Sustainable Energy Transformation Technologies, SH2706

Lecture No 14

Title:

Design and Operation of Thermal Power Plants

Henryk Anglart
Nuclear Engineering Division
Department of Physics, School of Engineering Sciences
KTH

Autumn 2022

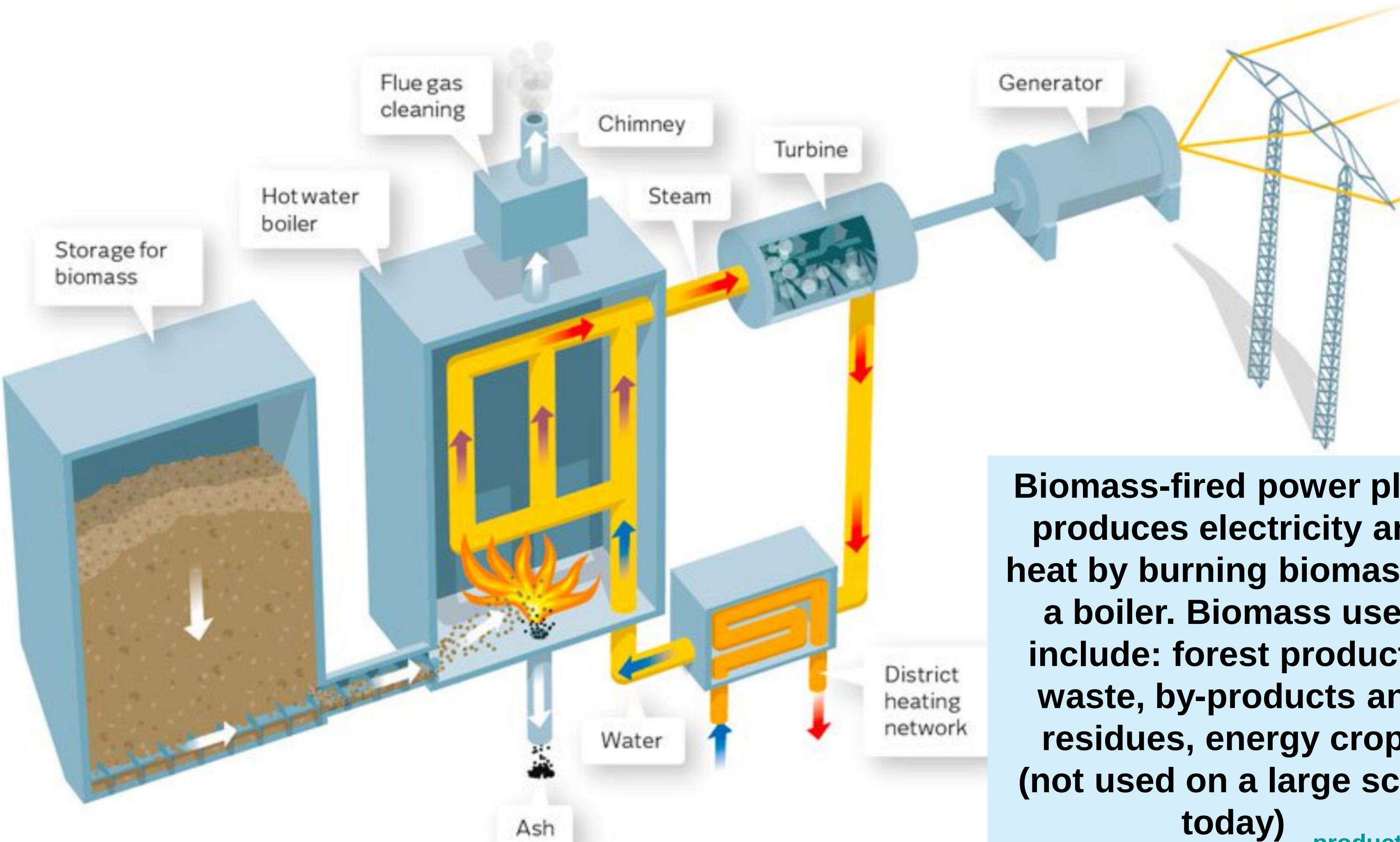
Outline

- Overview of major existing designs
- Principles of operation
- System efficiency
- Future perspectives

Major Existing Designs

- Condensing power systems, containing a boiler, a turbine and a condenser – working in Rankine cycle
  - Fossil fuel power stations, burning coal, fuel oil and natural gas
  - Biomass-fuelled power stations
  - Geothermal power stations
  - Solar thermal power
  - Nuclear power plants
- Gas turbines – working in Brayton cycle
- Systems with serial, parallel or combined coupling of gas turbines with other technologies
  - gas-steam, two- and multi-fuelled, gas-steam with fuel cells, etc
- Cogeneration and trigeneration

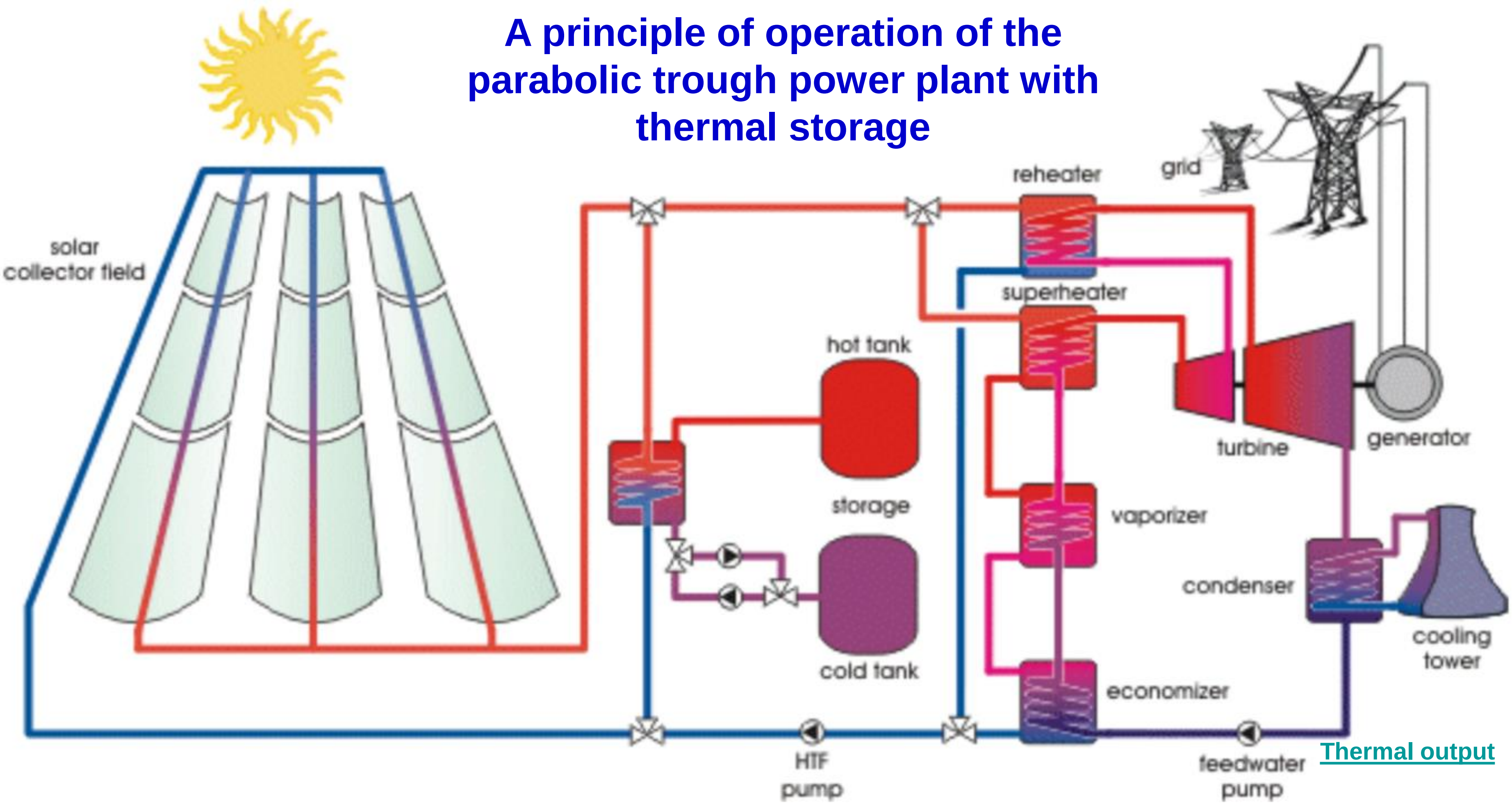
Biomass Fuelled Power Plant



Biomass-fired power plant produces electricity and heat by burning biomass in a boiler. Biomass used include: forest products, waste, by-products and residues, energy crops (not used on a large scale today)

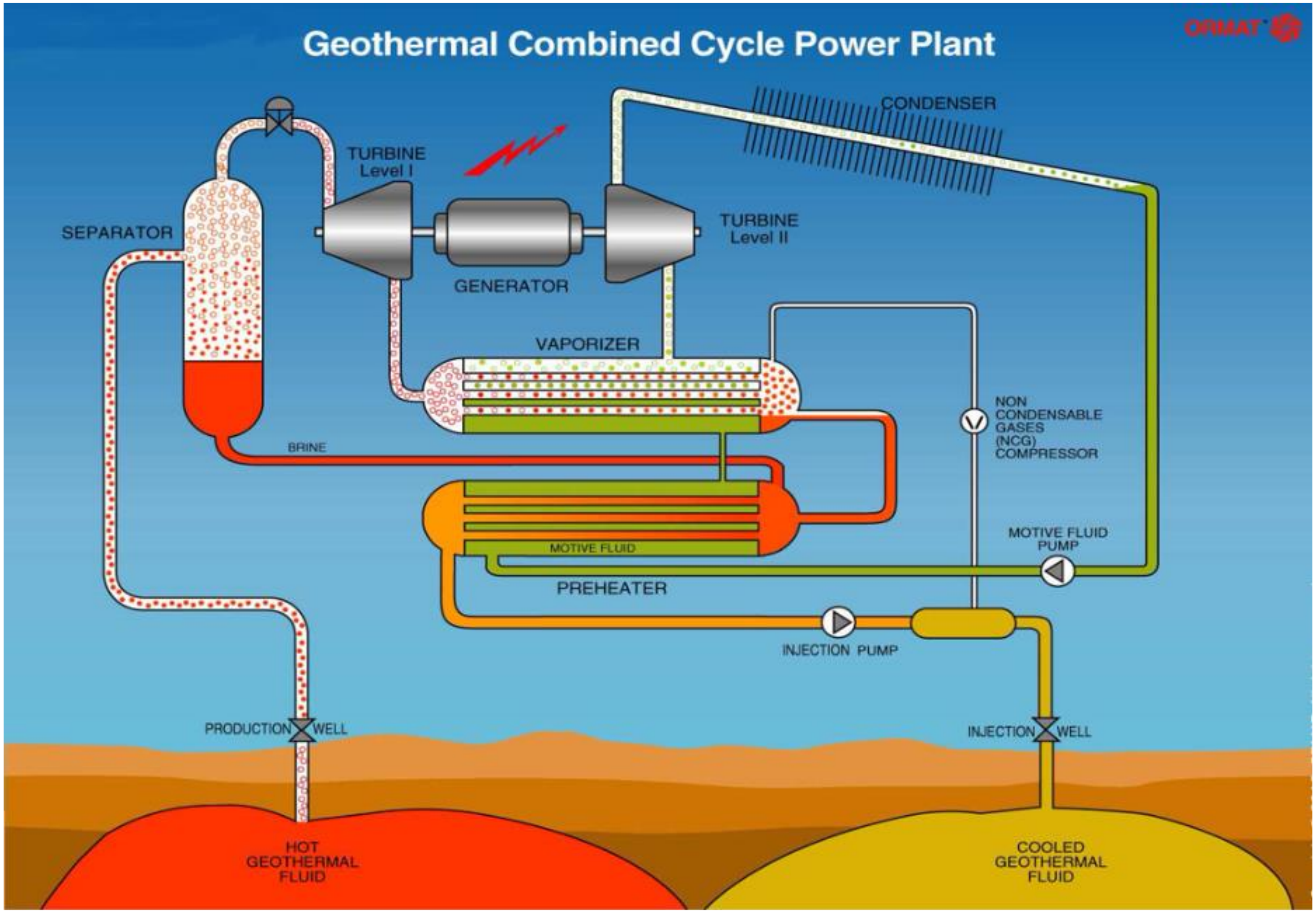
production

Concentrated Solar Thermal Power



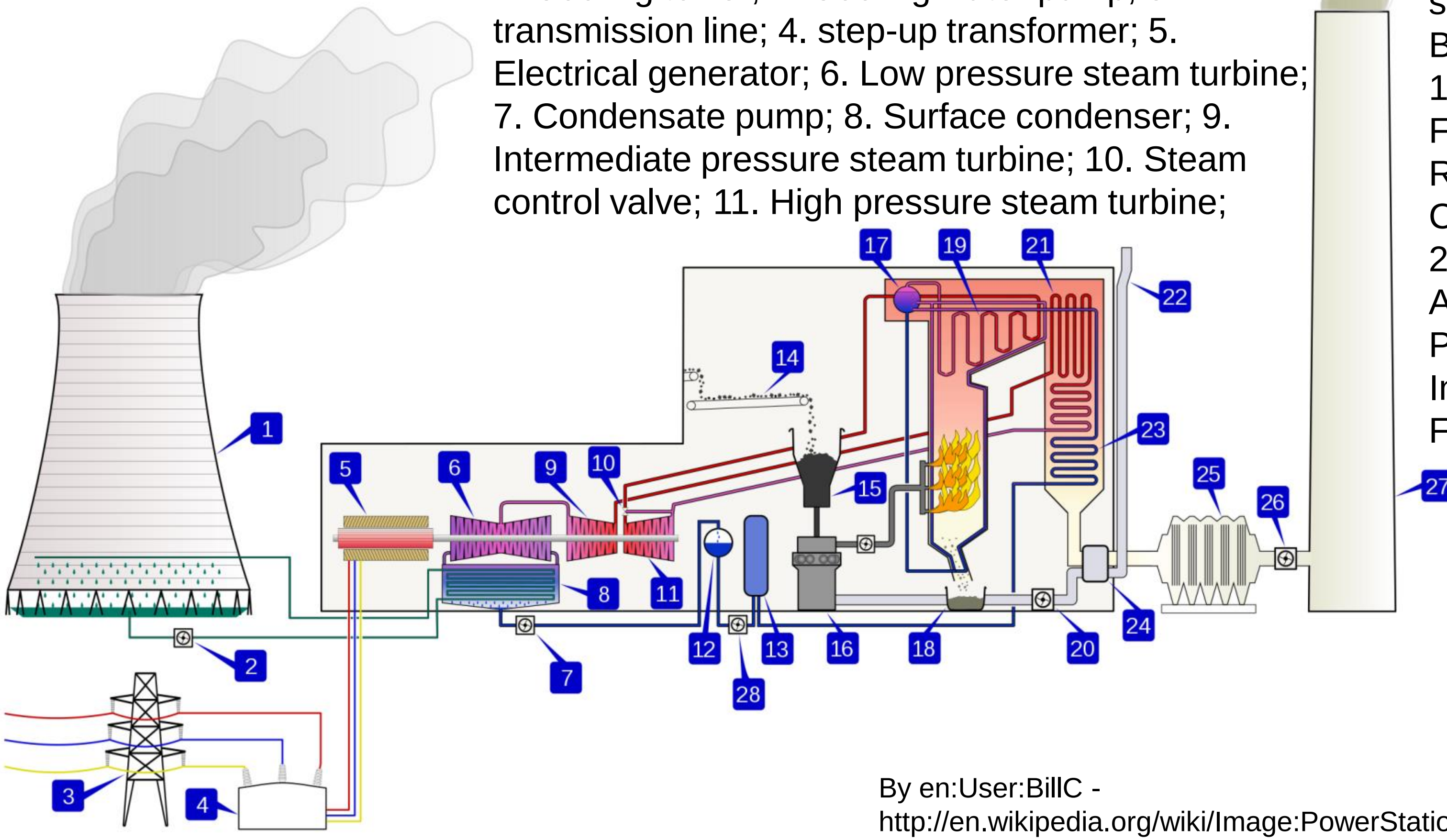
[Thermal output]

Geothermal Power Plant

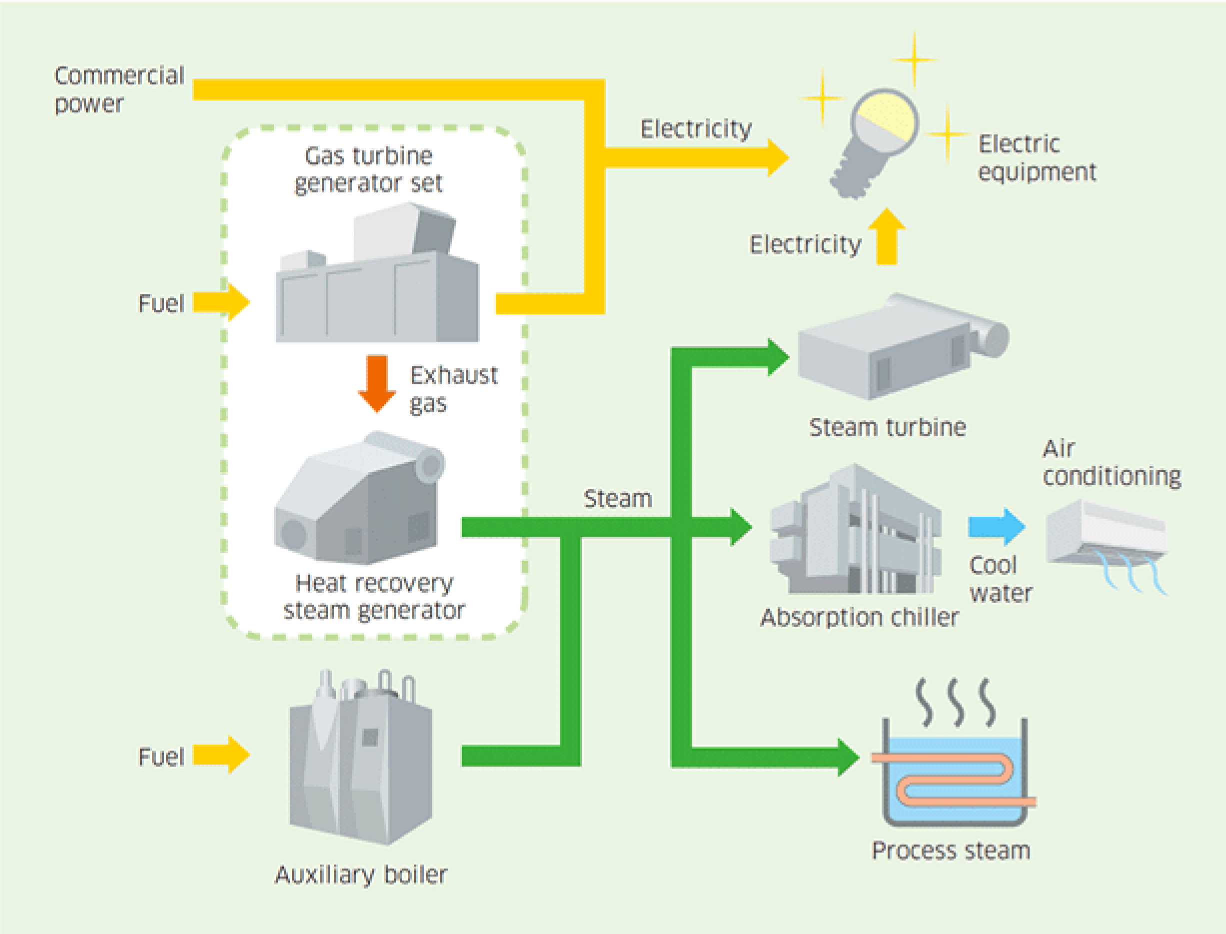


Coal-fired Plant

Coal-fired thermal power station:
1. Cooling tower; 2. Cooling water pump; 3. transmission line; 4. step-up transformer; 5. Electrical generator; 6. Low pressure steam turbine; 7. Condensate pump; 8. Surface condenser; 9. Intermediate pressure steam turbine; 10. Steam control valve; 11. High pressure steam turbine; 12. Deaerator; 13. Feedwater heater; 14. Coal conveyor; 15. Coal hopper; 16. Coal pulverizer; 17. Boiler steam drum; 18. Bottom ash hopper; 19. Superheater; 20. Forced draft fan; 21. Reheater; 22. Combustion air intake; 23. Economizer; 24. Air preheater; 25. Precipitator; 26. Induced draft fan; 27. Flue-gas stack



A Cogeneration System

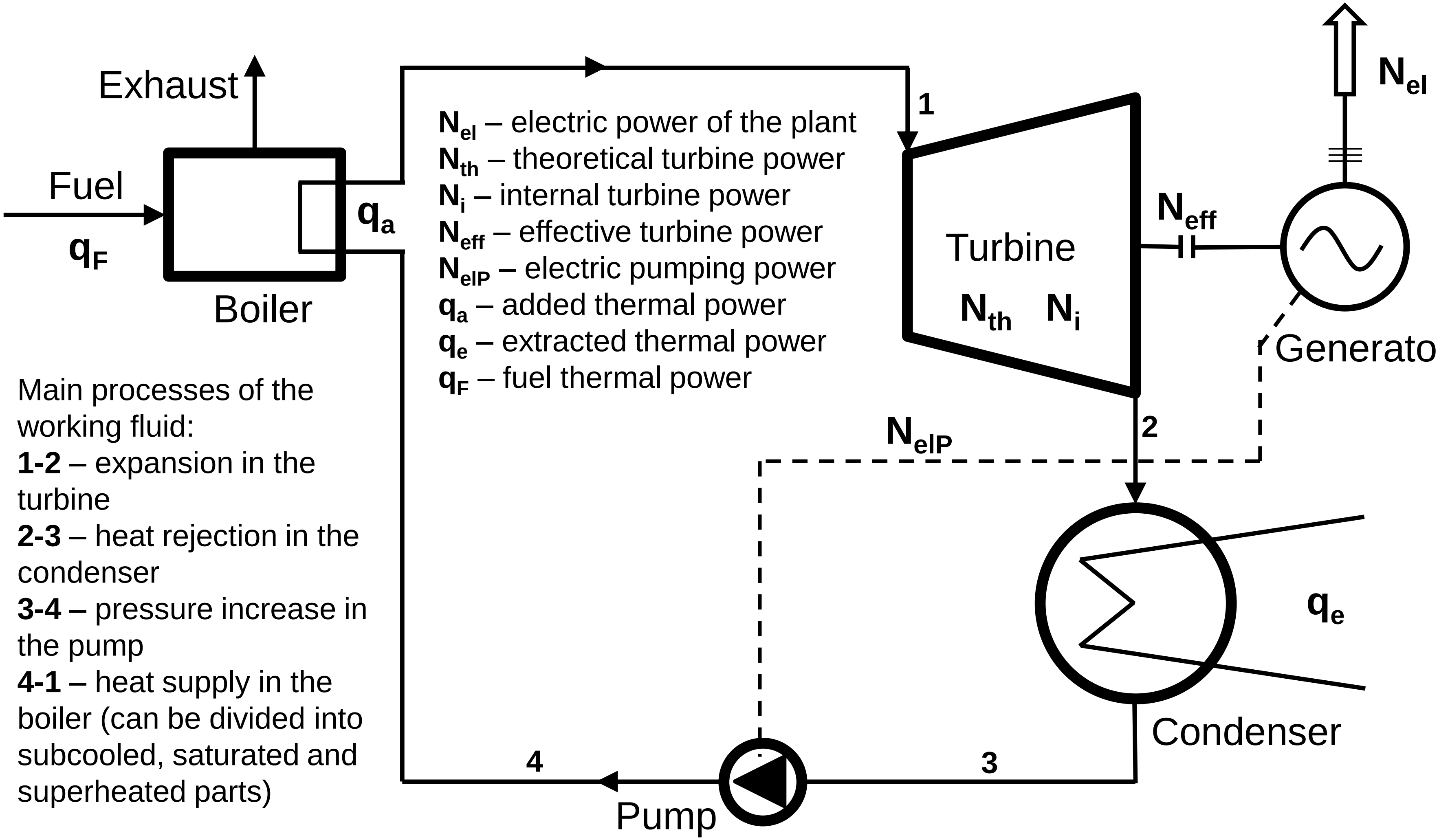


A cogeneration system drives a gas turbine by using primary energy (fuel), and produces multiple types of secondary energy (e.g., electricity, steam) continuously. In a gas turbine cogeneration system, fuel is used as the primary energy, and multiple types of energy are produced in order to use energy more effectively. Furthermore, the system curbs NOx production and reduces environmental impact by using a gas turbine as the drive source.

Condensing Power

- Condensing power system are using Rankine cycle with water steam as a working fluid
- The steam is expanding in a turbine providing a shaft power
- After passing through the turbine, the steam is condensed in a condenser
- The energy efficiency of the condensing power cycle is limited by the Carnot efficiency
- Typically the efficiency is in a range 33 to 48%
- The upper limit efficiency is achieved in supercritical designs (working fluid pressure above 22.1 MPa)

Condensing Power Schematic



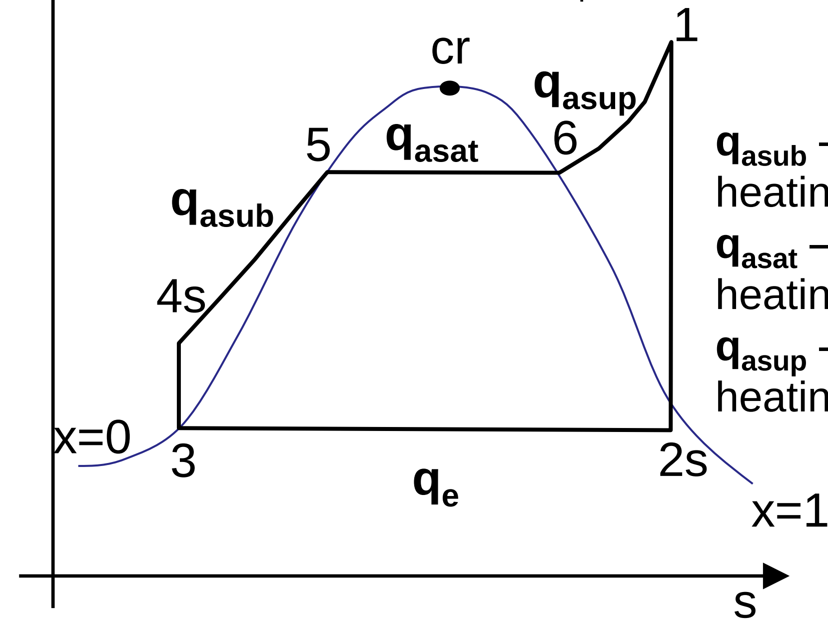
- N_{el} – electric power of the plant
- N_{th} – theoretical turbine power
- N_i – internal turbine power
- N_{eff} – effective turbine power
- N_{elP} – electric pumping power
- q_a – added thermal power
- q_e – extracted thermal power
- q_F – fuel thermal power

Main processes of the working fluid:

1-2 – expansion in the turbine
2-3 – heat rejection in the condenser
3-4 – pressure increase in the pump
4-1 – heat supply in the boiler (can be divided into subcooled, saturated and superheated parts)

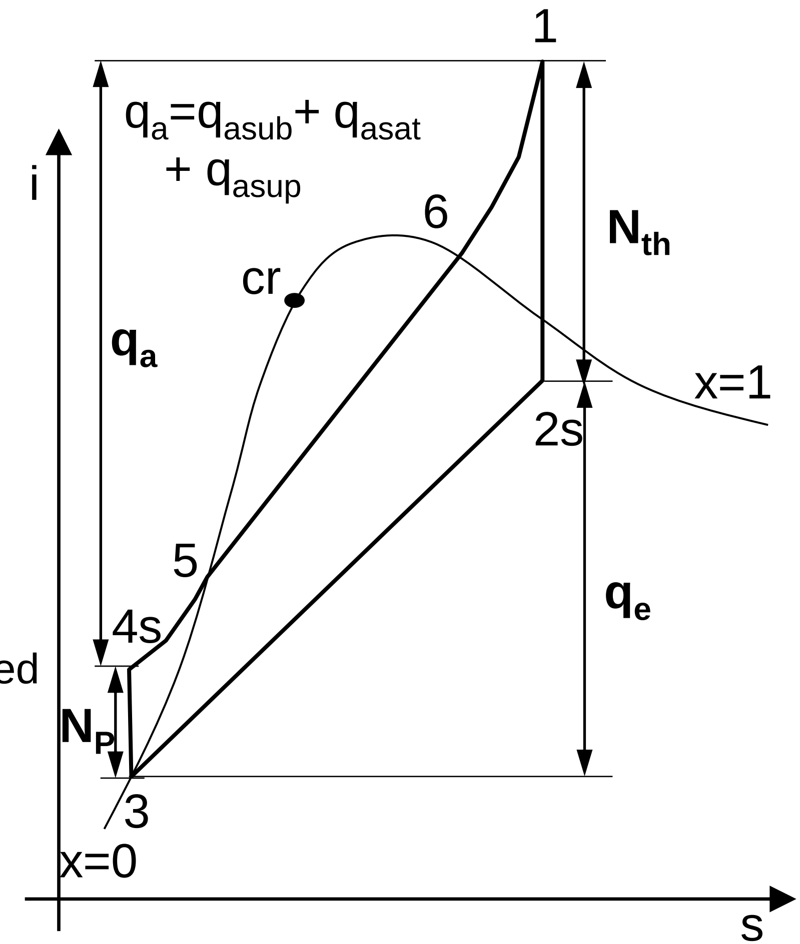
Ideal Sub-critical Rankine Cycle

1-2s isentropic expansion in turbine
2s-3 heat rejection
3-4s isentropic pumping
4s-5 heating, q_{asub}
5-6 boiling, q_{asat}
6-1 superheating, q_{asup}



cr – critical point

$\mathbf{q_{asub}}$ – subcooled heating power
$\mathbf{q_{asat}}$ – saturated heating power
$\mathbf{q_{asup}}$ – superheated heating power

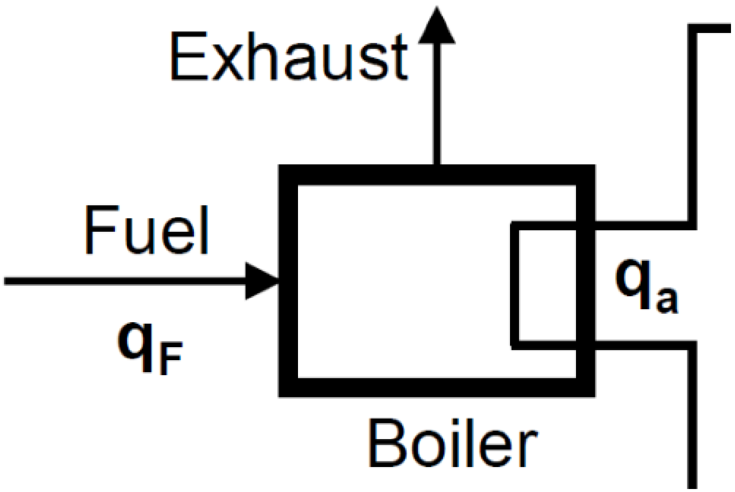


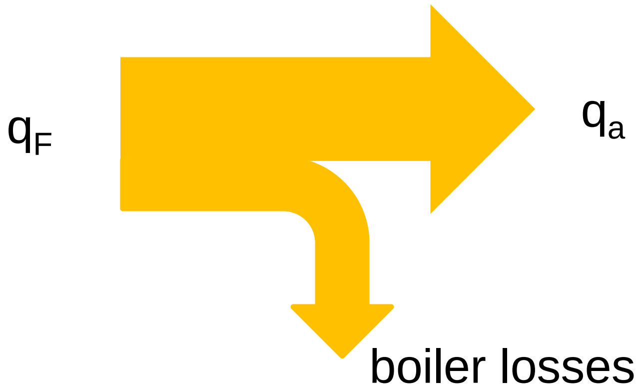
Burner and Boiler

- Fuel is burned in burner providing thermal power q_F
- We can defined the efficiency of the boiler as follows:

$$\eta_B = \frac{q_a}{q_F}$$

- Where q_F is known from fuel mass flow rate W_F and specific energy content, c_F: $q_F = W_F * c_F$





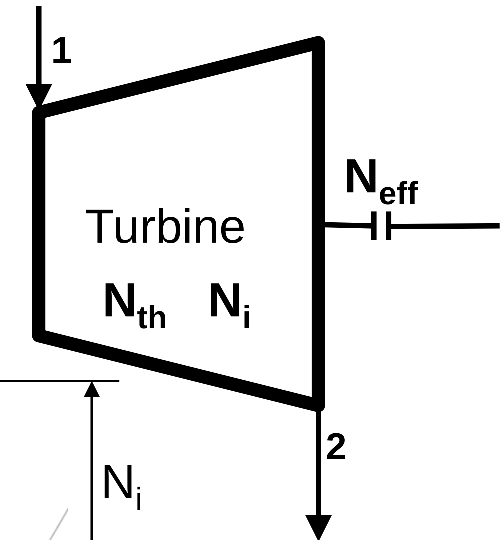
Turbine (1)

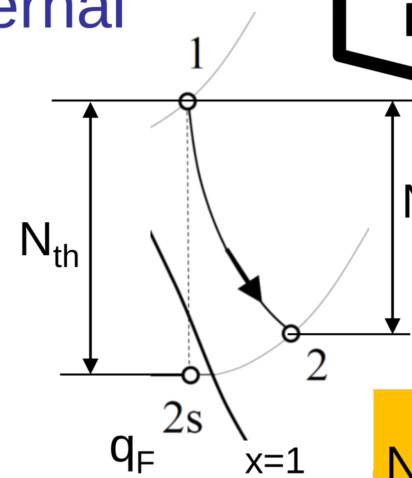
- We define the following turbine powers:
  - the theoretical (isentropic) power $N_{th} = W(i_1 - i_{2s})$
  - the internal turbine power $N_i = W(i_1 - i_2)$
- Based on these powers, the internal turbine efficiency is defined as

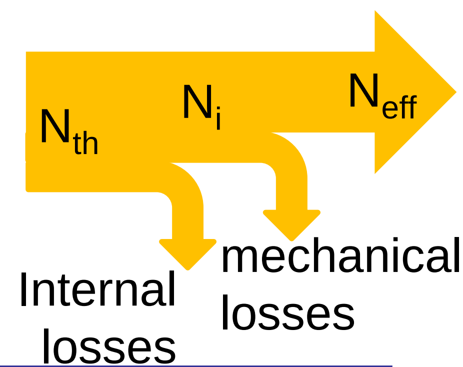
$$\eta_i = \frac{N_i}{N_{th}} \Rightarrow \eta_i = \frac{i_1 - i_2}{i_1 - i_{2s}}$$

- The turbine effective power is based on mechanical efficiency η_m and is given as

$$N_{eff} = \eta_m N_i = \eta_m \eta_i N_{th}$$

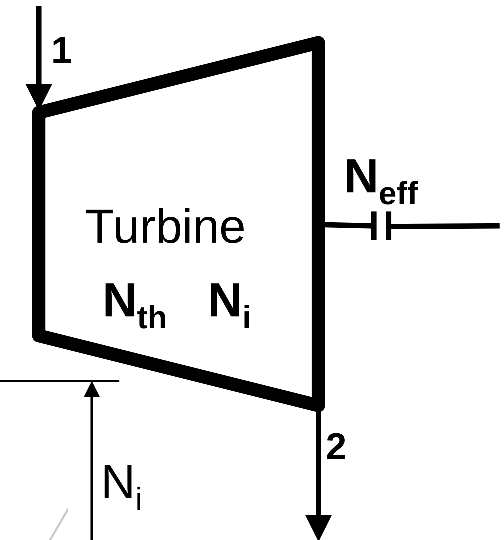


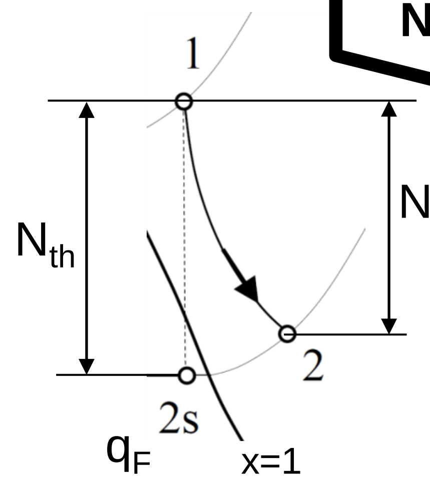




Turbine (2)

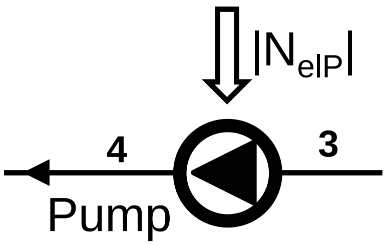
- In modelling a turbine, we usually know the following data:
  - pressure and temperature of steam at the inlet: p_1, T_1
  - pressure of steam at the exit: p_2
  - internal efficiency of turbine η_i
- Our task is to find the specific enthalpy of the steam at the exit, i_2 and N_i. The solution is:
  - 1) we find $i_1(p_1,T_1)$: using XSteam, we have: $i_1 = \text{XSteam}('\text{h\_pT}', p_1, T_1)$
  - 2) we find $s_1(p_1,T_1)$ as $s_1 = \text{XSteam}('\text{s\_ph}', p_1, i_1)$ and next we find i_{2s} as (3) $i_{2s} = \text{XSteam}('\text{h\_ps}', p_2, s_1)$ and finally (4) $i_2 = i_1 - \eta_i \left(i_1 - i_{2s}\right)$





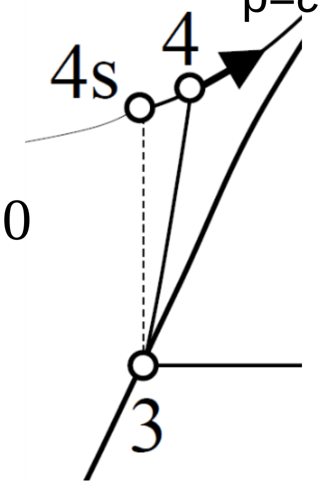
$$\eta_i = \frac{i_1 - i_2}{i_1 - i_{2s}}$$

Pump (1)



- To increase pressure from 3 to 4 pumping power $|N_{iP}|$ has to be supplied
- From the energy conservation principle for steady-state ($dE_T/dt=0$) we have

$$\frac{dE_T}{dt} = q - N_{iP} + W_3\left(i_3 + e_{P3} + e_{K3}\right) - W_4\left(i_4 + e_{P4} + e_{K4}\right) = 0$$

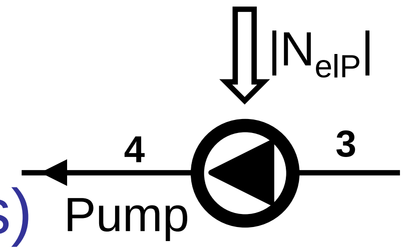


  - here we have to supply power to the system thus $-N_{iP} = |N_{iP}|$, no heat is added thus $q = 0$, we also neglect kinetic and potential energy changes and from mass conservation we have $W_3=W_4=W$

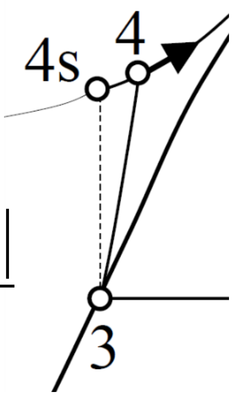
$$|N_{iP}| = W\left(i_4 - i_3\right) = W\left(\underbrace{e_{I4} - e_{I3}}_{\text{internal energy increase}} + \frac{p_4 - p_3}{\rho_e}\right) = \underbrace{W\frac{p_4 - p_3}{\rho_e}}_{N_{uP}=\text{useful pumping power}} + \underbrace{W\Delta e_I}_{\text{internal energy increase}}$$

Here ρ_e is an equivalent fluid density for process 3-4. Typically we assume $\rho_e \approx \rho_3 \approx \rho_4$ (incompressible)

Pump (2)



- The pumping power $|N_{thP}|$ is a theoretical pumping power (used in ideal cycle analyses)
- For real process 3-4, we obtain the pumping power $|N_{iP}|$ from energy conservation as $\left|N_{iP}\right| \equiv W\left(i_4 - i_3\right)$ and call this internal power



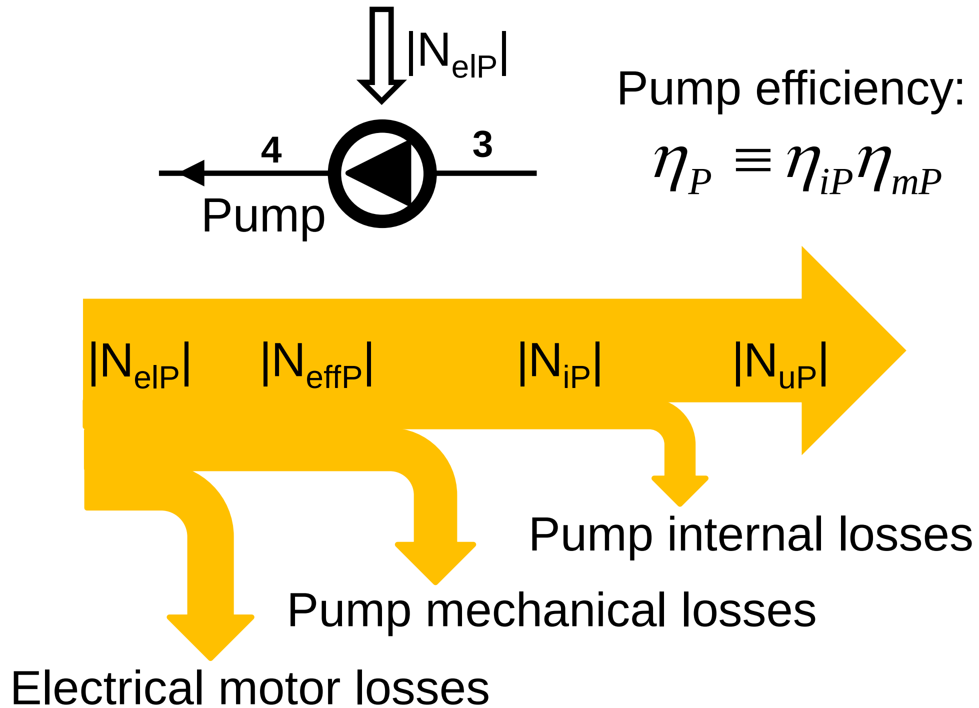
- Due to internal losses, internal power is: $\left|N_{iP}\right| = \dfrac{\left|N_{uP}\right|}{\eta_{iP}}$
- We also define an effective pumping power, $N_{effP}=N_{mP}$ due to pump mechanical efficiency η_{mP} (= mechanical eff.): $\left|N_{effP}\right| = \dfrac{\left|N_{iP}\right|}{\eta_{mP}}$

N_{uP} – useful pumping power

- Finally, the electric motor power for pumping is found as: $\left|N_{elP}\right| = \dfrac{\left|N_{effP}\right|}{\eta_{EM}}$

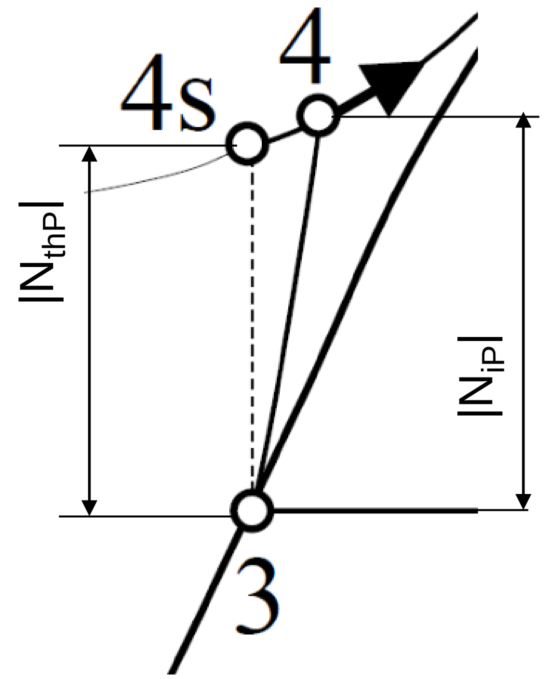
Here η_{EM}: is the electrical motor efficiency

Pump (3)



Pump efficiency:

$$\eta_P \equiv \eta_{iP}\eta_{mP}$$



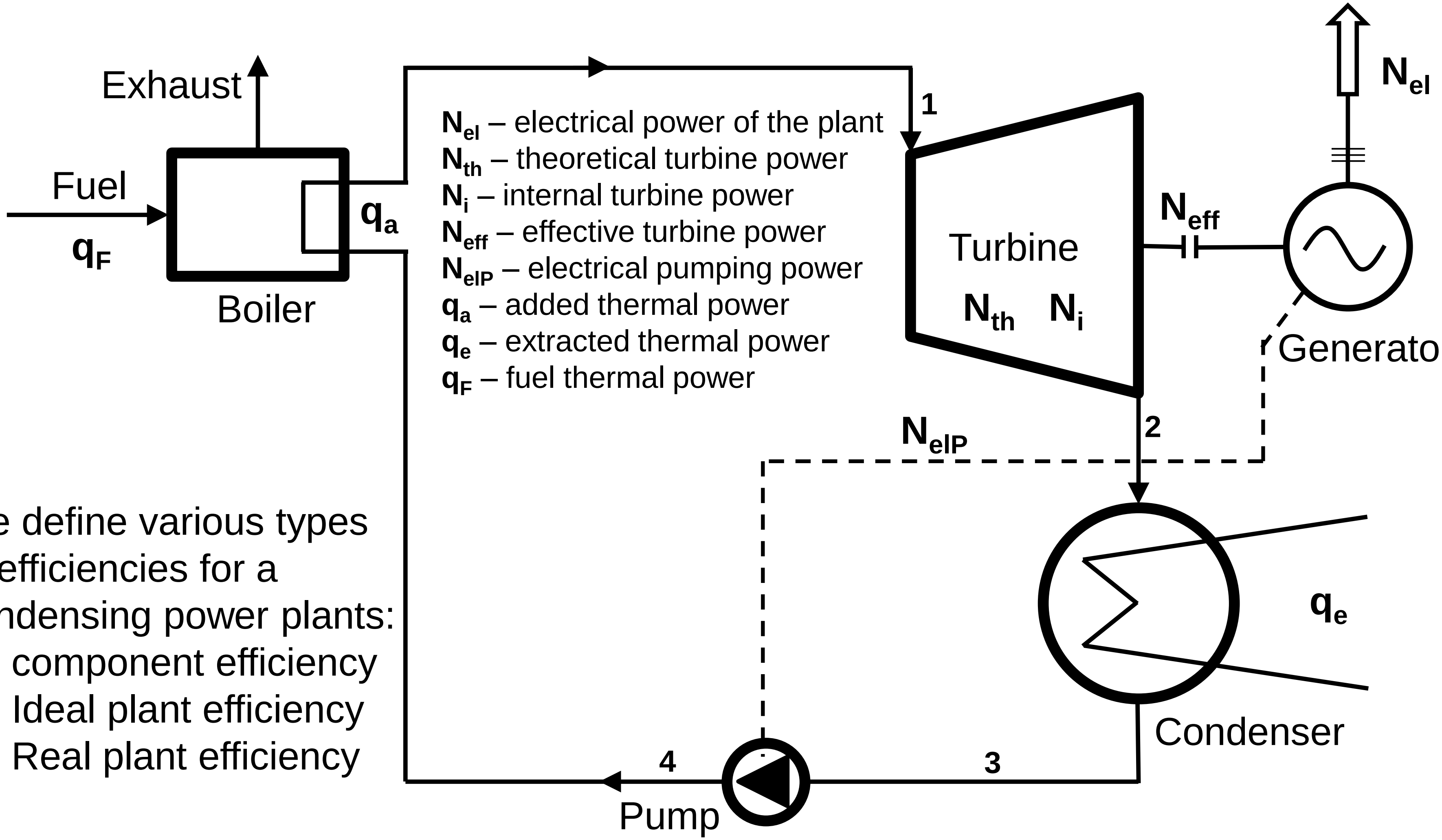
1) $$\left|N_{elP}\right| = W\frac{p_4 - p_3}{\eta_{iP}\eta_{mP}\eta_{EM}\rho_e}$$

2) $$i_4 - i_3 = \frac{\eta_{mP}\eta_{EM}\left|N_{elP}\right|}{W}$$

3) $$i_4 - i_3 = \frac{p_4 - p_3}{\rho_e \eta_{iP}}$$

Typical tasks: (**1**) calculate required electrical power to produce given pressure difference; (**2**) calculate specific enthalpy at pump discharge for given electrical power; (**3**) the same as in (2) for given pressure drop

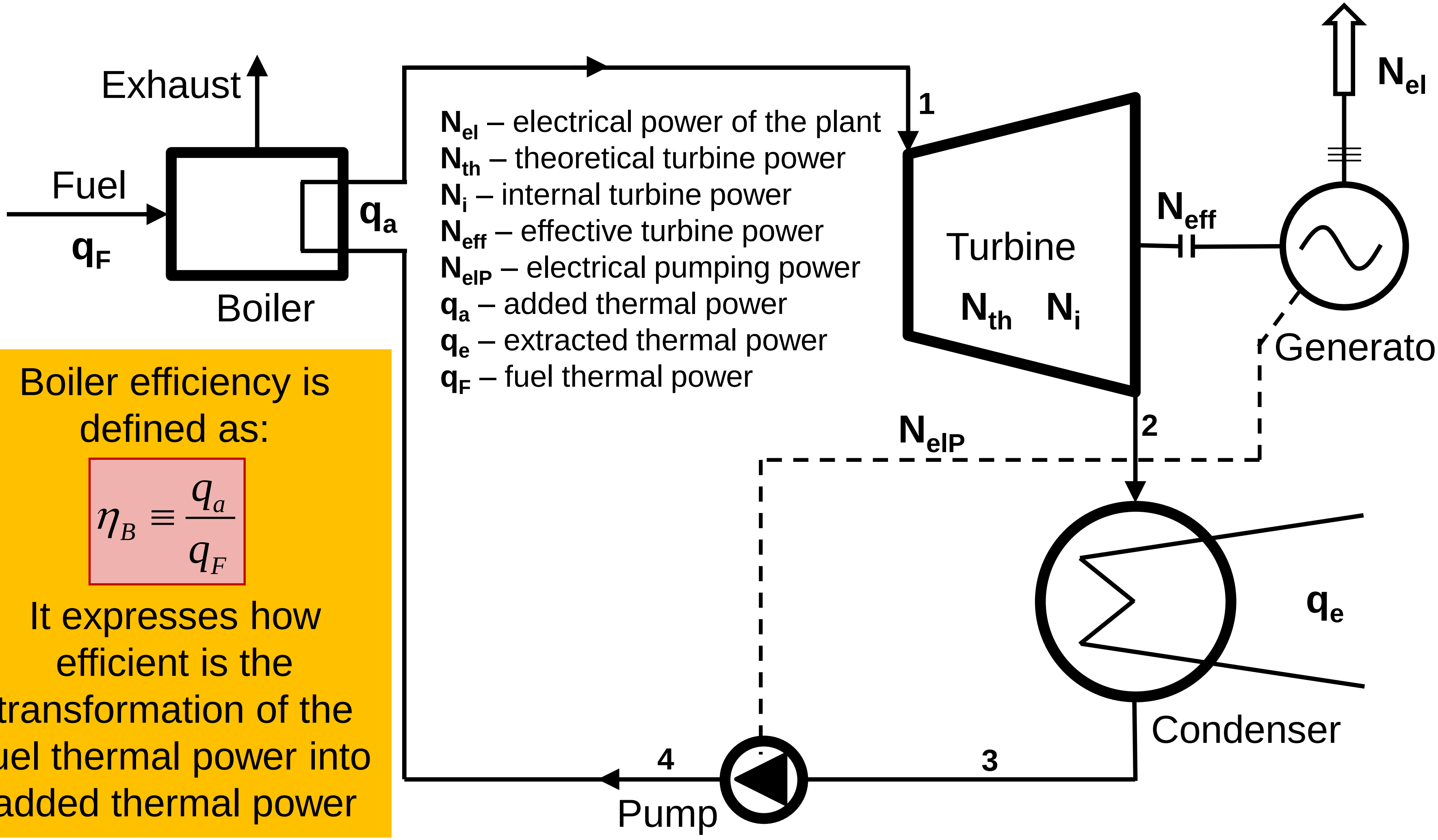
Condensing Power Plant (CPP)



We define various types of efficiencies for a condensing power plants:

1) component efficiency
2) Ideal plant efficiency
3) Real plant efficiency

CPP – Boiler Efficiency



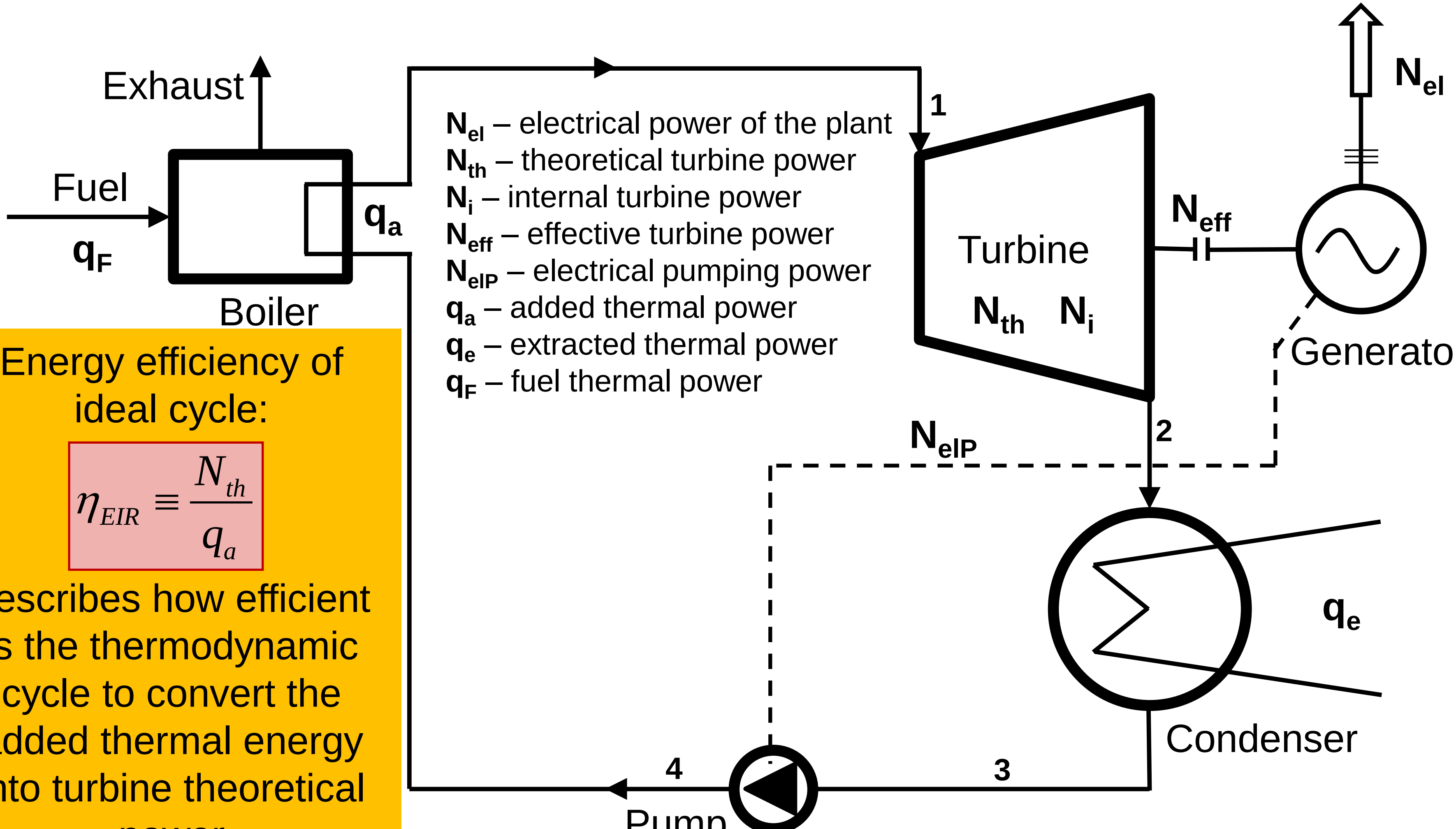
- N_{el} – electrical power of the plant
- N_{th} – theoretical turbine power
- N_i – internal turbine power
- N_{eff} – effective turbine power
- N_{elP} – electrical pumping power
- q_a – added thermal power
- q_e – extracted thermal power
- q_F – fuel thermal power

Boiler efficiency is defined as:

$$\eta_B \equiv \frac{q_a}{q_F}$$

It expresses how efficient is the transformation of the fuel thermal power into added thermal power

CPP – Energy Efficiency of Ideal Cycle



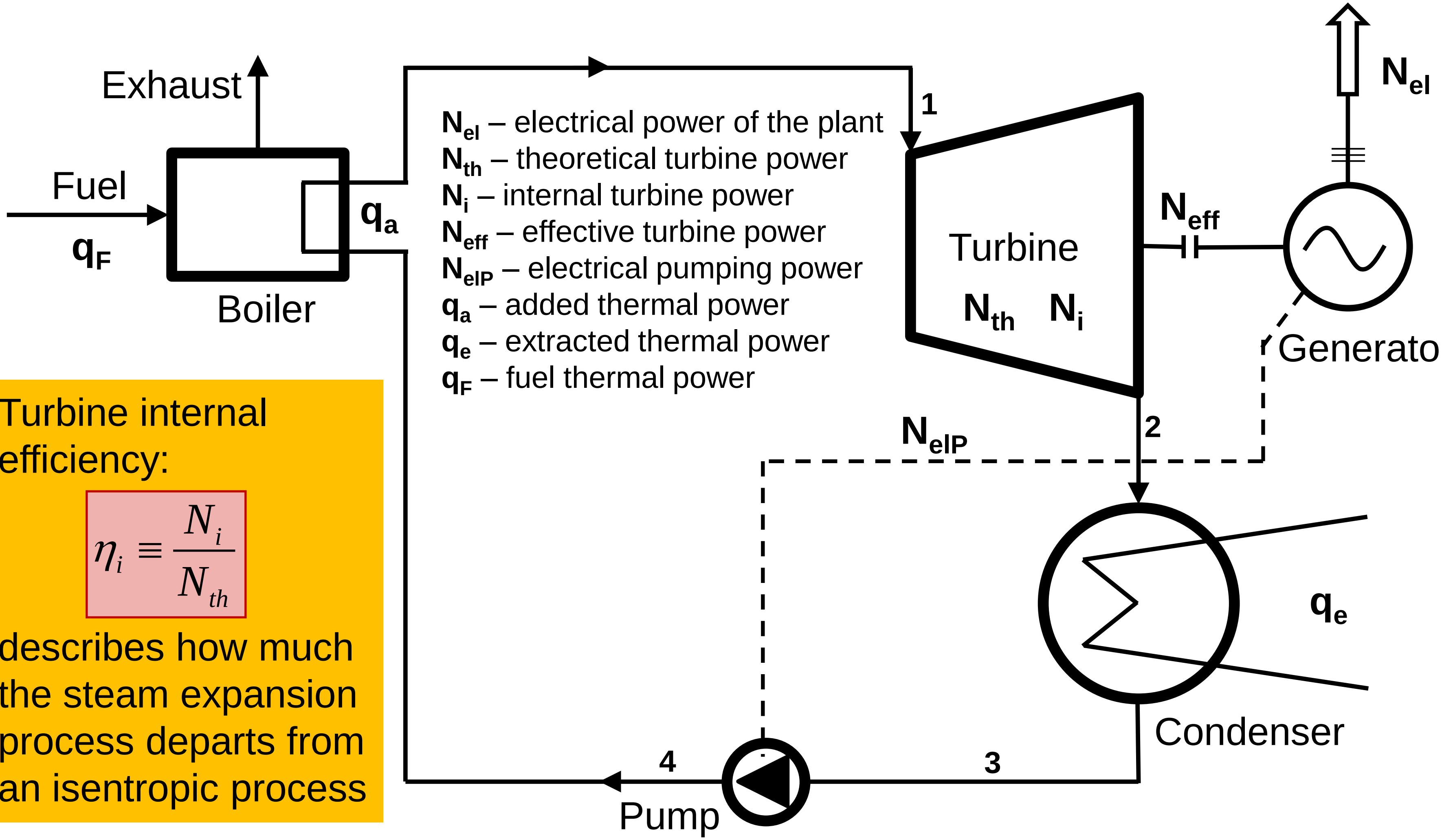
N_{el} – electrical power of the plant
N_{th} – theoretical turbine power
N_i – internal turbine power
N_{eff} – effective turbine power
N_{elP} – electrical pumping power
q_a – added thermal power
q_e – extracted thermal power
q_F – fuel thermal power

Energy efficiency of ideal cycle:

$$\eta_{EIR} \equiv \frac{N_{th}}{q_a}$$

describes how efficient is the thermodynamic cycle to convert the added thermal energy into turbine theoretical power

CPP – Turbine Internal Efficiency

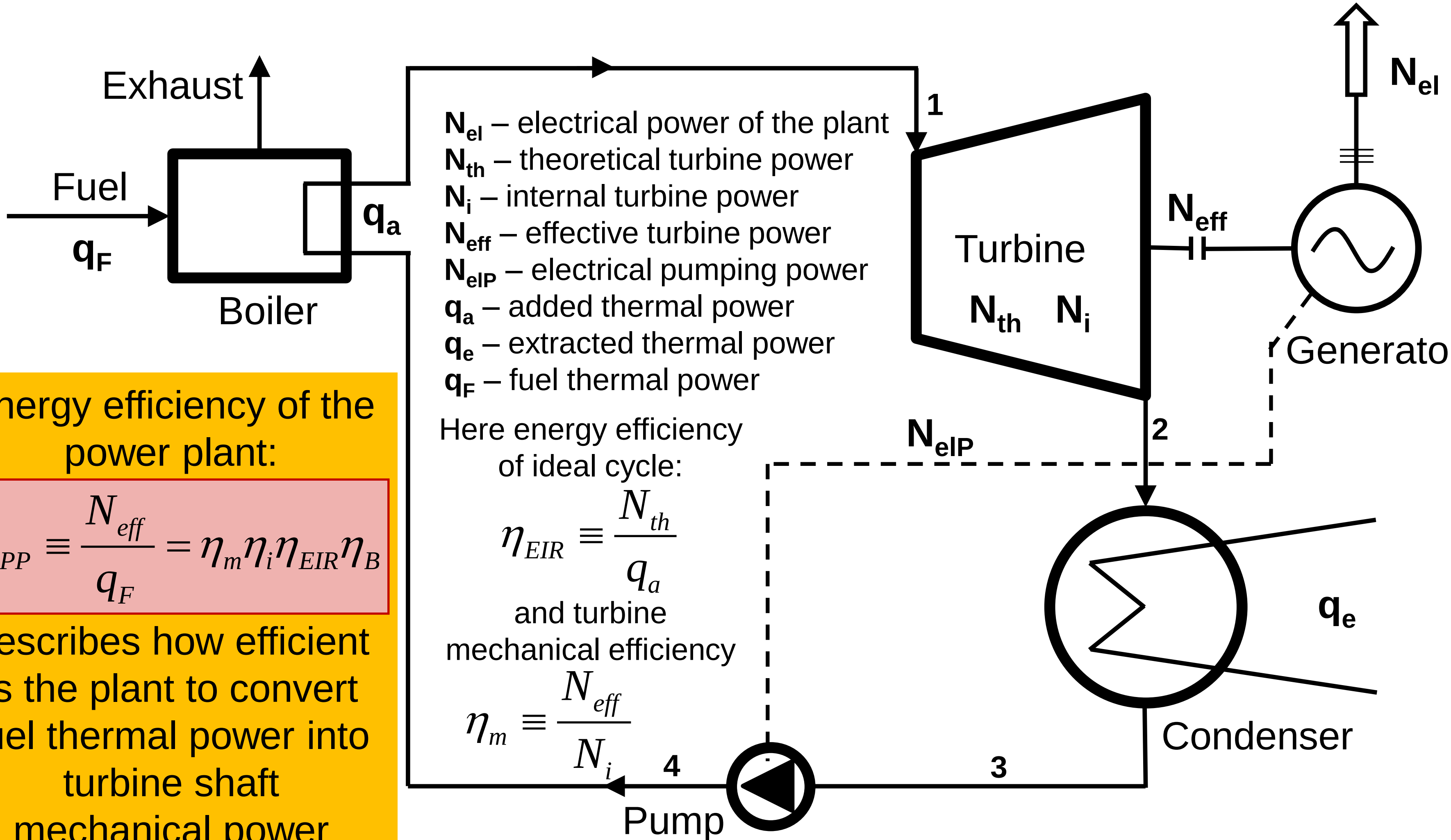


Turbine internal efficiency:

$$\eta_i \equiv \frac{N_i}{N_{th}}$$

describes how much the steam expansion process departs from an isentropic process

CPP – Energy Efficiency of Power Plant



N_{el} – electrical power of the plant
N_{th} – theoretical turbine power
N_i – internal turbine power
N_{eff} – effective turbine power
N_{elP} – electrical pumping power
q_a – added thermal power
q_e – extracted thermal power
q_F – fuel thermal power

Here energy efficiency of ideal cycle:

$$\eta_{EIR} \equiv \frac{N_{th}}{q_a}$$

and turbine mechanical efficiency

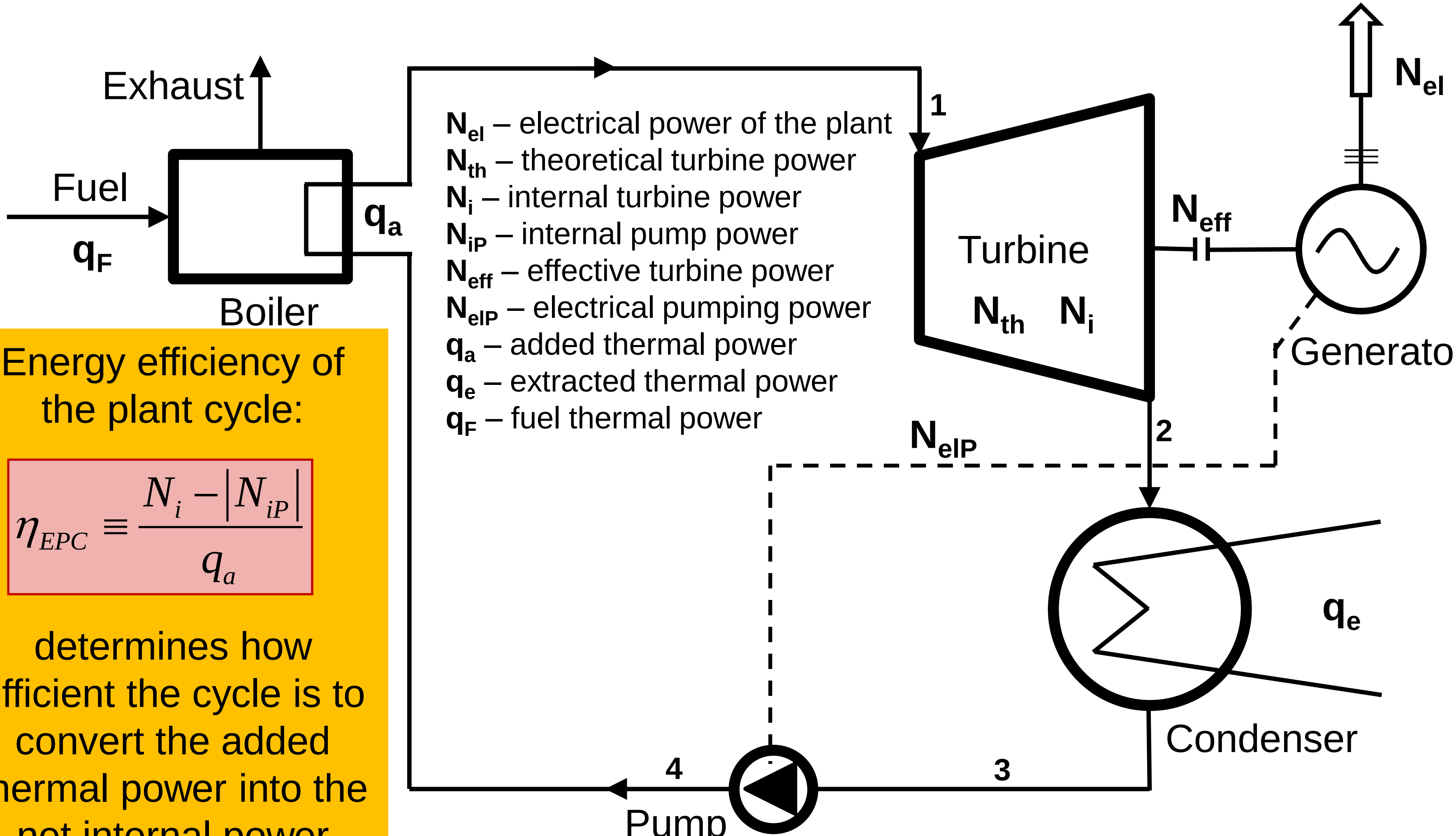
$$\eta_m \equiv \frac{N_{eff}}{N_i}$$

Energy efficiency of the power plant:

$$\eta_{EPP} \equiv \frac{N_{eff}}{q_F} = \eta_m \eta_i \eta_{EIR} \eta_B$$

describes how efficient is the plant to convert fuel thermal power into turbine shaft mechanical power

CPP – Energy Efficiency of Plant Cycle



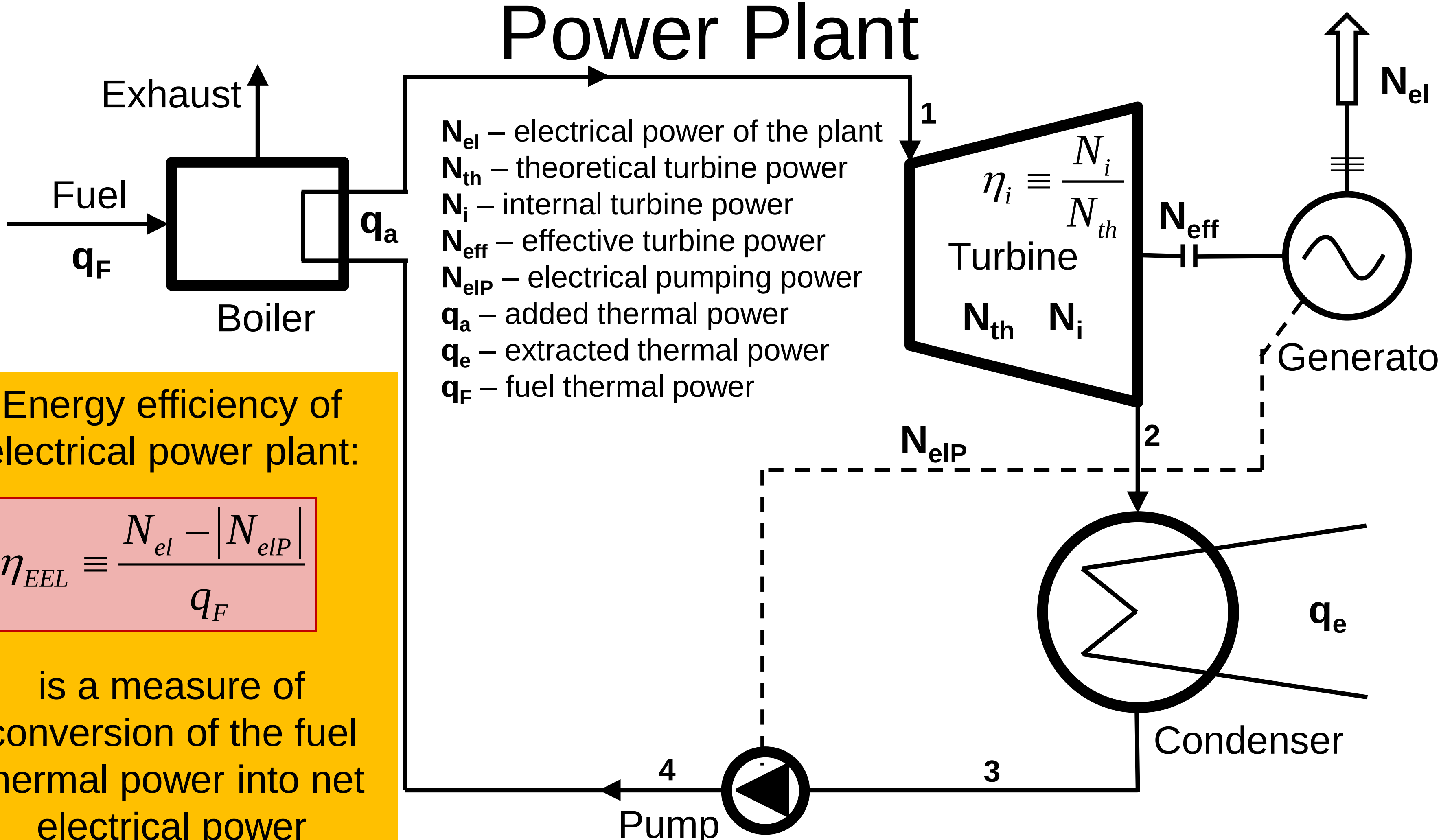
N_{el} – electrical power of the plant
N_{th} – theoretical turbine power
N_i – internal turbine power
N_{iP} – internal pump power
N_{eff} – effective turbine power
N_{elP} – electrical pumping power
q_a – added thermal power
q_e – extracted thermal power
q_F – fuel thermal power

Energy efficiency of the plant cycle:

$$\boxed{\eta_{EPC} \equiv \frac{N_i - |N_{iP}|}{q_a}}$$

determines how efficient the cycle is to convert the added thermal power into the net internal power

CPP – Energy Efficiency of Electrical Power Plant



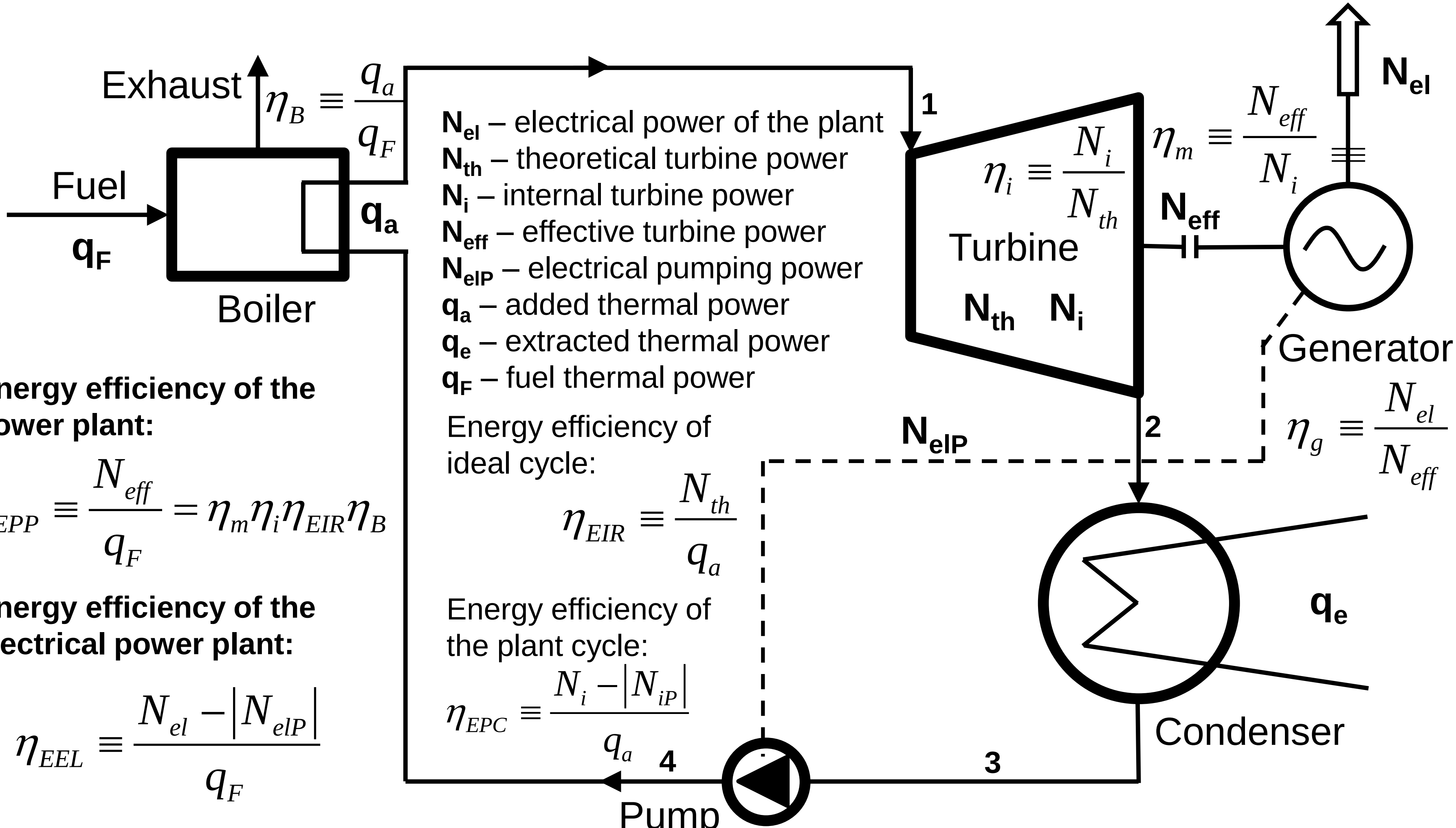
- N_{el} – electrical power of the plant
- N_{th} – theoretical turbine power
- N_i – internal turbine power
- N_{eff} – effective turbine power
- N_{elP} – electrical pumping power
- q_a – added thermal power
- q_e – extracted thermal power
- q_F – fuel thermal power

Energy efficiency of electrical power plant:

$$\eta_{EEL} \equiv \frac{N_{el} - |N_{elP}|}{q_F}$$

is a measure of conversion of the fuel thermal power into net electrical power

Condensing Power Efficiencies



$$\eta_B \equiv \frac{q_a}{q_F}$$

$$\eta_i \equiv \frac{N_i}{N_{th}}$$

$$\eta_m \equiv \frac{N_{eff}}{N_i}$$

$$\eta_g \equiv \frac{N_{el}}{N_{eff}}$$

N_{el} – electrical power of the plant
N_{th} – theoretical turbine power
N_i – internal turbine power
N_{eff} – effective turbine power
N_{elP} – electrical pumping power
q_a – added thermal power
q_e – extracted thermal power
q_F – fuel thermal power

Energy efficiency of ideal cycle:

$$\eta_{EIR} \equiv \frac{N_{th}}{q_a}$$

Energy efficiency of the plant cycle:

$$\eta_{EPC} \equiv \frac{N_i - |N_{iP}|}{q_a}$$

Energy efficiency of the power plant:

$$\eta_{EPP} \equiv \frac{N_{eff}}{q_F} = \eta_m \eta_i \eta_{EIR} \eta_B$$

Energy efficiency of the electrical power plant:

$$\eta_{EEL} \equiv \frac{N_{el} - |N_{elP}|}{q_F}$$

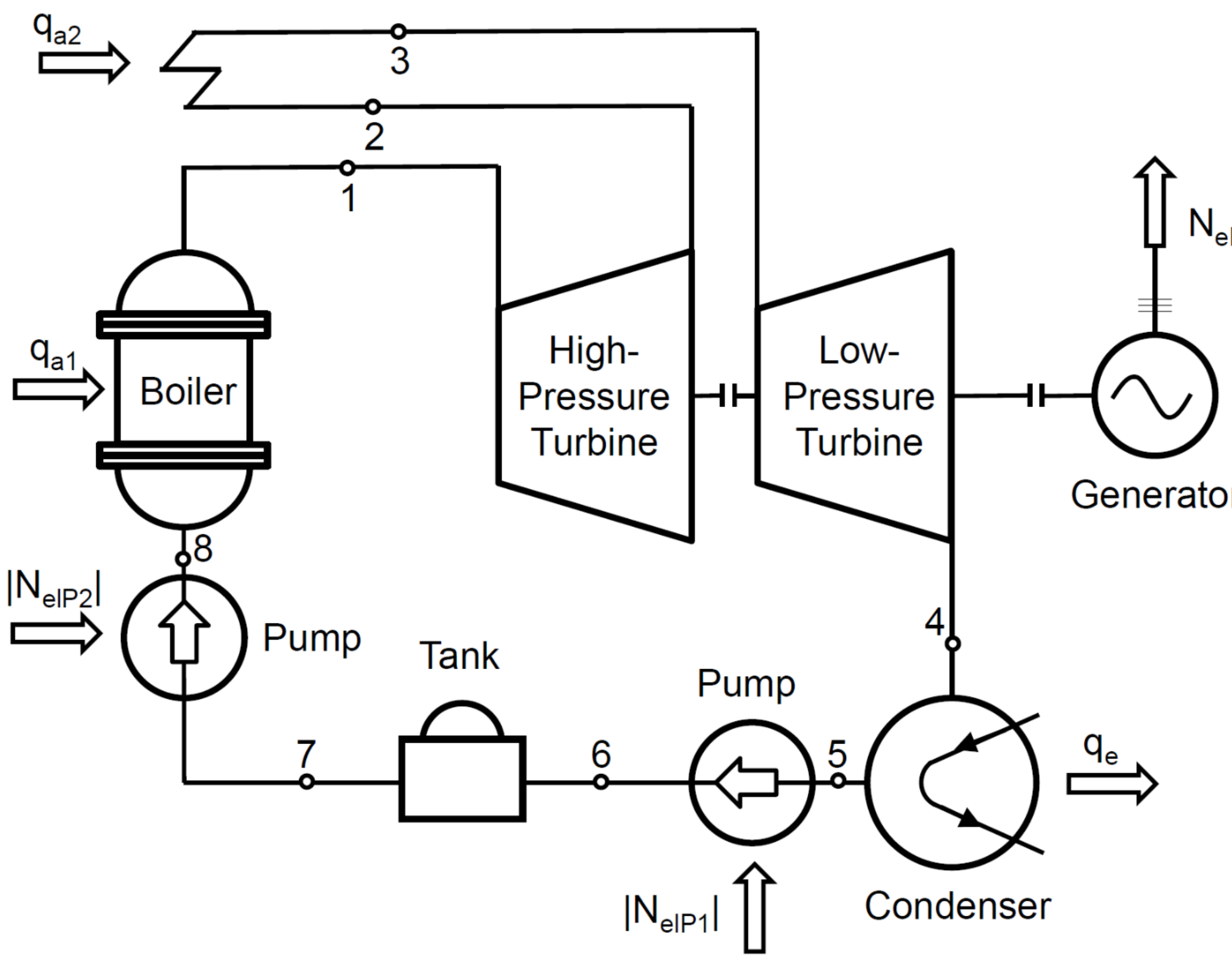
System Efficiency Improvement

- There are several methods to improve the over-all system efficiency

- Two most common are:
  - intermediate steam reheating
  - regeneration

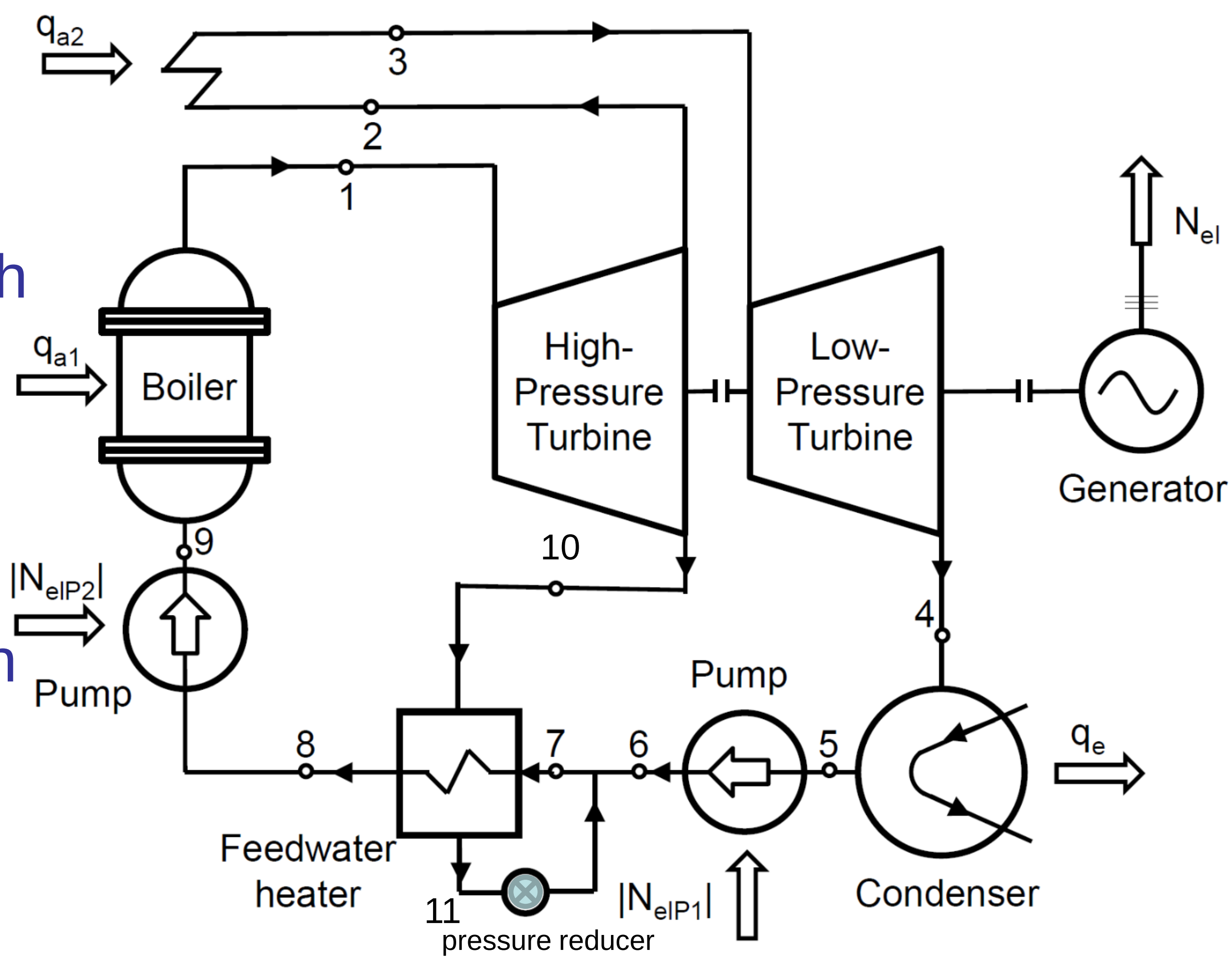
Intermediate Steam Heating

- Steam from high-pressure turbine returns to boiler for intermediate heating
- Superheated steam is then entering low-pressure turbine



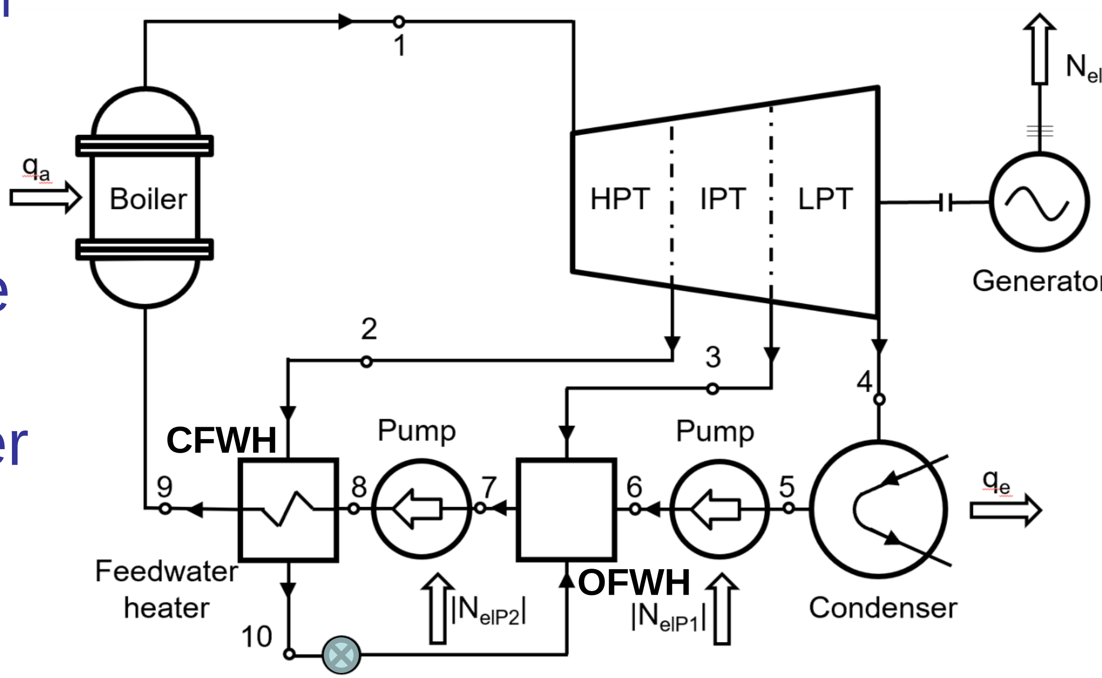
Regeneration (1)

- Steam from high-pressure turbine is passing through the feedwater heater
- Feedwater temperature increases when entering to the boiler



Regeneration (2)

- In modern systems with regeneration at least 7 regeneration stages are employed
- Two types of feedwater heaters are present:
  - Open feedwater heater (OFWH)
  - Closed feedwater heater (CFWH)
- In OFWH streams are directly mixed
  In CFWH heat transfer occurs through tube walls



Regeneration (3)

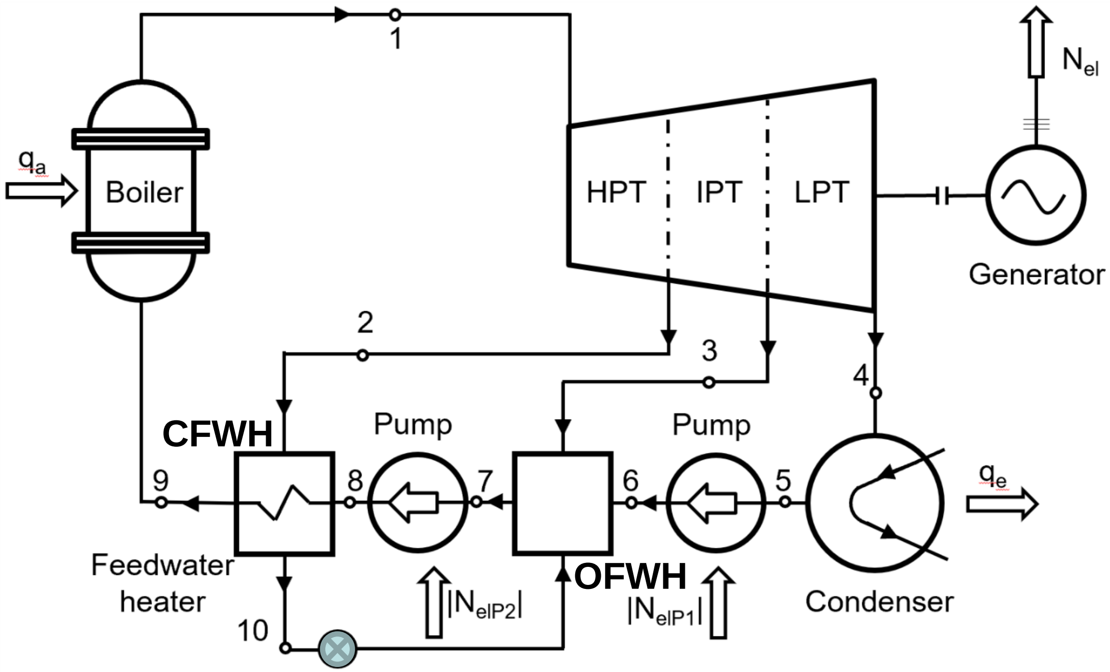
- For the system shown in the figure, the mass and energy conservation equations for CFWH are as follows:

$$W_9 = W_8, W_{10} = W_2 \qquad W_9 i_9 + W_{10} i_{10} = W_8 i_8 + W_2 i_2$$

- For OFWH, the equations are as follows:

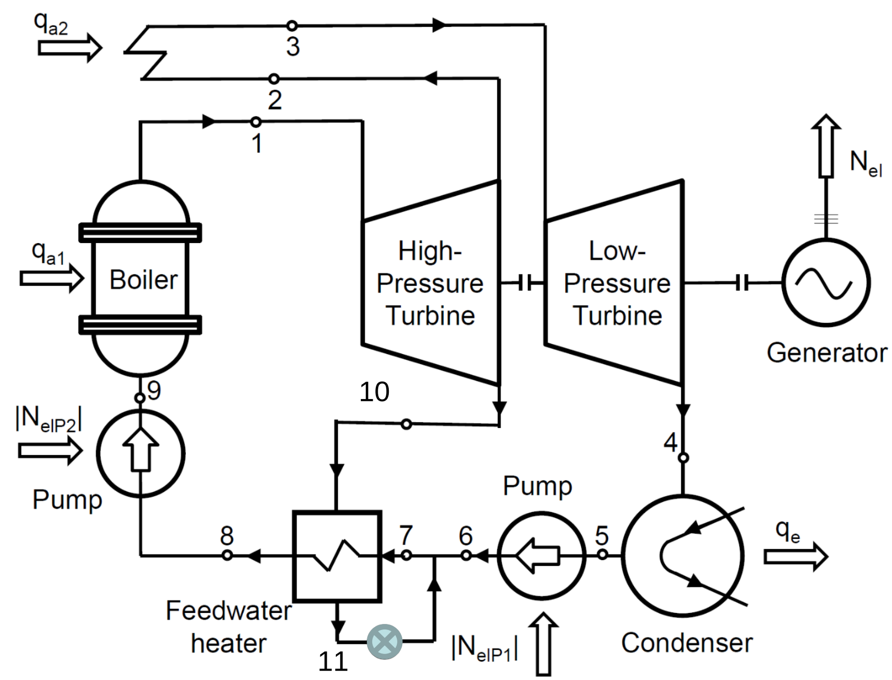
$$W_3 + W_6 + W_{10} = W_7$$

$$W_3 i_3 + W_6 i_6 + W_{10} i_{10} = W_7 i_7$$



System Modelling (1)

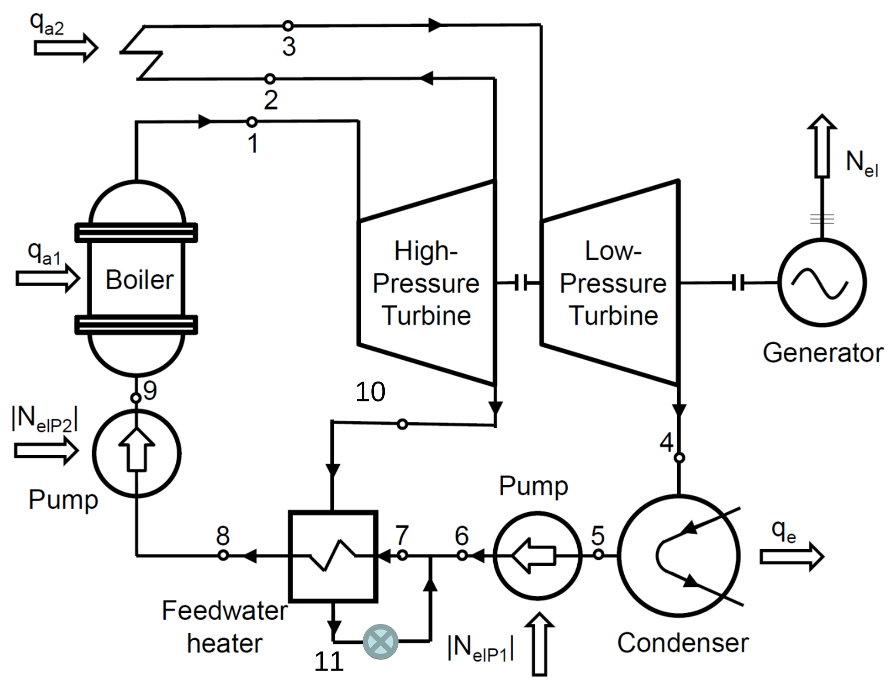
- The purpose of a system modelling is to find the plant efficiencies, mass flow rates and specific enthalpies at characteristic points of the cycle
- The given data include the required electrical power, steam pressures and temperatures at selected points, pump and turbine efficiencies, etc.



System Modelling (2)

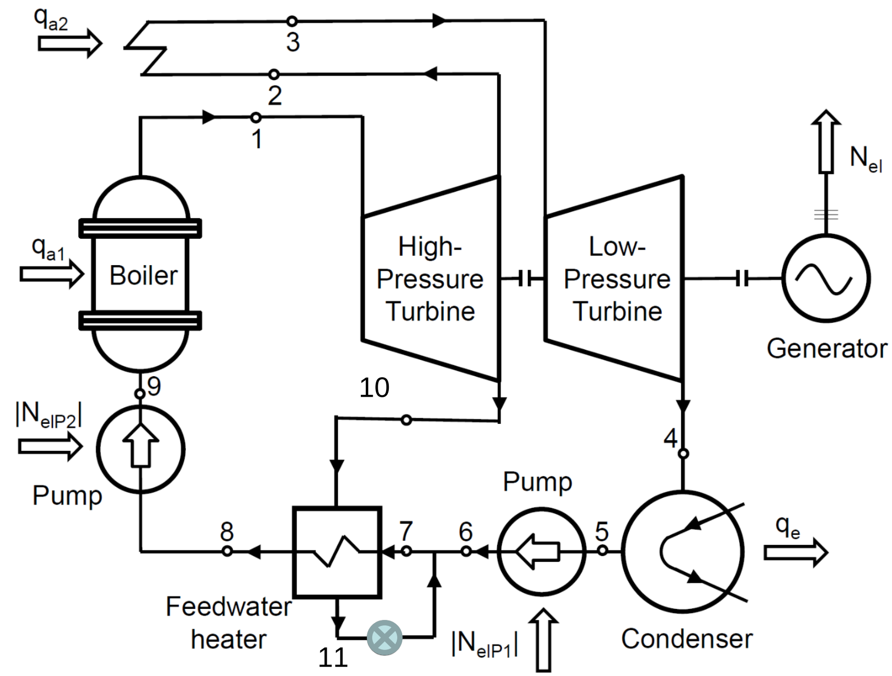
Assume the following data given:

N_{el} – electric power of generator
p_1, T_1 – pressure and temperature at 1
p_2 – pressure at 2
p_3, T_3 – pressure and temperature at 3
p_4 – pressure at 4
p_6 – pressure at 6
p_9 – pressure at 9
$\Delta T_{FWH}=T_8-T_7$ – temperature increase in FWH
ΔT_{sFWH}= stagnation temperature in FWH
η_{FWH} – efficiency of FWH
η_{iHPT}, η_{iLPT} – high- and low pressure turbine internal efficiencies
η_{iP} – pump internal efficiency
η_m – turbine mechanical efficiency
η_g – generator efficiency



System Modelling (3)

We write the mass and energy balance equations:



Turbines:

$$W_1 i_1 - W_2 i_2 - W_{10} i_{10} + W_3 i_3 - W_4 i_4 = \frac{N_{el}}{\eta_m \eta_g}$$

$$W_1 - W_2 - W_{10} = 0$$

$$W_3 - W_4 = 0$$

Feedwater heater:

$$W_7 \left(i_8 - i_7 \right) - W_{10} \left(i_{10} - i_{11} \right) \eta_{FWH} = 0$$

$$W_7 - W_8 = 0$$

$$W_{10} - W_{11} = 0$$

Condensate pump:

$$i_6 - i_5 - \frac{p_6 - p_5}{\rho_5 \eta_{iP}} = 0$$

$$T_6 = \mathrm{XSteam}('\mathrm{T\_ph}', p_6, i_6)$$

Feedwater pump:

$$i_9 - i_8 - \frac{p_9 - p_8}{\rho_8 \eta_{iP}} = 0$$

$$T_9 = \mathrm{XSteam}('\mathrm{T\_ph}', p_9, i_9)$$

System Modelling (4)

To close the system of equations, we determine specific enthalpies as:

$$i_1 = \mathrm{XSteam}('\mathrm{h\_pT}', p_1, T_1)$$

$$i_3 = \mathrm{XSteam}('\mathrm{h\_pT}', p_3, T_3)$$

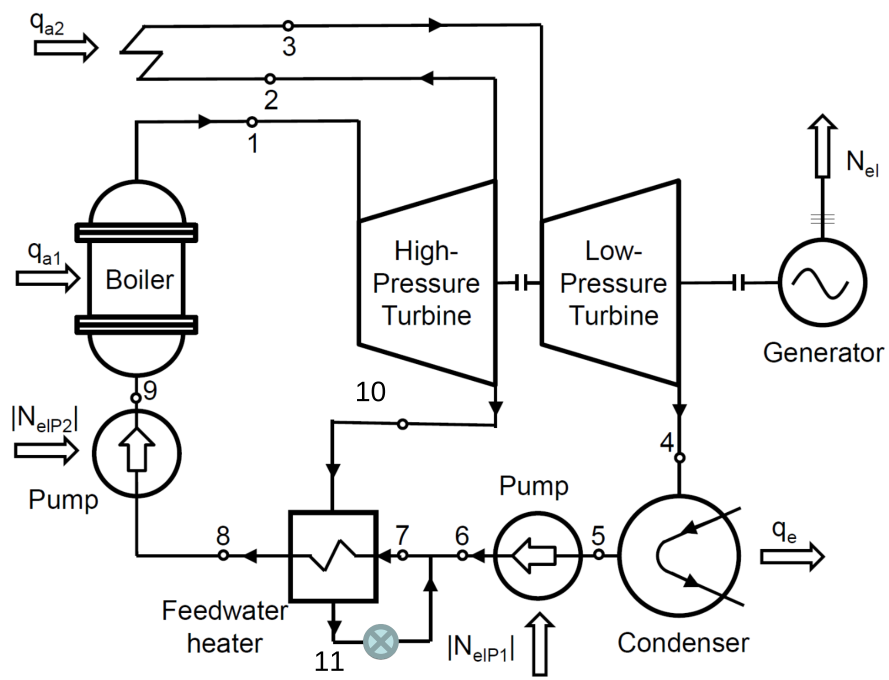
Specific enthalpy at the exit from the condenser can be found as:

$$i_5 = \mathrm{XSteam}('\mathrm{hL\_p}', p_5)$$

If the condensate is subcooled and its subcooling is known as ΔT_{cond}, we have:

$$i_5 = \mathrm{XSteam}('\mathrm{h\_pT}', p_5, T_{sat}(p_5) - \Delta T_{cond})$$

here $T_{sat}(p_5)$ is the saturation temperature at condenser pressure p_5.



Exit enthalpies from turbines are:

$$i_4 = i_3 - (i_3 - i_{4s})\eta_{iLPT} \qquad i_2 = i_1 - (i_1 - i_{2s})\eta_{iHPT}$$

$$i_{4s} = \mathrm{XSteam}('\mathrm{h\_ps}', p_4, s_3) \qquad i_{2s} = \mathrm{XSteam}('\mathrm{h\_ps}', p_2, s_1)$$

System Modelling (5)

The temperature downstream of the feedwater reheater (T_8) is found as:

$$T_8 = T_7 + \Delta T_{FWH}$$

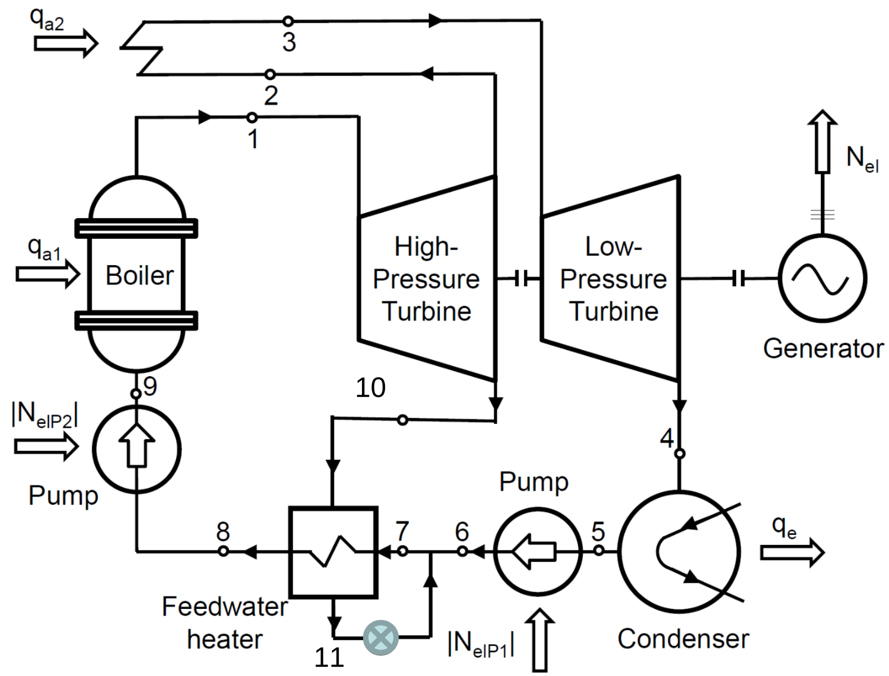
and the pressure:

$$p_8 = p_7 - \Delta p_{FWH}$$

Here we assume that the temperature increase and pressure drop over the feedwater heater are known.
Now, the specific enthalpy at 8 is:

$$i_8 = \mathrm{XSteam}('\mathrm{h\_pT}', p_8, T_8)$$

Additional balance equations can be written for mixing of streams 11 and 6:



$$W_{11} i_{11} + W_6 i_6 - W_7 i_7 = 0$$

$$W_{11} + W_6 - W_7 = 0$$

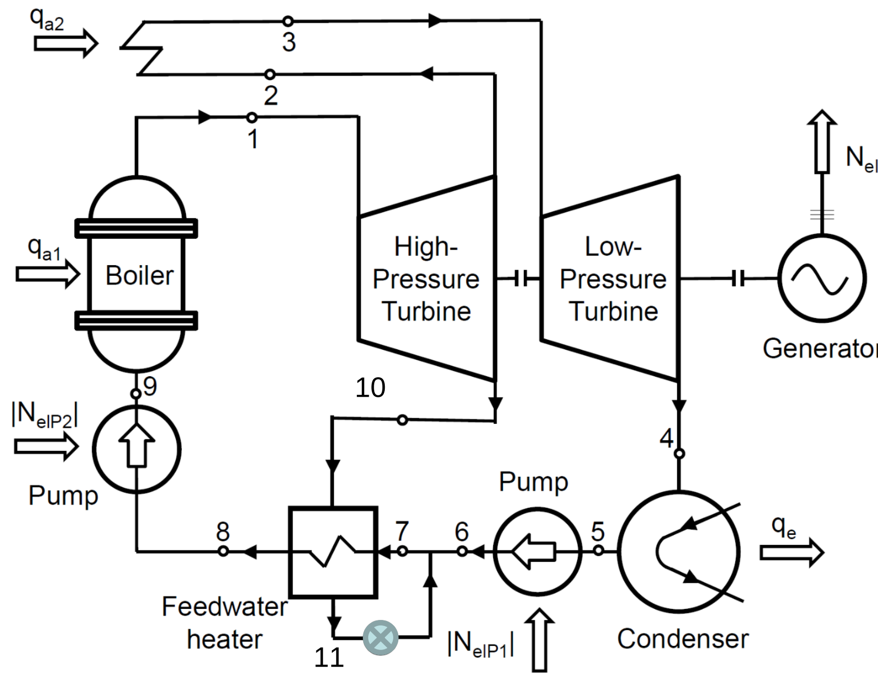
System Modelling (6)

The pressure of the stream used for the regeneration (p_{10}) can be established using the following consideration:

We assume that this pressure should be equal to the saturation pressure based on the temperature T_8 (downstream FWH) + the stagnation temperature ΔT_{sFWH} :

$$p_{10} = \mathrm{XSteam}('\mathrm{psat\_T}', T_8 + \Delta T_{sFWH})$$

NOTE: in actual calculations we should include pressure losses in pipes as well, since it will affect the plant efficiency.

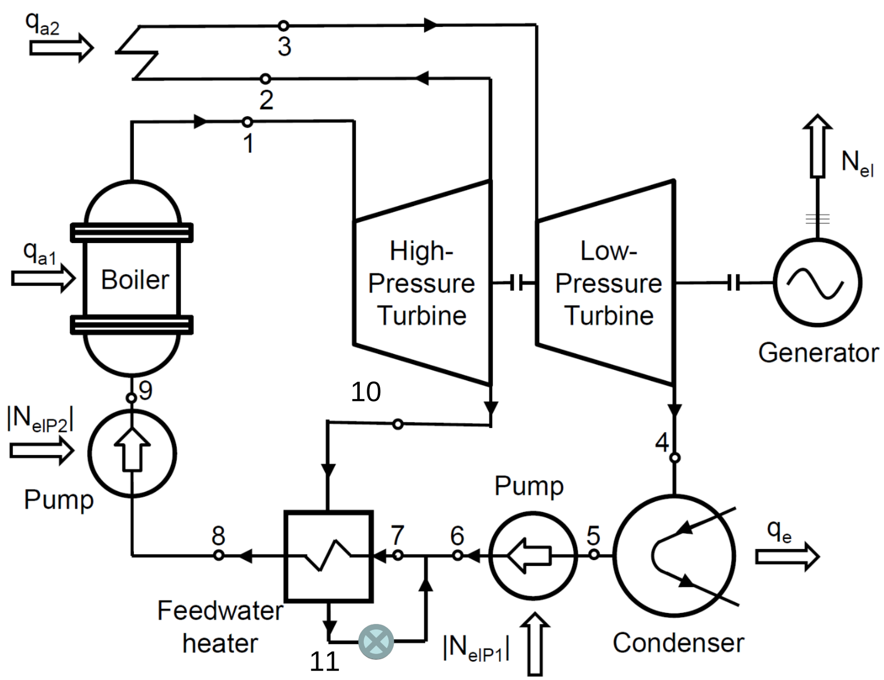


System Modelling (7)

The balance equations lead to the following system of equations:

$$\mathbf{A} \cdot \mathbf{X} = \mathbf{Y}$$

where **X = [W$_1$, W$_2$, ..., W$_n$]^T** is a vector of unknown mass flow rates, **Y** is a vector of known terms on right-hand sides of balance equations and **A** is a matrix of know equation coefficients. The current system of equations is:



$$\begin{bmatrix} i_1 & -i_2 + i_3 - i_4 \\ i_{11} - i_7 & i_6 - i_{11} \end{bmatrix} \cdot \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} = \begin{bmatrix} N_{el} / \left(\eta_m \eta_g \right) \\ 0 \end{bmatrix}$$

After the system of equations is solved and flow rates are found, the plant efficiencies can be found

Current Development

- Current development trend is to significantly increase the parameters (pressure and temperature) of the working fluid leaving the boiler, including transition to supercritical and ultra-supercritical pressures

	Main Steam Pressure, MPa	Main Steam Temperature, °C	Reheat Steam Temperature, °C
Subcritical	< 22.1	Up to 565	Up to 565
Supercritical	22.1 - 25	540 - 580	540 - 580
Ultra-supercritical	> 25	> 580	> 580

Progress in Material Technology

- Recent progress in material engineering currently allows to have the following steam parameters:
  - main steam pressure and temperature: 27-29 MPa, 570-580(600) °C
  - reheat temperature: 610(620) °C
- The corresponding energy efficiency can be as high as 44-46% (with cooling towers) or 46-47% (cooling with sea water)
- It is expected that recent development (usage e.g. of Inconel alloy) will allow pressures 35 – 37.5 MPa and temperatures 700(720) °C. The efficiency will then increase up to 52-55%.

Additional Improvements

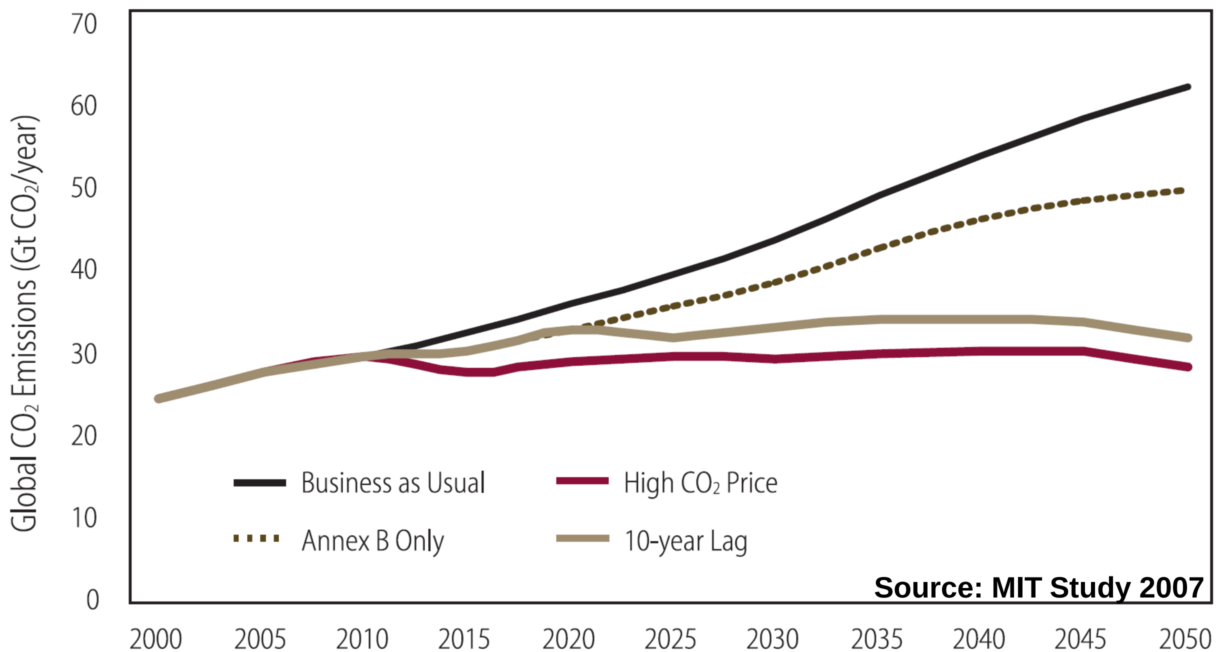
- Additional improvements include:
  - secondary reheat
  - higher efficiency of turbines
  - reduction of pressure losses and power for own needs
  - reduction of exhaust gas losses
  - Usage of fluidized bed combustion (FBC) and pressurized FBC (PFBC)
  - usage of pulverized coal-fired boilers
  - usage of co-generation and tri-generation

CO_2 Capture and Sequestration

- CO_2 emission from thermal power plants, in particular coal-fired ones, is the most important issue for future development
- To reduce the emissions, several measures are undertaken
  - by regulation, introducing a carbon charge imposed on CO_2 emissions
  - by technology, introducing systems that allow CO_2 capture and sequestration (CCS) ⇨
- In the interdisciplinary study performed at MIT in 2007 it is concluded that coal will be in significant use in 2050, irrespective of the implemented measures (ISBN 978-0-615-14092-6)

CO_2 Capture and Sequestration

- The same study suggests that, if CCS is successfully adopted, utilization of coal likely will expand even with stabilization of CO_2 emissions.



CO_2 emissions as predicted under various scenarios

High-CO_2-price scenario leads to a stabilized CO_2 emission

500 MWe Plant without CCS

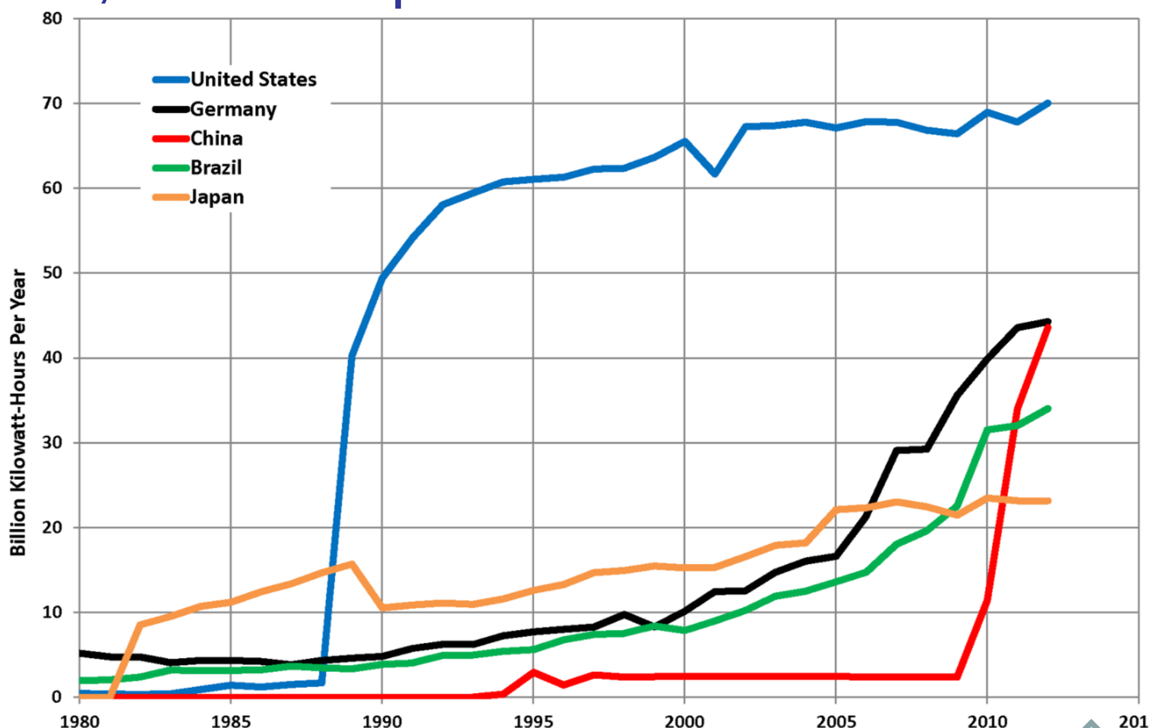
500 MWe Plant with CCS

Appendix

- Additional material that is linked to the presentation follows

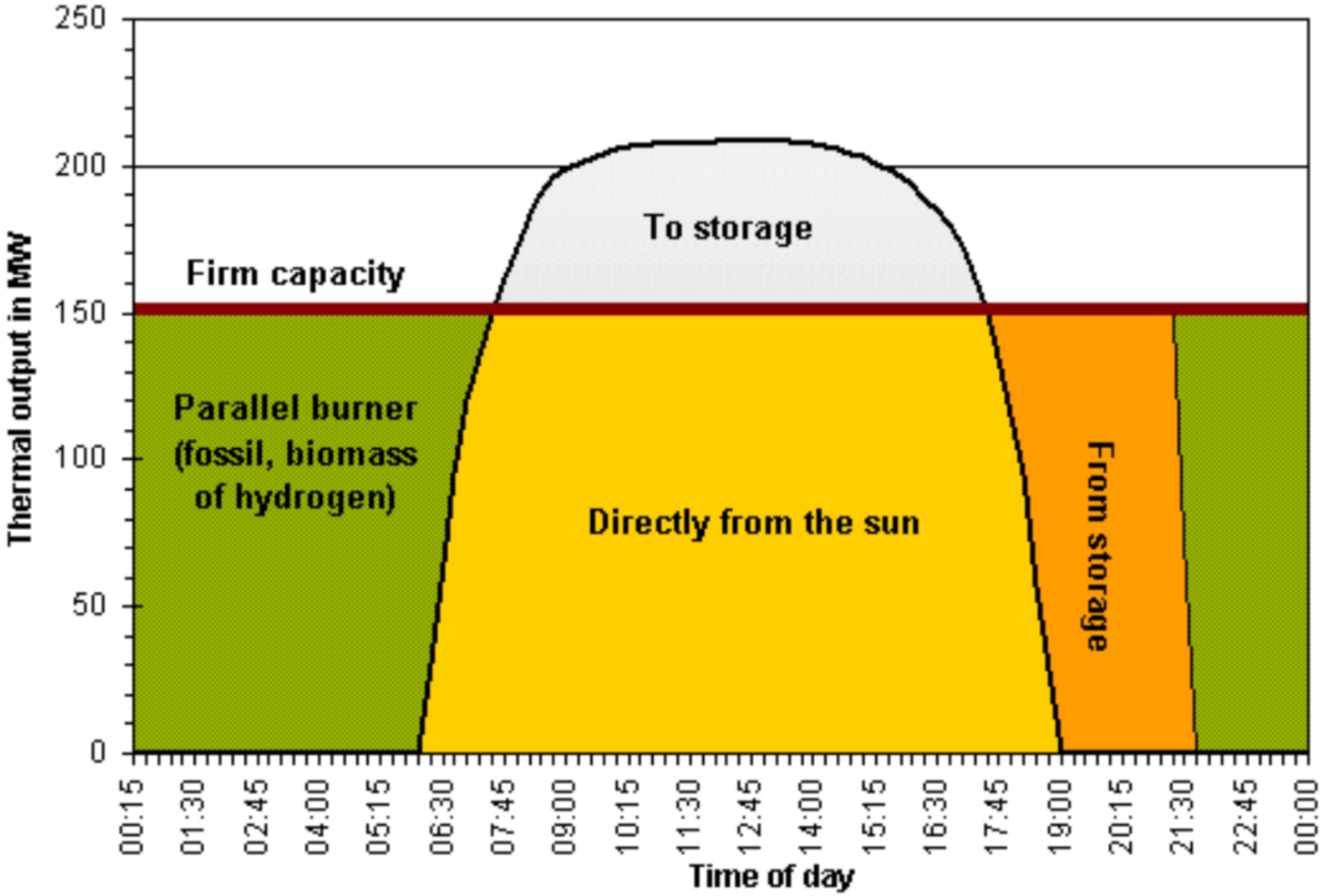
Biomass Electricity Production

- Burning biomass releases carbon emissions, but has been classed as a renewable energy transformation system by EU and UN, because plant stocks can be replaced with new growth

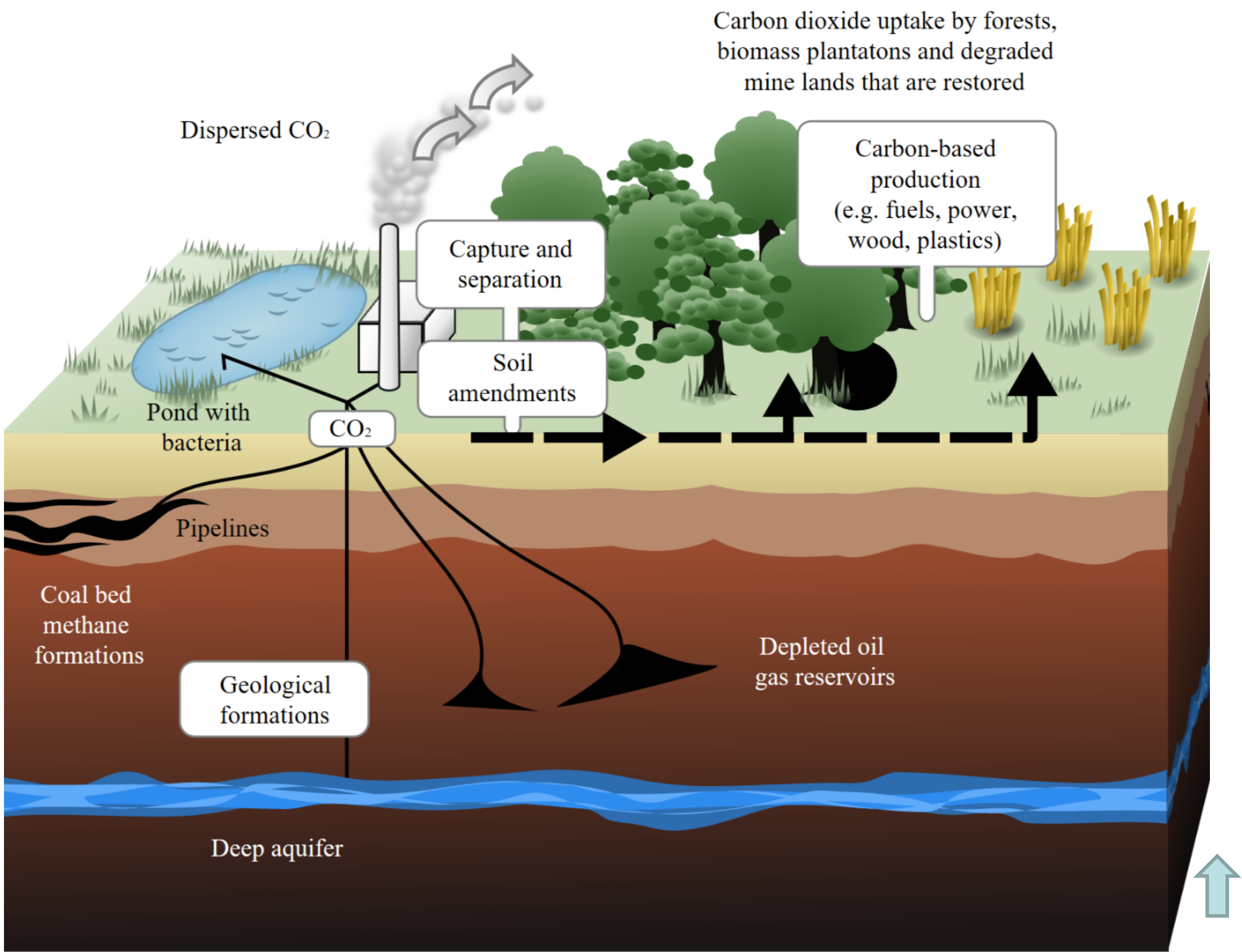


Top-five countries using biomass for electricity production

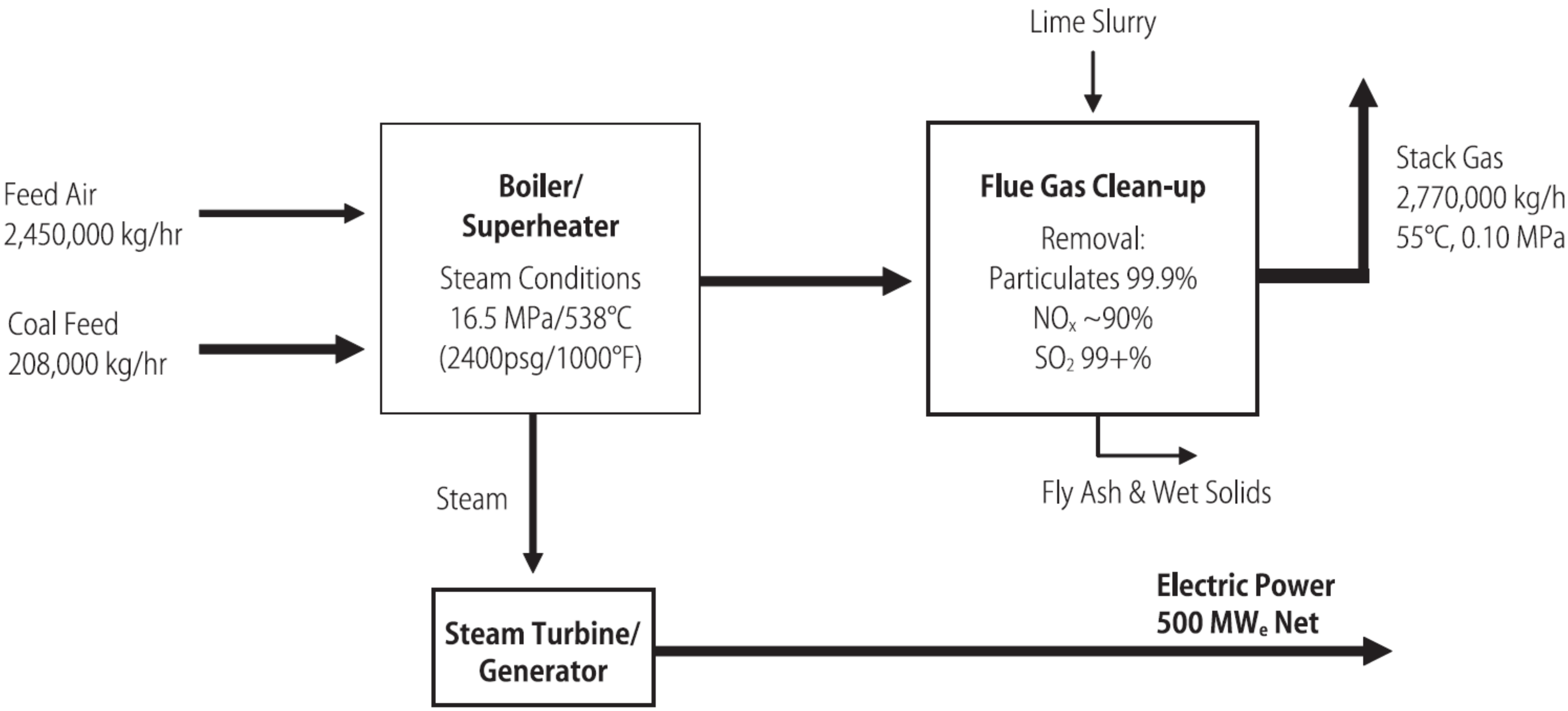
Solar Thermal Power with Storage



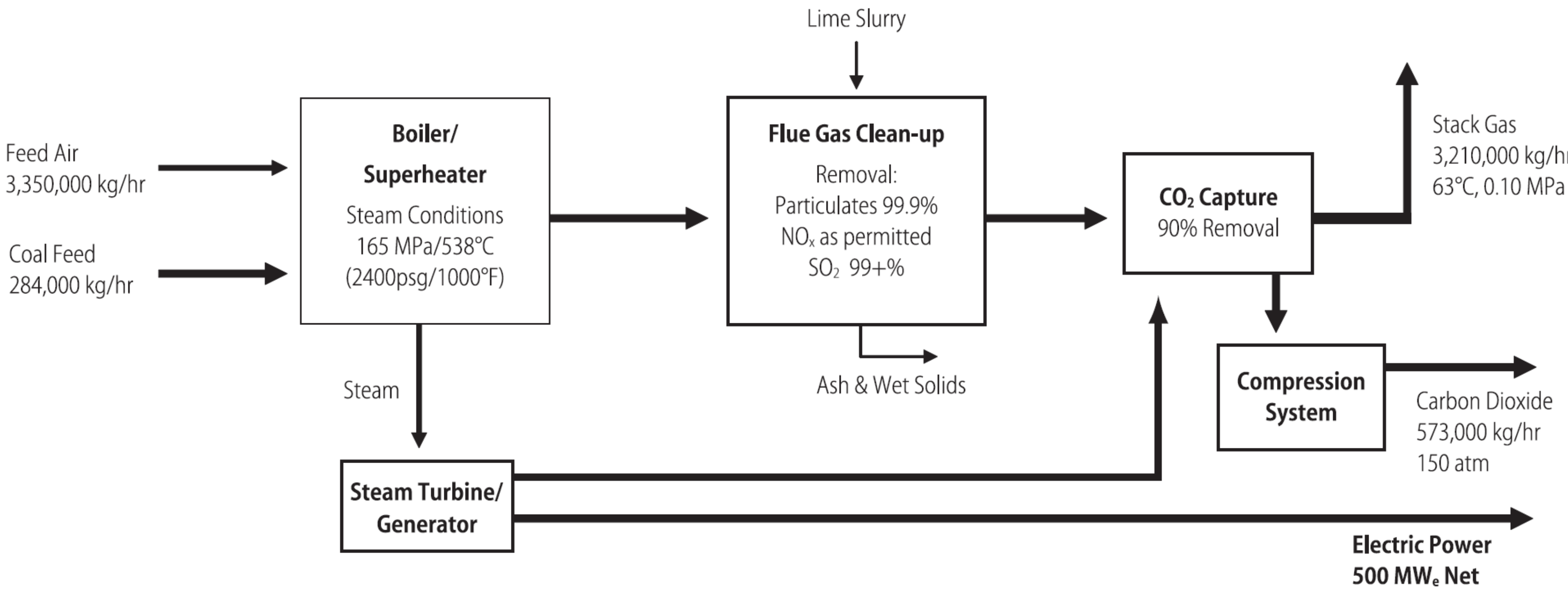
Expected output of a solar thermal power plant with two-hour thermal storage and backup heater on a sunny day


Carbon dioxide uptake by forests, biomass plantatons and degraded mine lands that are restored
Dispersed CO₂
Capture and separation
Carbon-based production (e.g. fuels, power, wood, plastics)
Soil amendments
Pond with bacteria
CO₂
Pipelines
Coal bed methane formations
Geological formations
Depleted oil gas reservoirs
Deep aquifer

500 MWe Pulverised Coal Unit without CCS



500 MWe Pulverised Coal Unit with CCS



The efficiency due to CCS drops from 34.3 to 25.1 %. The primary factors in efficiency reduction associated with addition of CO_2 capture are: thermal energy needed for CO_2 recovery (5 percentage points), energy required to CO_2 compression from 0.1 MPa to 15 MPa (3.5 percentage points)