Modeling of heat pumps and excess heat sources in energy system models
Electrification – Heat Pumps

• Denmark 2050 Fossil fuel independence
• District heating
  – Copenhagen 2035 ~150 MW heat
• Industry
  – 20 % of energy demand
Excess heat integration

1 kWh Electric Power  →  Heat Pump  →  3 kWh Heat Supply

2 kWh low temperature source
The Technology Catalogue

- Technology Data for Energy Plants for Electricity and District heating generation
- Accepted basis for planning models
  - TIMES-DK, Balmorel, EnergyPlan, ...

### Data sheets

<table>
<thead>
<tr>
<th>Technology</th>
<th>2015</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
<th>Uncertainty (2020)</th>
<th>Uncertainty (2050)</th>
<th>Note</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat generation capacity for one unit (MW$_{\text{heat}}$)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>6</td>
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<tr>
<td>Total efficiency, net (%), name plate</td>
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</tr>
<tr>
<td>Total eff., net (%), annual average, ambient heat source, no dev. in supply temp.</td>
<td>350</td>
<td>360</td>
<td>380</td>
<td>410</td>
<td>350</td>
<td>380</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>Total eff., net (%), annual average, ambient heat source, reduced supply temp.</td>
<td>350</td>
<td>400</td>
<td>480</td>
<td>600</td>
<td>350</td>
<td>450</td>
<td>350</td>
<td>700</td>
</tr>
<tr>
<td>Total eff., net (%), annual average, waste heat 20°C, reduced supply temp.</td>
<td>440</td>
<td>500</td>
<td>600</td>
<td>740</td>
<td>440</td>
<td>600</td>
<td>440</td>
<td>850</td>
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<tr>
<td>Total eff., net (%), annual average, waste heat 40°C, reduced supply temp.</td>
<td>700</td>
<td>900</td>
<td>1,200</td>
<td>1,800</td>
<td>700</td>
<td>1,200</td>
<td>700</td>
<td>2,000</td>
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<td>Electricity consumption for pumps etc. (% of heat gen)</td>
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<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>4</td>
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</tbody>
</table>

Note: A, B, C, J, K

Ref: 3, 4

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*Credits:*

- TIMES-DK
- Balmorel
- EnergyPlan
- ...
Heat Pump characteristics
Excess heat potential in Denmark

Excess heat in Denmark: 212.0 PJ per year
- Manufacturing industry: 23.0 PJ per year
- Thermal processes: 12.6 PJ per year
Excess Heat High Temperature

1 MW @ 100 °C
Sensible heat – utilized by cooling

Direct integration – No heat pumping
Utilization – 44 %
Excess Heat Low Temperature

1 MW @ 60 °C
Sensible heat – utilized by cooling

Direct integration not possible – heat pumping
Utilization up to 100 %
Heat Pump Integration

R134a example
COP 2.8
Heat production 1.6 MW

Heat transfer finite
Temperature difference

Non-isentropic compression

Non-isentropic expansion

Pressure loss, motor, heat loss,...
Carnot cycle v. Lorenz Cycle

Carnot cycle integration
COP 5,0
Heat production 1,25 MW
No internal irreversibility

Lorenz cycle integration
COP 11
Heat production 1,1 MW
No internal and external irreversibility
Credit goes where credit’s due

Hendrik Antoon Lorentz (1853-1928) Netherlands
Lorentz transformation

Ludvig Valentin Lorenz (1829 –1891) Denmark
Refraction, conductivity

Edward Norton Lorenz (1917-2008) USA
Meteorology, chaos theory

Hans Lorenz (1865-1945) Germany
Refrigeration, thermodynamics

Hendrikus Albertus Lorentz (1871-1944) Netherlands
Explorer

Gustav Lorentzen (1915-1995) Norway
Transcritional CO₂ cycles, heat pump

Gustav Fredrik Lorentzen (1947-2010) Norway
Engineer, musician

Hans Lorenz (1845-1945) German
Refrigeration, thermodynamics

A Lorenz (Published 1973-75) DDR
Refrigeration, zeotropic mixtures
Heat Pump performance

\[ \text{COP}_C = \frac{T_H}{T_H - T_L} \]

Sadi Carnot

Lorenz efficiency

\[ \eta_{\text{Lorenz}} = \frac{\text{COP}_{\text{actual}}}{\text{COP}_L} \]

\[ \text{COP}_L = \frac{T_{H,\text{lm}}}{T_{H,\text{lm}} - T_{L,\text{lm}}} \]

Hans Lorenz
Technology catalogue data

• COP from excess heat 40 ºC in 2050 : 18
• Lorenz limit: \((273+45)/(45-25)=16\)
• Highly optimistic for some

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Analysis of impact TIMES-DK

- TIMES long-term analysis and planning of energy systems
- TIMES minimization of total system costs
- TIMES-DK covers all sectors
- Time-slices - non-chronological and not equal length
- District heating networks: Central and Decentral

36 Cases
- Carbon budget, Frozen Policy and High Risk Constant/Reduced DH temperature
- With/without transmission constraints
- 3 methods for calculating COP - Simple DEA, Corrected DEA, Advanced
3 methods for calculating COPs

- Simple DEA
  - COPs directly from DEA Technology Catalogue

- Corrected DEA
  - Three temperature levels for excess heat: LT, MT, HT
  - HT direct integration
  - LT and MT with heat pump – re-evaluated COP

- Advanced
  - Three temperature levels for excess heat: LT, MT, HT
  - HT direct integration
  - LT and MT with heat pump – Lorenz efficiency 55 % - temperature differences
Results overall energy system

District heating origin in 2030

- Excess heat
- Waste
- Woody biomass
- Straw
- Solar
- Natural gas
- Electricity
- Biogas
- Ambient heat
Difference in COP

- Annual average COP values as calculated by the TIMES-DK model
  - Simple approach
  - Advanced approach
District heating Origin

• There are only a limited variation by using the two different approaches
• With a lower COP value, more solar heating appears at the cost of particular excess heat from datacentres
Annual average production costs of heat

Production costs of heat

- Central District heating Calculated
- Central District heating Simple
- Decentral District heating Calculated
- Decentral District heating Simple
Observations TIMES-DK

• Waste incineration and biorefinery excess heat are prioritized compared to heat pumps
• Data centers, biorefineries and high temperature excess heat in central areas
• Ambient source heat pumps in decentral areas
• No network investment is prioritized – data centers, ambient source
• Industrial excess heat with heat pumps has lowest priority
  – even if COP is highest – because of distance and network investment
• So under the given conditions and for the Danish system, the mistake by calculating the COP wrong is not so big. Only little industrial excess heat will be installed.
Conclusion

• Excess heat – Heat pump integration requires
  – Capacity
  – COP
  – May conflict

• COP estimates should account for thermodynamics

• Important for techno-economic analysis

• Excess heat-based heat pumps may be challenged socio-economically
  – High temperature excess heat – biorefineries
  – Network installation
  – Heat pumps using ambient sources in decentral grids
Heat pumps for the future energy system
The Laws of Thermodynamics

• 1st Law: Energy is conserved – can only be transformed

• 2nd Law: Heat cannot pass spontaneously from a colder to a warmer body

\[ T_{\text{high}} \rightarrow Q \]

\[ T_{\text{low}} \rightarrow Q \]
Heat pump realized performance
TIMES-DK model (if needed)
Comments on Brain's overall conclusions

I understand the overall conclusions are:

• So under the given conditions and for the Danish system, the mistake by calculating the COP wrong is not so big. Only little industrial excess heat will be installed.

I agree that the difference won't be so big. Some of the main explanations:

• Waste CHPs come in because we need to burn the waste
• Carbon budget scenarios put a big pressure on the transport sector, we need to produce biofuels, high temperature excess heat becomes available. The cost assumptions are that we build big biorefinaries and we assume that we can place them in the Central DH areas
• There is no big difference in total capacity of heat pumps, only in the sources. This is due to lack of alternatives - waste CHPs are almost fixed, biomass is need for fuel production, only heat pumps are left.
• The effect of COPs on the whole system (objective function for example) is very small - it is just one parameter in one of the sectors. Since heat pumps are always in (different sources), the only difference between the scenarios is the (average) COP. This can't affect the electricity price - it is determined by the neighboring countries. It can affect the electricity consumption, but the effect is minor. The DH price is mostly affected by the COP through the choice of sources for heat pumps. (For example, if the model chooses EH from biorefinaries, the DH price is lower than if the model chooses air-source.)
Discussion of TIMES-DK results

• How do we make sure that in particular decentral district heating grids have incentive to use heat pumps rather than biomass resources.

• Excess heat from industries might be better utilised as an internal optimisation process, in particular if heat pumps improve and become able to lift temperatures to 150-200 degrees.