Large-scale heat pump integration model: A case study of Tallinn district heating

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I. Introduction

- Heat pumps part of “Smart Energy Systems”
- Balance intermittent power generation
- Use surplus electricity
- Use existing storage capacity in DH networks

![Large-scale heat pump projects in Denmark](chart1)

![Share of wind energy on final electricity consumption in Denmark](chart2)
I. Introduction

Energy planning tools:
- Variety of technologies included (boiler, CHP, ...)
- Considering investments and O&M costs
- Hourly calculations for full year
- Simulation or optimization models
- Limitations on HP:
  - Constant COP or varying COP with constant Lorenz efficiency
  - Same investment costs for HPs
  - Only few heat sources

Aim of this study:
- Reduce these limitations for large-scale HPs
- More realistic representation → more realistic solution
II. Model

- GAMS, optimization using mixed integer linear programming
  - minimize investment and O&M costs [1]
  - Seasonal variation of heat source and heat sink temperatures
  - Capacity limitations
  - Hourly calculations for one year
- Model determines:
  - Best suitable heat sources
  - Optimal HP capacities
  - Technical, economic and environmental parameters

\[
\text{COP} = \text{COP}_L \left( 1 + \frac{\Delta T_{r,H} + \Delta T_{pp}}{1 + \frac{\Delta T_{r,H} + \Delta T_{r,c} + 2\Delta T_{pp}}{\Delta T_{lift}}} \right) \eta_{is,c} \left( \frac{1 - \eta_{is,e}}{\eta_{is,c}} \right) + 1 - \eta_{is,c} - f_Q
\]

- Red: fitted based on linear approximation
- Paper link on reference slide [2]
II. Case study: DH network of Tallinn

- Tallinn: 400,000 inhabitants
- B: Biomass
- W: Waste incineration
- NG: Natural gas

<table>
<thead>
<tr>
<th>Production units</th>
<th>Parameter</th>
<th>Share in 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 x biomass CHP</td>
<td>170 MW</td>
<td>35%</td>
</tr>
<tr>
<td>1 x waste incineration</td>
<td>50 MW</td>
<td>15%</td>
</tr>
<tr>
<td>5 x NG boiler houses</td>
<td>&gt;500 MW</td>
<td>50%</td>
</tr>
<tr>
<td>Total production</td>
<td>1970 GWh</td>
<td></td>
</tr>
<tr>
<td>Pipe length</td>
<td>438 km</td>
<td></td>
</tr>
<tr>
<td># of buildings supplied</td>
<td>3873</td>
<td></td>
</tr>
<tr>
<td>Heat loss</td>
<td>14.5%</td>
<td></td>
</tr>
<tr>
<td>Avg. supply/return temp.</td>
<td>77/51 °C</td>
<td></td>
</tr>
</tbody>
</table>
II. Load duration curve

- Peak demand (2016): 660 MW
- 220 MW from non-fossil fuels
II. Potential heat supply for HPs

- Supply temperature up to 110 °C
- Temperature limit for ammonia HPs: 85 °C
- Max. 4000 (4500) h of potential heat supply
- Number of full load hours depends on HP capacity
II. Possible HP locations

<table>
<thead>
<tr>
<th>#</th>
<th>Location</th>
<th>Heat source</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biomass CHP*</td>
<td>Groundwater</td>
<td>2 MW</td>
</tr>
<tr>
<td>2</td>
<td>Sewage plant</td>
<td>Sewage water</td>
<td>4000 – 14000 m³/h</td>
</tr>
<tr>
<td>3</td>
<td>Boiler house</td>
<td>Ambient air</td>
<td>10 MW</td>
</tr>
<tr>
<td>4</td>
<td>Boiler house</td>
<td>Groundwater</td>
<td>1 MW</td>
</tr>
<tr>
<td>5</td>
<td>City center</td>
<td>Seawater</td>
<td>No limit</td>
</tr>
<tr>
<td>6</td>
<td>Boiler house</td>
<td>Lake water</td>
<td>27000 m³/h</td>
</tr>
<tr>
<td>7</td>
<td>Boiler house</td>
<td>Groundwater</td>
<td>1 MW</td>
</tr>
<tr>
<td>8</td>
<td>Boiler house</td>
<td>Ambient air</td>
<td>10 MW</td>
</tr>
<tr>
<td>9</td>
<td>Biomass CHP*</td>
<td>River water</td>
<td>6000-25000 m³/h</td>
</tr>
<tr>
<td>10</td>
<td>Biomass CHP*</td>
<td>Ambient air</td>
<td>24 MW</td>
</tr>
<tr>
<td>11</td>
<td>Biomass CHP*</td>
<td>Groundwater</td>
<td>6 MW</td>
</tr>
<tr>
<td>12</td>
<td>Maardu**</td>
<td>Seawater</td>
<td>Local heat demand</td>
</tr>
<tr>
<td>13</td>
<td>100 m from DH</td>
<td>Groundwater</td>
<td>6 MW each</td>
</tr>
</tbody>
</table>

*Distribution costs avoided
**Heat loss of 13 km transmission pipe avoided
### III. Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>#3</th>
<th>#6</th>
<th>#10</th>
<th>#11</th>
<th>#12</th>
<th>Total</th>
<th>Denmark [3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td></td>
<td>Sew</td>
<td>Lake</td>
<td>Air</td>
<td>GW</td>
<td>Sea</td>
<td>Mix</td>
<td></td>
</tr>
<tr>
<td>Q&lt;sub&gt;HP&lt;/sub&gt;</td>
<td>MW</td>
<td>45</td>
<td>43</td>
<td>24</td>
<td>6</td>
<td>12</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>SCOP</td>
<td></td>
<td>3.4</td>
<td>3.2</td>
<td>2.9</td>
<td>3.2</td>
<td>3.3</td>
<td>3.2</td>
<td>3.5 – 4.5</td>
</tr>
<tr>
<td>FLH</td>
<td>h</td>
<td>3356</td>
<td>2263</td>
<td>1838</td>
<td>2846</td>
<td>2797</td>
<td>2638</td>
<td>3000 - 6000</td>
</tr>
<tr>
<td>Cost&lt;sub&gt;HP,inv+el&lt;/sub&gt;</td>
<td>€/MWh&lt;sub&gt;h&lt;/sub&gt;</td>
<td>30.2</td>
<td>34.8</td>
<td>39.3</td>
<td>33.5</td>
<td>35.4</td>
<td>33.3</td>
<td>42 - 49</td>
</tr>
<tr>
<td>Cost&lt;sub&gt;HP,el&lt;/sub&gt;</td>
<td>€/MWh&lt;sub&gt;h&lt;/sub&gt;</td>
<td>16.4</td>
<td>18.3</td>
<td>17.8</td>
<td>15.5</td>
<td>17.5</td>
<td>17.2</td>
<td>25 - 32</td>
</tr>
<tr>
<td>Cost&lt;sub&gt;el&lt;/sub&gt;</td>
<td>€/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>53.5</td>
<td>56.0</td>
<td>48.9</td>
<td>47.4*</td>
<td>54.8</td>
<td>53.4</td>
<td>90 - 100</td>
</tr>
<tr>
<td>NPV</td>
<td>M€</td>
<td>33</td>
<td>15</td>
<td>4</td>
<td>3</td>
<td>9**</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>PBT&lt;sub&gt;simple&lt;/sub&gt;</td>
<td>yrs</td>
<td>6.4</td>
<td>8.2</td>
<td>10.4</td>
<td>8.1</td>
<td>6.5**</td>
<td>7.5</td>
<td>4 – 8</td>
</tr>
<tr>
<td>CO2&lt;sub&gt;ratio&lt;/sub&gt;</td>
<td></td>
<td>1.32</td>
<td>1.39</td>
<td>1.53</td>
<td>1.39</td>
<td>1.37</td>
<td>1.38</td>
<td>0.29</td>
</tr>
</tbody>
</table>

*Distribution costs avoided   **Heat loss of 13 km transmission pipe avoided
III. Load duration curve with HPs

- 344 GWh HP operation (17%)
- Share of NG reduced from 50% to 33%
III. Lorenz efficiency

- Lorenz efficiency
  - varies during the year
  - differs between heat sources
IV. Discussion

- Limited applicability of HPs due to existing biomass CHP and waste incineration

- Solution considers different benefits:
  - No distribution costs (air, groundwater)
  - Reduction of heat loss (seawater)
  - Reduction of part of the investment (building, land, evaporator)

- Sustainability of HPs depends on electricity mix
  - 0.95 tonCO₂/MWh_{el} in Estonia (for energy generation: 75% oil shale)
    - 2009: 1.19 tonCO₂/MWh_{el}
    - Needed for HPs: <0.69 tonCO₂/MWh_{el}
  - 0.2 tonCO₂/MWh_{el} in Denmark
V. Conclusion

It was found:
- Optimal HP capacities, heat sources and HP operation
- Best economic solution: 130 MW HP capacity
- Heat sources: sewage water, lake water, groundwater, ambient air and seawater

- Sustainability of HPs depends on electricity mix
Thank you for your attention

Questions?
References

Investment costs of large-scale heat pumps:

COP estimation:

Danish examples of large-scale HPs:
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II. Potential heat supply for HPs

• Max. 4000 (4500) h of potential heat supply
• Number of full load hours depends on HP capacity
III. COP of HPs
### III. Sensitivity analysis: electricity price +30%

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>#3</th>
<th>#6</th>
<th>#10</th>
<th>#11</th>
<th>#12</th>
<th>Total</th>
<th>Total change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td></td>
<td>Sew</td>
<td>Lake</td>
<td>Air</td>
<td>GW</td>
<td>Sea</td>
<td>Mix</td>
<td>Rel. Abs.</td>
</tr>
<tr>
<td><strong>Q_{HP}(Input)</strong></td>
<td>MW</td>
<td>45</td>
<td>43</td>
<td>24</td>
<td>6</td>
<td>12</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>SCOP</td>
<td></td>
<td>-</td>
<td>3.4</td>
<td>3.2</td>
<td>2.9</td>
<td>3.2</td>
<td>3.3</td>
<td>3.2</td>
</tr>
<tr>
<td>FLH</td>
<td>h</td>
<td>3356</td>
<td>2261</td>
<td>1840</td>
<td>2849</td>
<td>2804</td>
<td>2640</td>
<td></td>
</tr>
<tr>
<td>Cost_{HP,inv+el}</td>
<td>€/MWh</td>
<td>33.2</td>
<td>38.1</td>
<td>42.8</td>
<td>36.6</td>
<td>38.6</td>
<td>36.5</td>
<td>+9.6% +3.2</td>
</tr>
<tr>
<td>Cost_{HP,el}</td>
<td>€/MWh</td>
<td>19.4</td>
<td>21.6</td>
<td>21.4</td>
<td>18.6</td>
<td>20.7</td>
<td>20.4</td>
<td>+18.6% +3.2</td>
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<tr>
<td>Cost_{el}</td>
<td>€/MWh</td>
<td>63.6</td>
<td>66.4</td>
<td>59.3*</td>
<td>57.5*</td>
<td>65.0</td>
<td>63.6</td>
<td>+19.1% +10.2</td>
</tr>
<tr>
<td>NPV</td>
<td>M€</td>
<td>27</td>
<td>11</td>
<td>2</td>
<td>2</td>
<td>8**</td>
<td>50</td>
<td>-21.9% -14</td>
</tr>
<tr>
<td>PBT_{simple}</td>
<td>yrs</td>
<td>7.1</td>
<td>9.2</td>
<td>11.9</td>
<td>9.0</td>
<td>7.1**</td>
<td>8.3</td>
<td>+10.7% +0.8</td>
</tr>
<tr>
<td>CO2_ratio</td>
<td></td>
<td>1.32</td>
<td>1.39</td>
<td>1.53</td>
<td>1.39</td>
<td>1.37</td>
<td>1.38</td>
<td></td>
</tr>
</tbody>
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