Combined Heat and Power Plants - Sizing and Integration

ATIC

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Combined Heat and Power Generation

Back to basics

Heat to Work Conversion Efficiency

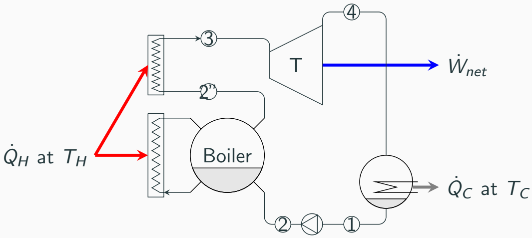


Figure 1 – Backpressure turbine

Applying the first and second principles of Thermodynamic leads to :

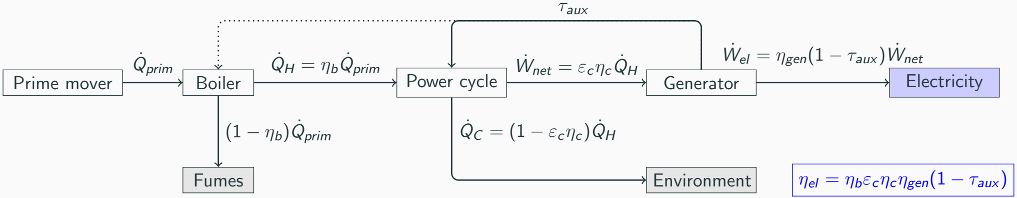
$$\begin{cases} \dot{W}_{net} = \varepsilon_c \eta_c \dot{Q}_H \\ \dot{Q}_C = \dot{Q}_H - \dot{W}_{net} \end{cases}$$

Where

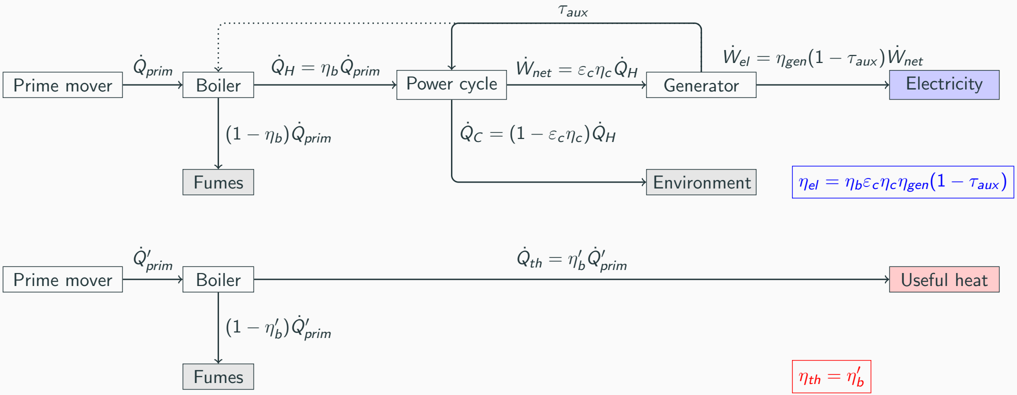
$$\eta_c = 1 - \frac{T_C}{T_H}$$

$$\varepsilon_c = 50\,\% ... 75\,\%$$

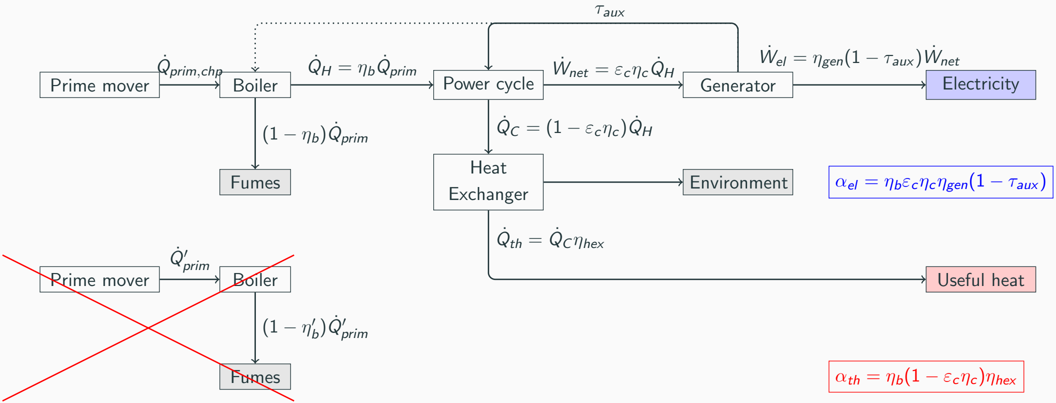
Energy Balance



Energy Balance



Energy Balance



Performance of CHP Plants

Efficiency of CHP Plants

Based on energy

$$\begin{cases} \alpha_{el} = \dfrac{\dot{W}_{el}}{\dot{Q}_{prim,chp}} = \eta_b(1 - \varepsilon_c \eta_c)\eta_{hex} \\ \alpha_{th} = \dfrac{\dot{Q}_{th}}{\dot{Q}_{prim,chp}} = \eta_b(1 - \varepsilon_c \eta_c)\eta_{hex} \end{cases} \rightarrow \ \eta_{chp} = \alpha_{el} + \alpha_{th}$$

Based on exergy where T_{th} is the temperature of the useful heat.

$$\eta_{ex,chp} = \frac{\dot{W}_{el} + \dot{Q}_{th}\left(1 - \frac{T_0}{T_{th}}\right)}{\dot{m}_c \ e_c} = \frac{\alpha_{el}}{f}\left[1 + \phi\left(1 - \frac{T_0}{T_{th}}\right)\right]$$

Primary Energy Saving

For separate production : $\dot{Q}_{prim,sep} = \frac{\dot{W}_{el}}{\eta_{el}} + \frac{\dot{Q}_{th}}{\eta_{th}}$

For combined generation : $\dot{Q}_{prim,chp} = \frac{\dot{W}_{el}}{\alpha_{el}} + \frac{\dot{Q}_{th}}{\alpha_{th}}$

The primary energy saving is thus :

$$PES \triangleq \frac{\dot{Q}_{prim,sep} - \dot{Q}_{prim,chp}}{\dot{Q}_{prim,sep}} = 1 - \frac{1}{\frac{\alpha_{el}}{\eta_{el}} + \frac{\alpha_{th}}{\eta_{th}}}$$

Different Types of CHP Plants

Backpressure Steam Cycles

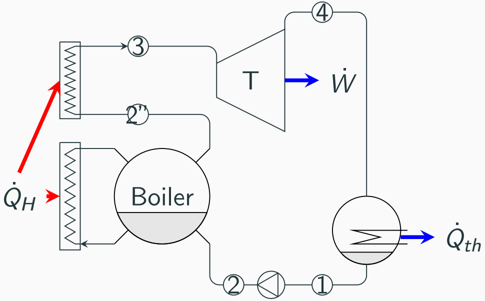


Figure 2 – Backpressure turbine

$$\alpha_{el} = 18\,\%\ldots 26\,\%$$

$$\alpha_{th} = 70\,\%\ldots 60\,\%$$

$$\eta_{chp} \simeq 88\,\%$$

$$\eta_{ex,chp} = 32\,\%\ldots 39\,\%$$

$$PES = 22\,\%\ldots 30\,\%$$

Gas Turbines

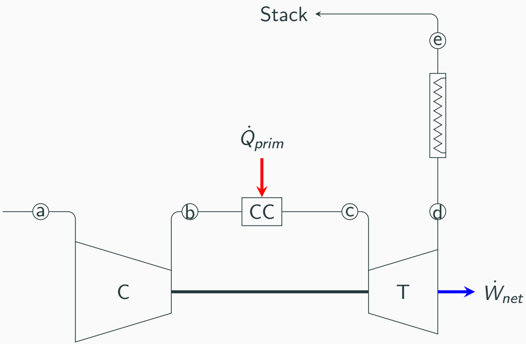


Figure 3 – Gas Turbine

$$\alpha_{el} \simeq 30\,\%$$

$$\alpha_{th} \simeq 55\,\%$$

$$\eta_{chp} \simeq 85\,\%$$

$$\eta_{ex,chp} = 55\,\%$$

$$PES \simeq 10\,\%$$

Combined cycles

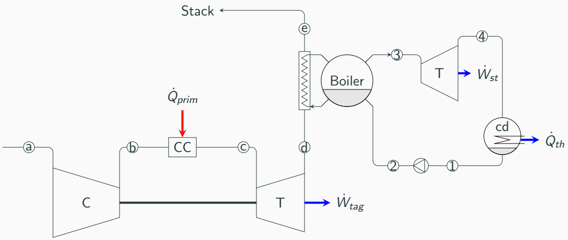


Figure 4 – Combined Cycle

$\alpha_{el} \simeq 35\,\%$

$\alpha_{th} \simeq 50\,\%$

$\eta_{chp} \simeq 85\,\%$

$\eta_{ex,chp} \simeq 45\,\%$

$PES \simeq 15\,\%$

Internal Combustion Engine

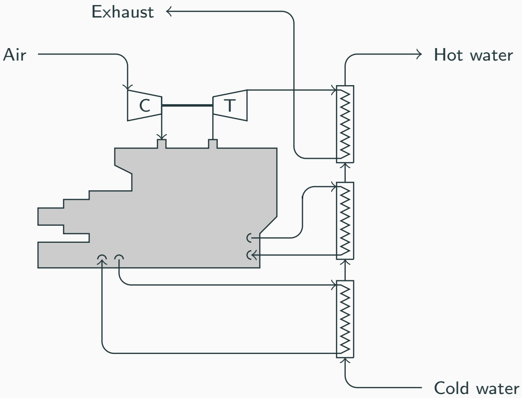


Figure 5 – Internal combustion engines

$\alpha_{el} \simeq 40\,\%$

$\alpha_{th} \simeq 46\,\%$

$\eta_{chp} \simeq 86\,\%$

$\eta_{ex,chp} \simeq 48\,\%$

$PES \simeq 20\,\%$

Economical Evaluation of Combined Heat and Power

The Net Present Value

Definition
The excess of the present value (PV) of cash inflows generated by the project over the amount of the initial investment C_0.

$$NPV = PV - C_0 = \sum_{k=1}^{N} A_k (1+d)^{-k} - C$$

For constant cash inflows, $NPV = A/\psi - C$ where $\psi = \dfrac{d}{1-(1+d)^{-N}}$.

Decision rule
If NPV is positive, accept the project. Otherwise, reject it.

Estimating the Installation Cost

The rule of “six tenths”
As size increases, cost increases by an exponent of six-tenths.

$$C = C_{ref} \left(\frac{P_{rated}}{P_{rated,ref}} \right)^{0.6}$$

- Generally speaking, costs are increasing with an exponent a whose value is between 0.3 (building, civil works) to 1.0 (scale-up by installation of multiple units).
- Inflation λ can influence the reference cost C_{ref} according to $C_{ref,N} = C_{ref,0}(1+\lambda)^N$.
- For developing technologies, reference costs may decrease due to increasing production volumes.

CHP Investment Costs

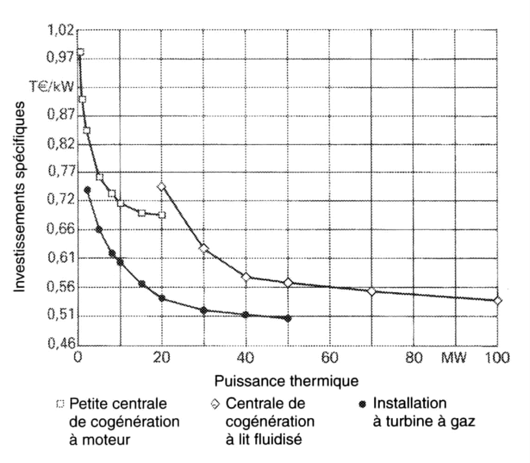


Figure 6 – Coûts spécifiques de différentes installations

Levelized Cost of Energy (LCOE)

For constant equivalent utilisation time and constant conversion efficiency over the project lifetime, the total system cost is :

$$TSC = \sum_{k=1}^{N} \left[C\psi(1+d)^{-k} + \left(\frac{P_{rated}\tau_e C_f}{\eta} + U_{fix} + u_{var} P_{rated}\tau_e \right) (1+d)^{-k} \right]$$

$$= \frac{P_{rated}\tau_e}{\psi} \left(\frac{C\psi}{P_{rated}\tau_e} + \frac{C_f}{\eta} + \frac{U_{fix}}{P_{rated}\tau_e} + u_{var} \right)$$

$$LCOE = \frac{TSC}{\frac{P_{rated}\tau_e}{\psi}} = \overbrace{\frac{C\psi}{P_{rated}\tau_e}}^{\text{CAPEX}} + \overbrace{\frac{U_{fix}}{P_{rated}\tau_e} + \underbrace{\frac{C_f}{\eta} + u_{var}}_{\text{marginal cost}}}^{\text{OPEX}}$$

Evaluating the Cost of Heat

- Electricity is already available at low cost (without tax ! !) from the grid while there is no global market for heat.
- Heat is difficult to transport.

Heat is the main product and electricity is the by-product !

$$COH = \overbrace{\frac{C\psi}{P_{th,rated}\tau_e}}^{\text{CAPEX}} + \overbrace{\frac{U_{fix}}{P_{th,rated}\tau_e} + \underbrace{\frac{C_f}{\eta} + u_{var} - (Y_{el} + \tau_{cv} Y_{cv})\frac{\alpha_{el}}{\alpha_{th}}}_{\text{marginal cost}}}^{\text{OPEX}}$$

Example Case Study

Energy Integration of a CHP Plant

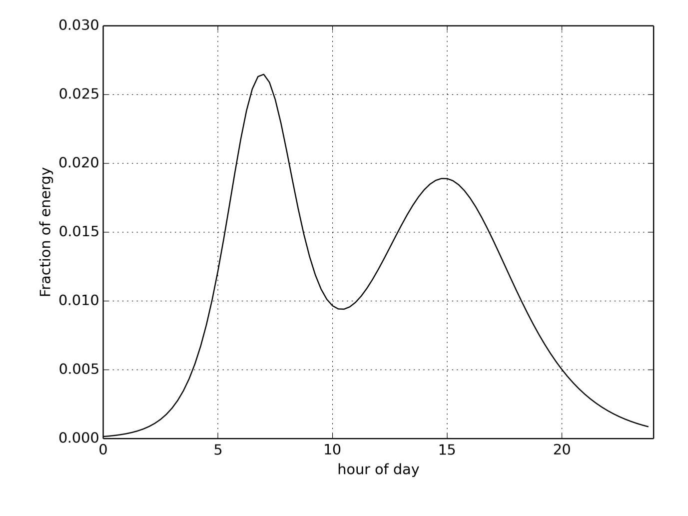


Figure 7 – Non-dimensional heat consumption profile (Sart-Tilman Campus)

Load curve for heat demand

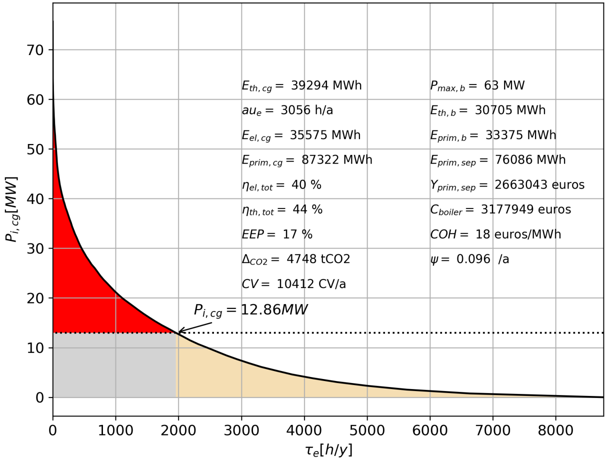


Figure 8 – Cumulative heat load for Sart-Tilman campus (total of 70 000 MWh/y).

Optimizing the Size of a CHP

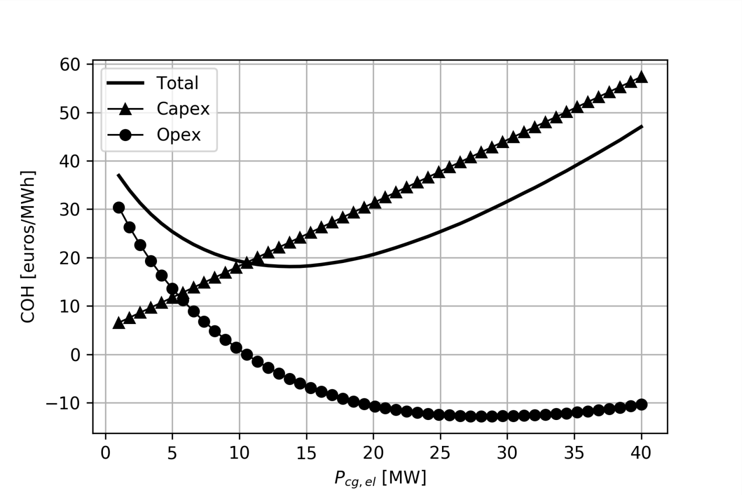


Figure 9 – COH versus CHP plant size