Lecture 5

Topic: Industrial power plant and Rankine process

Learning outcome: To understand the operational principle of an industrial CHP plant in the forest industry and to recognize requirements of an industrial energy system

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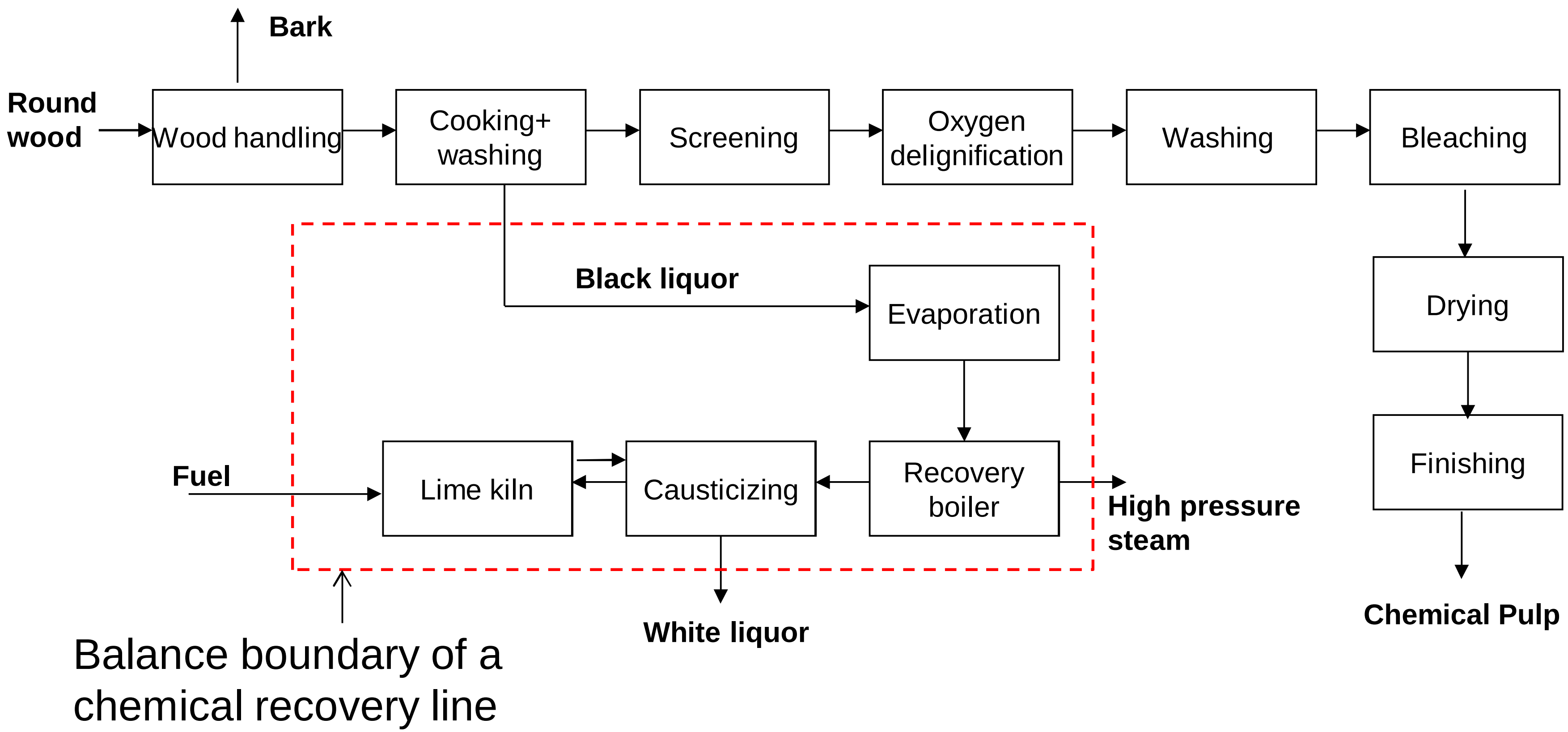
Main unit processes of a pulp mill



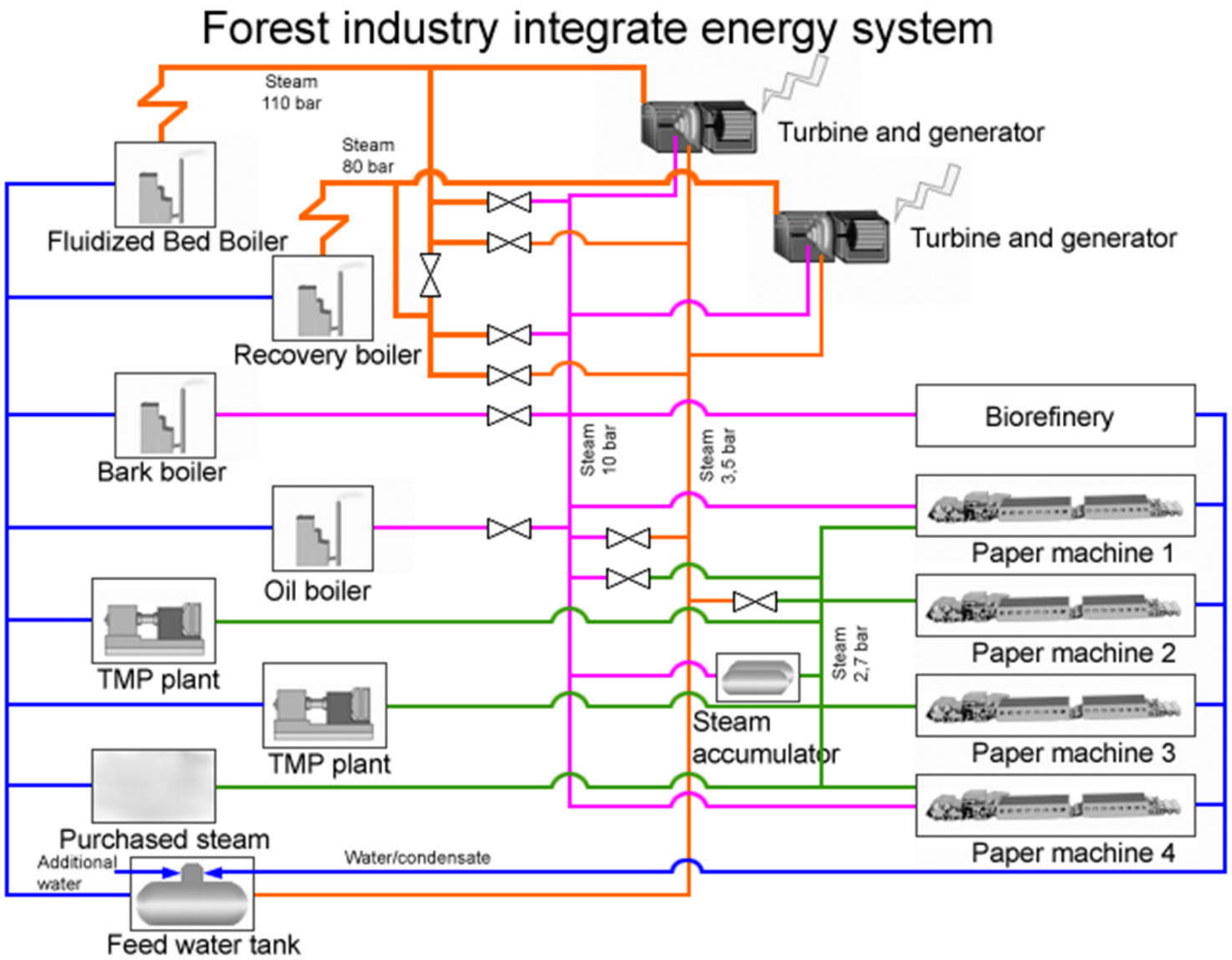
Base mill types (rough classification)

- A pulp mill (Joutseno mill)
- An integrated pulp and paper mill (Kaukopää mill in Imatra)
- A paper mill with mechanical pulping (Jämsänkoski mill, Jämsä)
- A paper mill (Tervakoski mill, Janakkala)

Energy system of the mill dpends on the mill type, for example a pulp mill vs. a paper mill with mechanical pulping.

The main function of the energy system is to satisfy the heat demand of the mill.

Energy system of a forest industrial mill



The main function of the energy system is to satisfy the heat demand of the mill.

Power plant typically consists of a fluidized bed boiler (bark boiler), recovery boiler (pulp mills only), auxiliary boiler (oil, gas boiler) and/or Gas Turbine Combined Cycle, GTCC (mechanical pulping). Heat accumulators are also possible.

Electricity is a secondary product and its production may be optimized on the basis of electricity price.

Typical pressure of high pressure steam 90-110 bar
Typical pressure of back pressure steam 3-6 bar
Typical pressure of middle pressure/extraction/bleed steam 10-12 bar

About middle and back pressure steam

- Middle pressure steam (MP steam) may also be called intermediate steam, extraction steam or bleed steam.
- Back pressure (BP steam) steam may also be called low pressure steam (LP steam).
- Typical pressure levels of middle and back pressure steam are 10-12 bar and 3-6 bar, respectively. Pressure levels depend on what kind of steam mill processes need.
- Back pressure steam demand is usually higher than the demand of extraction steam.
- Back pressure steam is also produced in mechanical pulping, if it exists at a mill.
- Both Steams have their own steam networks.
- Pressure and temperature of steam are adjusted to desired ones for various processes by reduction valves and feed water spraying.
- Steam condenses in processes and condensate is returned back to the feed water tank. Return percent usually < 1.

Note that some mills may also have three different process steam levels, for example 12 bar, 6 bar and 3 bar.

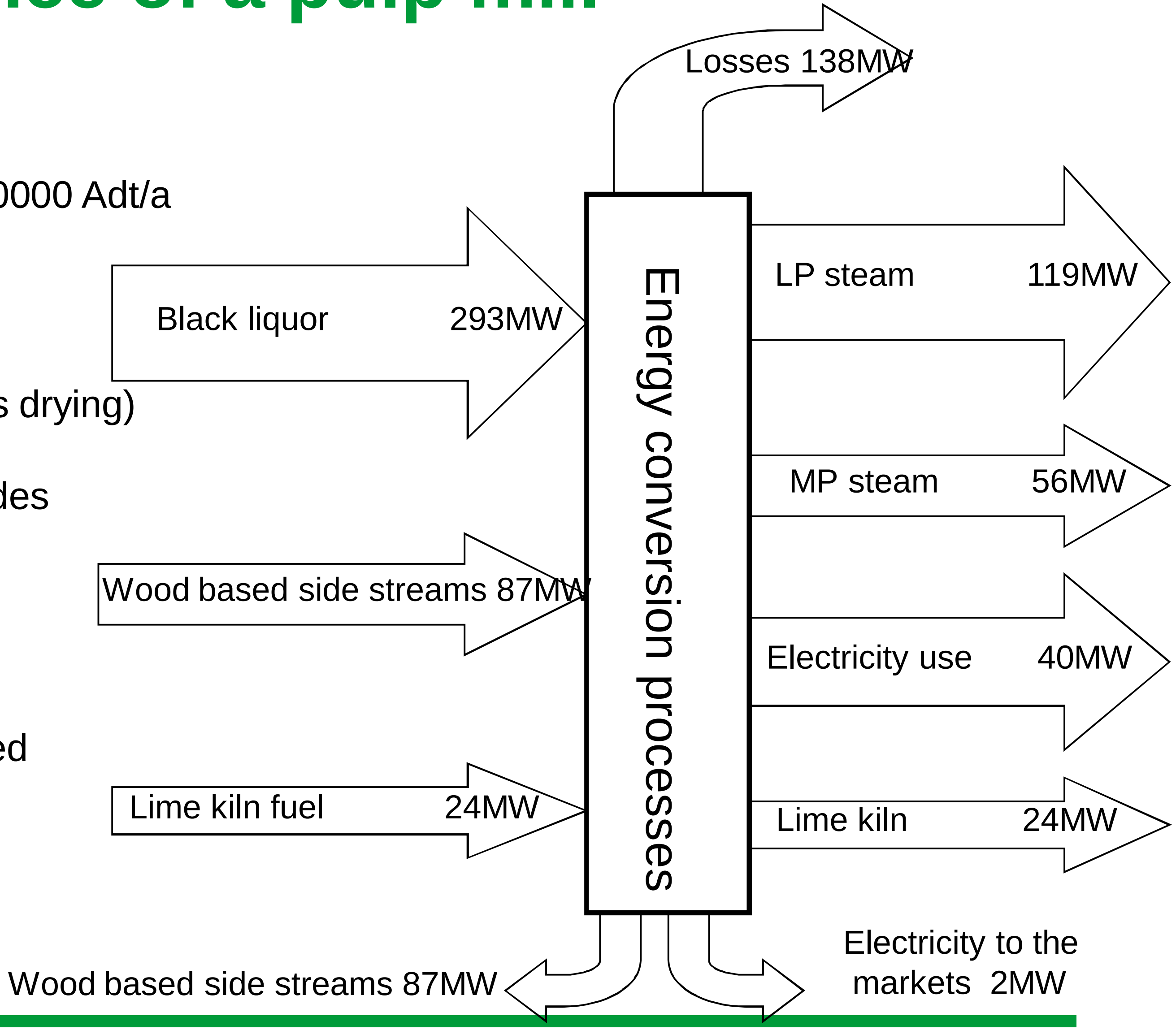
Energy balance of a pulp mill

Production: chemical pulp 470000 Adt/a

Energy consumptions
LP steam 7.5 GJ/Adt (includes drying)
MP steam 3.6 GJ/Adt
Electricity 710 kWh/Adt (includes drying)

Turbine is equipped with a condenser (pressure 0.1bar)

Moisture content of wood based Side streams 40% w.b.



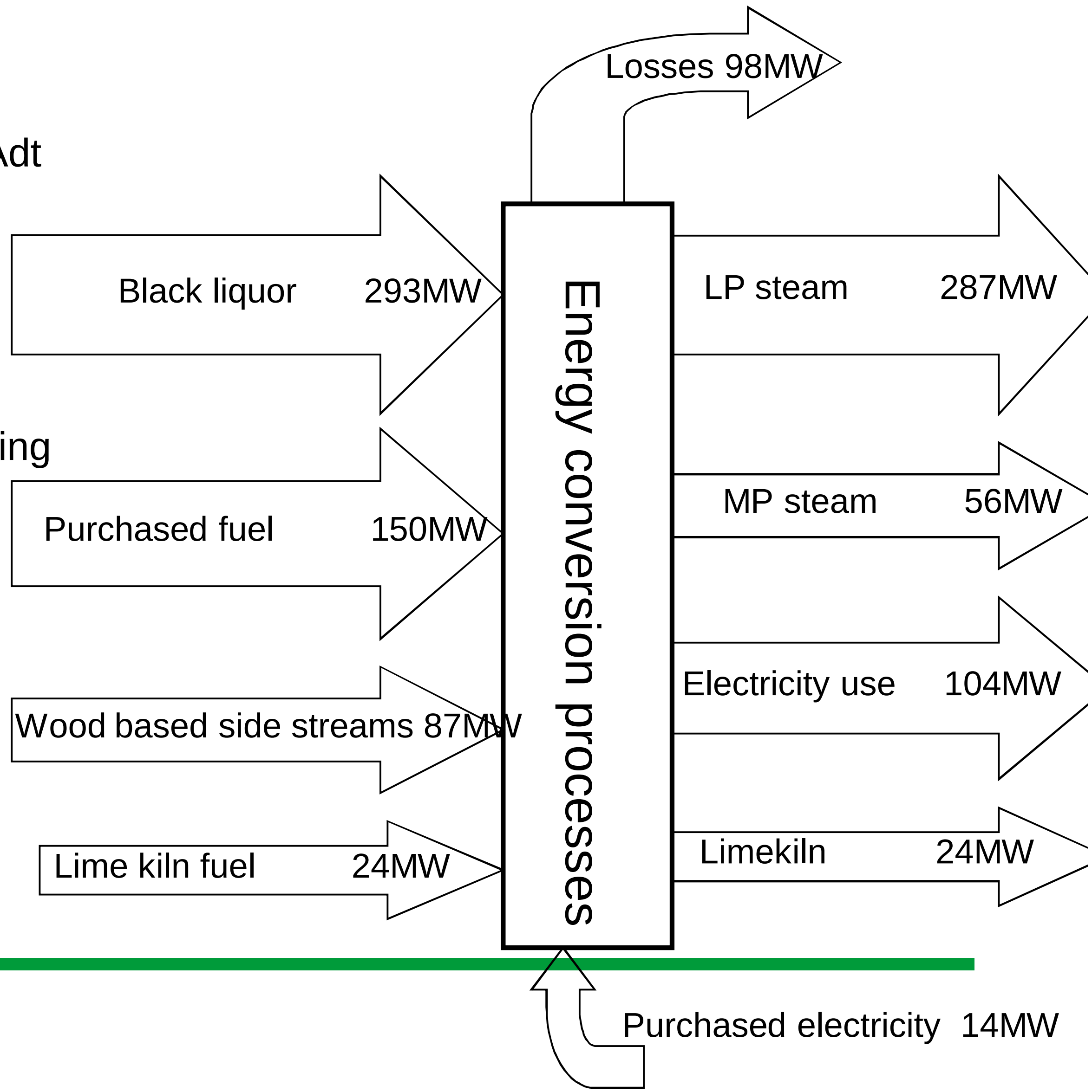
Energy balance of an integrated pulp and paper mill

Production: Chemical pulp 470000 Adt
Wood free non-coated paper 940000 Adt

Energy consumptions in paper making
LP steam 6.85 GJ/ADT
Electricity 665 kWh/ADT

Energy consumptions in chemical pulping
LP steam 4.6 GJ/ADT
MP steam 3.6 GJ/tADT
Electricity 520 kWh/ADT

Outlet pressure of turbine 5bar (abs.), moisture content of wood based side stream 40% w.b.



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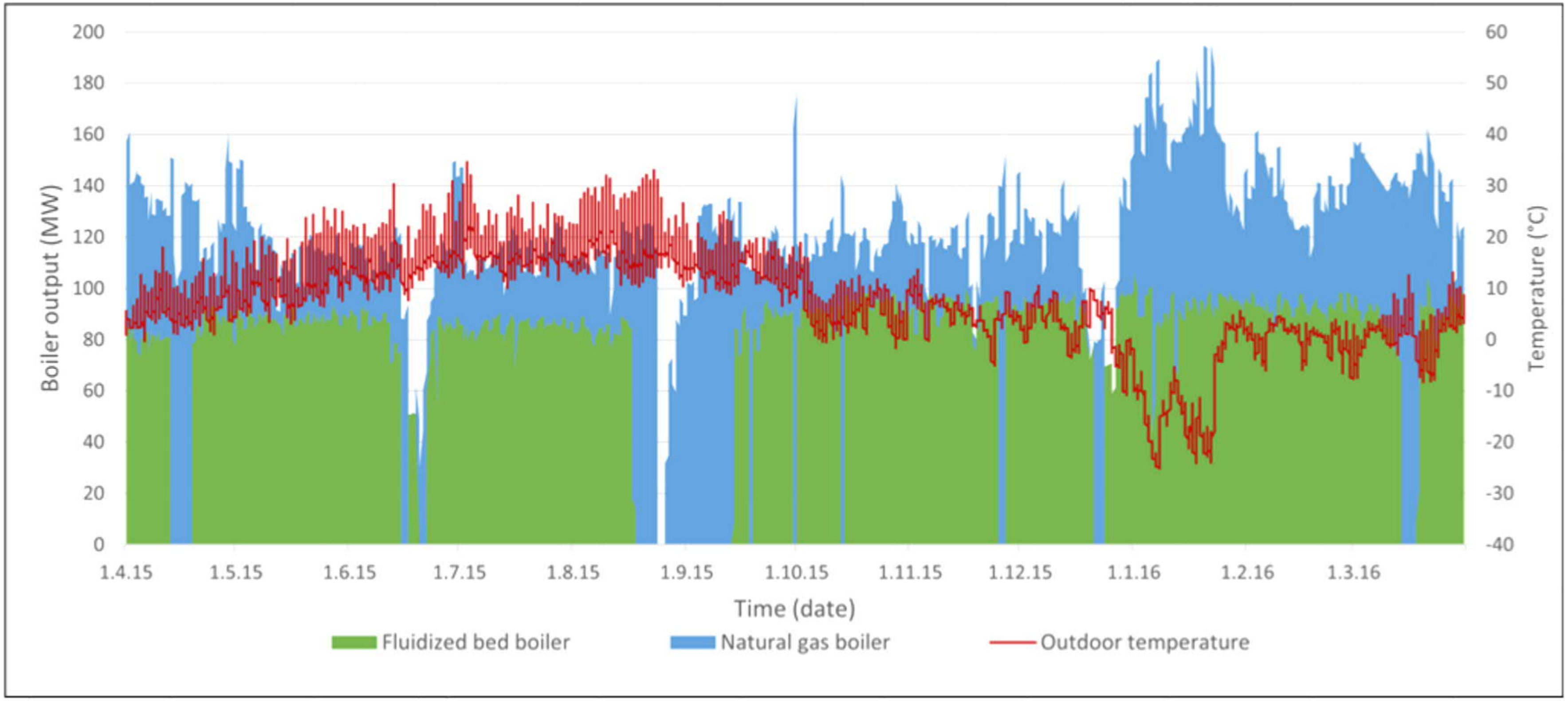
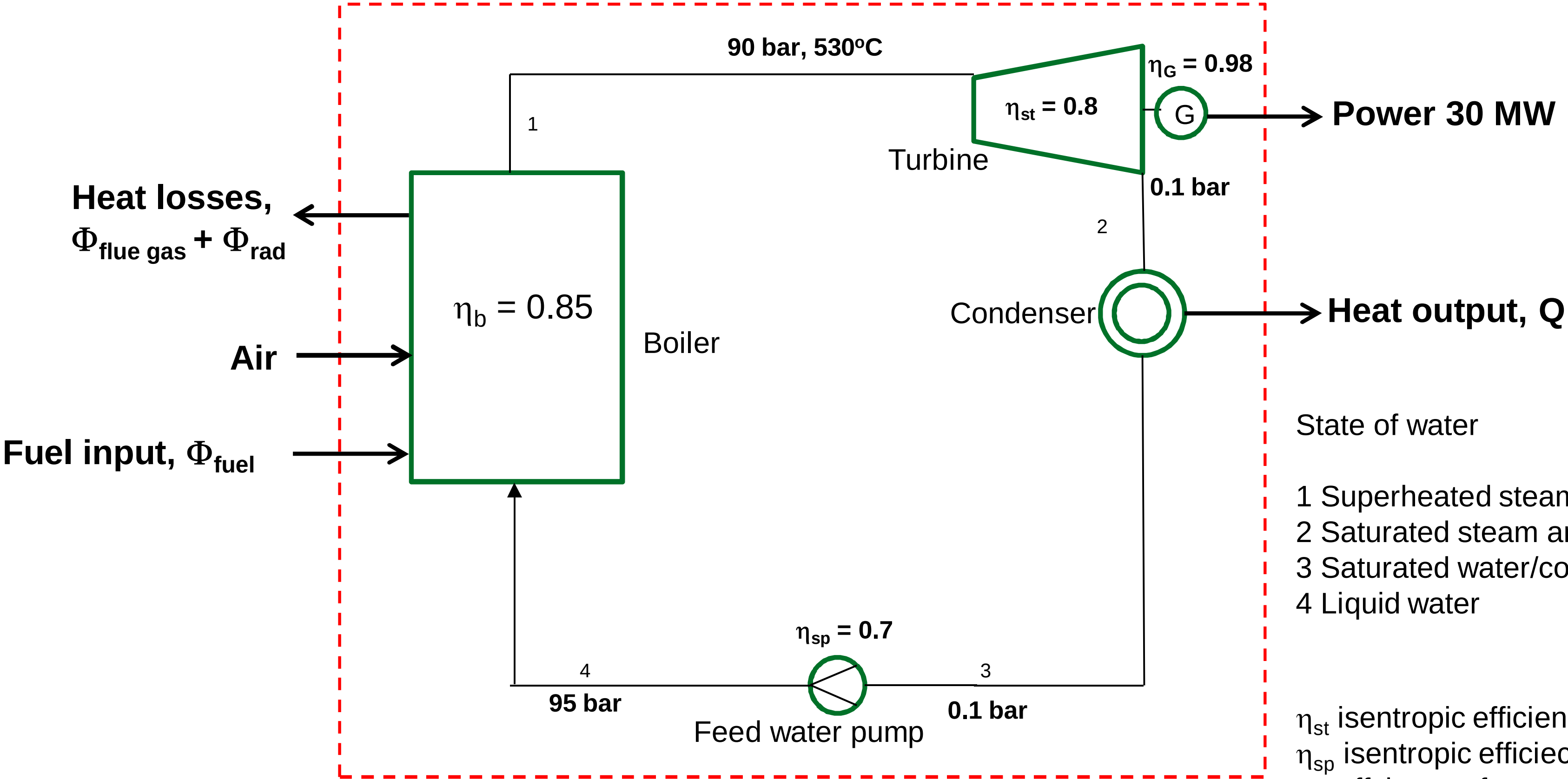
Steam production at a paper mill with mechanical pulping



Basic Rankine process



State of water

1 Superheated steam
2 Saturated steam and water
3 Saturated water/condensate
4 Liquid water

η_{st} isentropic efficiency of a turbine
η_{sp} isentropic efficiecny of a pump
η_G effciency of a generator
η_b boiler efficiecny

$$\eta_b = \frac{\dot{m}_4 (h_1 - h_4)}{\Phi_{fuel}} = 1 - \frac{\Phi_{flue\ gas} + \Phi_{rad}}{\Phi_{fuel}}$$

$$\Phi_{fuel} = \dot{m}_{fuel} LHV$$

LHV = lower heating value of fuel

Basic Rankine process

Define **fuel input, heat output, thermal efficiency** and **power plant efficiency**

Shaft power

$$P_t = \frac{P_e}{\eta_G} = \frac{30}{0.98} = 30.61 \text{ MW}$$

Mass flow rate of superheated steam $P_t = \dot{m}_1\left[(h_1 - h_2) - (h_4 - h_3)\right] \Rightarrow \dot{m}_1 = \frac{30610}{(3462 - 2403 - (206 - 192))} = 29.3 \text{ kg}/s$

$$h_1(90\text{bar}, 530^{o}\text{C}) = 3462 \text{ kJ/kg}$$

$$h_2 = h_1 - \eta_{st}(h_1 - h_{2s}) = 3462\text{-}0.8\cdot(3462 - 2139) = 2404 \text{ kJ/kg}$$

$$h_3 = h'(0.1\text{bar}) = 192 \text{ kJ/kg}$$

$$h_4 = h_3 + \frac{v(p_4 - p_3)}{\eta_{sp}} = 192 + 0.001\cdot\frac{(95 - 0.1)\cdot 10^5}{1000\cdot 0.7} = 206 \text{ kJ/kg}$$

Fuel input $\Phi_{fuel} = \frac{\dot{m}_1(h_1 - h_4)}{\eta_b} = \frac{29.3\cdot(3462 - 206)}{0.85} = 112.2 \text{ MW}$

Heat output $Q_{out} = \dot{m}_2(h_2 - h_3) = 29.3\cdot(2404 - 192) = 64.8 \text{ MW}$

Thermal efficiecny $\eta_{th} = \frac{P_t}{Q_{in}} = \frac{P_t}{\dot{m}_1(h_1 - h_4)} = \frac{30610}{29.3\cdot(3462 - 206)} = 0.321$

Power plant efficiecny $\eta_{plant} = \frac{P_e}{\Phi_{fuel}} = \frac{30}{112.2} = 0.267$

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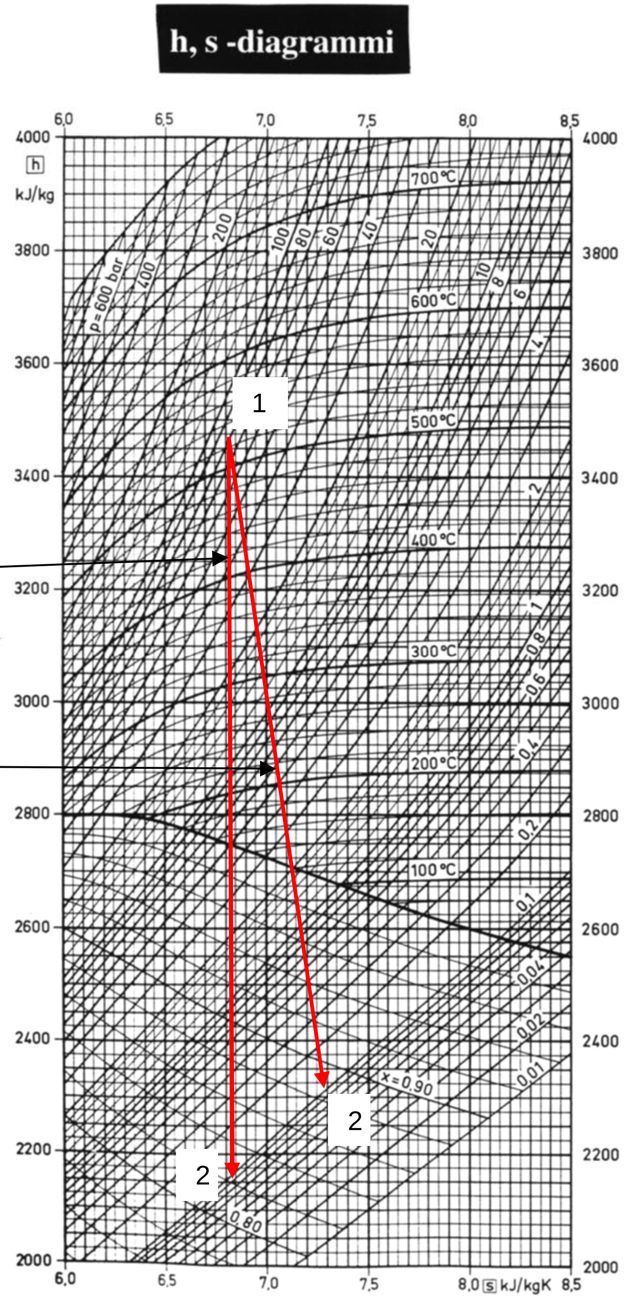
h_{2s} is the enthalpy of steam after an isentropic expansion in a turbine when the outlet pressure is 0.1bar ($s_1 = s_2$)
v = specific voilume of water ≈ 1/1000 = 0.001 m^3/kg

Expansion of steam on a h,s diagram

Isentropic expansion
$\eta_{st} = 1 \Rightarrow s_2 = s_1$
no entropy generation

Real expansion
$\eta_{st} < 1 \Rightarrow s_2 > s_1$
entropy is generated in a turbine



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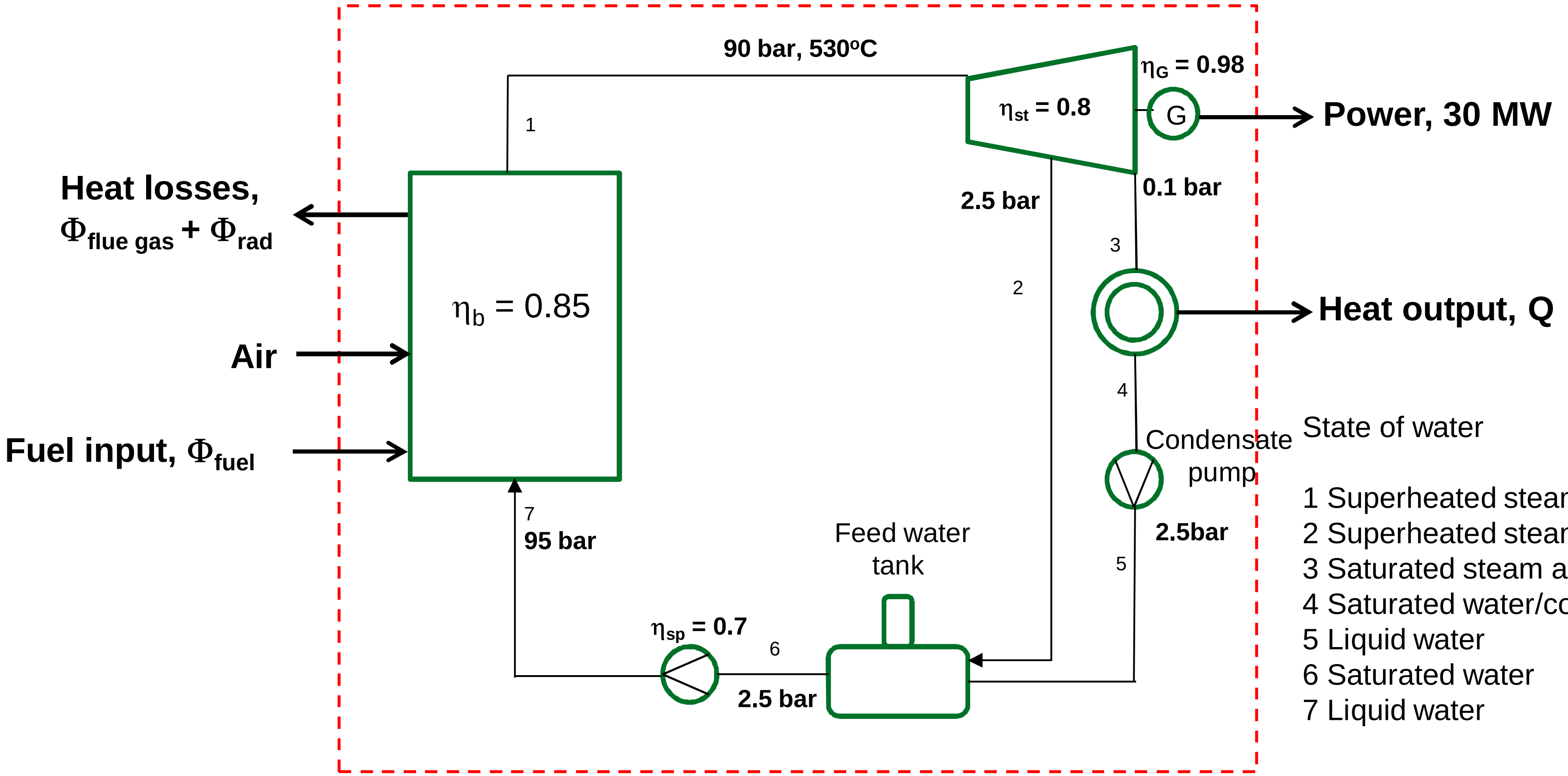
Rankine process with a feed water tank



State of water

1 Superheated steam
2 Superheated steam
3 Saturated steam and water
4 Saturated water/condensate
5 Liquid water
6 Saturated water
7 Liquid water

Rankine process with a feed water pump

Define **fuel input, heat output, thermal efficiency** and **power plant efficiency**

Shaft power

$$P_t = \frac{P_e}{\eta_G} = \frac{30}{0.98} = 30.61\ \text{MW}$$

Mass and energy balances

$$P_t = \dot{m}_1 (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2)(h_2 - h_3) - \dot{m}_6 (h_7 - h_6)$$

$$\dot{m}_6 h_6 = \dot{m}_2 h_2 + \dot{m}_5 h_5$$

$$\dot{m}_6 = \dot{m}_2 + \dot{m}_5$$

=>

$$\dot{m}_1 = 30.7\ \text{kg/s}$$

$$\dot{m}_2 = 4.1\ \text{kg/s}$$

$$\dot{m}_5 = 26.6\ \text{kg/s}$$

Enthalpies

$$h_1(90\text{bar}, 530^{\circ}\text{C}) = 3462\ \text{kJ/kg}$$

$$h_2 = h_1 - \eta_{st}(h_1 - h_{2s}) = 3462 - 0.8 \cdot (3462 - 2597) = 2770\ \text{kJ/kg}$$

$$h_3 = h_1 - \eta_{st}(h_1 - h_{3s}) = 3462 - 0.8 \cdot (3462 - 2139) = 2404\ \text{kJ/kg}$$

$$h_4 = h'(0.1\text{bar}) = 192\ \text{kJ/kg}$$

$$h_5 \approx h_4 = 192\ \text{kJ/kg}$$

$$h_6 = h'(2.5\text{bar}) = 535\ \text{kJ/kg}$$

$$h_7 = h_6 + \frac{v(p_7 - p_6)}{\eta_{sp}} = 535 + 0.001 \cdot \frac{(95 - 2.5) \cdot 10^5}{1000 \cdot 0.7} = 548\ \text{kJ/kg}$$

h_{2s} and h_{3s} are enthalpies of steam after an isentropic expansion in a turbine ($s_1 = s_2 = s_3$) when p_2 = 2.5 bar and p_3 = 0.1 bar

Precise value of $h_5 = h_4 + v \cdot (p_5 - p_4)/\eta_{sp} = 192.3$ kJ/kg $\approx h_4$

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Rankine process with a feed water tank

Fuel input $\Phi_{fuel} = \frac{\dot{m}_1(h_1 - h_7)}{\eta_b} = \frac{30.7 \cdot (3462 - 548)}{0.85} = 105.3\ \text{MW}$

Heat output $Q_{out} = \dot{m}_3(h_3 - h_4) = 26.6 \cdot (2404 - 192) = 58.9\ \text{MW}$

Thermal efficiecny $\eta_{th} = \frac{P_t}{Q_{in}} = \frac{P_t}{\dot{m}_1(h_1 - h_7)} = \frac{30610}{30.7 \cdot (3462 - 548)} = 0.342$

Power plant efficiecny $\eta_{plant} = \frac{P_e}{\Phi_{fuel}} = \frac{30}{105.3} = 0.285$

Thermal and power plant efficiencies become better as a result of a feed water tank.

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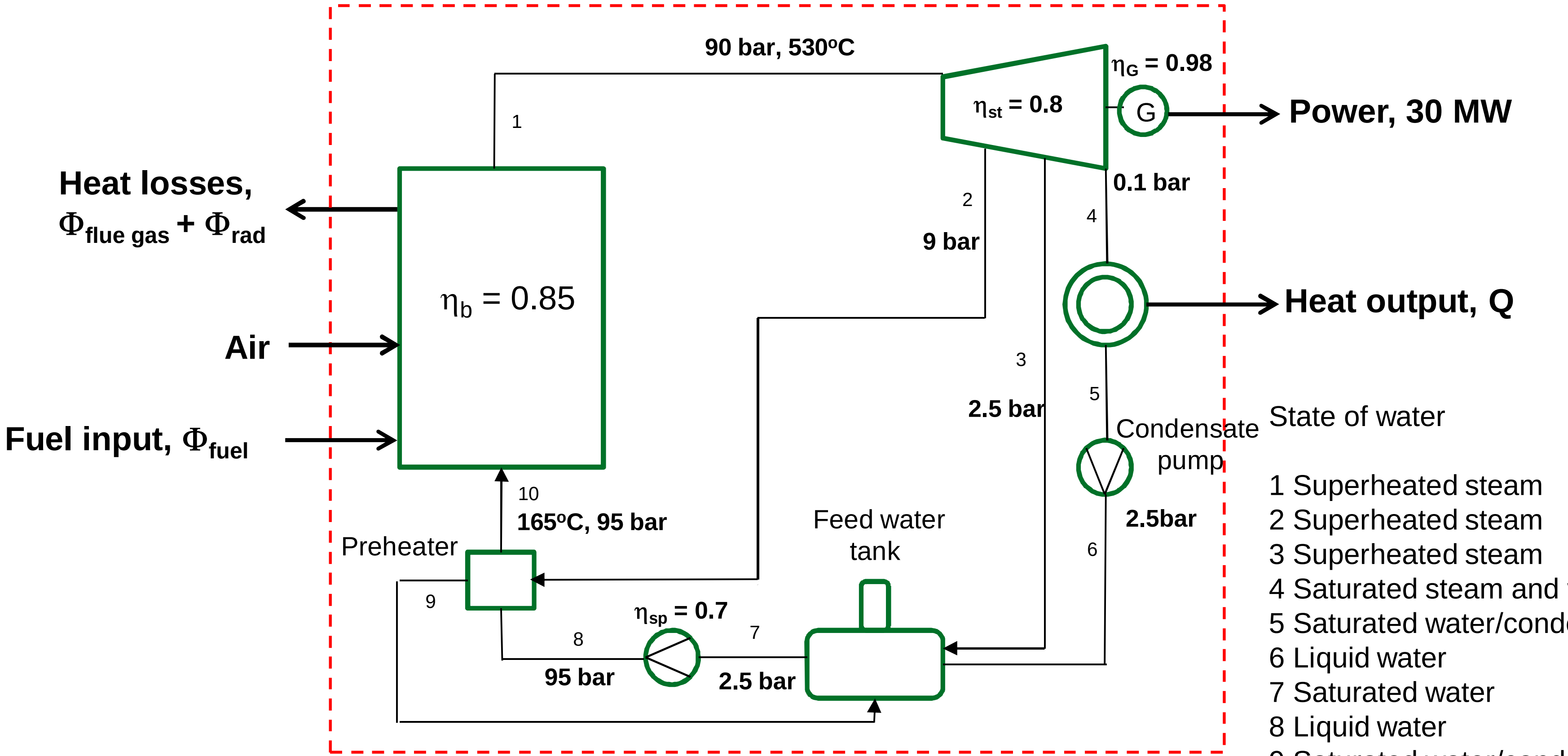
Note that we can also write for P_t

$P_t = Q_{in} - Q_{out} = \dot{m}_1(h_1 - h_7) - \dot{m}_3(h_3 - h_4)$

Rankine process with a feed water tank and a preheater



State of water

1 Superheated steam
2 Superheated steam
3 Superheated steam
4 Saturated steam and water
5 Saturated water/condensate
6 Liquid water
7 Saturated water
8 Liquid water
9 Saturated water/condensate
10 liquid water

Preheater is a recuperative heat exchanger where flows are not mixed with each other

Rankine process with a feed water pump and a preheater

Define **fuel input, heat output, thermal efficiency** and **power plant efficiency**

Shaft power

$$P_t = \frac{P_e}{\eta_G} = \frac{30}{0.98} = 30.61 \text{ MW}$$

Mass and energy balances

$$P_t = \dot{m}_1 (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2)(h_2 - h_3) +$$
$$(\dot{m}_1 - \dot{m}_2 - \dot{m}_3)(h_3 - h_4) - \dot{m}_7 (h_8 - h_7)$$
$$\dot{m}_7 h_7 = \dot{m}_9 h_9 + \dot{m}_3 h_3 + \dot{m}_6 h_6$$
$$\dot{m}_2 h_2 + \dot{m}_8 h_8 = \dot{m}_9 h_9 \quad \dot{m}_2 h_2 + \dot{m}_{10} h_{10}$$
$$\dot{m}_7 = \dot{m}_3 + \dot{m}_6 + \dot{m}_9$$

=>

$$\dot{m}_1 = 31.7 \text{ kg/s}$$
$$\dot{m}_2 = 2.1 \text{ kg/s}$$
$$m_3 = 3.8 \text{ kg/s}$$
$$\dot{m}_6 = 25.8 \text{ kg/s}$$

Enthalpies

$$h_1(90\text{bar}, 530^\circ\text{C}) = 3462 \text{ kJ/kg}$$
$$h_2 = h_1 - \eta_{st}(h_1 - h_{2s}) = 3462 - 0.8 \cdot (3462 - 2834) = 2960 \text{ kJ/kg}$$
$$h_3 = h_1 - \eta_{st}(h_1 - h_{3s}) = 3462 - 0.8 \cdot (3462 - 2597) = 2770 \text{ kJ/kg}$$
$$h_4 = h_1 - \eta_{st}(h_1 - h_{4s}) = 3462 - 0.8 \cdot (3462 - 2139) = 2404 \text{ kJ/kg}$$
$$h_5 = h'(0.1\text{bar}) = 192 \text{ kJ/kg}$$
$$h_6 \approx h_5 = 192 \text{ kJ/kg}$$
$$h_7 = h'(2.5\text{bar}) = 535 \text{ kJ/kg}$$
$$h_8 = h_7 + \frac{v(p_8 - p_7)}{\eta_{sp}} = 535 + 0.001 \cdot \frac{(95 - 2.5) \cdot 10^5}{1000 \cdot 0.7} = 548 \text{ kJ/kg}$$
$$h_9 = h'(9\text{bar}) = 743 \text{ kJ/kg}$$
$$h_{10} = h(95\text{bar}, 165^\circ\text{C}) = 698 \text{ kJ/kg}$$

h_{2s} , h_{3s} and h_{4s} are enthalpies of steam after an isentropic expansion in a turbine ($s_1 = s_2 = s_3 = s_4$) when p_2 = 9 bar, p_3 = 2.5 bar and p_4 = 0.1 bar

Precise vale of $h_6 = h_5 + v \cdot (p_6 - p_5)/\eta_{sp} = 192.3$ kJ/kg $\approx h_6$

Rankine process with a feed water tank and a preheater

Fuel input $\Phi_{fuel} = \frac{\dot{m}_1(h_1 - h_{10})}{\eta_b} = \frac{30.7 \cdot (3462 - 698)}{0.85} = 103.3 \text{ MW}$

Heat output $Q_{out} = \dot{m}_5(h_4 - h_5) = 25.8 \cdot (2404 - 192) = 57.2 \text{ MW}$

Thermal efficiecny $\eta_{th} = \frac{P_t}{Q_{in}} = \frac{P_t}{\dot{m}_1(h_1 - h_{10})} = \frac{30610}{31.7 \cdot (3462 - 698)} = 0.349$

Power plant efficiecny $\eta_{plant} = \frac{P_e}{\Phi_{fuel}} = \frac{30}{103.3} = 0.291$

Thermal and power plant efficiencies still improve compared to a Rankine cycle with a feed water tank only.

Note that we can also write for P_t

$$P_t = Q_{in} - Q_{out} = \dot{m}_1(h_1 - h_{10}) - \dot{m}_4(h_4 - h_5)$$

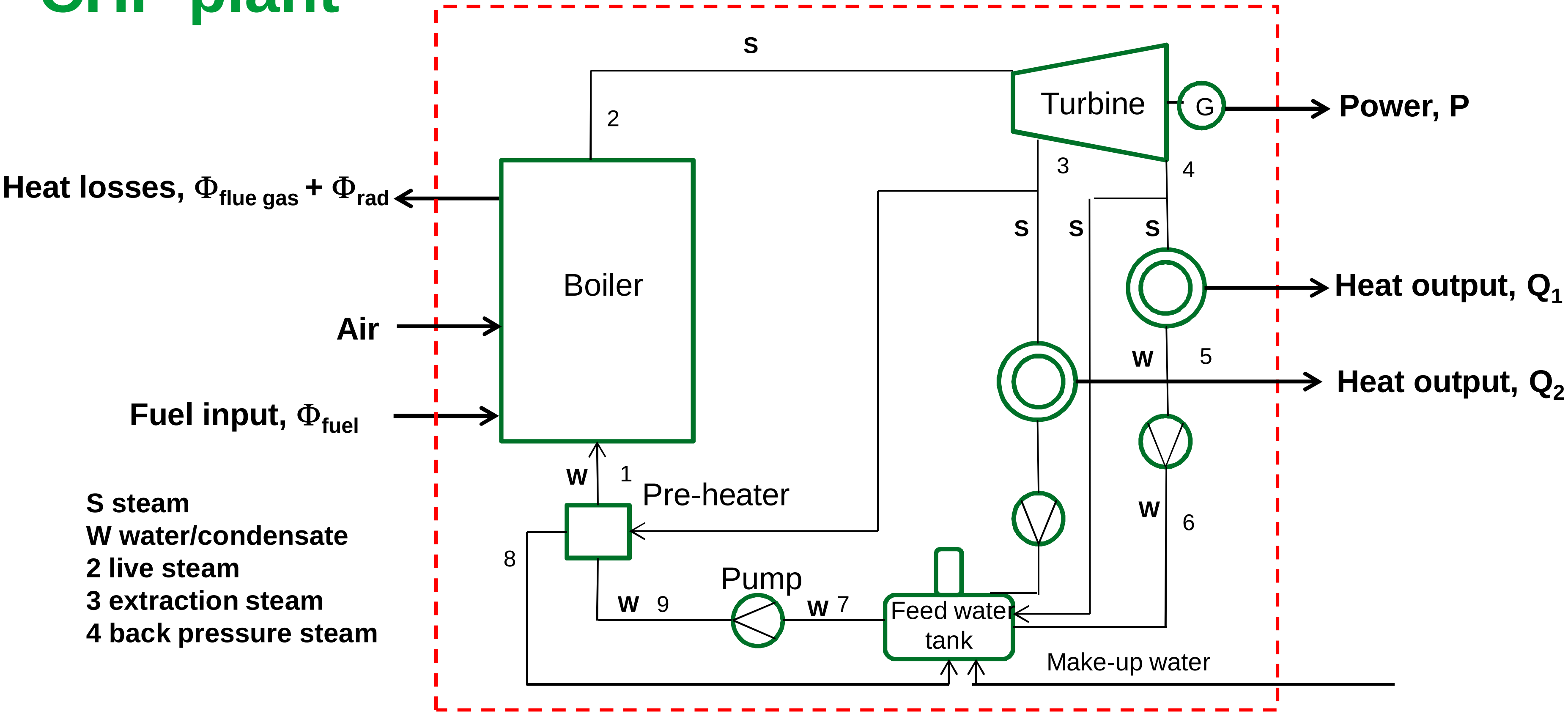
About power plant calculations

We can only calculate shaft powers (e.g. shaft power of a turbine or pump) using thermodynamic state functions in energy balances.

There are also mechanical losses as well as motor and generator losses that increase electricity consumption of pumps and reduce power production in a genertor. In previous calculation examples, only genrator losses have been taken into account.

There are also other apparatuses that consume electricity at a power plant. These are for example flue gas fans, combustion air fans, feedstock systems of fuel etc. Electricity consumption of these apparatuses still reduses net power production of the plant.

CHP plant



Power to heat ratio of the plant

$$\alpha = \frac{P}{Q_1 + Q_2}$$

Power plant efficiecny

$$\eta_{CHP} = \frac{P + Q_1 + Q_2}{\Phi_{fuel}}$$

Boiler efficiecny

$$\eta_{boiler} = 1 - \frac{\Phi_{fluegas} + \Phi_{rad}}{\Phi_{fuel}}$$

$$\eta_{CHP} \approx \eta_{boiler}$$

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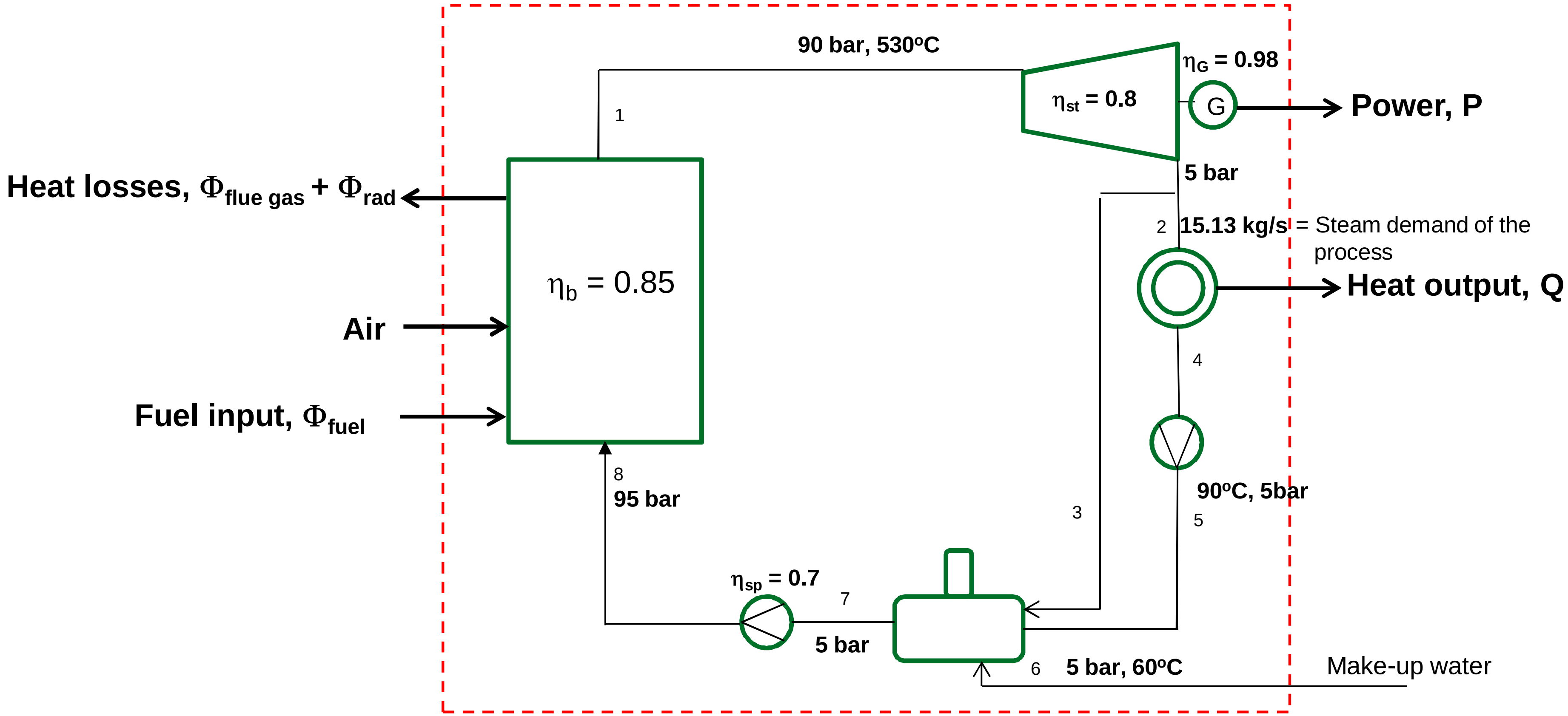
Auxiliary systems of the power plant (e.g. flue gas fans, air fans, fuel processing systems) consume electricity which must be taken into account in accurate calculations.

Example 1

A) What is the power to heat ratio of the power plant?
B) What is the efficiency of the power plant?



- Return percent of the condensate from mill processes is 90 %.
- Electricity consumption of auxiliary systems can be neglected.

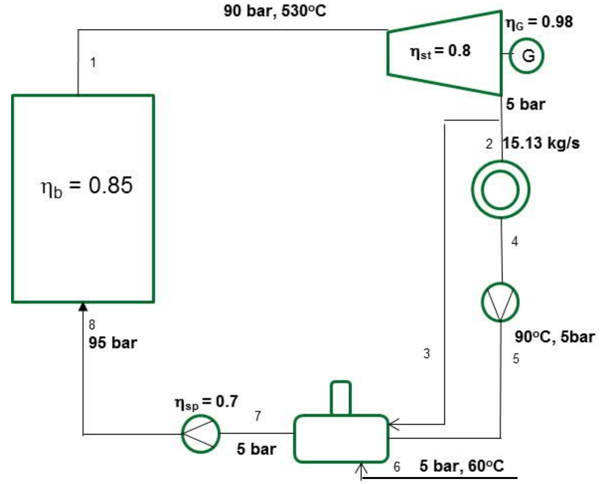
Example 1

Enthalpies (steam tables)

$h_1 = 3461.5$ kJ/kg $h_2 = h_1 - \eta_{st}(h_1 - h_{2s}) = 3461.5 – 0.8 \cdot (3461.5 – 2720) = 2868.1$ kJ/kg

$h_3 = h_2 = 2868.1$ kJ/kg $h_4 = 377.3$ kJ/kg $h_5 \approx h_4 = 377.3$ kJ/kg $h_6 = 251.6$ kJ/kg

$h_7 = 640.4$ kJ/kg $h_8 = h_7 + v(p_8 – p_7)/\eta_{sp} = 640.4 + 0.00109 \cdot (95 – 5) \cdot 10^2/0.7 = 654.4$ kJ/kg



Mass flow rates

$m_7 = m_1$ $m_4 = m_5 = 0.9m_2$ $m_6 = 0.1m_2$

Energy and mass balance over the feed water tank

$m_3h_3 + 0.9m_2h_5 + 0.1m_2h_6 = m_1h_7$

$m_1 = m_3 + m_2$

=> $m_1 = 17$ kg/s $m_2 = 15.13$ kg/s $m_3 = 1.87$ kg/s $m_5 = 13.62$ kg/s $m_6 = 1.51$ kg/s

Example 1

$P_e = \eta_G[m_1(h_1 – h_2) – m_7(h_8 – h_7)] = 0.98[17·(3461.5 -2868.1) - 17 ·(654.4 – 640.4)] = 9653$ kW

$Q = m_2h_2 – m_5h_5 – m_6h_6 = 15.13·2868.1 – 13.62·377.3 - 1.51·251.6 = 37870$ kW

$\alpha = P/Q = 9653/37870 = \underline{0.25}$

$\Phi_{fuel} = (P_t + Q)/\eta_b$,

where P_t is the shaft power of the turbine

$P_t = [17·(3461.5 -2868.1) - 17 ·(654.4 – 640.4)] = 9850$ kW

$\Phi_{fuel} = (9850+ 37870)/0.85 = 56142$ kW

$\eta_{CHP} = (P_e + Q)/ \Phi_{fuel} = (9653 + 37870)/56142 = \underline{0.846}$

The difference between the boiler and the plant efficiency would be bigger if electricity consumptions of auxiliary systems (flue gas fans, air fans etc.) would be taken into account.

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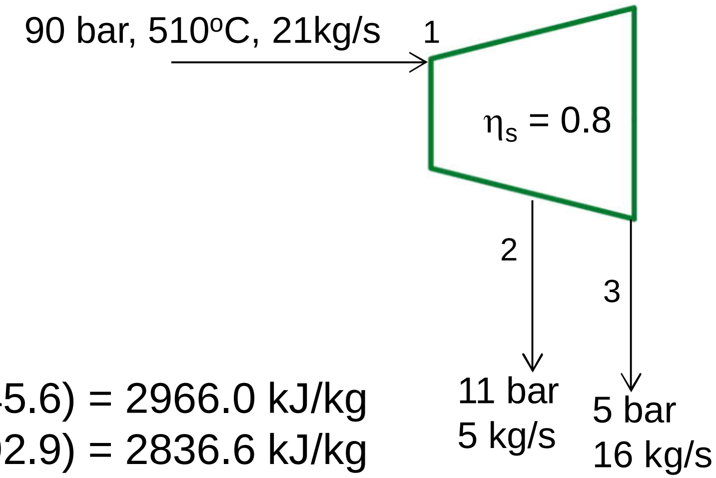
Example 2



Extraction steam demand reduces 3 kg/s. Calculate how much more shaft work the turbine produces, if live steam production remains unchanged?

h_1 = 3411.6 kJ/kg

$h_2 = h_1 - \eta_s(h_1 - h_{2s}) = 3411.6 - 0.8 \cdot (3411.6 - 2845.6) = 2966.0$ kJ/kg

$h_3 = h_1 - \eta_s(h_1 - h_{3s}) = 3411.6 - 0.8 \cdot (3411.6 - 2692.9) = 2836.6$ kJ/kg

$W_{original} = 21 \cdot (3411.6-2966) + (21-5) \cdot (2966-2836.6) = 7290$ kW

$\Delta W = \Delta m_2(h_2 - h_3) = 3 \cdot (2966-2836.6) = 388$ kW =>

Turbine work increases approximately by 5 %.

Note that $W_{original}$ represents the work done by the turbine and not by power plant. The work done by the power plant is smaller because the work needed by the feed water pump must be taken into account in calculations.

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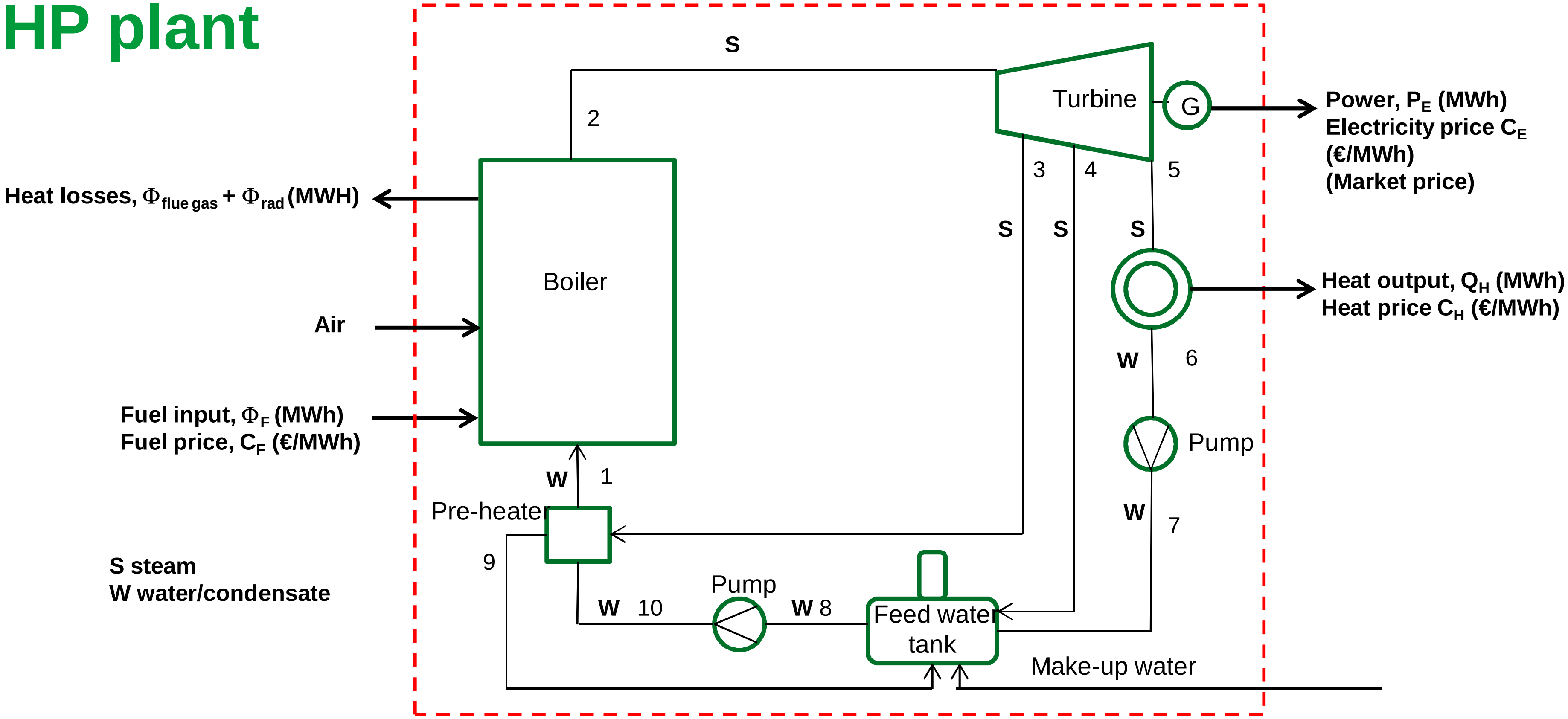
CHP plant



Pricing the heat (C_H) with the first residual method

Power to heat ratio

$$\alpha = \frac{P_E}{Q_H}$$

Power plant efficiecny

$$\eta_{CHP} = \frac{P_E + Q_H}{\Phi_F}$$

Production costs of heat (€)

$$C_{costs} = \frac{1+\alpha}{\eta_{CHP}} Q_H C_F - \alpha Q_H C_E$$

Heat price (€/MWh)

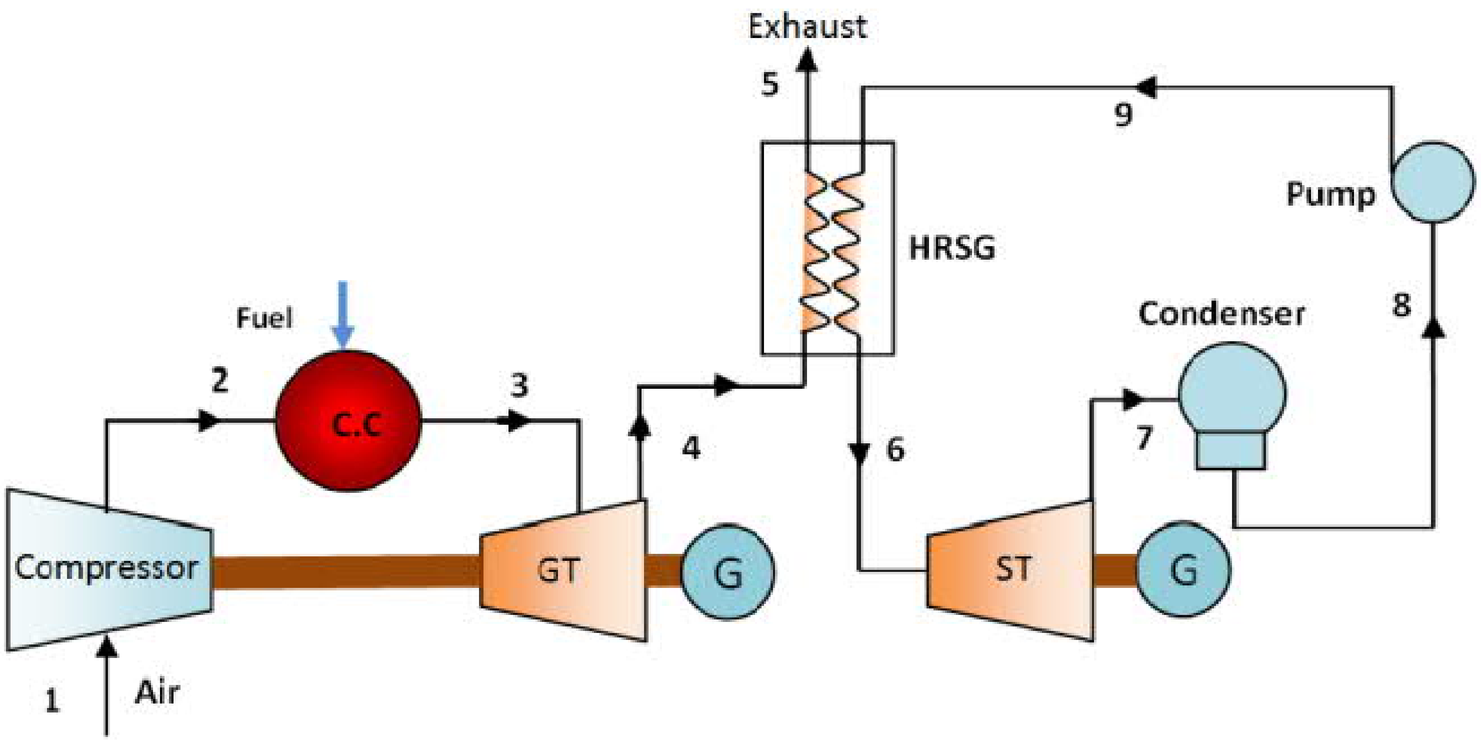
$$C_H = \frac{1+\alpha}{\eta_{CHP}} C_F - \alpha C_E$$

Some observations of the heat price when the first residual method is used

- If the electricity price is high and the fuel price is low the price of MP steam becomes higher than the price of BP steam, which makes sense. The use of MP steam reduces electricity production, which means that the mill must purchase more electricity outside the mill. This increases energy procurement cost.

- If the electricity price is low and the fuel price is high the price of MP steam may become lower than the price of BP steam. This makes also sense. The mill should minimize the fuel consumption and procude only heat to mill processes and forget electricity production. Cheap electricity is available from the markets and it is not economic to produce it at mill site.

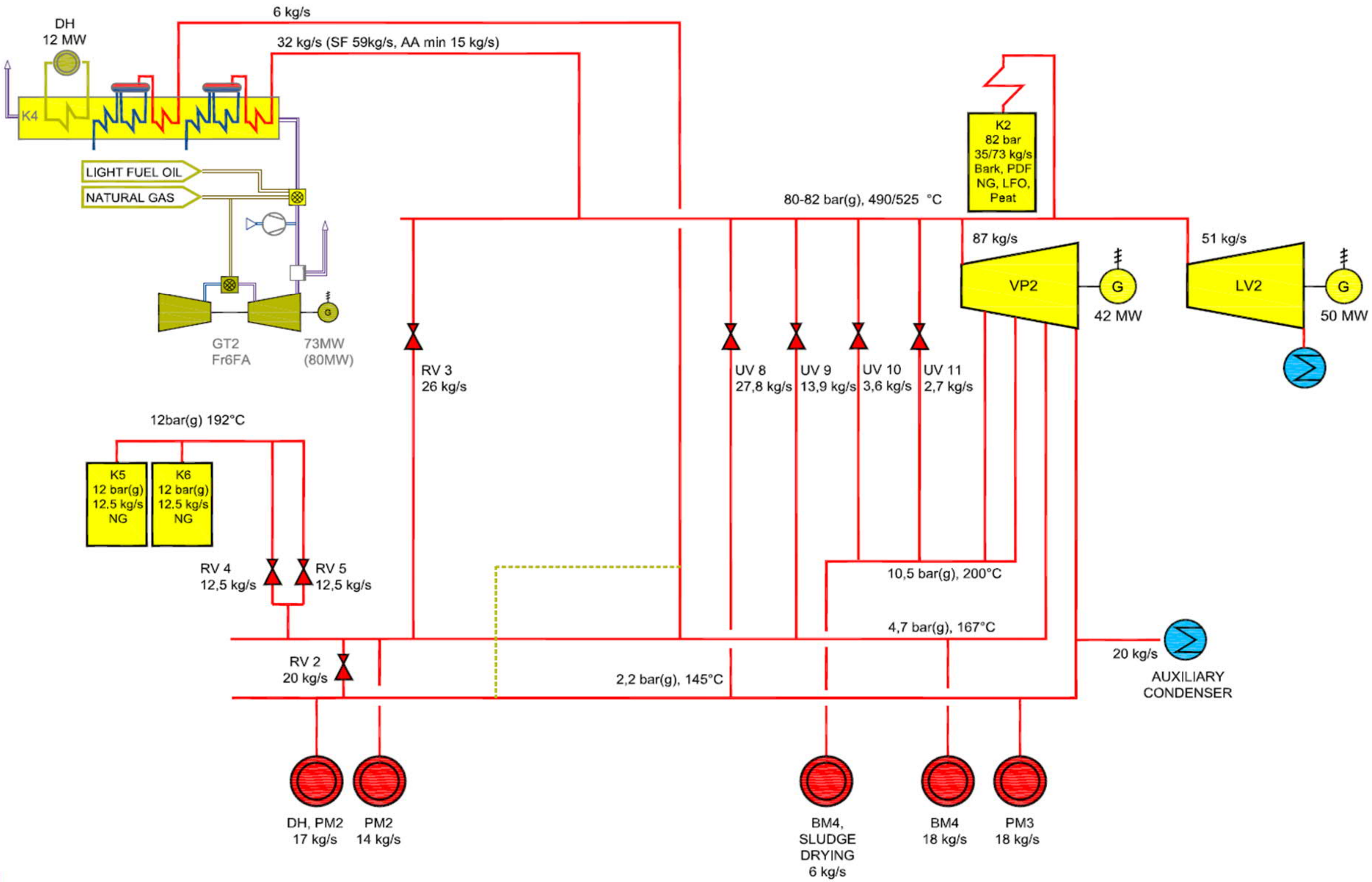
Gas turbine combined cycle, GTCC



About GTCC as an industrial CHP plant

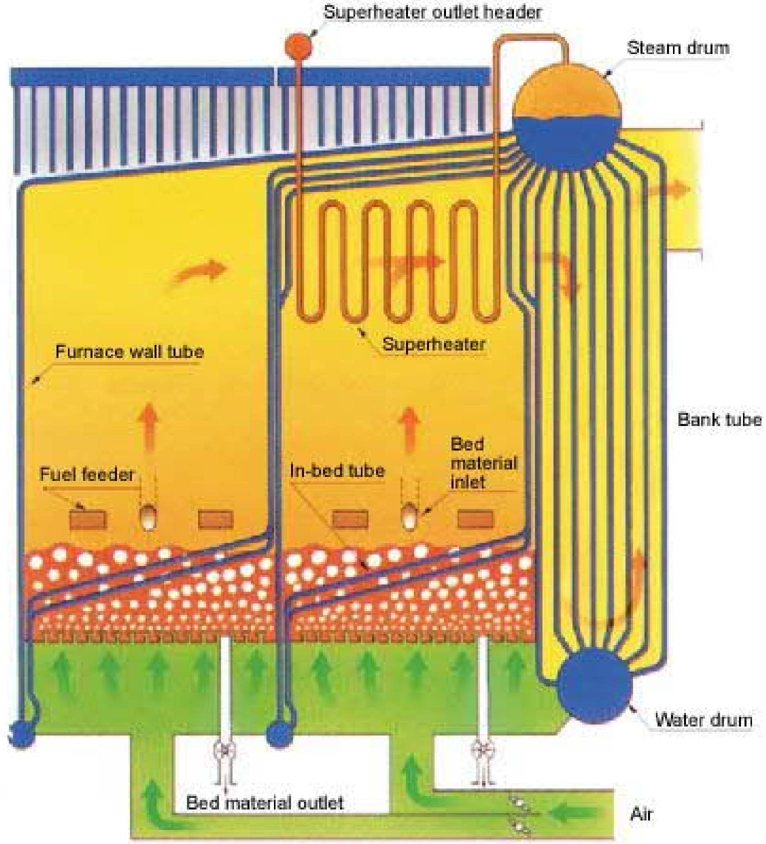
- GTCC plants are typically used at paper mills with mechanical pulping. Electricty demand is high due to mechanical pulping.
- The mill has also bark and auxilary boilers.
- Power to heat ratios of the entire power plant site can be even close to 1. Exact power to heat ratios always depend on the mill.
- The most common fuel is natural gas.
- Economy of the plant is strongly dependent on the fuel and electricty prices. High fuel price and low electricity price usually result in poor economy.
- In Finland, GTCC plants can be found at Kirkniemi and Anjalankoski mills.

GTCC plant at an industrial power plant site

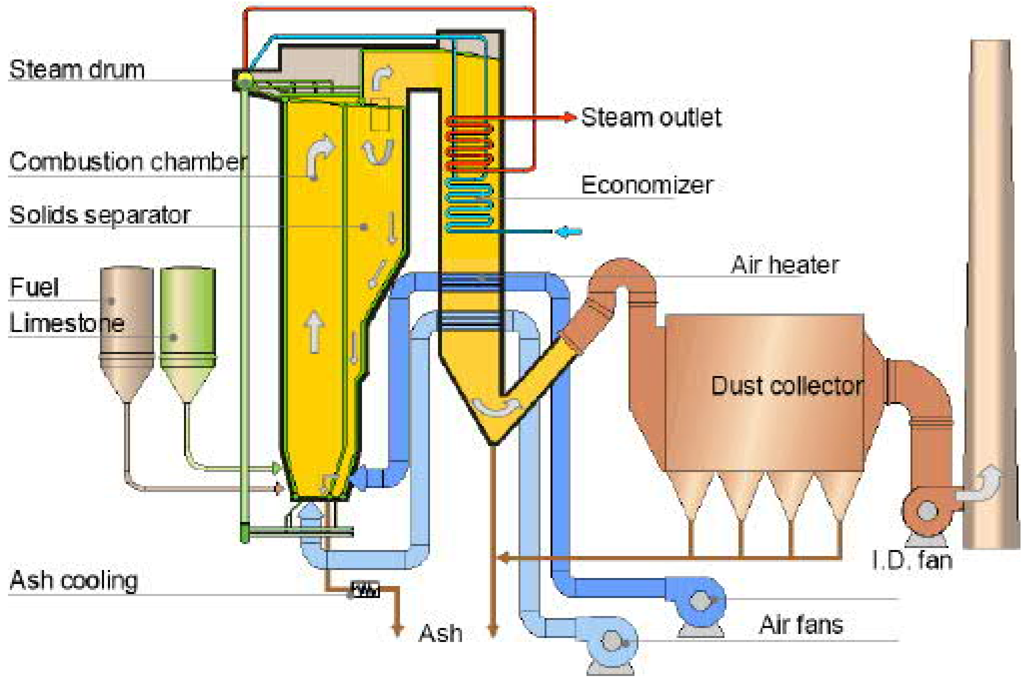


Bark/biomass boilers

Bubbling fluidized bed boiler (BFB-boiler)



Circulating fluidized bed boiler (CFB-boiler)

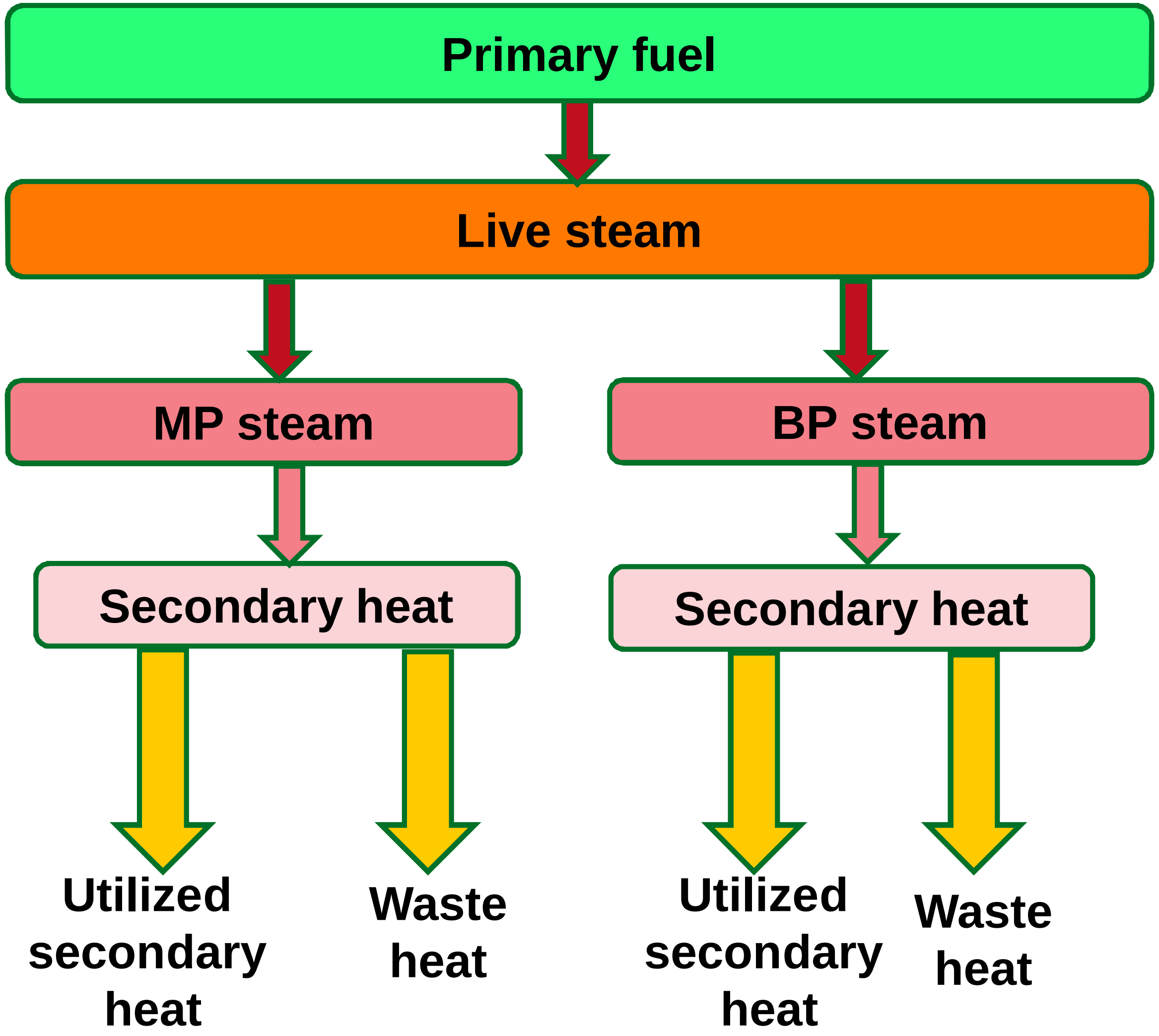


- Fuel is combusted together with sand which makes it possible to cobust fuels with poor quality.
- Typical bed temprature approximately 900°C.
- Bed temperature is basically uniform in the boiler.

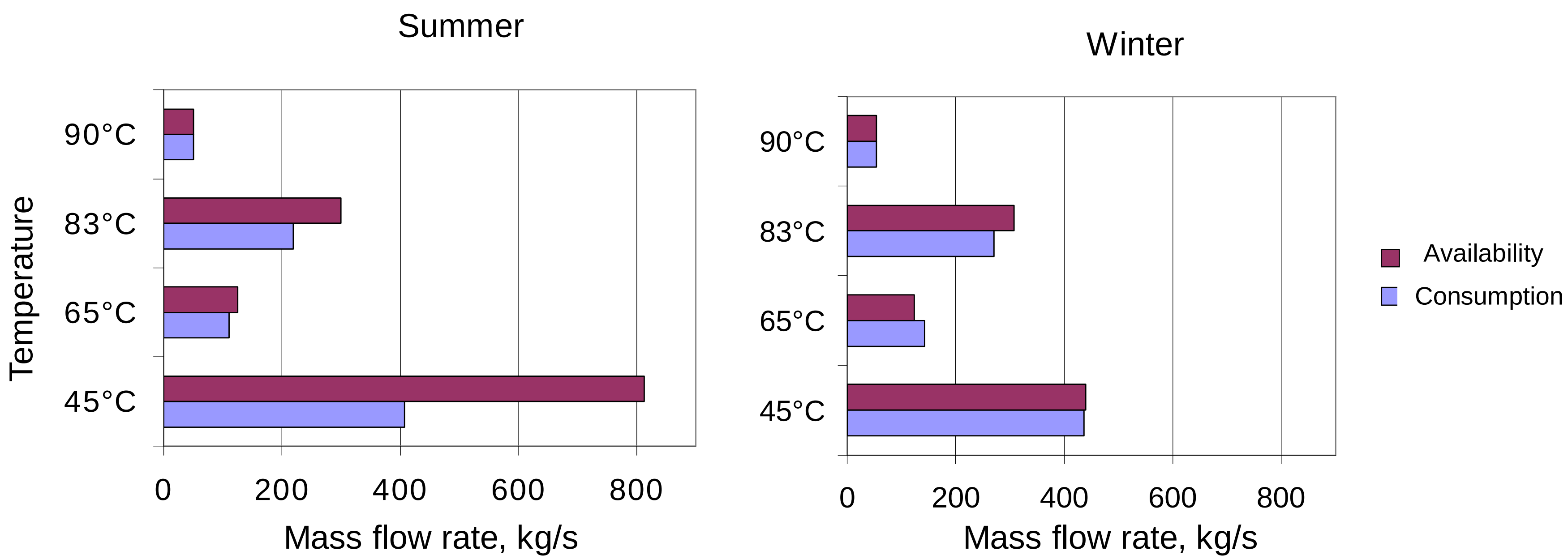
CFB-boiler vs. BFB-boiler

- Fluidizing rates are higher in CFB-boilers.
- CFB-boilers are more suitable for combusting fuels with fluctuations in fuel quality (e.g. high moisture content and a low percentage of volatile components).
- Electricity consumption of auxiliary systems is higher in CFB-boilers.
- Too high bed temperatures may cause agglomeration of the bed material in BFB-boilers.

Heat conversion at a mill



Secondary heat streams at a forest industrial mill in Finland



Secondary heat

- Secondary heat is heat recovered form mill processes.
- Secondary heat can be utilized in the same process or it can be utilized in other processes, usually as hot waters or condensates.
- The use of secondary heat reduces the primary heat consumption => reduces fuel consumption or increases electricity production.
- Typical temperature level of secondary heat is between 40 and 100^{o}C.
- Usually low temperature secondary heat is available much more than high temperature secondary heat.
- Secondary heat consumption varies seasonally. Usually, consumption is higher in the winter than in the summer.

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Defining power to heat ratios for MP and BP steams separately

MP steam

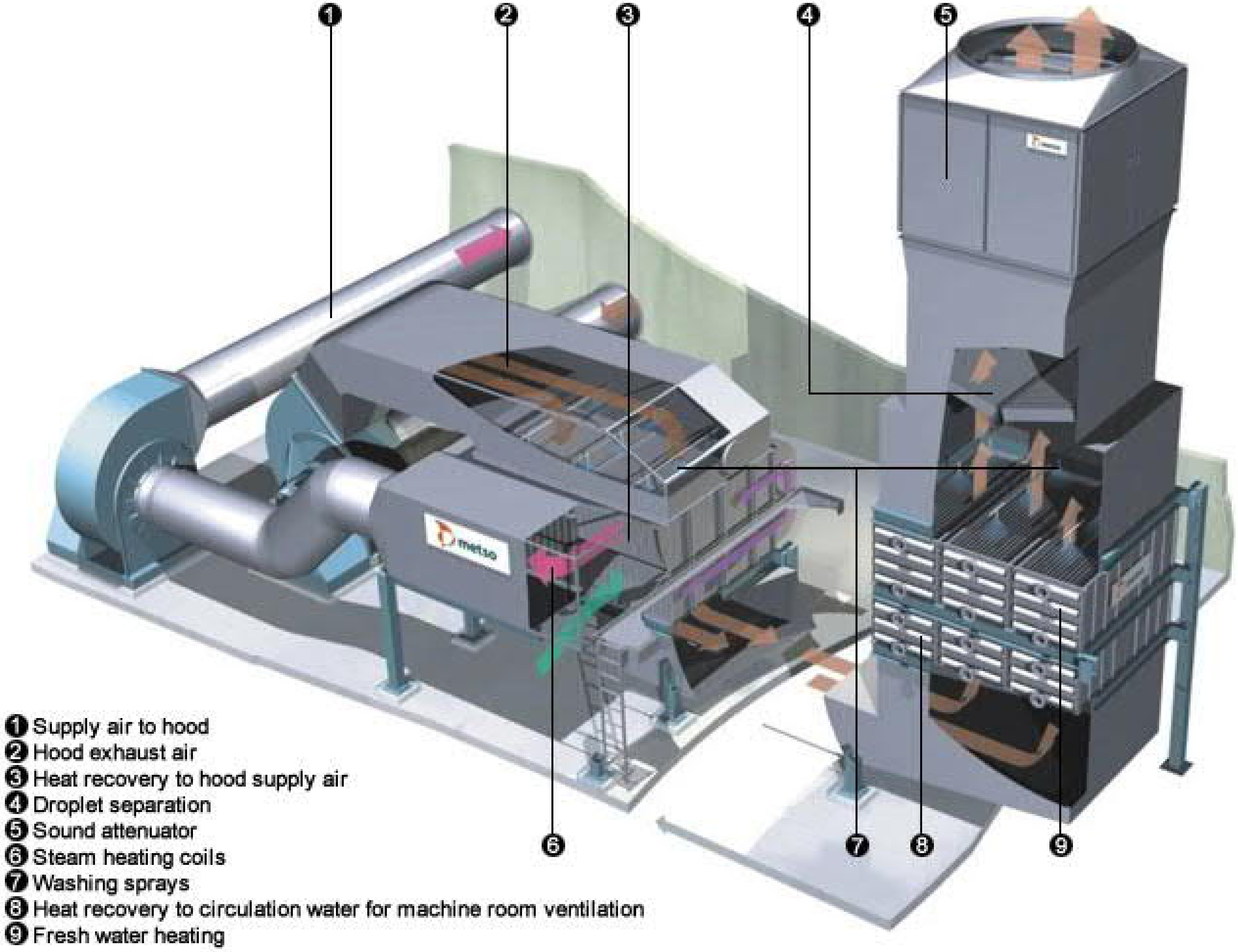
$$\alpha_{MP} = \eta_g \eta_{turb,mec}\left(\dot{m}_{MP} + \dot{m}_{heater}\frac{\dot{m}_{MP}}{\dot{m}_{MP} + \dot{m}_{BP}}\right)\left(h_{HP} - h_{MP} - \Delta h_{pump}\right) + \eta_g \eta_{turb,mec}\dot{m}_{feed\ water}\frac{\dot{m}_{MP}}{\dot{m}_{MP} + \dot{m}_{BP}}\left(h_{HP} - h_{BP} - \Delta h_{pump}\right)$$

BP steam

$$\alpha_{BP} = \eta_g \eta_{turb,mec}\left(\dot{m}_{BP} + \dot{m}_{feed\ water}\frac{\dot{m}_{BP}}{\dot{m}_{MP} + \dot{m}_{BP}}\right)\left(h_{HP} - h_{BP} - \Delta h_{pump}\right) + \eta_g \eta_{turb,mec}\dot{m}_{heater}\frac{\dot{m}_{BP}}{\dot{m}_{MP} + \dot{m}_{BP}}\left(h_{HP} - h_{MP} - \Delta h_{pump}\right)$$

MP = middle pressure steam
BP = back pressure steam
HP = high pressure steam
m_{heater} = mass flow rate of MP steam into the preheater of feed water
$m_{feed\ water}$ = mass flow rate of BP steam into the feed water tank
Δh_{pump}= enthalpy increase in the feed water pump
η_g = efficiency of the generator
$\eta_{turb,mec}$ = mechanical efficiency of the turbine

Heat recovery from exhaust air in the paper machine



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Defining power to heat ratios for MP and BP steams separately

MP steam

$$\alpha_{MP} = \eta_g \eta_{turb,mec}\left(\dot{m}_{MP} + \dot{m}_{heater}\frac{\dot{m}_{MP}}{\dot{m}_{MP}+\dot{m}_{BP}}\right)\left(h_{HP} - h_{MP} - \Delta h_{pump}\right) + \eta_g \eta_{turb,mec}\dot{m}_{feed\ water}\frac{\dot{m}_{MP}}{\dot{m}_{MP}+\dot{m}_{BP}}(h_{HP} - h_{BP} - \Delta h_{pump})$$

BP steam

$$\alpha_{BP} = \eta_g \eta_{turb,mec}\left(\dot{m}_{BP} + \dot{m}_{feed\ water}\frac{\dot{m}_{BP}}{\dot{m}_{MP}+\dot{m}_{BP}}\right)\left(h_{HP} - h_{BP} - \Delta h_{pump}\right) + \eta_g \eta_{turb,mec}\dot{m}_{heater}\frac{\dot{m}_{BP}}{\dot{m}_{MP}+\dot{m}_{BP}}(h_{HP} - h_{MP} - \Delta h_{pump})$$

MP = middle pressure steam
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