COMBINED HEAT AND POWER (CHP)
Smart Power Generation
- District Heating Solutions

Edward Nagelhout, WÄRTSILÄ POWER PLANTS
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Agenda

• District Heating
• Opportunities and Challenges
• CHP Technologies in DH Applications
• Economic Comparison
• Other Benefits
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District Heating

Heat

Next to electricity, modern society requires much heat for:
- industrial processes
- space heating
- hot water

Heat can be generated by:
- Solar (Radiation (glass) or solar boilers)
- Heat pumps
- Fuel-based boilers
- CHP (combined heat and power)
  - This is especially the case if the electricity generators are installed at the site where the heat is needed.
  - Examples: Hospitals, chemical industries, refineries, large greenhouse facilities and district heating

Source: IEA, *CHP, Evaluation the benefits of greater global investment, 2008*
District Heating

Cogeneration

Combined Heat and Power (CHP), also known as cogeneration, generates electricity while using residual (excess) heat for residential heating, hot water or steam.

- CHP currently accounts for 9-11%* of global power generation.
- CHP plants can use various fuels ranging from natural coal, gas, to even bio-mass.

Source: Cogen Europe.
Cogeneration

CHP Plant technologies

- Gas turbines (OCGT) with heat recovery steam generators (HRSG)
- Combined-cycle gas turbines (CCGT) consisting of a gas turbine with HRSG, which drives a steam turbine with a back pressure or a steam extraction system
- Internal combustion engines with electrical generators and heat extraction systems

Source: IEA ETSAP Technology Brief E04, May 2010
Source: Cogen Europe
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District Heating (DH)

DH systems

Heat Networks are a global happening
- North America (USA, Canada)
- North and Eastern Europe
- Russia
- Northern China and Japan
- South Korea

Built in Cities and Urban Areas
- Dense accumulation of buildings
- One common system covers one city
- System designs are country specific
- Most systems are based on
  - 110-170 °C Hot water
  - 90-100 °C Warm water
- Traditionally heated by centralised coal or oil fired thermal plants, which have been replaced by gas fired CHP

Source: IEA, CHP, Evaluation the benefits of greater global investment, 2008
District Heating (DH)

DH systems

Most CHP based DH systems are operated according to heat demand
- Electricity production is seen as a by-product to be sold to grid
- Typically only operated during cold seasons
- Summer heat load is lower than minimum requirements (So boilers take over)
- Summer E-prices are lower than winter prices (Less income)

Politically desirable
- Energy efficient (85-90%)
- Environmentally friendly (CO₂ reduction)

Feasibility is at question
- Large investments

Opportunities
- Product combination (DC, Heatpumps, RE)
- Maximise Earnings by increasing flexibility

Source: IEA, CHP, Evaluation the benefits of greater global investment, 2008
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District Heating

DH systems

To make CHP more flexible
- DH systems need to make electricity and heat generation partially independent by
  - Heat storage (thermal/electrical)
  - Backup generation

DH load
- DH load is generally scattered over a wide area with many smaller load points
  - Optimisation is challenging
  - CHP plant is economically viable at 40-50% of the annual peak load

Source: Heating data from a Central European City with a population of ~300,000
- District Heating
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Opportunities and Challenges

Efficient use of primary fuels

Following EU Energy Strategy

• CHP and DH systems have an important role in increasing efficient use of fuels
• Replacement of coal, oil and gas-fired boilers plants with CHP

New investment in CHP and DH systems have requirements

• Need accurate and reliable forecasts of heat loads and prices
• Potential income from electricity
• Stable regulatory frameworks, due to long lifespan (20-40 years)

Heat load

• Typically heat loads are low in summer, while during other seasons loads vary heavily. Winter has very short term heat demand peaks with a higher base load
• Also notable annual heat load variations which makes optimisation challenging
• Improvement in insulation, such as housing, leads also to annual decrease in heat demand.
  • Estimations range from 1-3% per year
  • Growth of connections and increase in consumer comfort will alleviate this partially
Opportunities and Challenges

Feasibility

Electricity
• Competitive markets
  – Leads to more price volatility
• Dispatch according to market price signals
• Higher shares of renewable plant (Wind and Solar)
  – Increase in electricity price variations, due to intermittency

CHP
• Heat load and electricity prices do not always correlate (match)
• Making CHP heat and electricity production (partially) independent will increase its profitability
• Some markets promote merit order of CHP plant, improving feasibility
• CHP bonus is also known, bonus electricity tariffs, based on annual total efficiency
Opportunities and Challenges

Spot Market Denmark
Opportunities and Challenges

Improved flexibility with DH storage

A heat storage system enables
• Efficient use CHP
• CHP flexibility

Utilisation of an accumulator
• High E-prices, CHP runs full load
  – Charges accumulator
• Low E-prices, storage discharges
  – CHP doesn’t need to run
  – E-boiler practical when in markets with high share of intermittent plant

• Fast dispatching CHP
  – Possible balancing services
  – Tertiary income (ancillary markets, ETS)

Source: www.emd.dk/desire/skagen
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CHP Technologies in DH Applications

In mid segment (50-300MW) choices

CCGT

• High electrical efficiency (48-58\%)\(^1\)
• Consists of a gas turbine with HRSG
  – driving a steam turbine with a back pressure
  – or a steam extraction system
• High gas pressure, High temperatures
• High quality materials and operators needed
• Gas turbine start 25 mins, CCGT 45 mins
• Minimum load 50\% E, 60\% Heat
• Once per year full maintenance with 50-100\% capacity loss

CCGT Configuration for DH

• Possible 1-1-1 or 2-2-1 setup
• The larger, the better the price per KW\(_e\)
  – Higher efficiency with larger turbines

Source: GTPro, Thermoflow software
In mid segment (50-300MW) choices

Reciprocating combustion engines
- Electrical efficiency (44-48%)\(^1\)
- Multiple generation sets in parallel
  - HRSG and Engine cooling system
  - Jacket water, lube oil, charge air
- Gas pressure 5 bar, temperatures 400°C
- Modular design, enabling short start up times
- Start 5 mins
- Maintenance can be run with minimal loss of capacity 5 engines 20%, 10 engines 10%
- Wide load range 5%-100% for both E and heat

Configuration for DH
- Easy to optimise due to multiple engines

Also biomass fired plants

Source: Wärtsilä
CHP Technologies in DH Applications

Comparisons

Efficiencies

• Gas turbines
  – E-efficiency decreases at part load
  – Heat efficiency increases at part load

• Combustion engines
  – High part load E-efficiency
  – Constant power-to-heat ratio at any load

• Minimum electrical load in the graphs is assumed at 50% for both technologies

Power-to-heat ratios

• As seen the CCGT can operate between a heat load range
  – 60-100% in 1-1-1 and
  – 30-100% in 2-2-1 configuration
  – 2-2-1 running in 1-1-1 can increase its power-to-heat ratio to 100% at 50% load

• Combustion engines can run at 5-100% heat load (10 units)
Comparisons

Load ranges and efficiencies on plant level

- **Plant total efficiency**
  - Combined cycle plant, 1-1-1 -total
  - Combined cycle plant, 2-2-1 -total
  - Combustion engine plant, 10 engines -total

- **Plant electrical efficiency**
  - Combined cycle plant, 1-1-1 -electrical
  - Combined cycle plant, 2-2-1 -electrical
  - Combustion engine plant, 10 engines -electrical

- **Plant load ranges**
  - Combined cycle plant, 1-1-1 -load range
  - Combined cycle plant, 2-2-1 -load range
  - Combustion engine plant, 10 engines -load range
CHP Technologies in DH Applications

Dynamic features

Note: Start up times from warm stand-by!
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Economic Comparison

Input data for model

Model data

• Electricity market
  – E produced sold to German National Grid (EEX)
  – E-prices 2009\(^1\), CHP get bonus of €15/MWh\(_{el}\)\(^2\)

• Gas market
  – €25/MWh\(^3\) (€6.9/GJ) fuel cost
  – Corresponding heat price at 91% efficiency is €27.5/MWh\(_{th}\)

• Economic variables
  – Lifespan is 20 years, with 6% WACC
  – Hourly evaluation for 1 operational year
  – 400 MW\(_{th}\) DH network, optimal 40% load setup

• Compared solutions [3]
  – 1-1-1 CCGT, 220 MW\(_{el}\), 50% efficiency
  – 2-2-1 CCGT, 2x100 MW\(_{el}\), 48% eff.
  – Combustion engine plant, 10x18MW\(_{el}\), 46% eff.
  – All: 88% efficiency total, 165 MW\(_{th}\) full load

E-Market price variation

E-Market price duration
Economic Comparison

Performance Values

Data

• Sources: Wärtsilä and GTPro, thermoflow software
  – Project and development costs are assumed at 25-30% of total investment
  – These also contain the investment for storage/accumulators
  – O&M are estimates based on data from multiple sites, calculating costs related to start/stop use

Performance values of the compared solutions

<table>
<thead>
<tr>
<th>Plant name</th>
<th>Combined cycle plant, 1-1-1</th>
<th>Combined cycle plant, 2-2-1</th>
<th>Combustion engine plant 10 engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant size</td>
<td>MW&lt;sub&gt;el&lt;/sub&gt; / MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>220 / 167</td>
<td>200 / 167</td>
</tr>
<tr>
<td>Plant net efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>%</td>
<td>50</td>
<td>48</td>
</tr>
<tr>
<td>Heat</td>
<td>%</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>%</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Plant load range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>%</td>
<td>50-100</td>
<td>25-100</td>
</tr>
<tr>
<td>Heat</td>
<td>%</td>
<td>68-100</td>
<td>34-100</td>
</tr>
<tr>
<td>Prices and costs</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Power plant (EPC)</td>
<td>EUR/kW&lt;sub&gt;el&lt;/sub&gt; net</td>
<td>900</td>
<td>1000</td>
</tr>
<tr>
<td>Project development / administration</td>
<td>EUR/kW&lt;sub&gt;el&lt;/sub&gt; net</td>
<td>300</td>
<td>300</td>
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<tr>
<td>Total investment</td>
<td>EUR/kW&lt;sub&gt;el&lt;/sub&gt; net</td>
<td>1200</td>
<td>1300</td>
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<tr>
<td>O&amp;M costs including consumables</td>
<td>EUR/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Economic Comparison

Optimal plant operating modes

Model output

- CCGT shut down during summer months, due to narrow load range + long start-up times
  - 1-1-1 configuration produces more E, because of size and higher efficiency
  - 2-2-1 configuration gets more operation hours due to its boarder range
  - Combustion engines produce more heat and electricity because it can operate during summer
  - Combustion engines reach higher annual running hours due to its wide load range (multiple units)

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</thead>
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<tr>
<td>Plant size</td>
<td>( MW_e / MW_{th} )</td>
<td>( MW_e / MW_{th} )</td>
<td>( MW_e / MW_{th} )</td>
</tr>
<tr>
<td>Electricity production balance</td>
<td>GWh_{el}</td>
<td>869</td>
<td>840</td>
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<tr>
<td>Fuel consumption</td>
<td>GWh_{fuel}</td>
<td>1 746</td>
<td>1 777</td>
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<tr>
<td>Annual running hours</td>
<td>h</td>
<td>4 192</td>
<td>4 698</td>
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<td>Heat production balance</td>
<td>GWh_{th}</td>
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<td>716</td>
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<td>GWh_{th}</td>
<td>375</td>
<td>328</td>
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<tr>
<td>Heat boiler</td>
<td>GWh_{th}</td>
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<td>328</td>
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<tr>
<td>Total</td>
<td>GWh_{th}</td>
<td>1 044</td>
<td>1 044</td>
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<td>Annual efficiencies</td>
<td>%</td>
<td>50</td>
<td>47</td>
</tr>
<tr>
<td>Electricity</td>
<td>%</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>Heat</td>
<td>%</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Total</td>
<td>%</td>
<td>88</td>
<td>88</td>
</tr>
</tbody>
</table>

Source: Wärtsilä, moduled via Plexos
Economic Comparison

Annual variation and duration curves for the compared solutions

Source: Wärtsilä, modulated via Plexos
Economic Comparison

Economic Results

CCGT <-> Combustion engines

• Feasibility Model
  – Annual operating profits of all 3 solutions are similar
  – Lower E-efficiency of combustion engine is compensated by its flexibility in summer
  – The relative low CAPEX costs gives the combustion plant healthier cash flow
    – This in return shortens the pay-back time, IRR and NPV is higher

Economic values of the compared solutions

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<td>Plant size</td>
<td>MWel / MWth</td>
<td>220 / 167</td>
<td>200 / 167</td>
</tr>
<tr>
<td>Revenues and cost division</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenues from sales of electricity</td>
<td>MEUR / year</td>
<td>39</td>
<td>37</td>
</tr>
<tr>
<td>CHP bonus</td>
<td>MEUR / year</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Total revenues</td>
<td>MEUR / year</td>
<td>52</td>
<td>49</td>
</tr>
<tr>
<td>Operating costs</td>
<td>MEUR / year</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Operating profit</td>
<td>MEUR / year</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>Capital Costs</td>
<td>MEUR / year</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Net cash flow</td>
<td>MEUR / year</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Feasibility of the investment</td>
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<td></td>
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<tr>
<td>Pay-Back Time</td>
<td>years</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>Internal Rate Of Return</td>
<td>%</td>
<td>6</td>
<td>5</td>
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<tr>
<td>Net present value</td>
<td>MEUR</td>
<td>0</td>
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<tr>
<td>Total Investment</td>
<td>MEUR</td>
<td>264</td>
<td>260</td>
</tr>
</tbody>
</table>

Source: Wärtsilä, modulated via Plexos
Economic Comparison

Economic Results

CCGT <-> Combustion engines

• Feasibility Model
  – Combustion engine has higher production costs, due to its higher running hours
  – On the other side it has a lower annual generation cost
    – High electrical output
    – Lower capital cost

Economic values of the compared solutions

<table>
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<th>Plant name</th>
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<td>MW&lt;sub&gt;el&lt;/sub&gt;/MW&lt;sub&gt;in&lt;/sub&gt;</td>
<td>220 / 167</td>
<td>200 / 167</td>
</tr>
<tr>
<td>Production costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>MEUR</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Variable O&amp;M</td>
<td>MEUR</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>- Fuel savings from heat recovery</td>
<td>MEUR</td>
<td>-18</td>
<td>-20</td>
</tr>
<tr>
<td>Total</td>
<td>MEUR</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Generating costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity production costs</td>
<td>EUR/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Capital costs</td>
<td>EUR/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td>Total</td>
<td>EUR/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>- CHP bonus</td>
<td>EUR/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>-15</td>
<td>-15</td>
</tr>
<tr>
<td>Net generating costs</td>
<td>EUR/MWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

Source: Wärtsilä, modeled via Plexos
The study showed, future CHP and DH systems should:

- Fulfil environmental norms
- Utilise heat storage
- Have high efficiency
- Have a high power-to-heat ratio
- Have good dynamic capabilities
  - fast start to full production, fast stop and good ramping possibilities
- Have a wide plant heat load range
The key findings from the comparison are:

- A wide heat load range enables flexible operation during variable heat demands
- Heat storage improves the system’s flexibility with optimal electricity and heat production
- A efficient plant with high power-to heat ratio enables more electricity production
- Multiple units with fast starts/stops enable dynamic operation in low heat demand seasons
- Good dynamic capabilities (multiple units) enable opportunities in ancillary services markets due to increasing shares of intermittent renewable generation. Is also therefore more profitable
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Other Benefits

Additional earning potential

CHP can earn extra income on dynamic markets

• Electricity market
  – Sell capacity (reserve) in summer mostly
  – Sell ancillary services, balancing and frequency balancing

• Decentralised plant locations
  – Multi unit combustion engine plants offer the same efficiencies and cost level regardless of the number of units
  – Improves reliability and efficiency of energy supply
  – Reduces electrical and heat transmission losses
  – Saves pumping energy in the DH system
  – May be connected directly to medium voltage systems, reducing connection fees to high voltage national grid

• Permit allowance (easier to get building permits)
Optimise CHP

- Combustion plant efficiency is dependant on DH system
  - The lower the return temperature, the higher the total efficiency possible

- Plant efficiency is dependant on ambient temperatures
  - When running in the summer combustion plants don’t suffer efficiency losses as much as GT’s
THANK YOU FOR YOUR ATTENTION!

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Smart Power Generation
www.smartpowergeneration.com