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

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

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

1. Introduction
2. Methods
3. Results and discussion
4. Conclusions
Gas pipeline in East Asia
Heating degree days and DHS

Above 2500 °C-day
10 prefectures in North Japan
DHS by countries

Energy supply [PJ/year]

<table>
<thead>
<tr>
<th>Country</th>
<th>Heating</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>13</td>
<td>(0.6)</td>
</tr>
<tr>
<td>Russia</td>
<td>255</td>
<td>(0.3)</td>
</tr>
<tr>
<td>China</td>
<td>355</td>
<td>(89)</td>
</tr>
<tr>
<td>USA</td>
<td>366</td>
<td>(0)</td>
</tr>
<tr>
<td>Germany</td>
<td>249</td>
<td>(3)</td>
</tr>
<tr>
<td>Poland</td>
<td>176</td>
<td>(1.3)</td>
</tr>
<tr>
<td>Sweden</td>
<td>172</td>
<td>(3.4)</td>
</tr>
<tr>
<td>Korea</td>
<td>114</td>
<td>(0.6)</td>
</tr>
<tr>
<td>Finland</td>
<td>106</td>
<td>(0)</td>
</tr>
<tr>
<td>Denmark</td>
<td>89</td>
<td>(0)</td>
</tr>
<tr>
<td>Czech Rep.</td>
<td>6</td>
<td>(3.2)</td>
</tr>
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<td>France</td>
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<td>(0)</td>
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<tr>
<td>Slovakia</td>
<td>83</td>
<td>(0.3)</td>
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<tr>
<td>Austria</td>
<td>81</td>
<td>(0.4)</td>
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<tr>
<td>Italy</td>
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<td>(0)</td>
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<td>Hungary</td>
<td>31</td>
<td>(0)</td>
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<td>Iceland</td>
<td>28</td>
<td>(0)</td>
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<tr>
<td>Netherlands</td>
<td>26</td>
<td>(0)</td>
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<tr>
<td>Switzerland</td>
<td>18</td>
<td>(0)</td>
</tr>
</tbody>
</table>

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

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
Outline

1. Introduction
2. Methods
3. Results and discussion
4. Conclusions
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
2. Heat demand estimation
3. System components allocation
4. System performance evaluation

Resource side
Demand side
Allocation
Evaluation
Available excess heat

**Waste incineration plants, WIP**

\[
EX_{WIP,i} = \frac{LHV_{WIP,i} \times m_{WIP,i} \times \eta_{WIP}}{1000} \tag{1}
\]

- \( EX_{WIP} \): 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]
- \( \eta_{WIP} \): Excess heat available rate (= 65%) [-]
- \( i \): Waste incineration plants

**Thermal power plants, TPP**

\[
EX_{TPG,j} = \frac{Cap_{TPG} \times \eta_{TPG} \times 8760 \times 3.6}{1000} \tag{2}
\]

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

Process of heat demand estimation by 1km mesh

1km mesh data (GIS data)

The unit heat demand by
- Region
- Commercial type

The floor area by
- Prefecture
- Commercial type

Number of
- Office workers
- Schools
- Hotel rooms
- Medical facilities
- Welfare facilities at el.

Floor area of
- Retail store

Number of
- Households by
- family number

Unit heat demand by
- Region
- Households
- family number

Indexes for floor area calculation for each commercial type

Floor area according to
- 1km × 1km Mesh
- Commercial type

Heat demand from commercial sector for each mesh

Heat demand from residential sector for each mesh

Commercial

Residential

Heat demand for each mesh
Heat demand estimation

Commercial sector

\[ Q_{\text{com, mesh}} = \sum_{\text{type}} q_{\text{com, type, mesh}} \times \text{Area}_{\text{type, mesh}} \] (3)

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

Residential sector

\[ Q_{\text{res, mesh}} = \sum_{n} q_{\text{res, n, mesh}} \times \text{Households}_{n, \text{mesh}} \] (4)

- \( Q_{\text{res}} \): Annual heat demand of residential sector [TJ/km\(^2\)/year]
- \( q_{\text{res}} \): Heat demand unit [TJ/year/household]
- \( \text{Households} \): Number of household [household]
- \( \text{mesh} \): mesh
- \( n \): family number of household

DHS design modeling

**Inputs**

- **Resources**
  - Excess heat from:
    - Waste incineration (WI)
    - Thermal power generation (TPG)
  - Priority of resources

- **Demands**
  - Load duration curve
  - Heat demand by load types
  - Excess heat consumption

- **Spatial data**
  - Demand location
  - Excess heat location
  - Existing road network

- **Technologies**
  - Efficiency and cost data of:
    - Middle load boiler
    - Peak load boiler
    - Heat distribution pipe

- **Others**
  - Water temperature
    - Supply: 80°C
    - Return: 40°C

**DH system design**

- Obtain distances between system components based on the roads
- Determine the parent and child meshes based (expand the network)
- Calculate the heat loss from pipeline
- Calculate hourly heat supply based on load curve and heat loss

**Outputs**

- **DH system allocation**
  - Parent mesh
  - Child meshes
  - Pipeline route

- **Energy mix of DH**
  - Total heat supply
    - Hourly heat supply from:
      - Base load
      - Middle load boiler
      - Peak load boiler
The allocation of DHS components

Parent mesh: Highest heat demand mesh within 20 km from heat resources
Child mesh: $L_{H\text{D}_{\text{min}}} = 1.0 \text{ MW/m}$ from the parent mesh
Thermal load type definition

- **Peak load**: 40% of the total load duration
- **Middle load**: 40% of the total load duration
- **Base load**: 20% of the total load duration

- **Gas blr._parent&child**
- **Chip blr._parent**
- **WIP/ TPP**
- **WIP/ TPP**
## Technology parameters

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

Ref.  
IEA, IEA ETSAP - Technology Brief E05 Biomass for heat and power, 2010.  
A. Bejan, G. Tsatsaronis, and M. Moran, Thermal design & optimization. 1996.  
Pipeline heat loss and length

\[
\text{Loss}_{\text{pipe}} = K \cdot 2\pi \cdot d_a \cdot l \cdot G
\]  
(5)  

\[d_a = 0.0486 \times \ln\left(\frac{Q_s}{l}\right) + 0.0007\]  
(6)  

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

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

Ref.  
system performance evaluation

\[ \eta_{\text{DH}} = \frac{\sum Q_{\text{mesh}}}{Q_{\text{base}} + Q_{\text{middle}} + Q_{\text{peak}} + \text{Loss}_{\text{pipe}}} \]  

\[ \text{CO}_2,_{\text{DH}} = \frac{Q_{\text{peak}} \times \text{CO}_2,_{\text{gas}} + E_{\text{pump}} \times \text{CO}_2,_{\text{el}}}{\sum Q_{\text{mesh}}} \]

\[ \text{Cost}_{\text{DH}} = \frac{\text{Cost}_{\text{capital}} + \text{Cost}_{\text{fuel}} + \text{Cost}_{\text{O&M}}}{\sum Q_{\text{mesh}}} \]

- \( \eta_{\text{DH}} \): Energy efficiency [-]
- \( Q \): Annual heat demand [TJ/year]
- \( Q_{\text{base}} \): Heat supply for base load [TJ/year]
- \( Q_{\text{middle}} \): Heat supply for middle load [TJ/year]
- \( Q_{\text{peak}} \): Heat supply for peak load [TJ/year]
- \( \text{CO}_2 \): CO\(_2\) emission [g-CO\(_2\)/MJ]
- \( E_{\text{pump}} \): Electricity consumption [TJ/year]
- \( \text{CO}_2,_{\text{gas}} \): CO\(_2\) emission from natural gas [g-CO\(_2\)/MJ]
- \( \text{CO}_2,_{\text{gas}} \): CO\(_2\) emission from natural gas [g-CO\(_2\)/MJ]
- \( \text{Cost}_{\text{DH}} \): Heat supply cost [JPY/MJ]
- \( \text{Cost}_{\text{capital}} \): Capital cost [JPY/year]
- \( \text{Cost}_{\text{fuel}} \): Fuel [JPY/year]
- \( \text{Cost}_{\text{O&M}} \): O&M cost [JPY/year]
Outline

1. Introduction
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Excess heat potential distribution

159 facilities
Excess heat potential
26.4 PJ/year

500 TJ/year

20 facilities
Excess heat potential
367 PJ/year

10000 TJ/year

Chinai TPG 11000 TJ
Noshiro TPG 19000 TJ
Sakata TPG 11000 TJ
East-Nigata TPG 62000 TJ

Tomakomai TPG 4000 TJ
Date TPG 11000 TJ
Hachinohe TPG 3200 TJ
Sendai TPG 5600 TJ
Shin-Sendai TPG 24000 TJ
Kouno TPG 48000 TJ
Nakoso TPG 18000 TJ

(a) Waste incineration plants
(b) Thermal power plants
Heat demand distribution

Total heat demand
420 PJ/year

Sapporo city: 1,110 TJ/km²/year

<table>
<thead>
<tr>
<th>Heat demand [TJ/km²/year]</th>
<th>Total heat demand [PJ]</th>
<th>Share [%]</th>
<th>Area [km²]</th>
<th>Share [%]</th>
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<td>Zero</td>
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<td>0</td>
<td>137,507</td>
<td>70.3</td>
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<tr>
<td>0 – 15</td>
<td>105</td>
<td>25.0</td>
<td>52,086</td>
<td>26.6</td>
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<td>15 – 50</td>
<td>107</td>
<td>25.5</td>
<td>3,893</td>
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<td>50 – 150</td>
<td>143</td>
<td>34.0</td>
<td>1,756</td>
<td>0.9</td>
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<tr>
<td>150 -</td>
<td>65</td>
<td>15.5</td>
<td>224</td>
<td>0.1</td>
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<tr>
<td>Total</td>
<td>420</td>
<td>-</td>
<td>195,466</td>
<td>-</td>
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Analytical result by prefecture

<table>
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<tr>
<th></th>
<th>Unit</th>
<th>Hokkaido</th>
<th>Aomori</th>
<th>Iwate</th>
<th>Miyagi</th>
<th>Akita</th>
<th>Yamagata</th>
<th>Fukushima</th>
<th>Tochigi</th>
<th>Nigata</th>
<th>Nagano</th>
</tr>
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<tbody>
<tr>
<td>Number of DH</td>
<td>-</td>
<td>26</td>
<td>9</td>
<td>11</td>
<td>14</td>
<td>13</td>
<td>6</td>
<td>17</td>
<td>15</td>
<td>22</td>
<td>16</td>
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<tr>
<td>Energy property</td>
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<tr>
<td>Total heat supply (A)</td>
<td>PJ</td>
<td>12.7</td>
<td>3.7</td>
<td>2.4</td>
<td>18.1</td>
<td>6.7</td>
<td>3.1</td>
<td>7.4</td>
<td>3.8</td>
<td>8.9</td>
<td>3.9</td>
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<tr>
<td>TPES for systems (B)</td>
<td>PJ</td>
<td>15.6</td>
<td>4.5</td>
<td>3.1</td>
<td>20.4</td>
<td>7.7</td>
<td>3.8</td>
<td>9.2</td>
<td>5.0</td>
<td>10.7</td>
<td>4.9</td>
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<tr>
<td>Average efficiency (A/B)</td>
<td>-</td>
<td>0.81</td>
<td>0.81</td>
<td>0.77</td>
<td>0.89</td>
<td>0.87</td>
<td>0.81</td>
<td>0.80</td>
<td>0.77</td>
<td>0.83</td>
<td>0.79</td>
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<td>Excess heat consumption</td>
<td>PJ</td>
<td>8.3</td>
<td>2.8</td>
<td>1.1</td>
<td>16.0</td>
<td>5.8</td>
<td>2.1</td>
<td>5.3</td>
<td>1.8</td>
<td>7.0</td>
<td>1.7</td>
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<td>Systems' network</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total pipeline length</td>
<td>km</td>
<td>2639</td>
<td>1159</td>
<td>807</td>
<td>4690</td>
<td>1717</td>
<td>996</td>
<td>3153</td>
<td>1169</td>
<td>3125</td>
<td>901</td>
</tr>
<tr>
<td>District heated area</td>
<td>km²</td>
<td>126</td>
<td>47</td>
<td>34</td>
<td>166</td>
<td>68</td>
<td>46</td>
<td>122</td>
<td>45</td>
<td>116</td>
<td>33</td>
</tr>
</tbody>
</table>

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

(a) Sendai city
- 3 WIP
- 2 TPP
- 129 meshes
- 15,800 TJ

(b) Kakuda city
- 1 WIP
- 0 TPP
- 6 meshes
- 252 TJ

(c) Iwaki city
- 0 WIP
- 2 TPP
- 47 meshes
- 1,970 TJ
Performance comparison with three DHS

<table>
<thead>
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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Sendai city</td>
<td>95.4</td>
<td>7.9</td>
<td>1.2</td>
<td>18085</td>
<td>4.4</td>
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<tr>
<td>Kakuda city</td>
<td>79.9</td>
<td>7.9</td>
<td>2.9</td>
<td>251</td>
<td>3.0</td>
</tr>
<tr>
<td>Iwaki city</td>
<td>87.4</td>
<td>6.8</td>
<td>1.9</td>
<td>1970</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Heat cost breakdown

- Initial cost of boiler
- O&M cost of boiler
- O&M cost of pipe
- Initial cost of pipe
- Fuel & Electricity
- Facility update cost

Heat supply cost [JPY/MJ]

- (a) Sendai
- (b) Kakuda
- (c) Iwaki

Heat supply cost [Euro/MJ]

- 3.5 Denmark
- 2.7 Germany
- 2.3 Sweden
- 1.7 Korea
- 0.4 Iceland

1 Euro = 130 JPY
Outline

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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.