Combined Heat And Power Production - Valuing Flexible Operation In An Uncertain Environment

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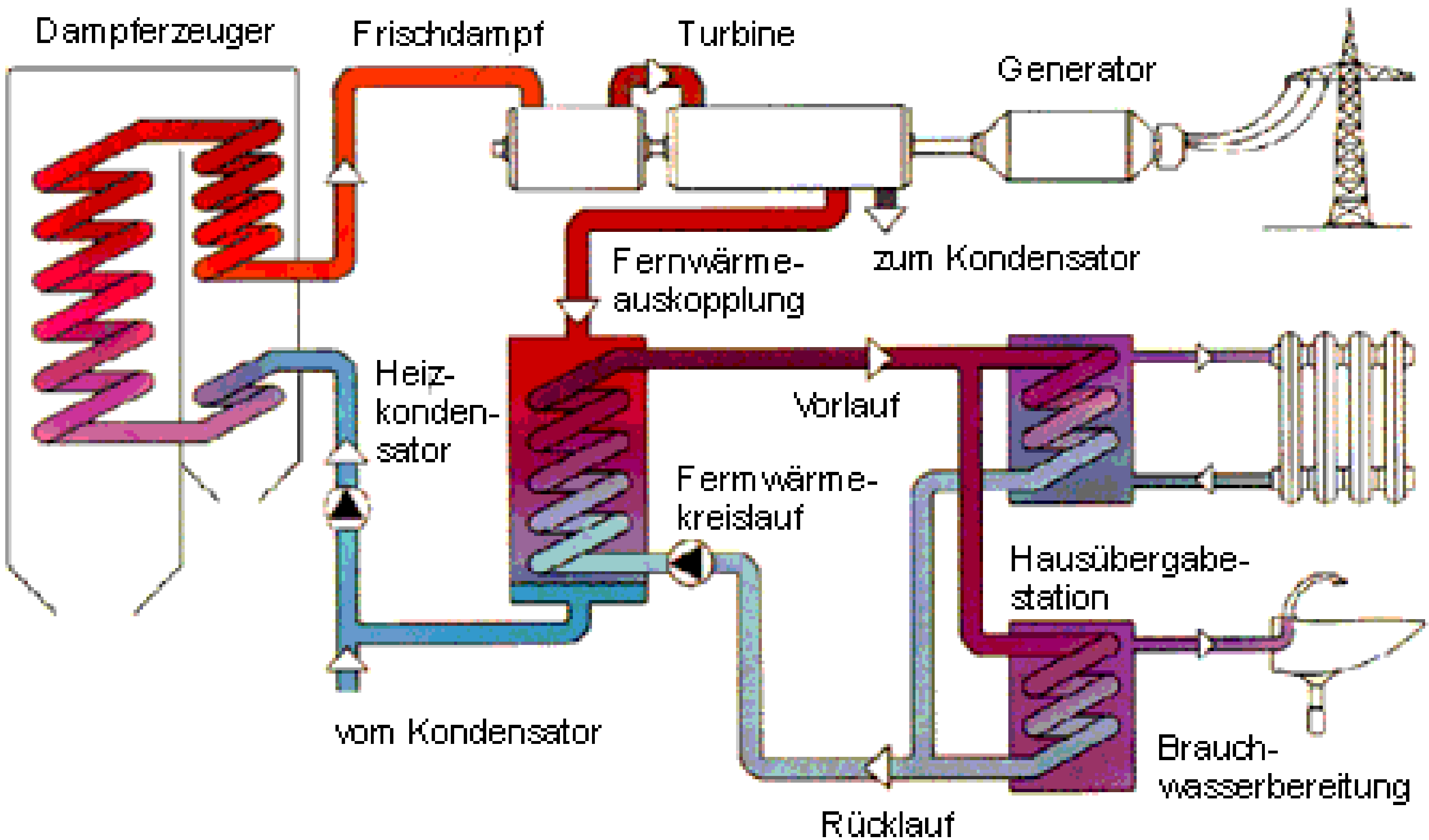
Motivation

- CHP: Combined Production of electricity and heat
- Traditionally used in countries with cold and moderate climate
  (e.g. Scandinavia, Netherlands, Austria, Eastern Europe, Germany)

- Combined efficiency higher than for electricity-only plant
- But heat forms also another restriction for the power plant operation
- Overall impact on profitability dependent on operation alternatives

- Coherent, as analytical as possible treatment looked for

CHP plant based on steam cycle



Related literature

- On the pricing of weather derivatives, e.g.
  - Acaton et al (2002)
- On stochastic optimization of CHP operation under uncertainty, e.g.
  - Woll, Weber (2006)
- On valuation of CHPs & Heat storage in the stochastic price framework, e.g.
  - Wottka (2016)
  - Kitapbayev, Moriarty, Mancarella (2015)
- On CHP plant investments as real options, e.g.
  - Wickmann; Madlener (2007)
  - Jouvet et al (2012)
  - Westner; Madlener (2012)

➢ Own contribution on valuation of operational flexibility

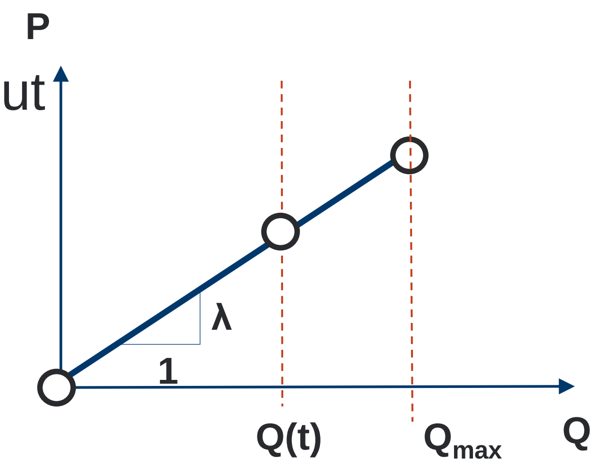
➢ Analytical insights on key drivers

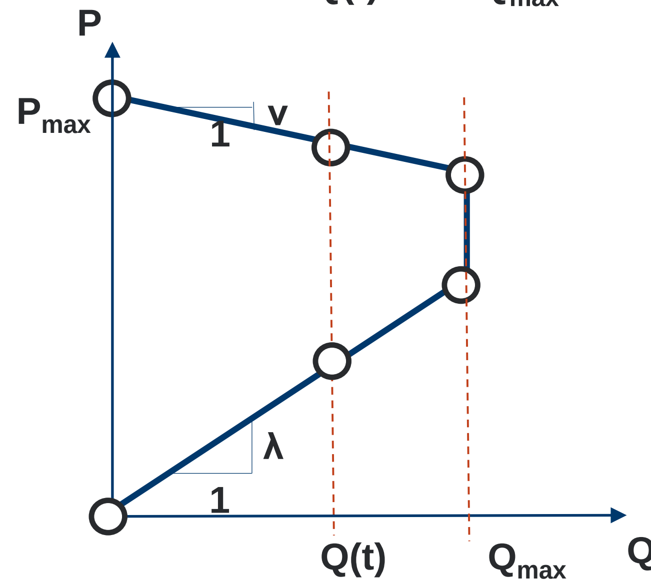
Types of CHP power plants

Key distinction:

- Fixed proportion of electricity relative to heat output
  - ➢ One degree of freedom
  - ➢ Heat restriction eventually strongly binding

    (notably little electricity production in summer)
  - ➢ Backpressure steam turbines, small-scale motor-based CHP,…
  - ➢ **λ:power-to-heat ratio**
- Variable proportion of electricity to heat
  - ➢ Two degrees of freedom
  - ➢ Heat restriction more flexible
  - ➢ Extraction-condensing steam turbines
  - ➢ **ν: power loss coefficient**





Types of CHP systems

- Broad range of different system configurations
- Very rarely only CHP units
- Usually combination with some (peaking) boilers
- Reasons:
  - Peak-load coverage in winter
  - Back-up for outages
  - Boilers less capital-intensive, advantageous for low full-load hours
  - Cheaper generation at low electricity prices

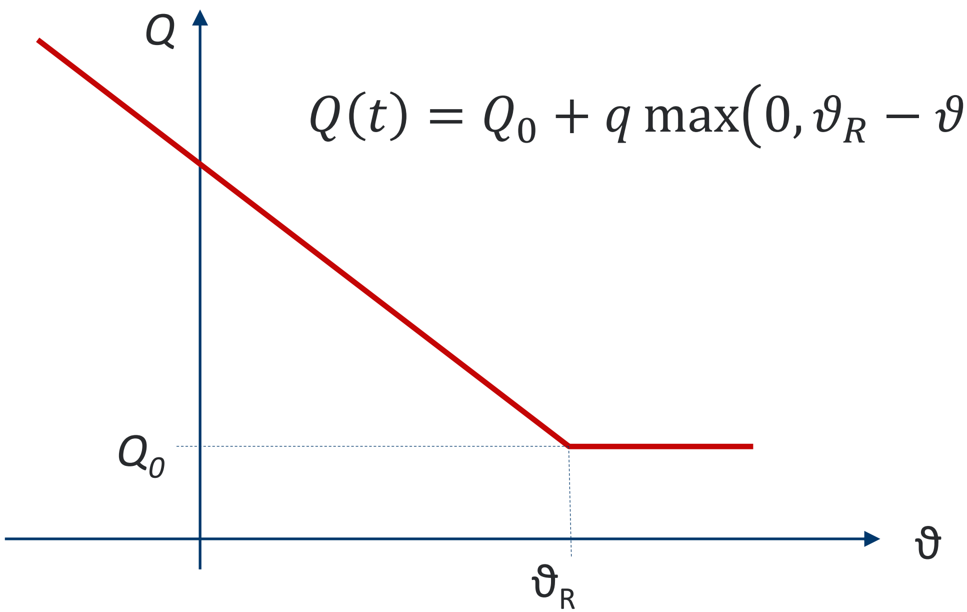
➢ Here focus on systems with one CHP plant and zero or one boiler

Systems studied

- Only backpressure steam turbine
- Backpressure steam turbine + auxiliary heat boiler
- Only extraction-condensing turbine
- Extraction-condensing turbine + auxiliary heat boiler
- Conventional condensing plant + separate heating boiler

Stochastic heat demand

- Heat demand is driven by the temperature
- Yet relationship is not linear: above a certain threshold, heating is no longer needed
- Heating demand as function of outside temperature:



Stochastic temperature modelling

- Based on model by Alaton et al.(2002)
- Seasonal temperature patterns described by sinusoidal function:

$$\vartheta_0(t) = \vartheta_m + \Theta \cdot \sin\left(\frac{2\pi}{T} t + \alpha\right)$$

- Stochastic mean-reversion process around time-varying mean

$$\begin{aligned} d\vartheta &= \left(\frac{d\vartheta_0}{dt} + \kappa_\vartheta(\vartheta_0(t) - \vartheta)\right) dt + \sigma_\vartheta dW_\vartheta \\ &= \kappa_\vartheta\left(\vartheta_m + \Theta^\# \sin\left(2\pi \frac{t}{T} + \alpha^\#\right) - \vartheta\right) dt + \sigma_\vartheta dW_\vartheta \end{aligned}$$

- Resulting (unconditional) expected heat demand:

$$\bar{Q}(t) = Q_0 + q\left(\bar{H}\Phi\left(\frac{\bar{H}}{\sigma_{\vartheta\infty}}\right) + \sigma_{\vartheta\infty}\phi\left(\frac{\bar{H}}{\sigma_{\vartheta\infty}}\right)\right)$$

with: $\bar{H} = \vartheta_R - \vartheta_m - \Theta^\# \cdot \sin\left(2\pi \frac{t}{T} + \alpha^\#\right)$

Backpressure turbine

- Link power to heat: $P(t) = \lambda Q(t)$
- Revenue stream:

$$R(t) = \left(p(t)\lambda + p_Q - p_F \frac{1}{\eta_{th}}\right) Q(t)$$

- Expected revenues

$$\bar{R}(t) = \left(\bar{p}(t)\lambda + p_Q - p_F \frac{1}{\eta_{th}}\right) \bar{Q}\,(t) + b\lambda Var[Q(t)]$$

With: $p(t) = \bar{p}(t) + b\,(Q(t) - E[Q(t)]) + v$, $\bar{m}(t) = \bar{p}(t)\lambda + p_Q - p_F \frac{1}{\eta_{th}}$

- Annual Revenues:

$$R_Y^{BP} = \int_0^T \int_{\Omega(t)} \left((\bar{m}(t) + v)(\bar{Q}\,(t) + u) + b\lambda Var[Q(t)]\right) d\omega\, dt$$

$$= m_Y Q_Y + \int_0^T (b\lambda Var[Q(t)]) dt$$

Backpressure turbine plus heatboiler

- Revenue stream:

$$R(t) = \max\left(\left(p(t)\lambda + p_Q - p_F \frac{1}{\eta_{th}}\right), p_Q - p_B \frac{1}{\eta_B}\right) Q(t)$$

- Similar as before

$$R_Y^{BP\&HB} = \int_0^T \int_{\Omega(t)} \left((\overline{m}'(t) + v)(\bar{Q}\,(t) + u) + b\lambda Var[Q(t)]\right) d\omega\, dt$$

$$= m_Y' Q_Y + V_{Q,Y}$$

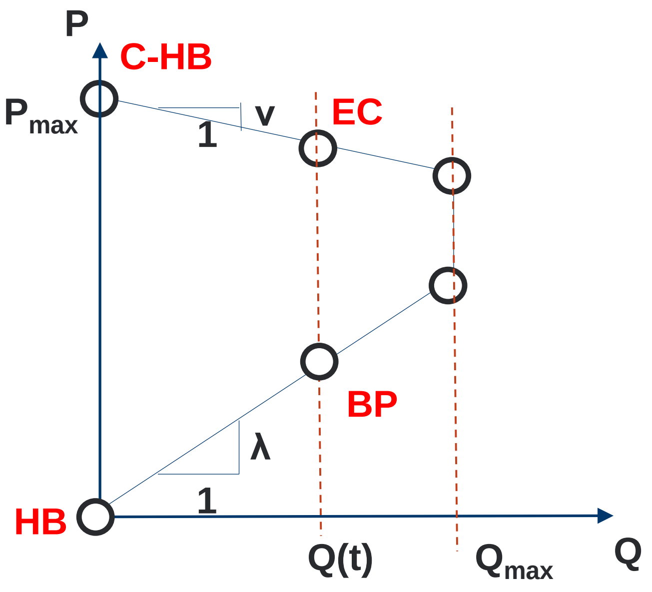
$$= R_Y^{BP} + \frac{Q_Y}{T} \int_0^T \int_{-\infty}^{m_{HB} - \overline{m}(t)} (m_{HB} - \overline{m}(t) - v) f(v) dv\, dt$$

With: $m_Y = \frac{1}{T} \int_0^T \overline{m}(t) dt$, $Q_Y = \int_0^T \bar{Q}(t) dt$

$V_{Q,Y} = \int_0^T Var[Q(t)] dt$

Choice sets depending on configuration

1. Single backpressure turbine:
   only **point BP**
2. Backpressure turbine & Heat boiler
   points BP & HB
3. Single extraction-condensing turbine:
   points BP & EC
4. Ext.-condensing turbine & Heat boiler
   points HB, BP, EC & C-HB
5. Condensing turbine & Heat boiler
   points HB & C-HB



Case Study

- Power plant located at Düsseldorf, Germany
- Heat demand driven by local temperature
  - Share of temperature-independent demand: 0.1
- Prices taken from observed prices 2015
  - Avoids specifying stochastic processes
  - Valid results since focus on impact of flexibility
- No impact of temperature resp. heat demand on prices considered
  - Actual impact rather weak (0,2 EUR/MWh per °C) and hardly significant
  - Explanation: power plant revisions shifted to low demand seasons

Case Study – Parameter choices

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Key system and power plant parameters

Efficiency boiler	eta_Boiler	0.8
Fuel price for boiler	p_Boiler	24
Fuel price for power plant	p_Fuel	20
Marginal efficiency electricity production	eta_elm	0.56
Power-to-heat ratio	lambda	1.2
Power loss coefficient	nu	0.2
Thermal efficiency power plant in backpressure mode	eta_th	0.4
Overall efficiency in backpressure mode	eta_ges_BP	0.88
Maximum Power output	P_max	100
Maximum Heat extraction	Q_max	71.4
Ratio Maximum Heat CHP to theoretical heat demand at T_min	r_CHP	0.8
Share of temperature-independent heat max heat	s_Base	0.1
Minimum reference temperature	T_min	-10
Heat price	P_Heat	30

Case study results

- Average margin in $EUR/kW_{th,inst}$

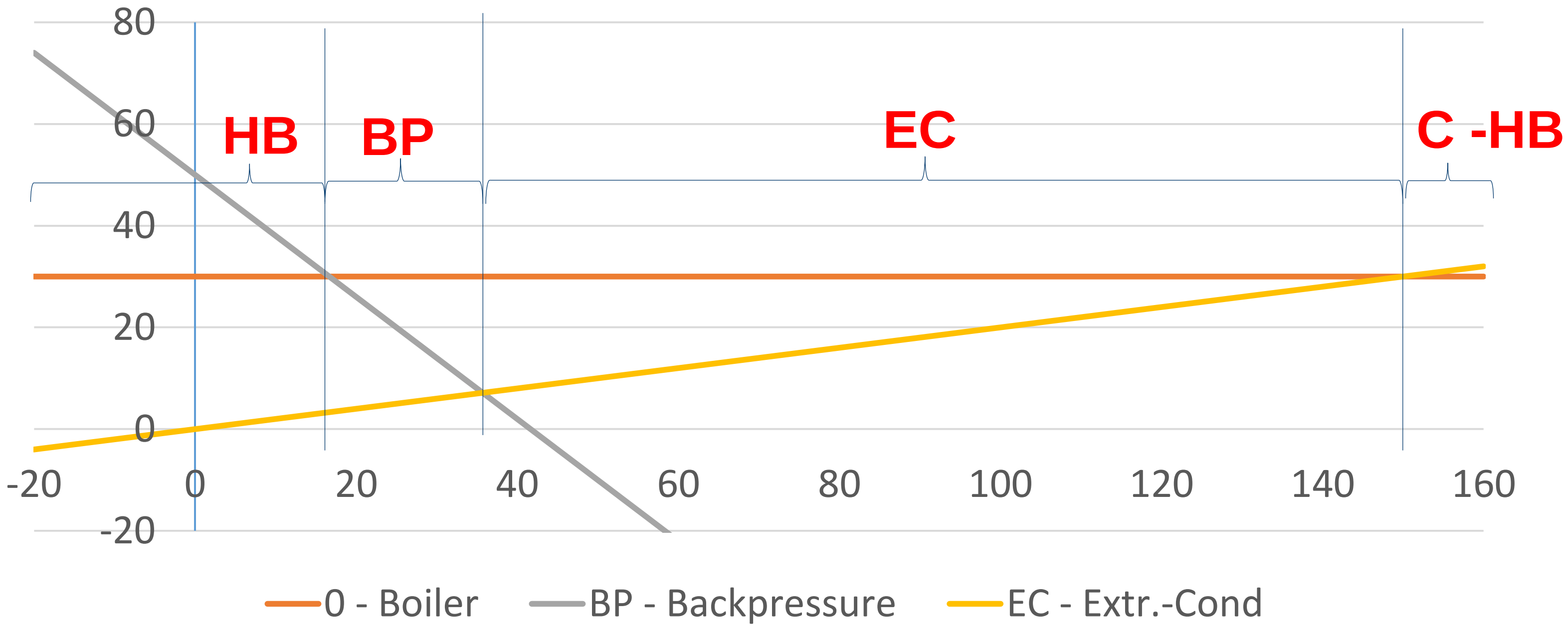
Only BP	BP & HB	Only EC	EC & HB	C & HB
51.50	54.17	76.01	78.67	38.60

- Additional value of a boiler is limited
- Additional value of extraction operation is much higher
- Pure condensing power plant + separate heat boiler is performing worse than other configurations

Key driver for operational decisions

- Marginal costs of heat provision:
- correspond to: $c_{m,Q}(t) = -\frac{dR_0(t)}{dQ}$

  with $R_0(t) = R(t) - p_Q Q(t)$



Conclusions

- CHP plants provide a means for heat and electricity production at high energy efficiency
- With (increasingly) volatile electricity prices, flexibility in heat provision becomes valuable
- The methodology developed allows to assess systematically the value of flexibility in combined heat & power production
- In the case study, especially the flexibility provided by extraction-condensing turbines turns out to be valuable

Thank you for your attention

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