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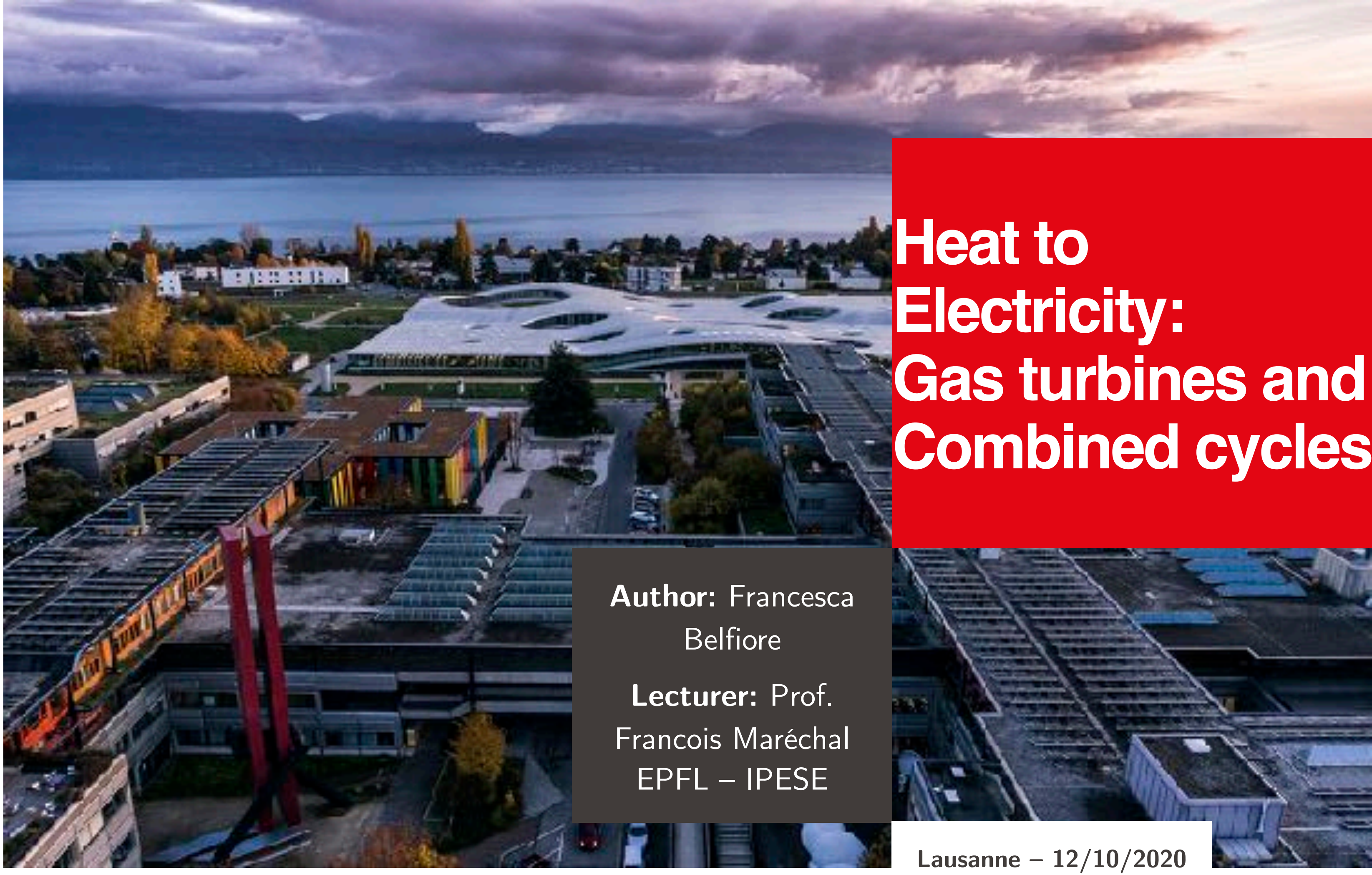

Heat to Electricity: Gas turbines and Combined cycles

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Outline

- **Gas Turbine**
  - Thermodynamic cycle
  - Advanced Gas Turbines
  - Classification
- **Combined Cycle Gas Turbine**
  - Working principle
  - Main components
  - Efficiency
- **GT and CCGT in the market**
  - Application
  - Levelized Cost Of Electricity (LCOE)
- **Take-home message**

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Introduction

Historical background

Thermodynamic overview

Basics and advanced

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EPFL gas turbine

- ME building
- Most likely used in the years 1949-1959 in the Weinfelden power plant
- Used as musical instrument

Gas turbine

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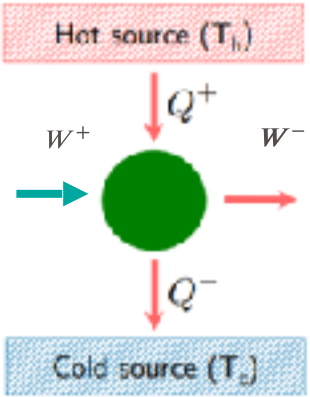
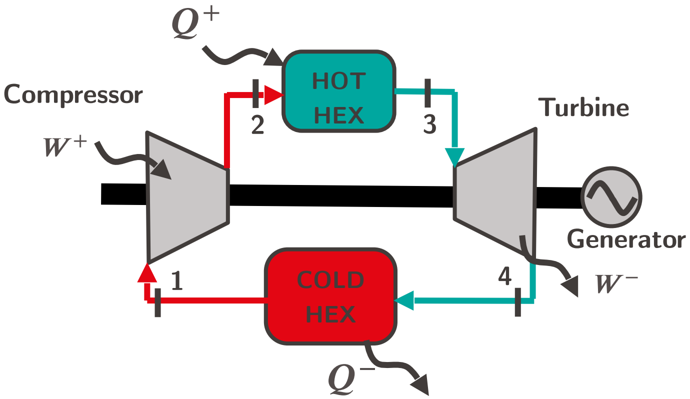
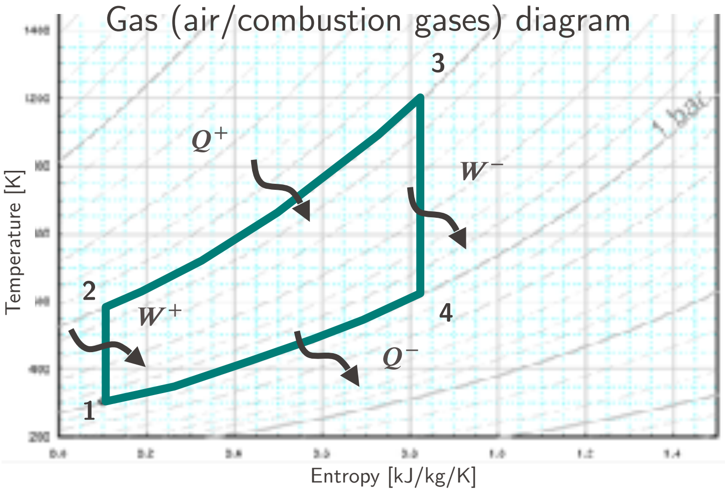
Gas Turbine : Brayton Cycle

Ideal closed gas-cycle



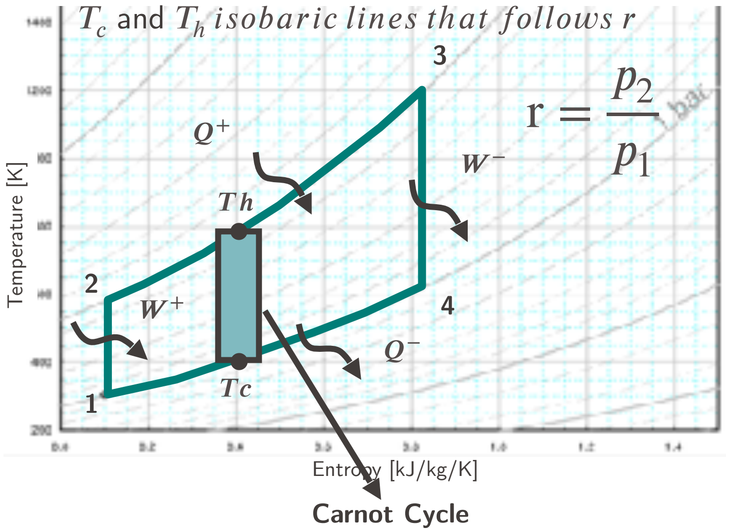


(1-2) isentropic compression
(2-3) isobaric heating
(3-4) isentropic expansion
(4-1) isobaric cooling



Brayton Cycle

Ideal closed gas-cycle



η depends on :

ONLY r and γ, ~~NOT~~ T_c ~~nor~~ T_h

Efficiency:

$$\eta = \frac{W^- - W^+}{Q^+} = \frac{w^- - w^+}{q^+}$$

The cycle can be divided in infinitesimal ideal Carnot cycles, whose efficiency is known:

$$\eta = \frac{1}{q^+}\int_2^3 de = \frac{1}{q^+}\int_2^3 dq^+\left(1 - \frac{T_c}{T_h}\right)$$

Carnot cycle efficiency

Isentropic process of ideal gas $pv^{\gamma} = const.$ and $pv = nRT$

$$\text{if } r = \frac{P_2}{P_1} \text{ then } \frac{T_c}{T_h} = r^{-\frac{\gamma-1}{\gamma}} = r^{-\theta}$$

$$\text{therefore } \eta = \frac{1}{q^+}\int_2^3 dq^+\left(1 - r^{-\theta}\right) = 1 - r^{-\theta}$$

Gas Turbine
Ideal closed gas-cycle

Specific work:

$w_{net} = w^{-} - w^{+} = \eta \cdot q^{+}$ and $q^{+} = cp(T_3 - T_2)$

with $r^{\theta} = \frac{T_2}{T_1}$, $q^{+} = cpT_1(\frac{T_3}{T_1} - \frac{T_2}{T_1})$ therefore

$$w_{net} = (1 - r^{-\theta}) \cdot cp \cdot T_1 \cdot (\frac{T_3}{T_1} - r^{\theta})$$

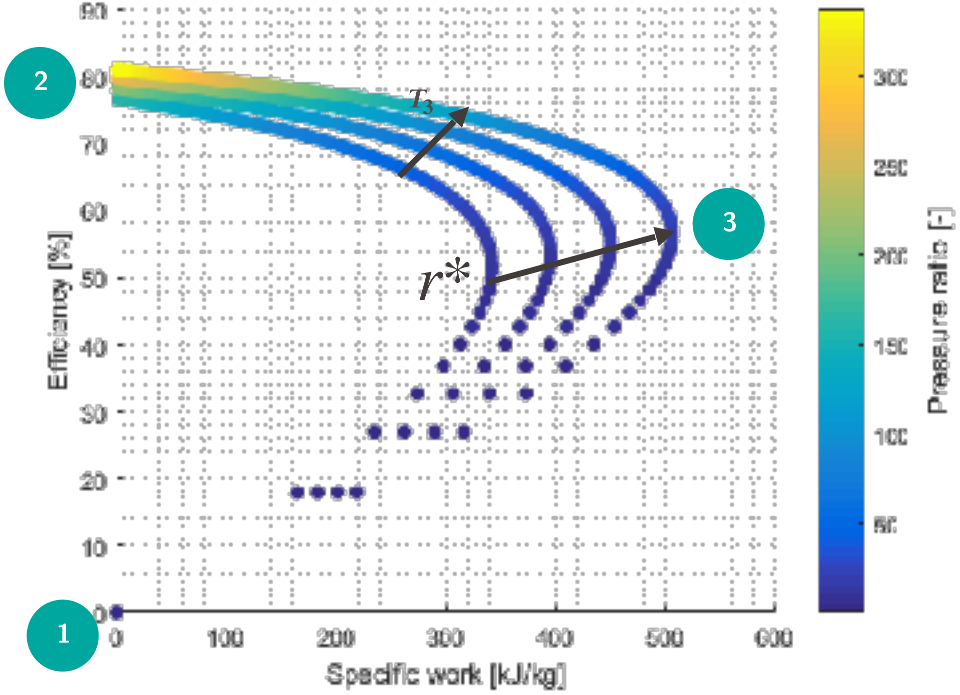
w_{net} depends on: T_1, T_3, r, fluid properties (γ, c_p).

1. $r = 1$ $\quad w_{net} = 0$, $\eta = 0$

2. $r = \left(\frac{T_3}{T_1}\right)^{\frac{1}{\theta}}$ $\quad w_{net} = 0$, $\eta = 1 - \frac{T_1}{T_3}$

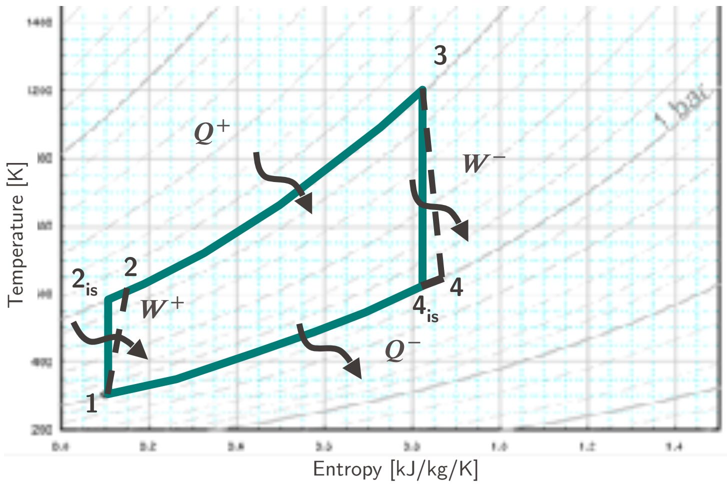
3. max w_{net} => $\frac{dw_{net}}{dr} = 0$ =>optimal pressure ratio : $r^* = (\frac{T_3}{T_1})^{\frac{1}{2\theta}}$

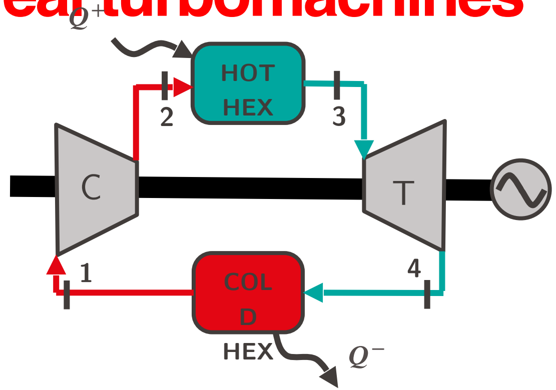
η as a function of w_{net} for different T_3



Gas Turbine

Closed gas cycle with real turbomachines





$$\eta_{iso,T} = \frac{w_T}{w_{Tis}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4is})}$$

$$\eta_{iso,C} = \frac{w_{Cis}}{w_c} = \frac{c_p(T_{2is} - T_1)}{c_p(T_2 - T_1)}$$

$$w = w^- - w^+ = c_p(T_3 - T_{4is}) \cdot \eta_{iso,T} - \frac{c_p(T_{2is} - T_1)}{\eta_{iso,C}}$$

$$\eta = \frac{w}{q^+} = \left[c_p(T_3 - T_{4is}) \cdot \eta_{iso,T} - \frac{c_p(T_{2is} - T_1)}{\eta_{iso,C}}\right] / c_p(T_3 - T_2)$$

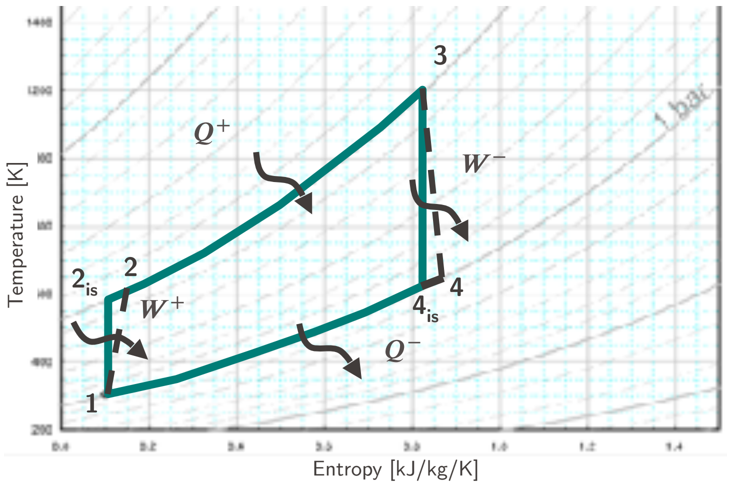
$$\eta = \frac{w}{q_{in}} = \eta_{\substack{ideal\\cycle}} \cdot \frac{\eta_{iso,T} - \frac{T_{2is}}{T_3} \cdot \frac{1}{\eta_{iso,C}}}{\left(1 - \frac{T_2}{T_3}\right)}$$

Assumptions:

- Perfect gas → c_p, c_v = const.
- Ideal HEX → dp=0
- Real turbomachines → $\eta_{iso,C} < \eta_{iso,T} < 1$

Gas Turbine

Closed gas cycle with real turbomachines

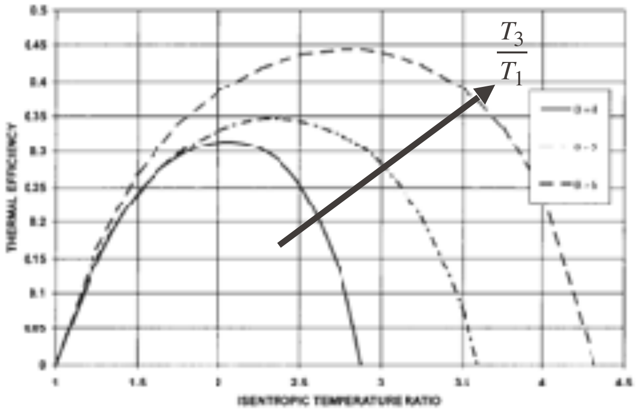


Remarks:

- Unlike the ideal cycle η does not constantly increase with r. There is a limit value for which $w^+ = w^-$ and η=0
- Unlike the ideal cycle, η depends on T_3/T_1

Assumptions:

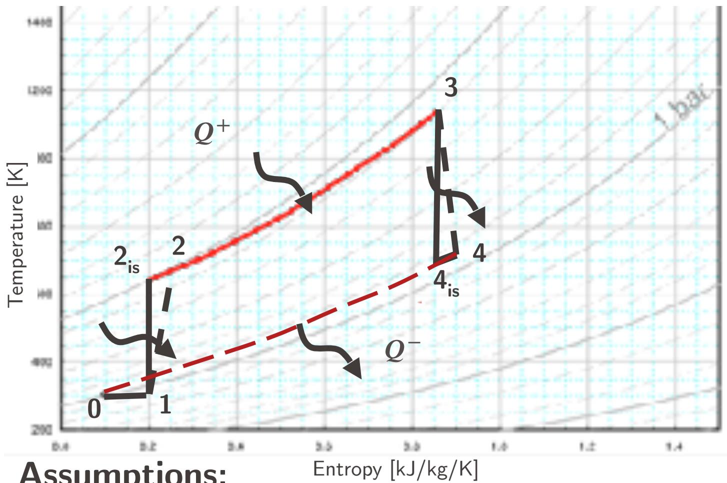
- Perfect gas → c_p, c_v = const.
- Ideal HEX → dp=0
- Real turbomachines → $\eta_{iso,T} < 1$ & $\eta_{iso,C} < 1$

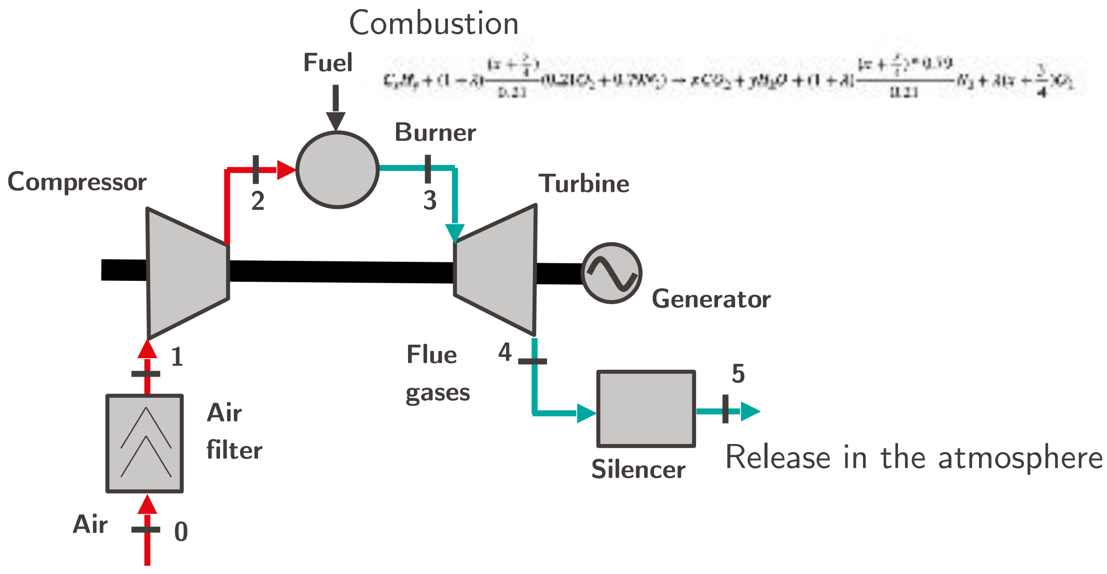


$$r^{\frac{\gamma-1}{\gamma}} = \frac{T_{2is}}{T_1}$$

Gas Turbine

Open real cycle





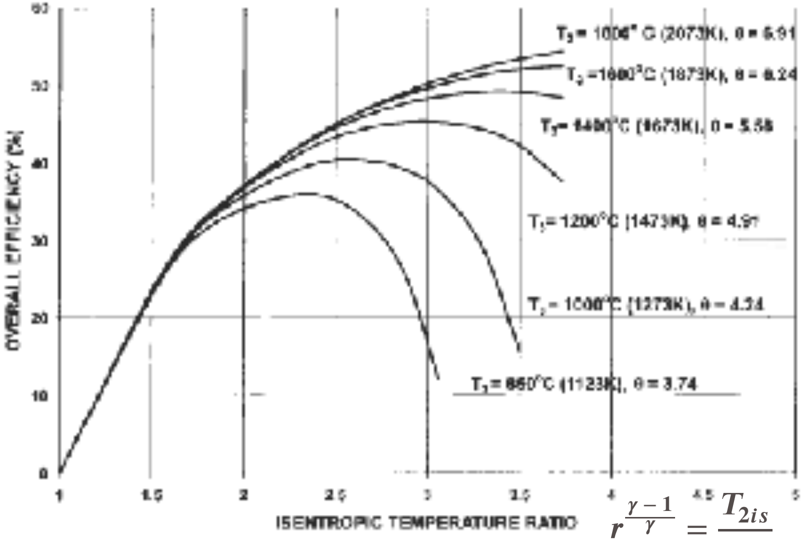
Assumptions:

- Real gas → c_p, $c_v \neq$ const.
- Different gases in compression and expansion
- Real burner → dp≠0
- Real turbomachines → $\eta_{iso,T} < 1$ & $\eta_{iso,C} < 1$

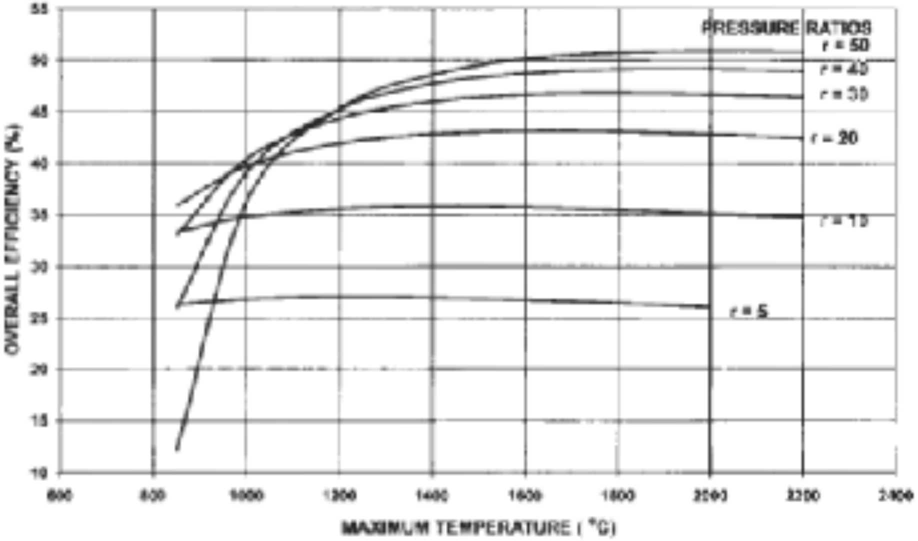
Assumptions:

- From external to internal combustion:
- **PROS:** NO HEX →↑ T_3 →↑ η -> blade cooling needed
- **CONS:** working fluid needs to carry an oxidant (typically air)
- Pressure drops in components (i.e. air filter, burner, silencer)

Gas Turbine : Open real cycle
Turbine inlet temperature is a key



$$r^{\frac{\gamma-1}{\gamma}} = \frac{T_{2is}}{T_1}$$



Assumptions:

- Polytropic efficiency for compressor and turbine $\eta_P = 0.9$
- Pressure loss fraction in combustion 0.03
- Fuel (methane) and air supplied at 1 bar and 27 °C

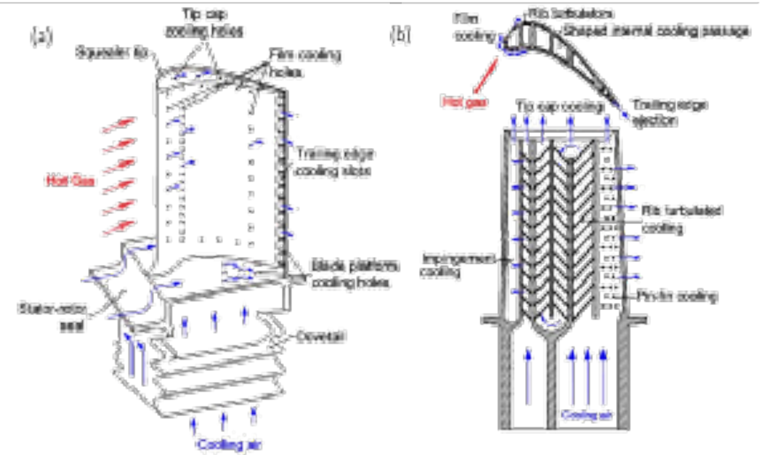
Optimal pressure ratio increases when T3max increases

Gas Turbine

Blade cooling to protect the turbine and increase the Turbine inlet temperature

- **Methodologies:**
  - **IMPINGEMENT:** air at high velocity creates turbulences next to the blade wall → h_i
  - **FILM COOLING:** air exits the blades through small holes and creates a film of cold air → h_g

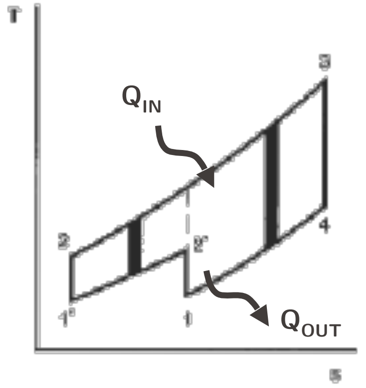
1. **OPEN LOOP:**
   - Air extracted from the compressor last stages is injected inside the small channels in the turbine blades and then mixed with the main flow
   - **Losses:**
     - Irreversibilities due to mixing process
     - Velocity triangle perturbated by mixing process
     - Portion of air following a low efficiency cycle
     - Turbine work decreased due to decreased T (v → $e_T = \int v \, dp$)
2. **CLOSED LOOP:**
   - Air after cooling the turbine is returned back to the combustion chamber
   - Possibility of choosing a different cooling fluid (SH steam)
   - Only impingement
   - **Losses:**
     - Additional compressor needed to balance pressure losses
     - Problem of safety: if the secondary compressor fails the turbine melts
     - No losses due to mixing or lower efficiency cycle

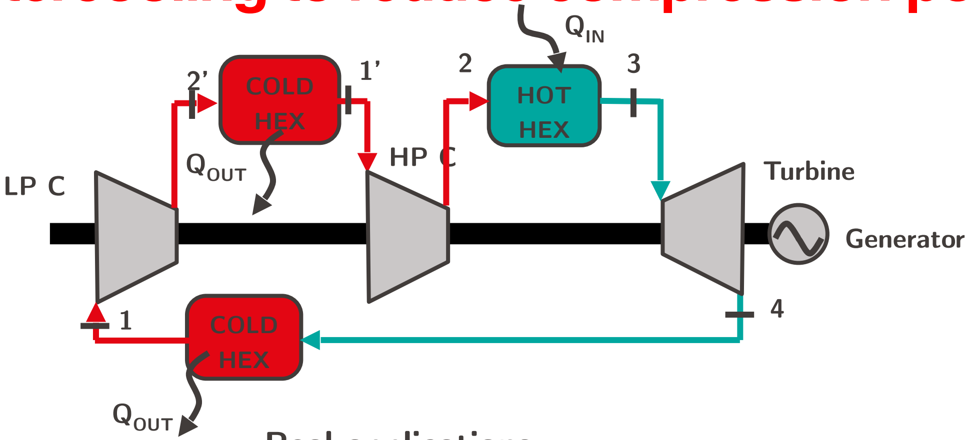


External (a) and internal (b) blade cooling schematic[1]

Gas Turbine

Advanced cycles - Intercooling to reduce compression power





Ideal cycle:

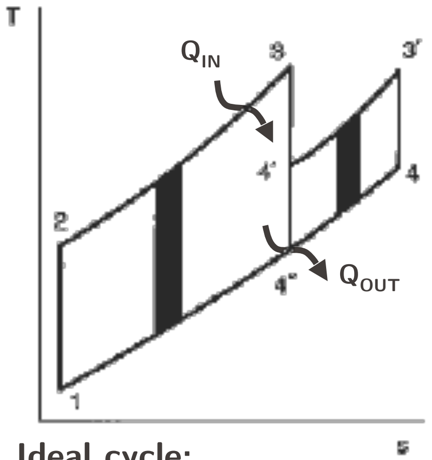
- The compression is split and intercooling introduced between a low pressure and a high pressure compressor
- Adding a cycle at lower efficiency: for the same r IC decreases η
- IC increases w because w_C decreases
- IC improves η if coupled with regeneration

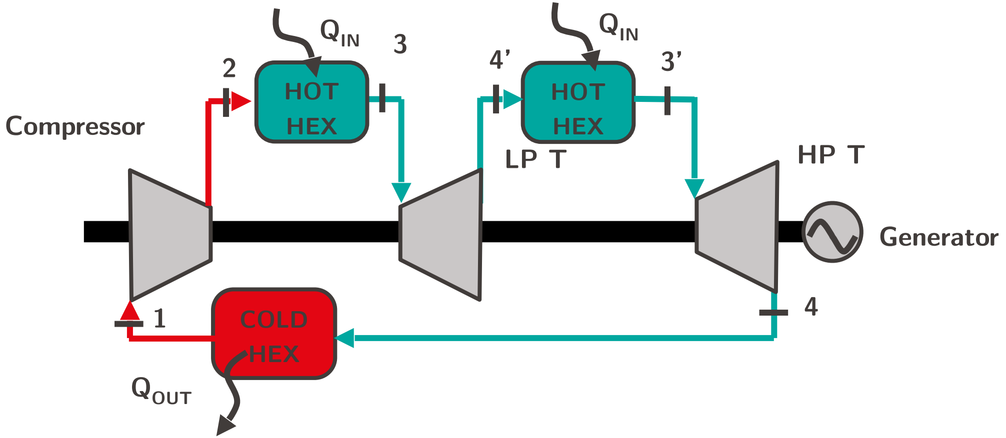
Real applications:

- IC improves w and slightly η
- IC decreases the weight of irreversibilities due to real turbomachines
- IC allows higher T_3 for the same material (colder cooling flows)

Gas Turbine

Advanced cycle - Reheating to maximise expansion efficiency





Ideal cycle:

- The expansion is split and reheating is introduced between a low pressure and a high pressure turbine
- Adding a cycle at lower efficiency: for the same r RH decreases η
- RH increases e because w_T increases
- RH improves η if coupled with regeneration

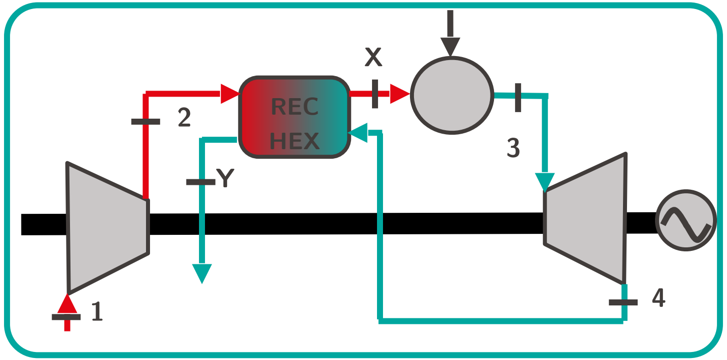
Real applications:

- increase w and slightly η
- decreases importance of irreversibilities due to real turbomachines

Gas Turbine

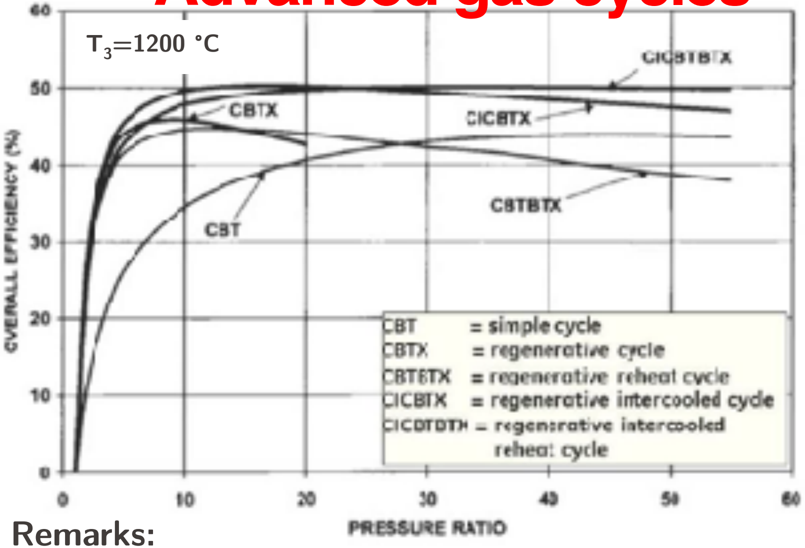
Advanced cycles regenerative cycle by heat recovery to optimise system efficiency

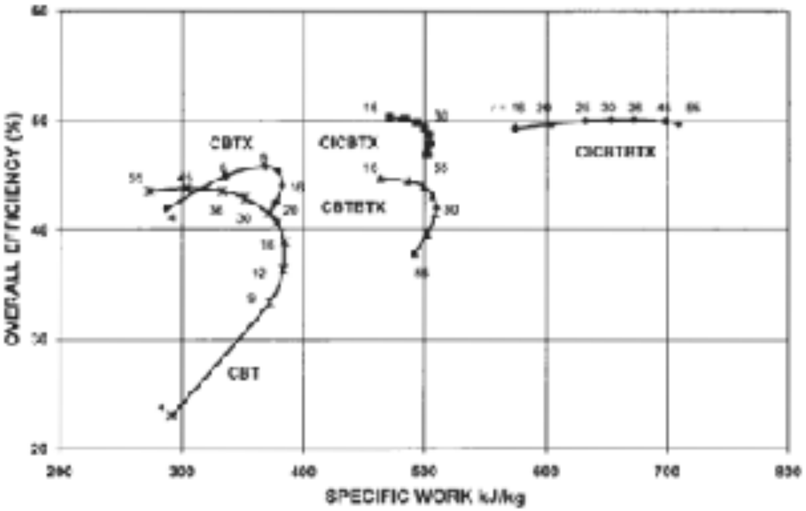
Reduce q^+ by heat recovery



Gas Turbine

Advanced gas cycles





Remarks:

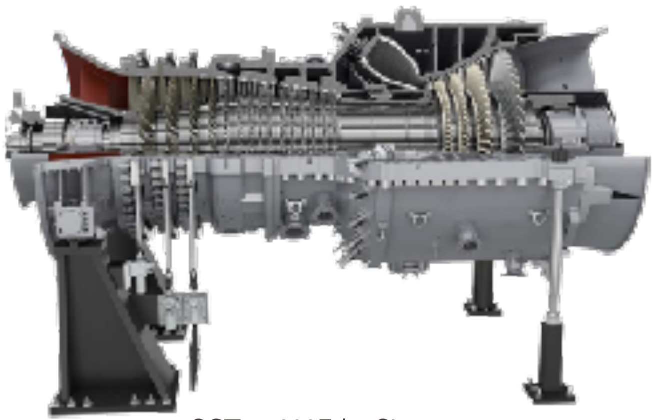
- Optimum r depends on type: simple cycle $\mathrm{r} \approx 45$, regenerative the lowest $\mathrm{r} \approx 9$
- Regeneration does not affect e_{net} but improves η for same r, specially at low r → small applications
- Substantial increase of e_{net} with RH and IC
- RH and IC improve η if combined with regeneration

Gas Turbine
Classification

- Heavy duty
- Aviation/propulsion
- Aeroderivative
- Small and microturbines

Gas Turbine
Heavy duty

- Usually designed for max work (e.g. $r \approx 15 \div 20$)
- Operation: base load, long/medium operating time
- Designed with no weight/space restrictions (heavy frame)
- Advantages: long life-time, medium/high efficiency (30 – 48 %)
- Often combined with a steam cycle in a CCGT (in this case $\mathrm{r} \approx 15 \div 20$ is optimal for turbine work and plant efficiency



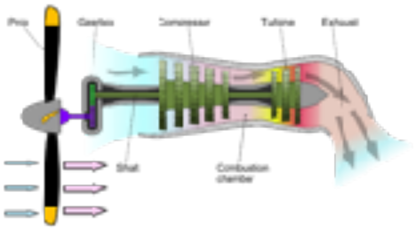
SGT5-4000F by Siemens

Performance:

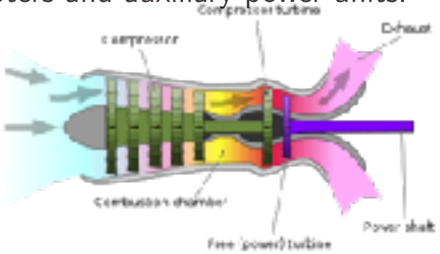
- E_{net} = 329 MW(e)
- $\eta = 41\%$
- $r \approx$ 20
- T3 =1200-1300 °C, T_4 = 600 °C

Gas Turbine
Aviation/propulsion

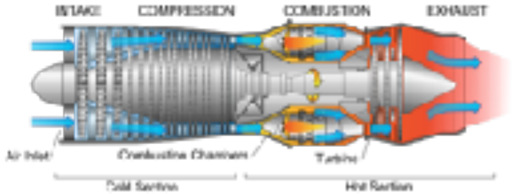
- **Turboprop**
  The turbine drives the compressor and the propeller. Civil airplanes



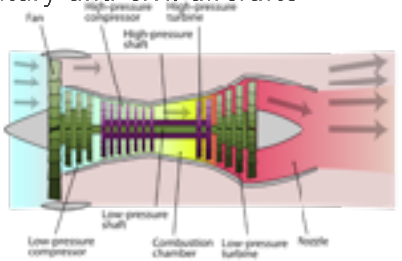
- **Turboshaft**
  Similar to turboprop with the difference that the engine drives a transmission and not the propeller directly. Helicopters and auxiliary power units.



- **Turbojet**
  Gas turbine and propelling nozzle. Replaced by turboprops and turbofan, still employed in cruise missiles due to high exhaust speed, small frontal area and simple design.

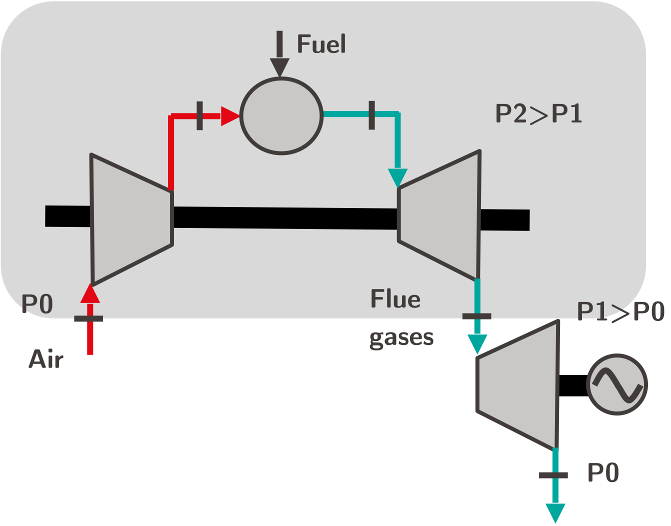


- **Turbofan**
  It is a turbojet that drives a ducted fan to improve the thrust. Military and civil aircrafts



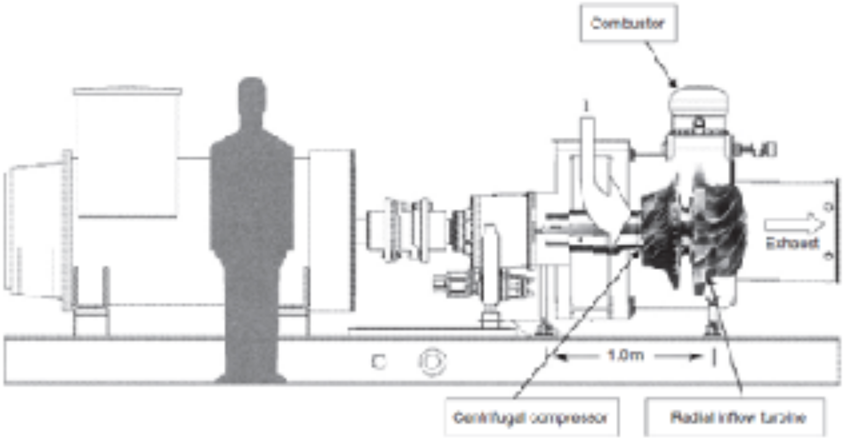
Gas Turbine
Aeroderivative

- Origin in the aerospace industry afterwards adapted to electricity generation
- Propelling nozzle is removed and a power turbine added
- Advantages: quickly start-up, shut down and load changes
- Operation: peak load, low operating time
- Marine industry to reduce weight



Gas Turbine
Small and microturbine

- Small: < 5 MW Micro: <350 kW
- No blade cooling → limited turbine inlet T → lower efficiency (18-23 %)
- Often single-stage centrifugal compressor and radial-inflow turbine (low efficiency)



A radial-inflow turbine

Gas turbine efficiencies

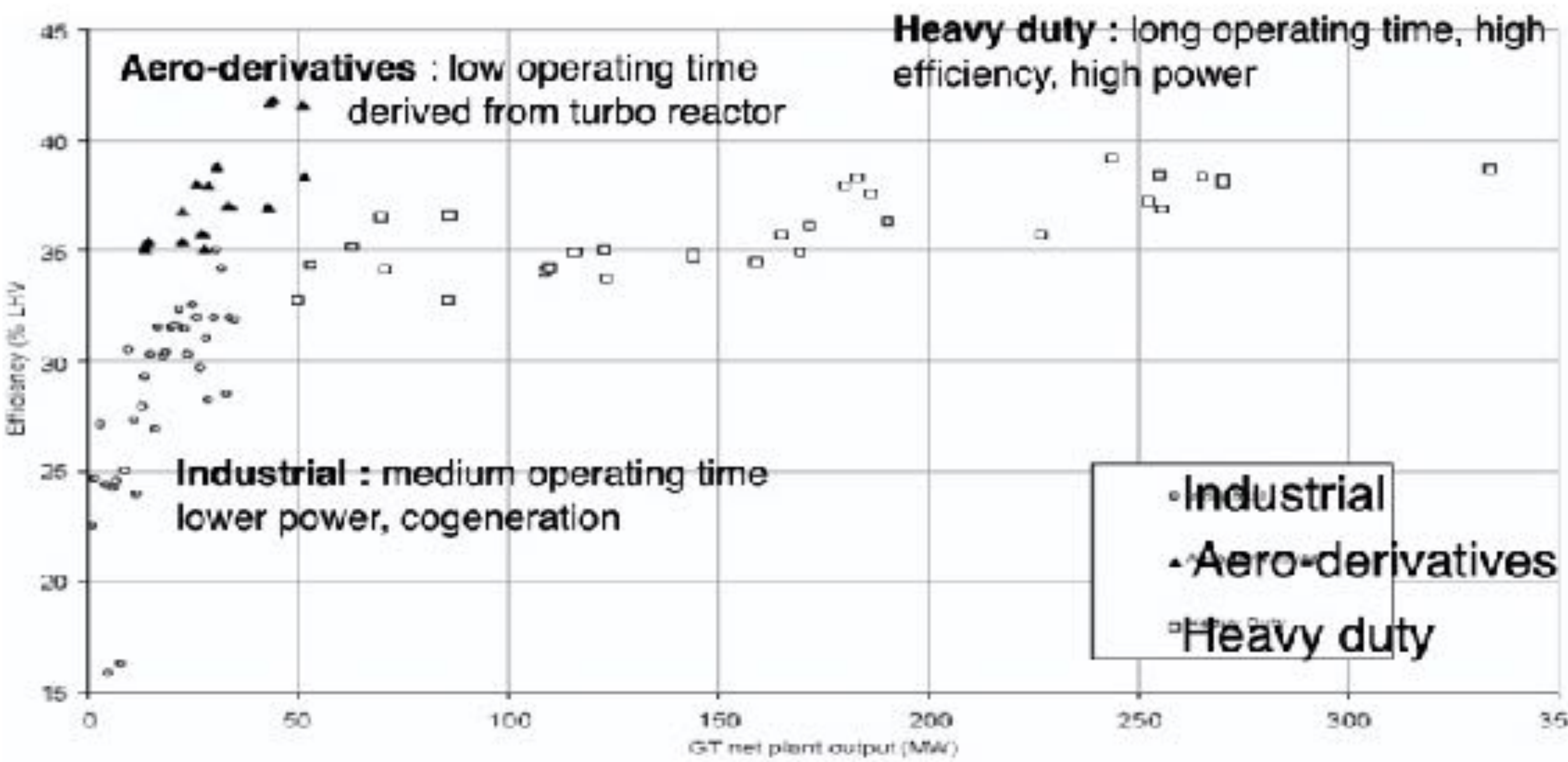


Fig. 3.4. Current efficiency of gas turbines (Source: *Gas Turbine World, 1996-2001*)

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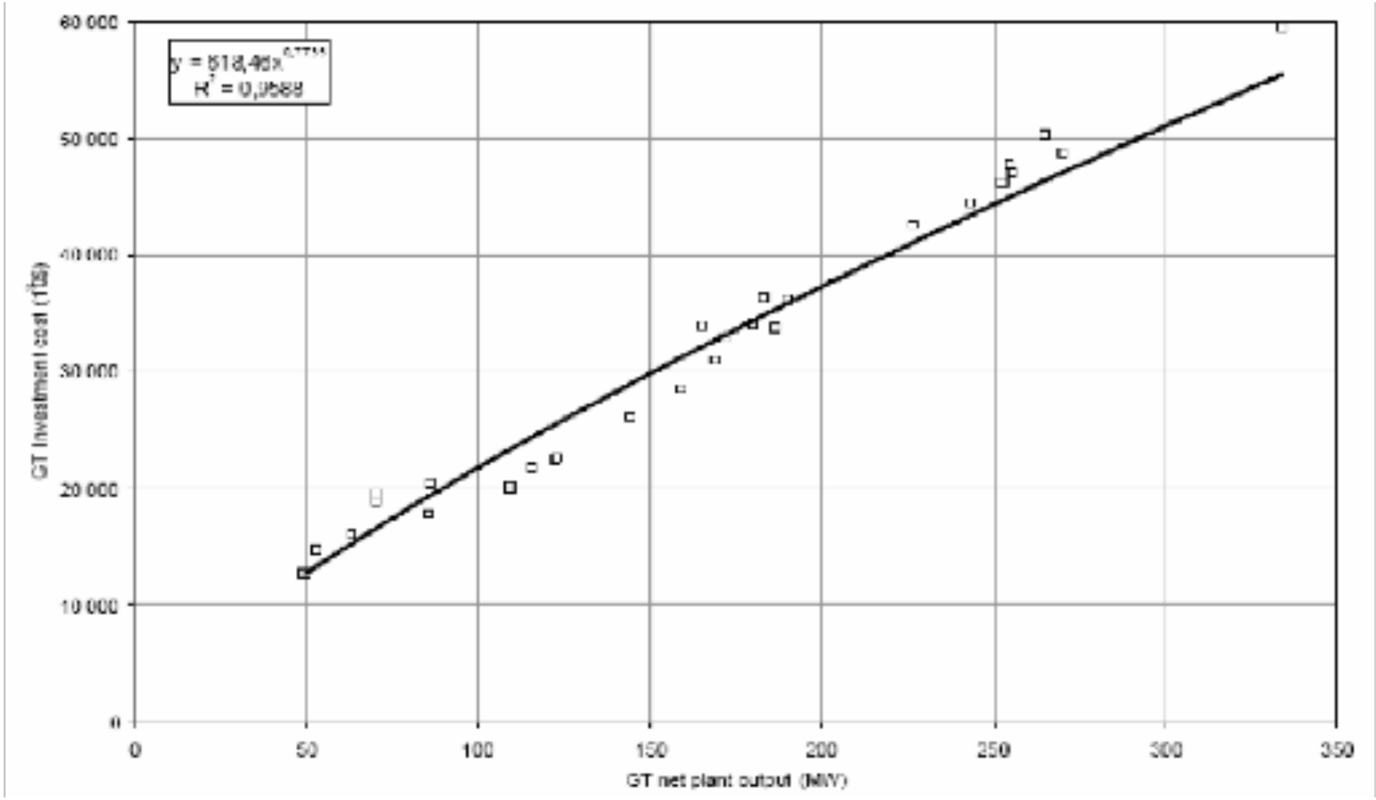
Gas turbine costs

Investment cost (k$ year : 2000)= 618.48 $(MWe)^{0.7}$



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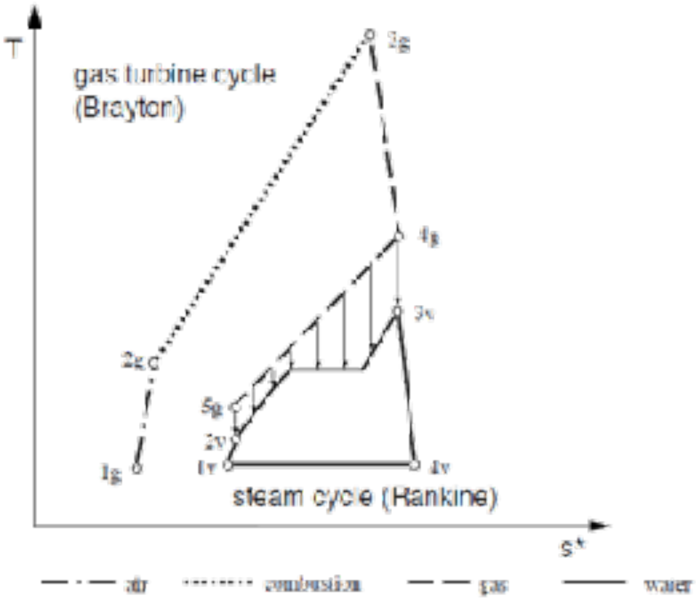
CCGT

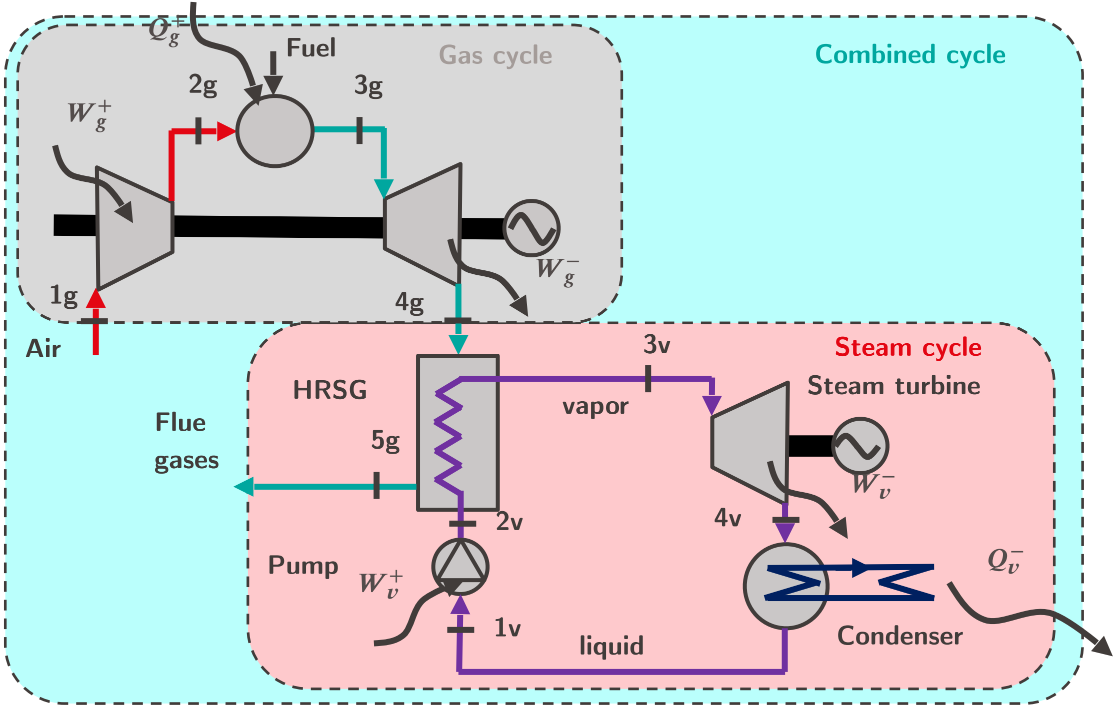
Combined cycle gas turbine

Combined cycle Gas turbine

Concept

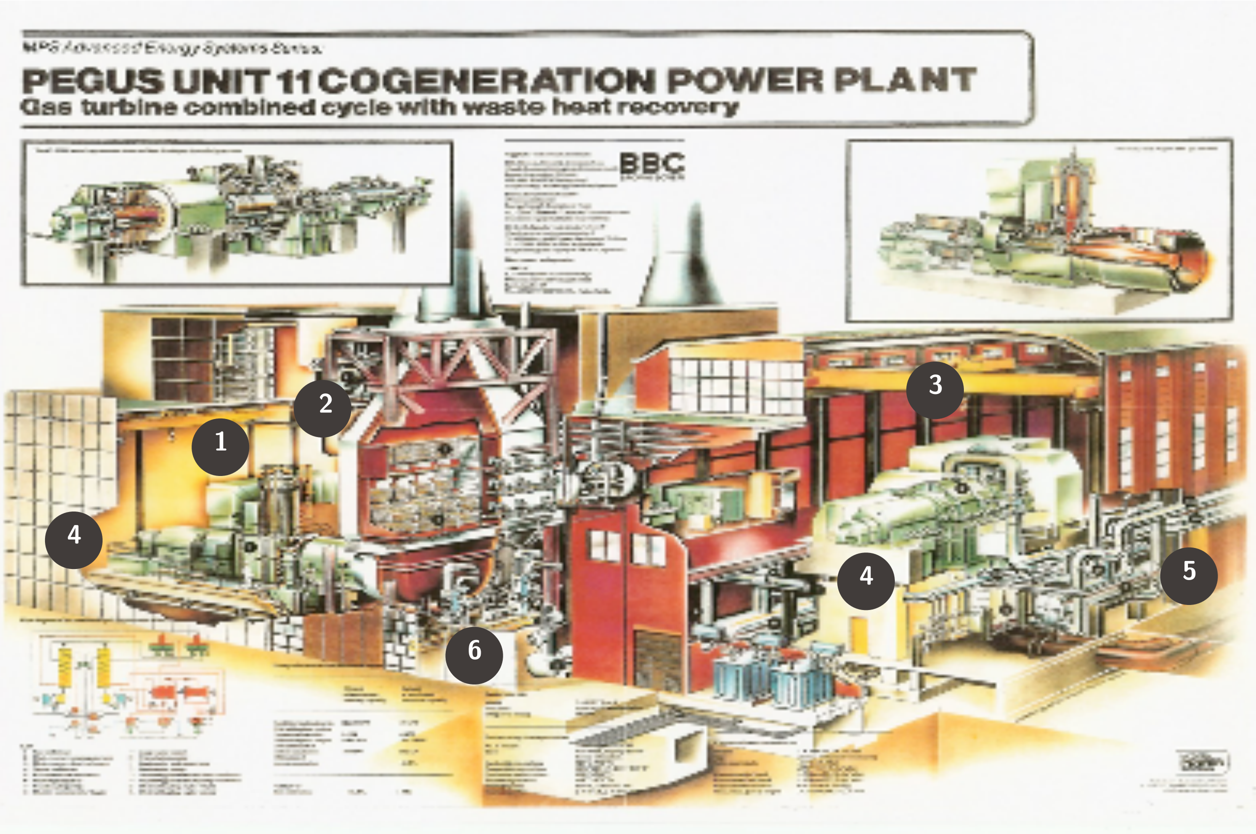
- Flue gases exit the Gas Turbine at high temperature (~600 °C) → energy wasted to the environment -> add a Rankine cycle





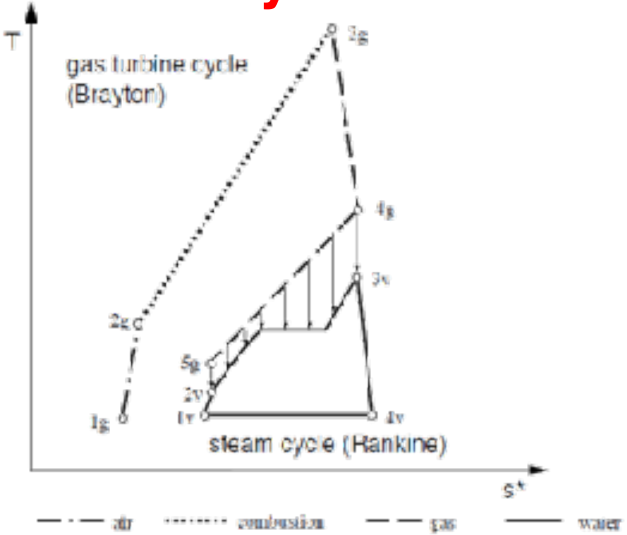
CCGT
Components

1. Gas Turbine
2. Heat Recovery Steam Generator
3. Steam turbine
4. Electric generator
5. Condenser (heat rejection)
6. Pump



Combined Cycle Gas Turbine

Efficiency



Heat released by combustion :

$$\dot{Q}^{+} = \dot{m}_{fuel} \cdot LHV_{fuel}$$

Heat available in the combustion gases :

$$Q_g^- = Q_g^+ - W_g^- = m_g \cdot c_{p,g} \cdot \left(T_{4,g} - T_{amb}\right)$$

Heat recovered by the heat recovery steam generator :

$$Q_s^+ = Q_g^- - Q_{g,amb}$$

Heat released in the environment :

$$Q_{g,amb} = m_g \cdot c_{p,g} \cdot \left(T_{5,g} - T_{amb}\right)$$

Conversion efficiencies

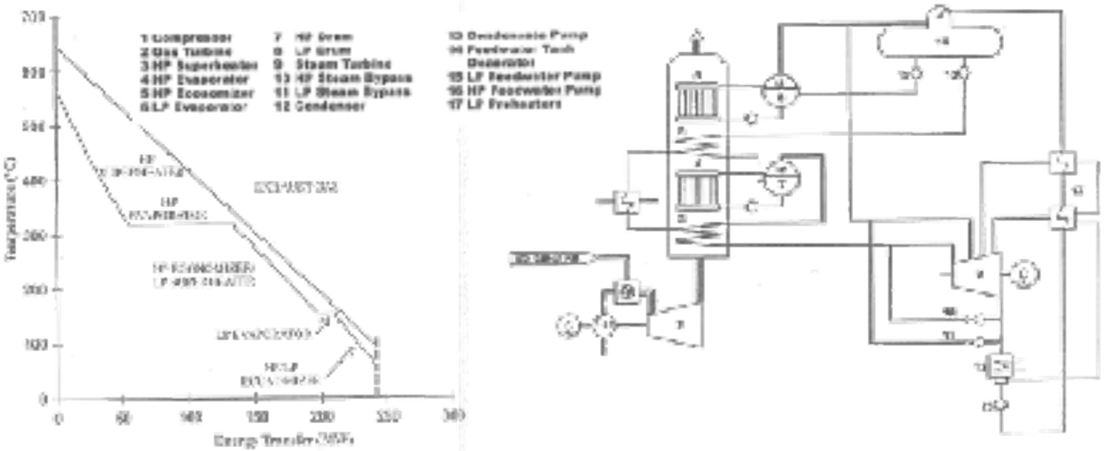
- Gas Turbine $\eta_g = \frac{W_g^-}{Q_g^+}$
- Heat recovery steam generator $\eta_{HRSG} = \frac{Q_s^+}{Q_g^-}$
- Steam Cycle $\eta_s = \frac{W_s^-}{Q_s^+} = \frac{W_s^-}{Q_g^+\left(1 - \eta_g\right) * \eta_{HSRG}}$

Overall CCGT cycle efficiency

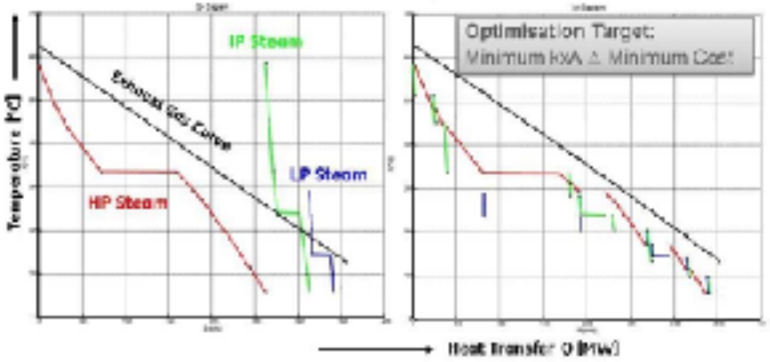
$$\eta_{CCGT} = \frac{W_g^- + W_s^-}{Q_g^+} = \eta_g + \eta_s * \left(1 - \eta_g\right) * \eta_{HRSG}$$

CCGT : Steam cycle

- Multi-pressure steam turbine to use the heat of the flue gasses to the lowest possible temperature
- Today 3 to 4 pressure levels



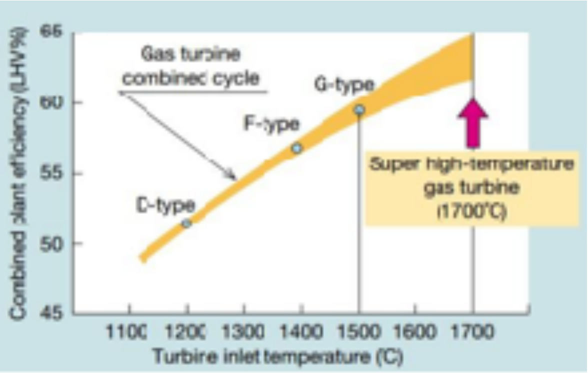
Scheme and T-s diagram for a dual pressure HRSG[1]



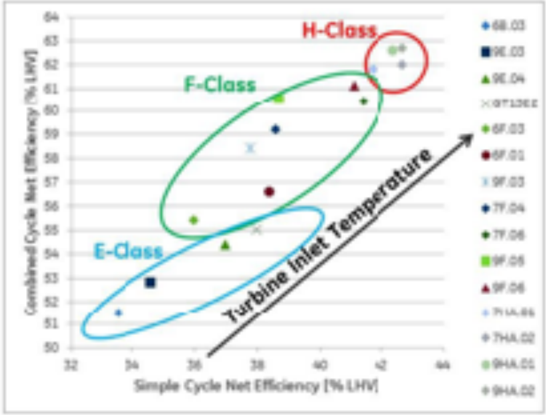
HRSG sequence optimization[2]

CCGT
Efficiency

- Combined cycle is a state of the art technology
  - 64 % is the new efficiency benchmark
- Means to improve the efficiency:
  - Enhancements in the GT cycle: pressure ratio, turbine inlet temperature, improved combustion, advanced materials
  - Advanced cooling technologies (i.e. external blade cooling with steam)
  - Reduced losses in rotating equipment
  - Advanced materials and process design for the HRSG Heat Recovery Steam Generator, including optimization
  - Supercritical steam / multi-pressure (3-4) steam cycles
  - Advanced plant configuration (i.e. intercooling, regenerative GT, etc.)



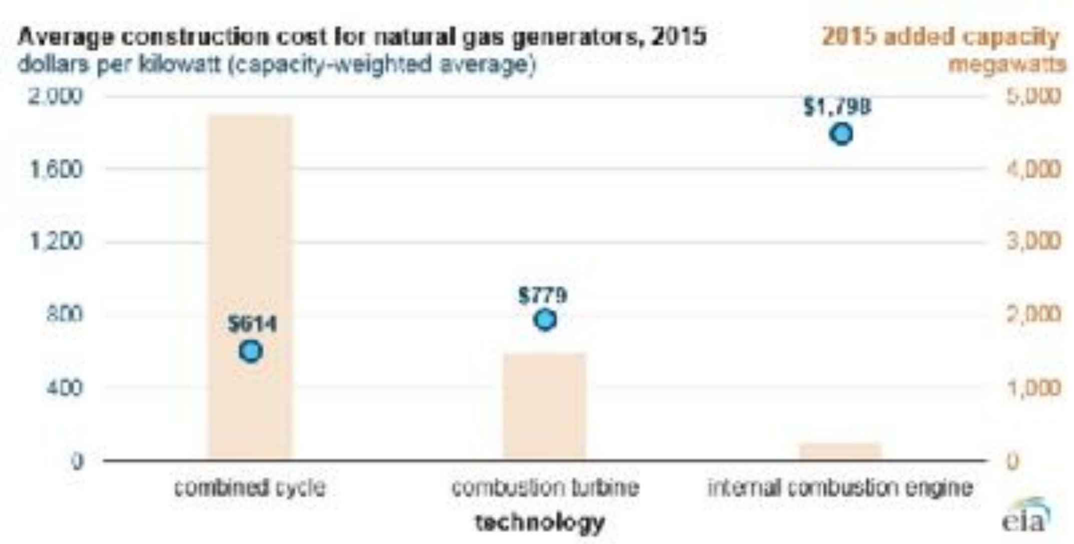
GTCC efficiency as a function of the gas turbine inlet temperature[1]



Declared efficiency of some GTCC available in GE Power Portfolio 2017[2]

CCGT investment

Cost (k$ 2020) = 3800(MWe)$^{0.7}$
400 MWe = 614 $/kWe
2020 : up to 64 % LHV efficiency



https://www.eia.gov/todayinenergy/detail.php?id=31912

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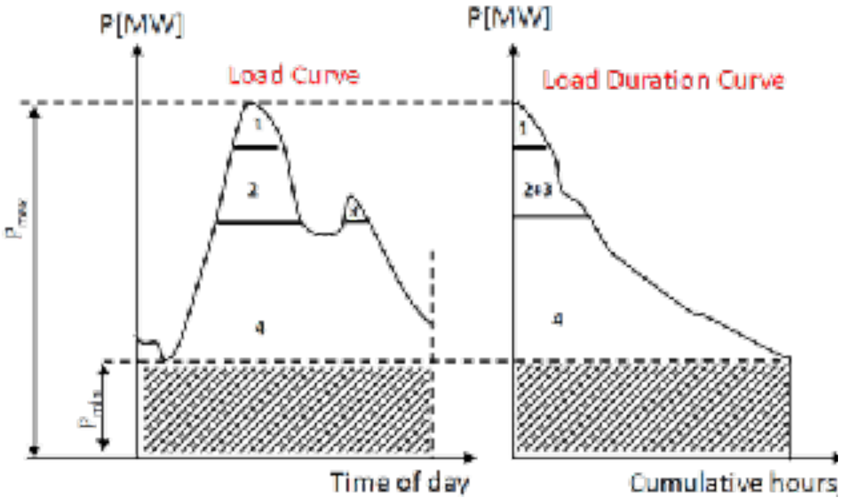
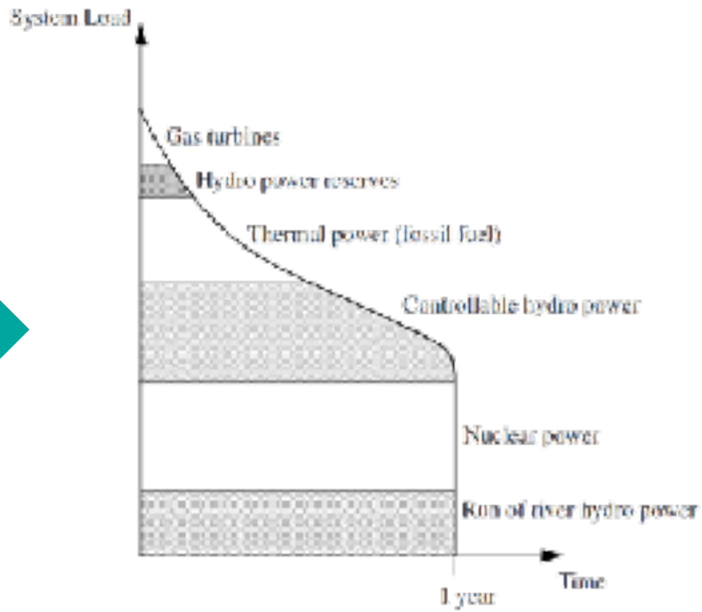
GT and CCGT in the market

GT and CCGT in the electrical market

- Gas turbine can be started within minutes and ramped up and down quickly
- Designed for base load applications, today suffering for RES dispatching priority.



Load duration curve[1]



Duration curve showing the use of different kinds of power plants[2]

GT and CCGT in the market

Levelized Cost of Electricity (LCOE)

Efficiency*cost of fuel

Fossil dependence

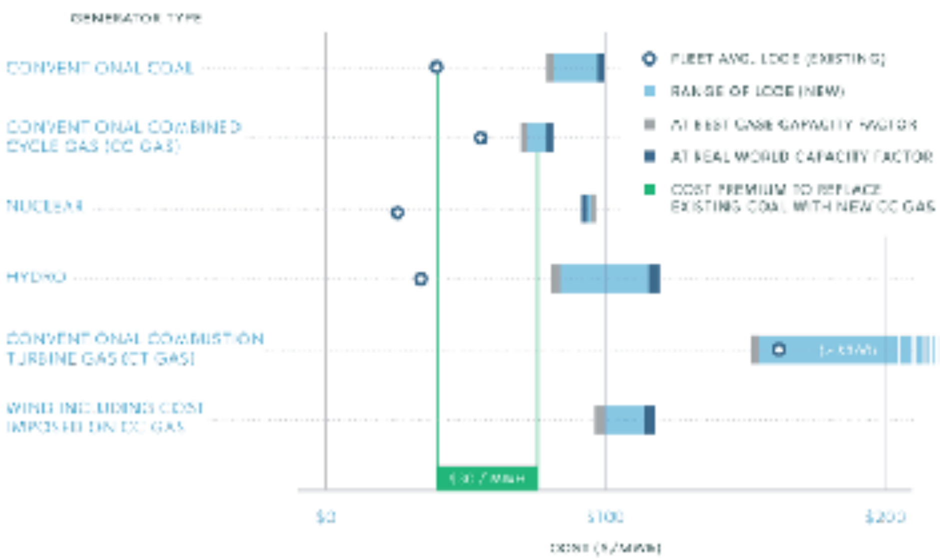
$$LCOE = \frac{\tau C_{inv} + C_{maint} + C_{op}}{E^{-} t_{op}} = \frac{\frac{i(i+1)^n}{(i+1)^n - 1} C_{inv} + C_{maint} + (\dot{m}^{-}_{fuel} LHV_{fuel} c_{op,fuel} + \dot{m}^{-}_{CO_2} c_{CO_2}) t_{op}}{E^{-} t_{op}}$$

- LCOE: [€/MWh_e]
- τ [-]: annualization factor
- C_{inv} [€]: total investment cost
- C_{maint} [€/y]: yearly Operation&Mainteance (O&M) cost, excluding fuel cost
- C_{op} [€/y]: yearly operating cost
- E^{-} [MW_e]: installed electricity production capacity
- t_{op} [h/y]: hours of full load operation equivalent in 1 year
- **c_p** [-] := t_{op}/8760: yearly capacity factor

- i [-]: discount rate
- n [years]: technology lifetime
- m_{fuel} [kg/h]: nominal flow rate of fuel input
- LHV_{fuel} [kWh_{fuel}/kg]: lower heating value of fuel
- $c_{op,fuel}$ [€ /kWh_{fuel}]: fuel cost
- m_{CO2} [kg/h]: CO2 emissions
- c_{CO2}[€/kg_{CO2}]: CO_2 tax

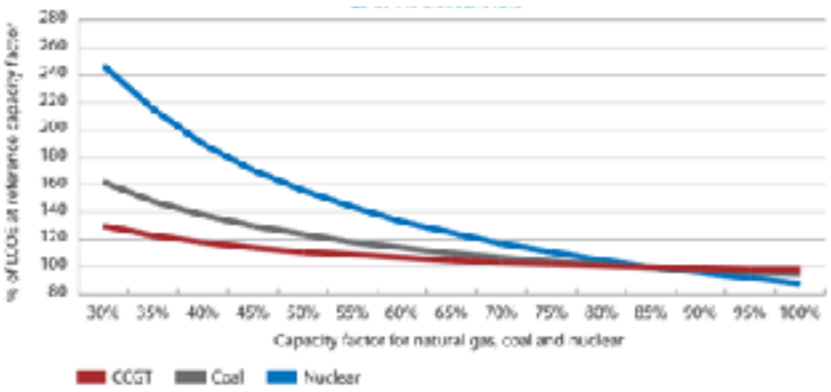
GT and CCGT in the market

LCOE



Levelized cost of electricity for different technologies[

$$Capacity factor = \frac{hours_{operational}[h/year]}{8760[h/year]}$$



LCOE of coal, natural gas and nuclear as a function of capacity factor

Take-home message

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Take-home message

GAS TURBINE:

- Based on the Joule-Brayton cycle
- In real applications: open cycle with irreversibilities in turbomachines and pressure drops
- Efficiency ~42 %
- Efficiency improved by optimal pressure ratio, increase T_3 (blade cooling technologies), advanced cycle configuration (regeneration, intercooling, reheating)
- Different types: from heavy duty for base load to aeroderivative for peak loads
- Due to the high flexibility mainly exploited for peak loads

COMBINED CYCLE:

- Combination of a gas turbine and a steam cycle where the heat from the flue gases is recovered to generate steam
- The link between the gas turbine and the steam cycle is the HRSG, key plant component
- Efficiency *up to* 64 %
- Efficiency improved by enhanced GT, advanced materials and plant configuration, supercritical steam cycle
- Technology born for big power plants, base load and long operating time, now suffering due to RES volatility

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Questions?

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