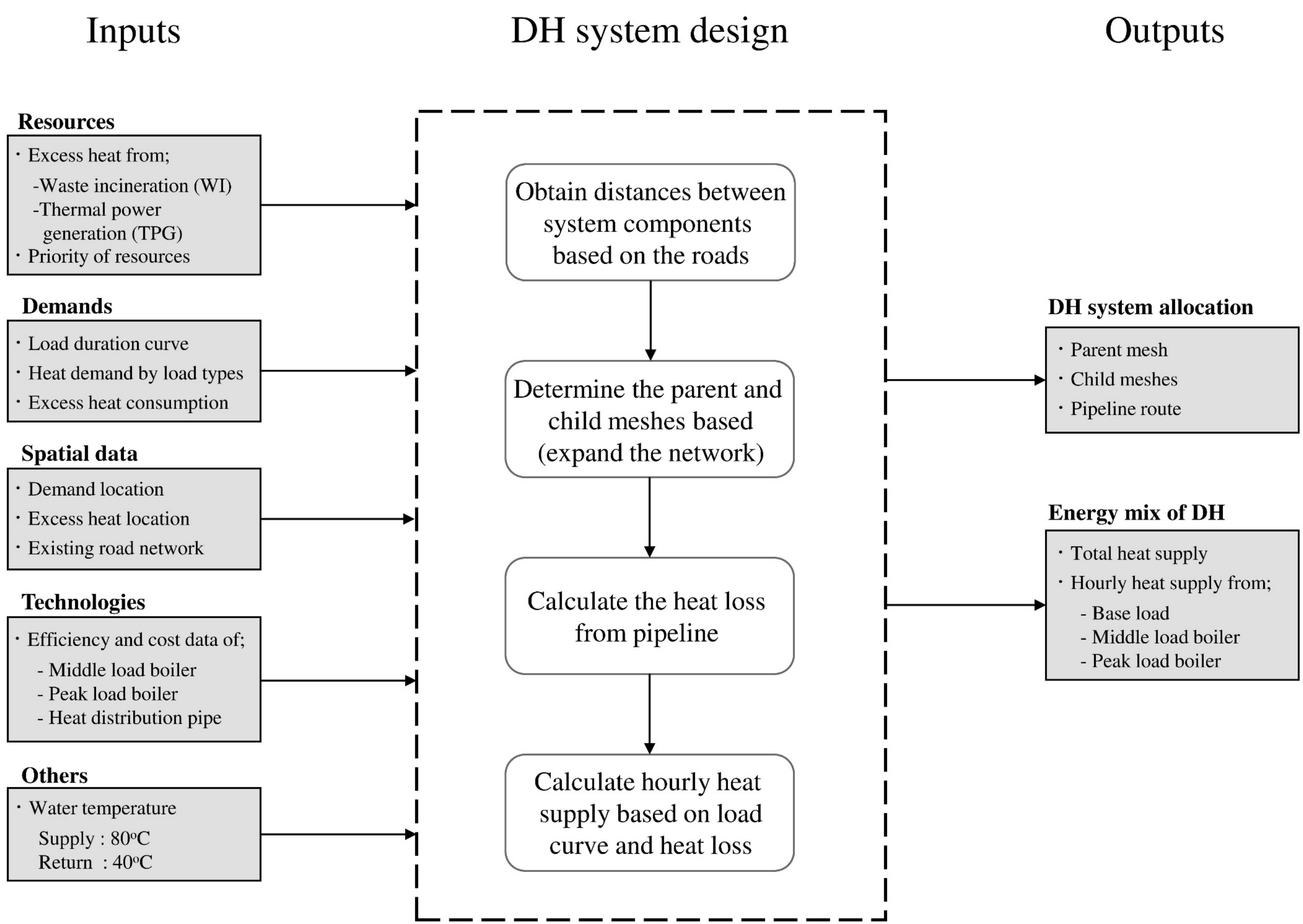
Residential sector

$$Q_{\mathrm{res},mesh} = \sum_{n} q_{\mathrm{res},n,mesh} \times Households_{n,mesh} \qquad (4)$$

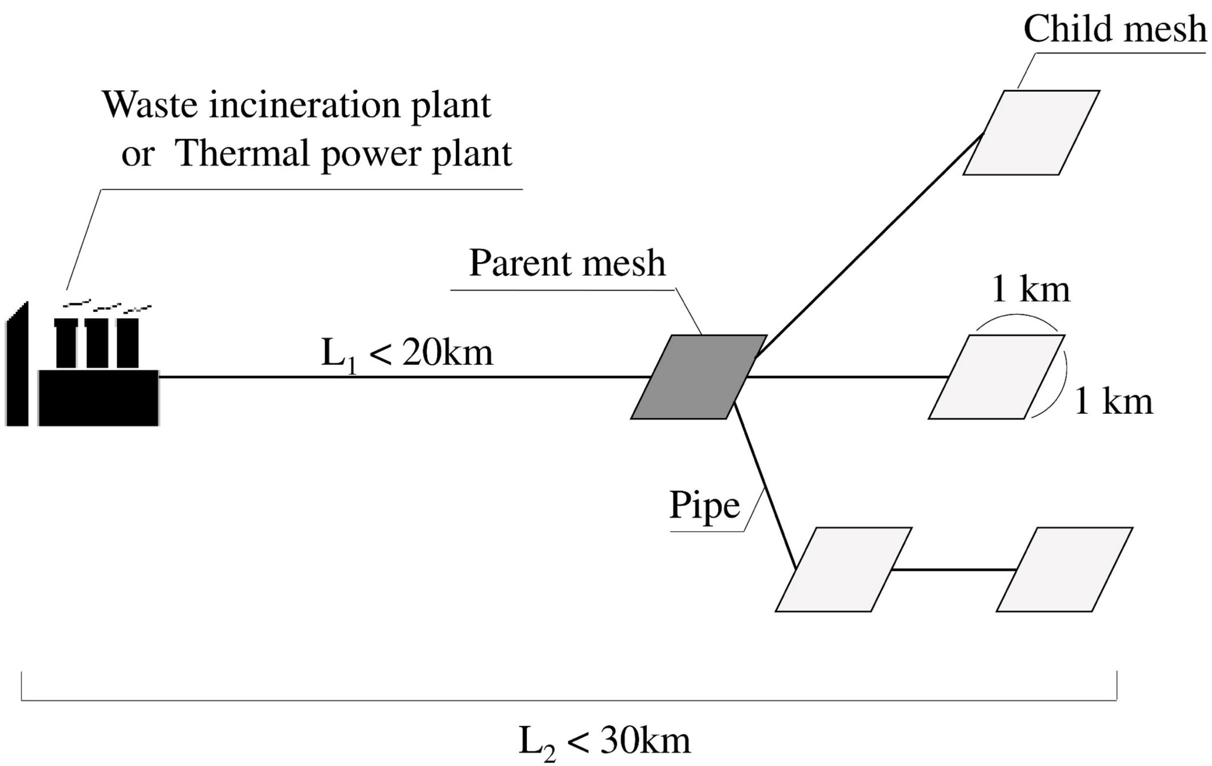
Q_{res}	: Annual heat demand of residential sector	[TJ/km^2/year]
q_{res}	: Heat demand unit	[TJ/year/household]
Housesolds	: Number of household	[household]
mesh	: *mesh*	
n	: family number of household	

Ref. Ministry of Environment, *A survey on the estimation of carbon dioxide emissions from households*, 2015.
Ministry of Internal Affairs and Communications of Japan, *Country affairs statistics 2015*, 2017.
General incorporated association of city environment and energy, *Project 2010, Investigation of potential of installing district heating and cooling,* 1994.
Ministry of Economy, Trade and Industry, *Commercial statistics by mesh in 2014,* 2016. et al.

DHS design modeling

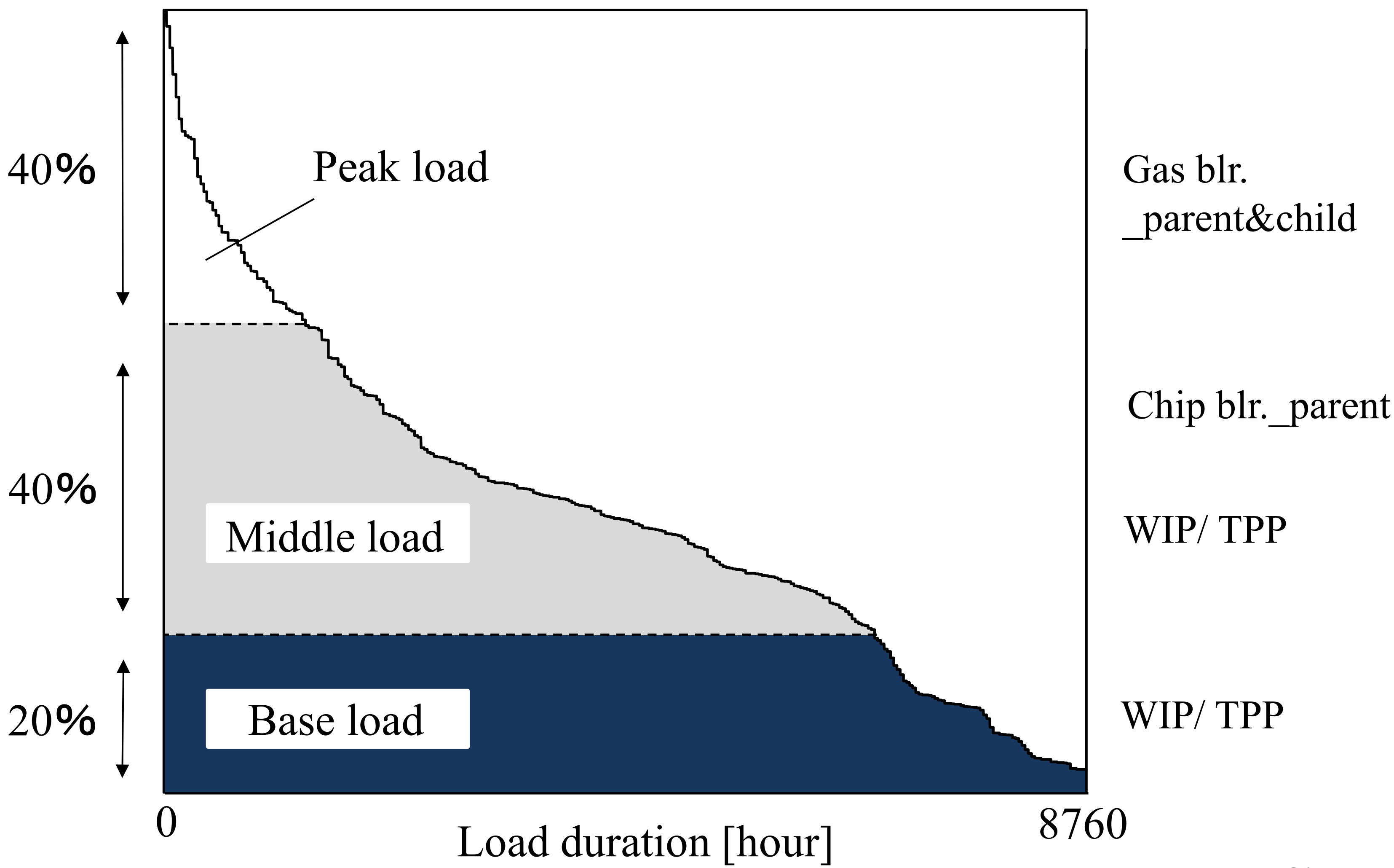


The allocation of DHS components



Parent mesh: Highest heat demand mesh within 20 km from heat resources
Child mesh : LHD_{min} = 1.0 MW/m from the parent mesh

Thermal load type definition



Technology parameters

Technology	Units	Capital cost (mmJPY per unit)	O&M (% of capital)	Life time [year]	Scale factor [-]	Efficiency [-]	Fuel cost [JPY/MJ]
Pipe	m	0.039 - 0.205	1.0%	30	-	-	-
Wood chip boiler (Middle load)	MW	91	4.1%	15	0.73	0.80	1.6
Gas boiler (Peak load)	MW	16	0.3%	15	0.73	0.90	2.2

Ref. IEA, *IEA ETSAP - Technology Brief E05 Biomass for heat and power*, 2010.
A. Bejan, G. Tsatsaronis, and M. Moran, *Thermal design & optimization*. 1996.
Asia Biomass Office, Wood pellet production and import, https://www.asiabiomass.jp/topics/1512_02.html
Sendai city gas, Sendai city gas contract, 2017, http://www.gas.city.sendai.jp/family/charge/uploads/2904_sendai_gas_kouri_yakkan.pdf

Pipeline heat loss and length

$$Loss_{\text{pipe}} = \mathrm{K} \cdot 2\pi \cdot d_a \cdot l \cdot \mathrm{G} \qquad (5)$$

$$d_{\text{a}} = 0.0486 \times \ln\left(\frac{Q_s}{l}\right) + 0.0007 \qquad (6)$$

$$l_{\text{inside},mesh} = 1207.36 \times n_{mesh}^{0.4106} \qquad (7)$$

$Loss_{\text{pipe}}$	: Heat loss from pipeline	[TJ/year]
da	: Average pipe diameter	[m]
l	: Total length of pipeline	[t/year]
K	: Total heat transmission coefficient (=0.6)	[W/m^{2}k]
G	: Degree time number of the average distribution difference (=525,600)	[$^{\text{o}}$Cs]
Q_{s}	: Heat supply	[TJ/year]
n	: Building number	[-]

Ref. S. Frederiksen and S. Wener, *District Heating and Cooling*. Studentlitteratur, 2013.
U. Persson and S. Werner, Heat distribution and the future competitiveness of district heating, *Appl. Energy*, Vol. 88, No. 3, pp. 568–576, 2011.
H. Gils, A GIS-based Assessment of the District Heating Potential in Europe, *Graz, Österreich*, No. 2, pp. 1–13, 2012
B. Eikmeier, J. Gabriel, W. Schulz, W. Krewitt, and M. Nast, *Project Report to the German Ministry for Economics and Technology, Bremen/Stuttgart*, 2005.

System performance evaluation

$$\eta_{\mathrm{DH}} = \frac{\sum_{mesh} Q_{mesh}}{Q_{\mathrm{base}} + Q_{\mathrm{middle}} + Q_{\mathrm{peak}} + Loss_{\mathrm{pipe}}} \quad (8)$$

η_{DH}	:	Energy efficiency	[-]
Q	:	Annual heat demand	[TJ/year]
Q_{base}	:	Heat supply for base load	[TJ/year]
Q_{middle}	:	Heat supply for middle load	[TJ/year]
Q_{peak}	:	Heat supply for peak load	[TJ/year]

$$CO_{2,\mathrm{DH}} = \frac{Q_{\mathrm{peak}} \times \mathrm{CO}_{2,\mathrm{gas}} + E_{\mathrm{pump}} \times \mathrm{CO}_{2,\mathrm{el}}}{\sum_{mesh} Q_{mesh}} \quad (9)$$

CO_2	:	CO_2 emission	[g-CO_2/MJ]
E_{pump}	:	Electricity consumption	[TJ/year]
$\mathrm{CO}_{2,\mathrm{gas}}$	:	CO2 emission from natural gas	[g-CO_2/MJ]
$\mathrm{CO}_{2,\mathrm{gas}}$	:	CO2 emission from natural gas	[g-CO_2/MJ]

$$Cost_{DH} = \frac{Cost_{\mathrm{capital}} + Cost_{\mathrm{fuel}} + Cost_{\mathrm{O\&M}}}{\sum_{mesh} Q_{mesh}} \quad (10)$$

$Cost_{\mathrm{DH}}$	:	Heat supply cost	[JPY/MJ]
$Cost_{\mathrm{capital}}$	:	Capital cost	[JPY/year]
$Cost_{\mathrm{fuel}}$	:	Fuel	[JPY/year]
$Cost_{\mathrm{O\&M}}$	:	O&M cost	[JPY/year]

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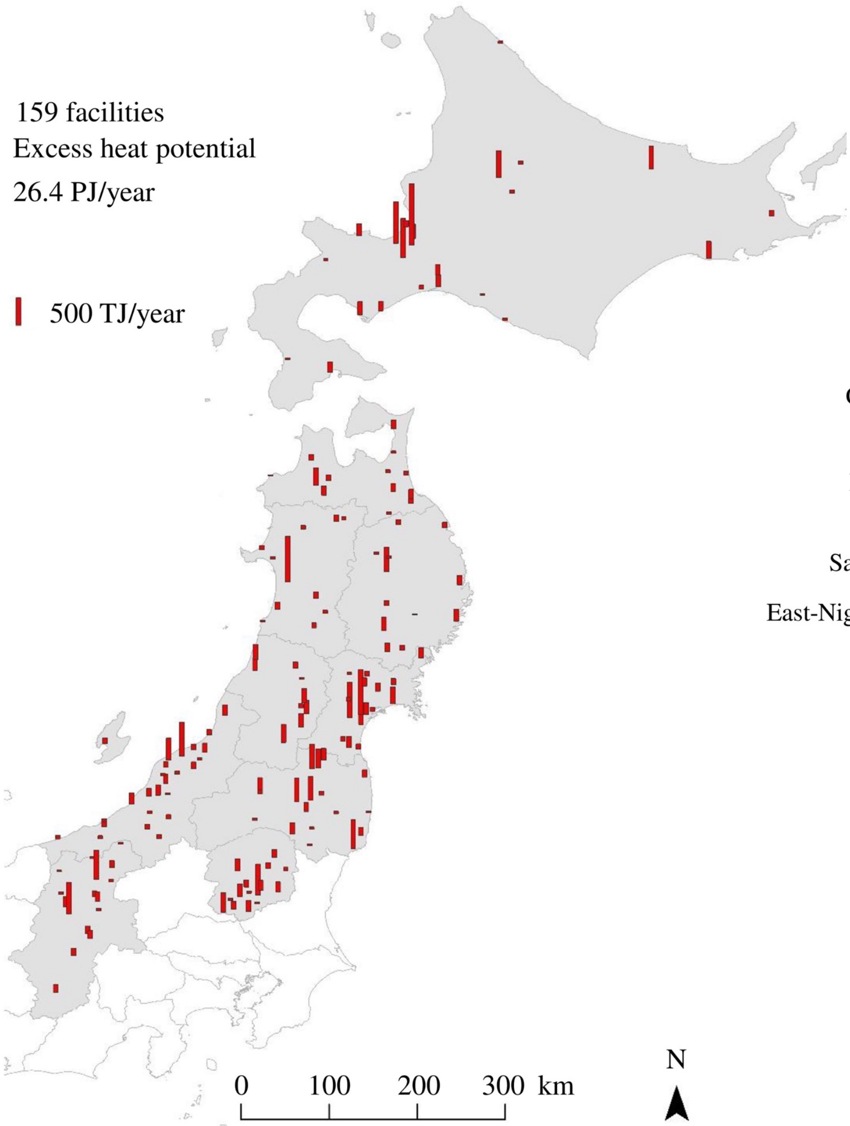
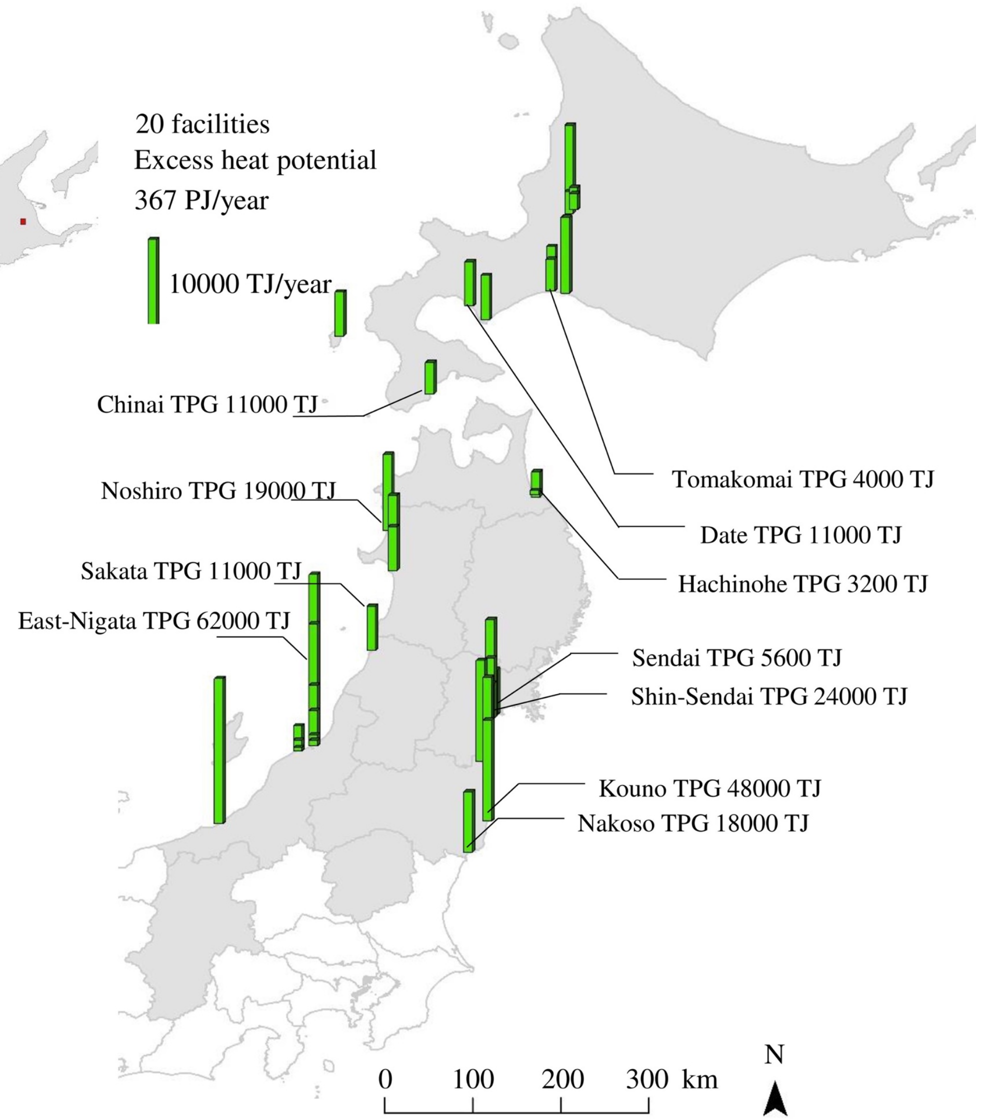
Excess heat potential distribution

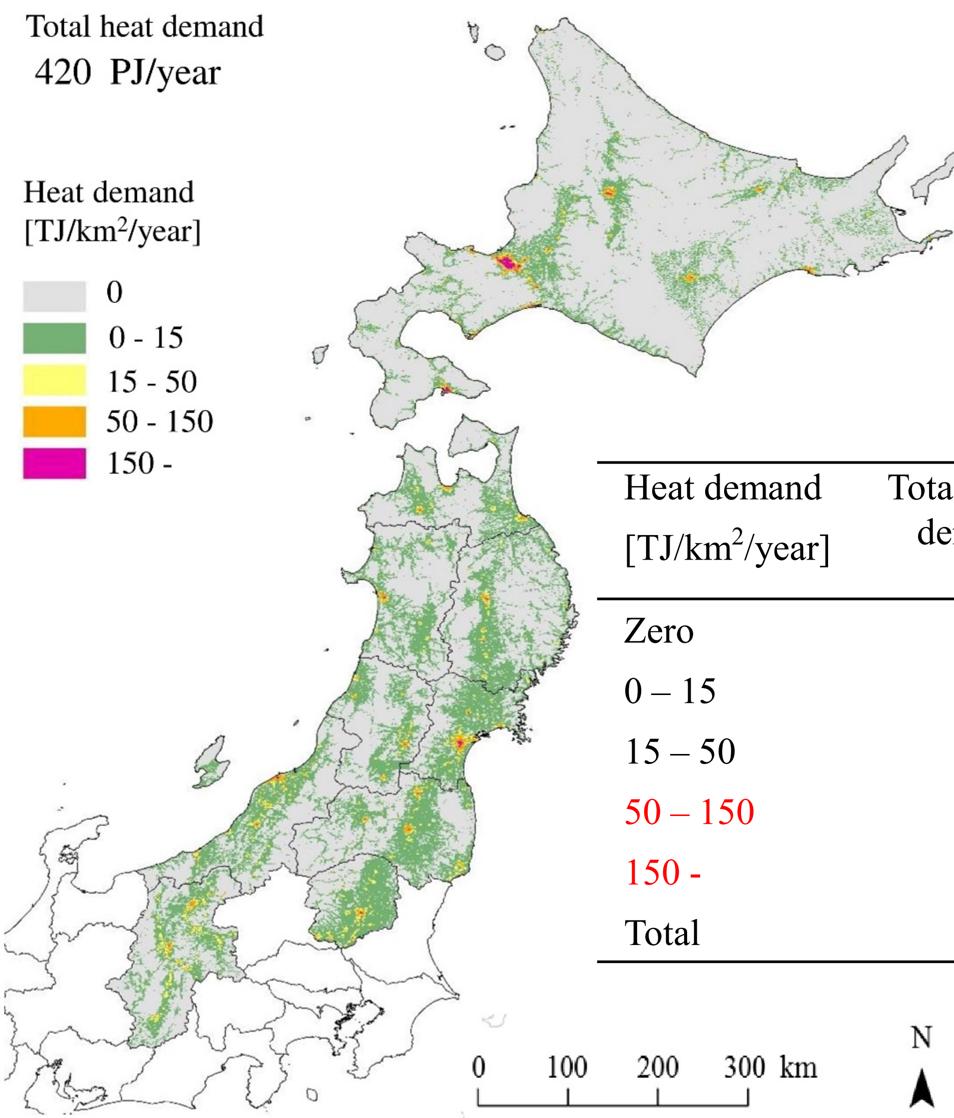


(a) Waste incineration plants



(b) Thermal power plants

Heat demand distribution



Sapporo city: 1,110 TJ/km²/year

Heat demand [TJ/km²/year]	Total heat demand [PJ]	Share [%]	Area [km²]	Share [%]
Zero	0	0	137,507	70.3
0 – 15	105	25.0	52,086	26.6
15 – 50	107	25.5	3,893	2.0
50 – 150	143	34.0	1,756	0.9
150 -	65	15.5	224	0.1
Total	420	-	195,466	-

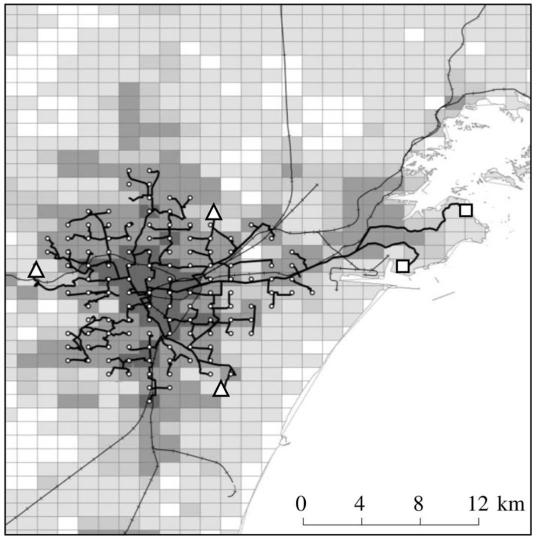
Analytical result by prefecture

	Unit	Prefecture									
		Hokkaido	Aomori	Iwate	Miyagi	Akita	Yamagata	Fukushima	Tochigi	Nigata	Nagano
Number of DH	-	26	9	11	14	13	6	17	15	22	16
Energy property											
Total heat supply (A)	PJ	12.7	3.7	2.4	18.1	6.7	3.1	7.4	3.8	8.9	3.9
TPES for systems (B)	PJ	15.6	4.5	3.1	20.4	7.7	3.8	9.2	5.0	10.7	4.9
Average efficiency (A/B)	-	0.81	0.81	0.77	0.89	0.87	0.81	0.80	0.77	0.83	0.79
Excess heat consumption	PJ	8.3	2.8	1.1	16.0	5.8	2.1	5.3	1.8	7.0	1.7
Systems' network											
Total pipeline length	km	2639	1159	807	4690	1717	996	3153	1169	3125	901
District heated area	km^2	126	47	34	166	68	46	122	45	116	33

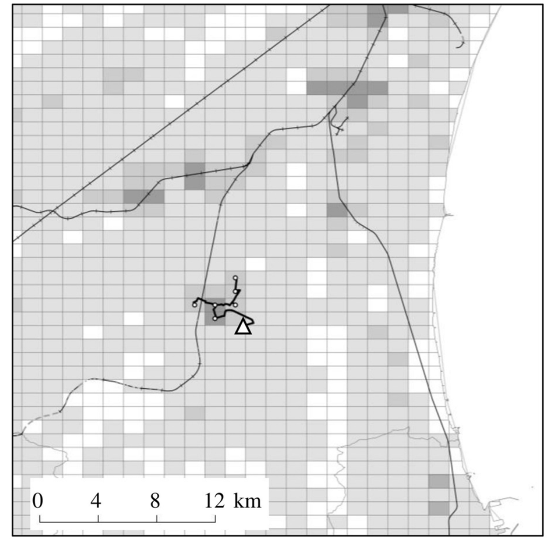
149 DHS in ten prefectures includes;
Hokkaido : 26 DHS with 12.7 PJ
Miyagi prefecture: 14 DHS with 18.1 PJ

Result of DHS design in three cases

3 WIP
2 TPP
129 meshes
15,800 TJ



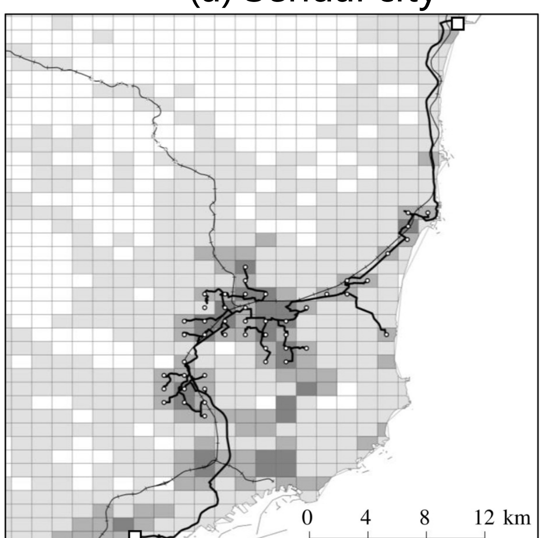
(a) Sendai city



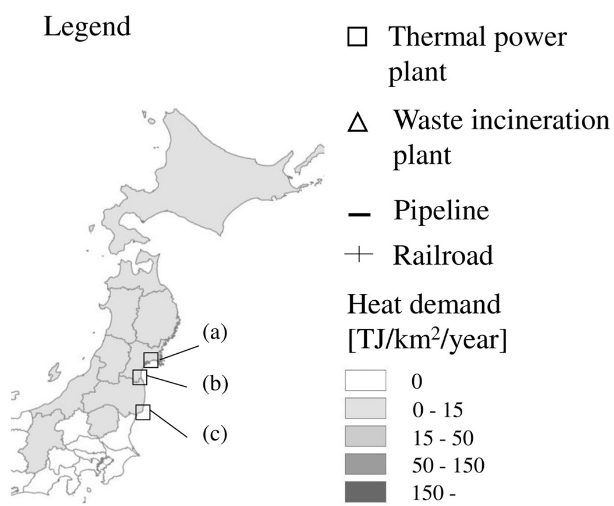
(b) Kakuda city

1 WIP
0 TPP
6 meshes
252 TJ

0 WIP
2 TPP
47 meshes
1,970 TJ



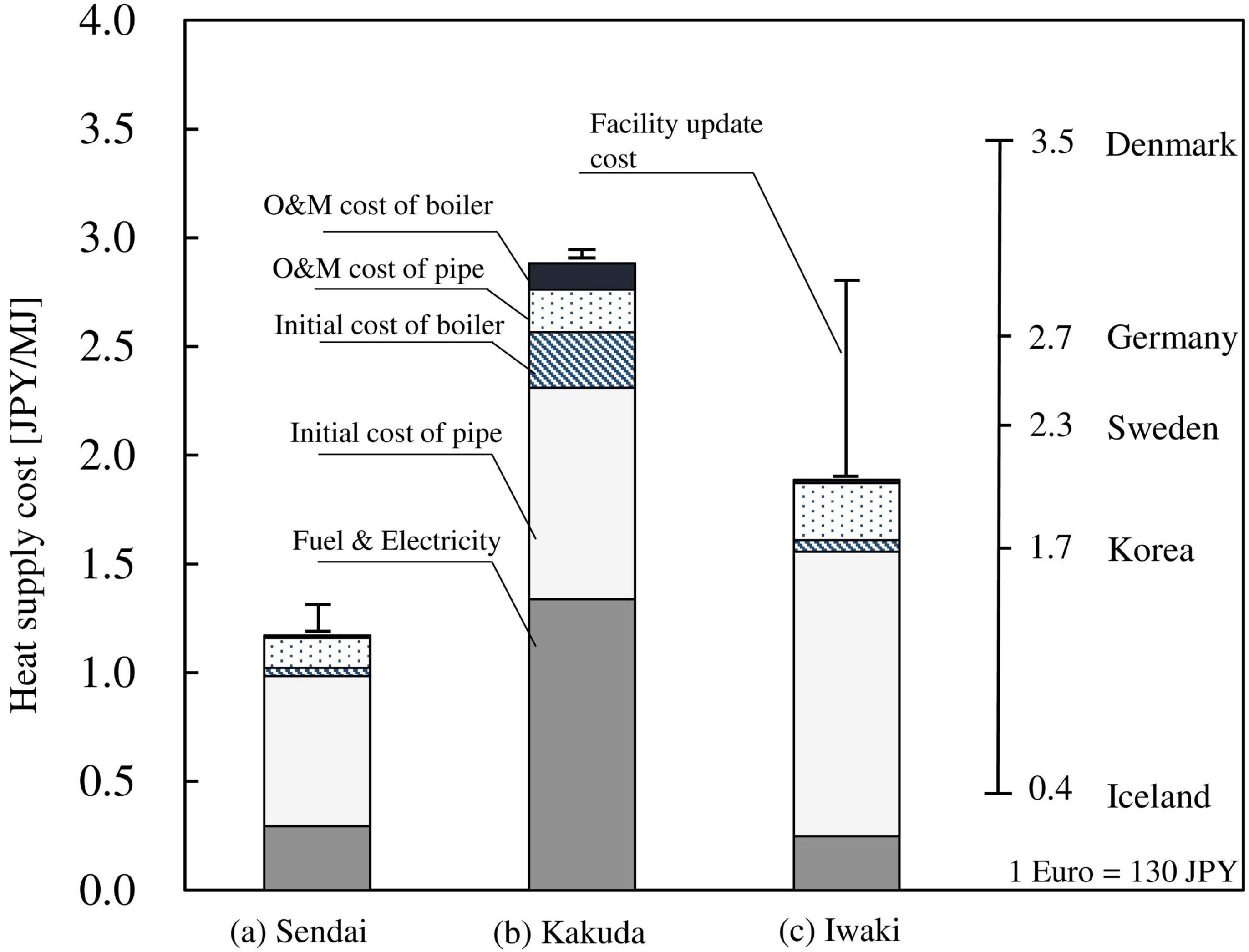
(c) Iwaki city



Performance comparison with three DHS

	Energy efficiency [%]	CO_2 emission [g-CO_2/MJ]	Cost [JPY/MJ]	Total heat supply [TJ/year]	Average LHD [GJ/m]
Sendai city	95.4	7.9	1.2	18085	4.4
Kakuda city	79.9	7.9	2.9	251	3.0
Iwaki city	87.4	6.8	1.9	1970	1.7

Heat cost breakdown



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Conclusion

The potential of DHS utilizing excess heat is investigated in North Japan.

- Total annual heat demand is 420 PJ and excess heat potential is 393 PJ in the 10 prefectures.
- DHS install potential is 70.5 PJ in North Japan, and 51.9 PJ is supplied by excess heat.
- Some DHS could supply heat with lower cost compared with European countries.

Thank you.