Sustainable Power Generation MJ2405

Combined Cycles
and
Heat Recovery Steam Generators

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Introductory description

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The combined cycle is a combination of a **topping cycle** (typically a gas turbine) and a **bottoming cycle** (typically a steam cycle) where the remaining heat (waste heat) of the topping cycle exhaust gas is transfered to the bottoming cycle for production of additional power.

The goal is to achieve maximum efficiency by utilizing the entire temperature interval from the GT combustion temperature down to condensing steam close to the ambient temperature. Indeed, the combined cycles are the most efficient energy conversion units reaching up to 60% el. efficiency.

The link between the gas turbine and the steam cycle is the Heat Recovery Steam Generator (HRSG) where water is being boiled and superheated from the flue gas heat. The efficiency of the overall combined cycle depends not only on the efficiency of the gas and steam turbines but also on how complex and how effective the HRSG is.

Additional fuel can be burned in the HRSG (called supplementary firing) or in a separate steam boiler (various hybrid cycle arrangements) for producing more steam than the one delivered by the GT exhaust alone, so many different variations of combined cycles are possible.

In general terms, any combination of a high-temperature topping cycle whose waste heat is utilized by a lower-temperature bottoming cycle producing additional work, can be called a combined cycle!

Reading material on combined cycles

There are several good textbooks or chapters of books dedicated to combined cycles!

The main suggested sources:

Combined-Cycle Gas and Steam Turbine Power Plants (3rd Edition); Kehlhofer, Rukes, Hannemann, Stirnimann; *PennWell Publishers 2009 – available free from a KTH-login on* **www.knovel.com**

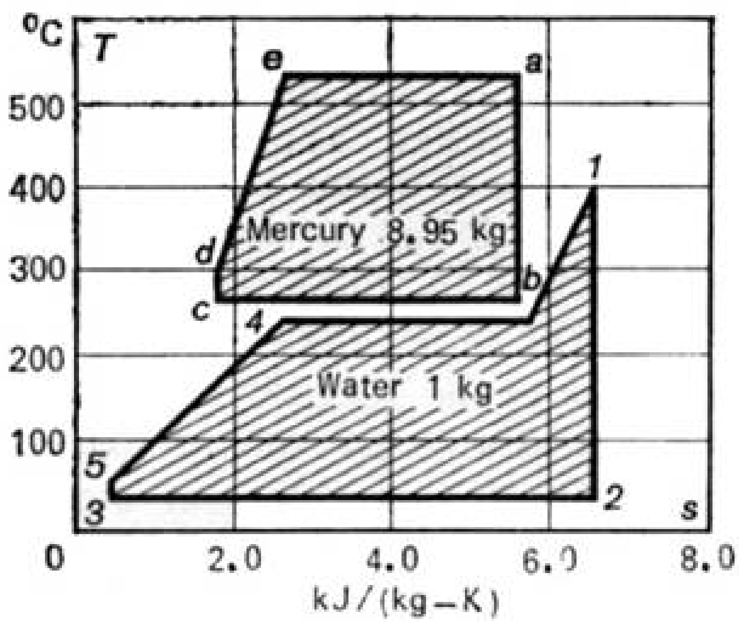
Advanced Energy Systems (Khartchenko & Kharchenko), *CRC Press 2014* – chapter 5.

Energy Conversion (Kenneth C. Weston) - *free e-book by courtesy of the University of Tulsa,* 2000 – (parts of chapter 9) **http://www.personal.utulsa.edu/~kenneth-weston/**

Unfortunately, there is no good literature available in Swedish language on this topic.

First suggested configurations

Combined cycles were initially proposed in a double vapor cycle arrangement already in the 1920-ies, with a topping cycle using vaporized mercury (!) and a regular water-steam bottoming cycle. The goal was to find a topping vapor cycle able to achieve high temperatures without the high pressures associated with water-steam, which the old materials couldn't handle.



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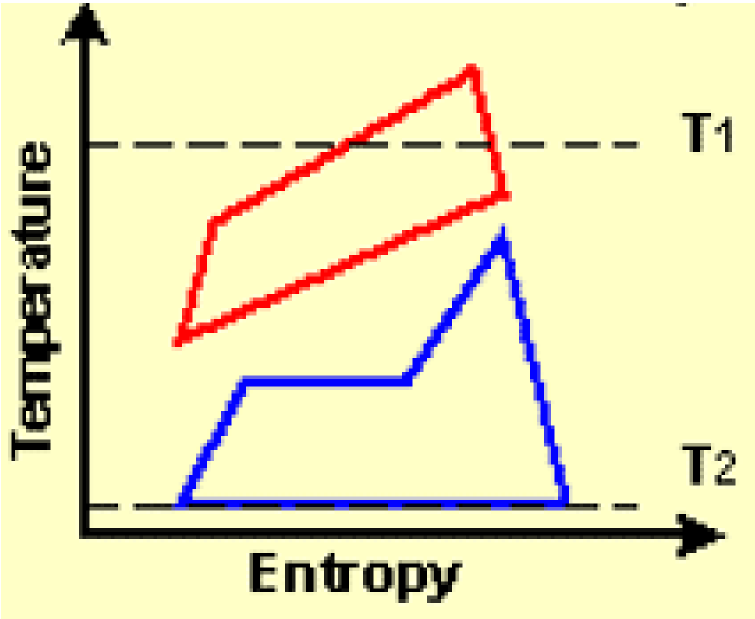
Modern combined cycles

The contemporary gas/steam combined cycle was devised when the gas turbine became a mainstream power generation technology in the 1960-ies, and quickly started to grow in popularity. The topping cycle is a regular gas turbine, the bottoming cycle is a regular water-steam circuit.



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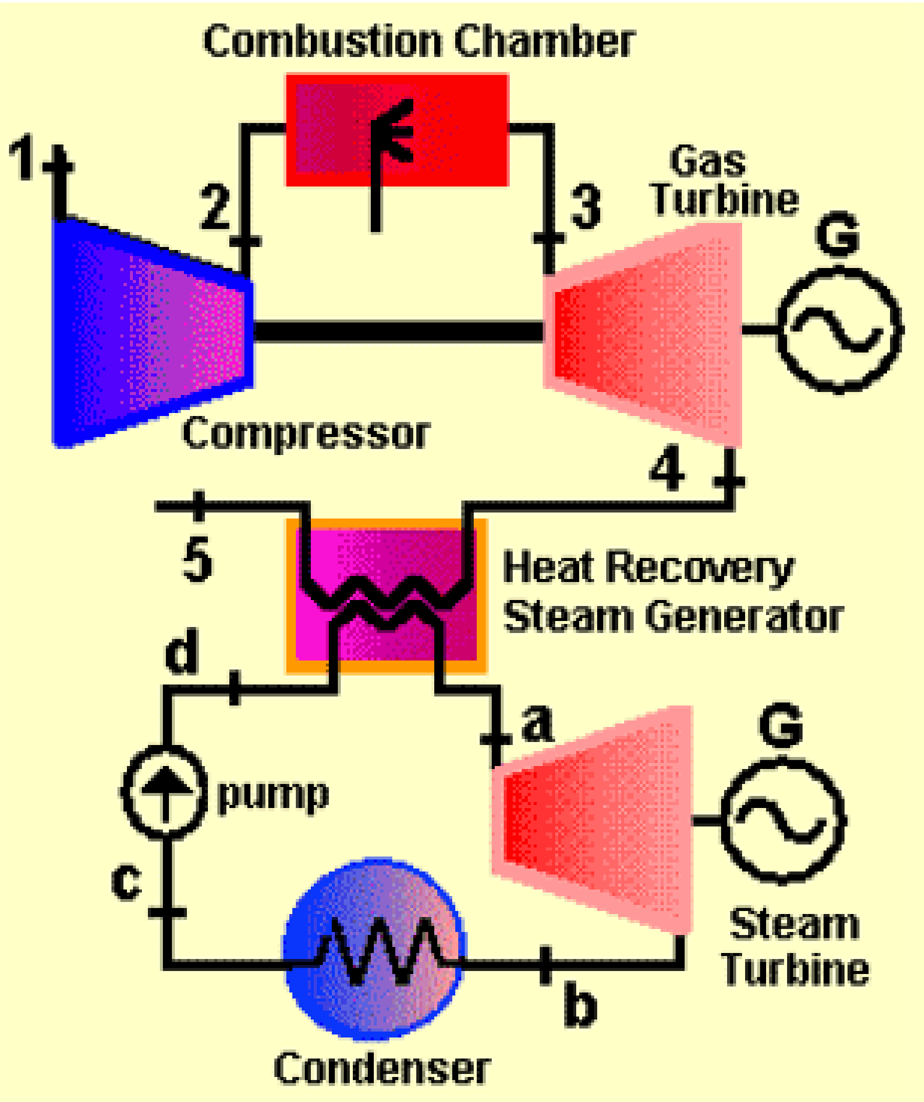
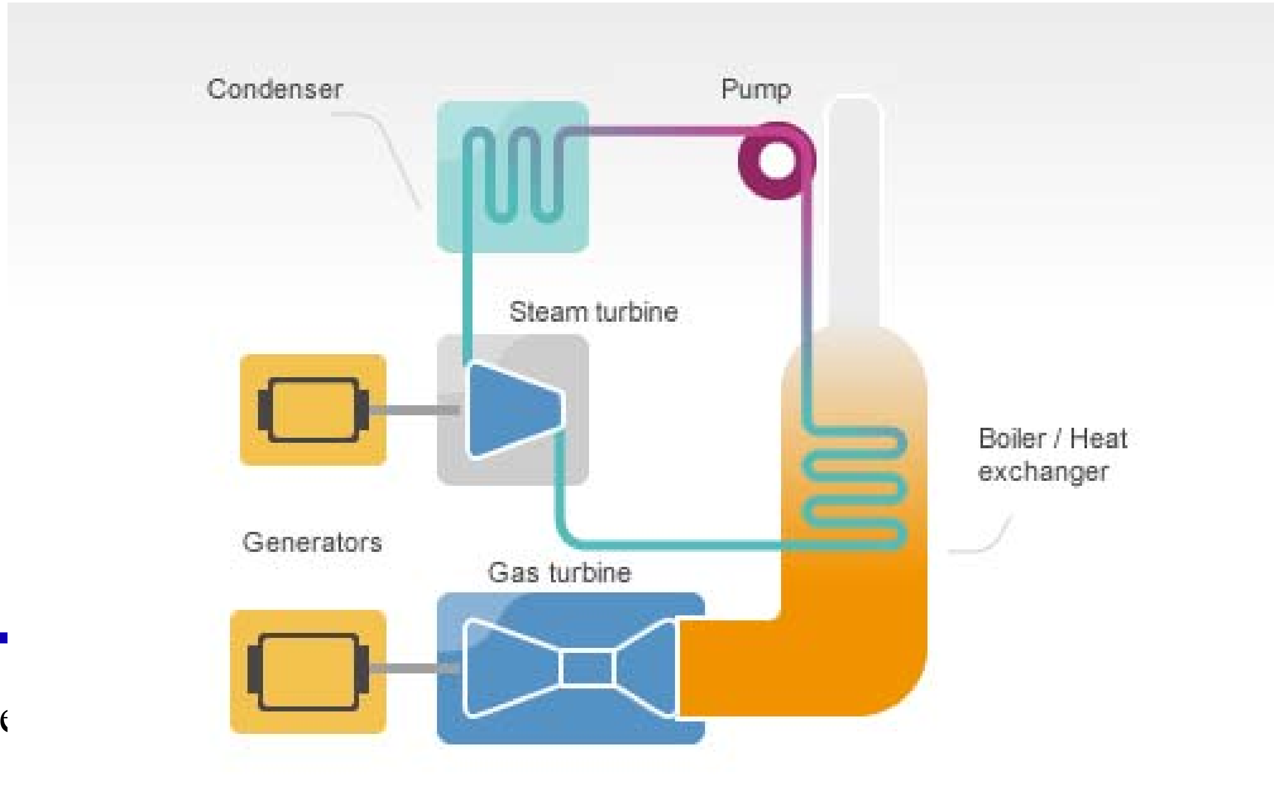
The straight combined cycle

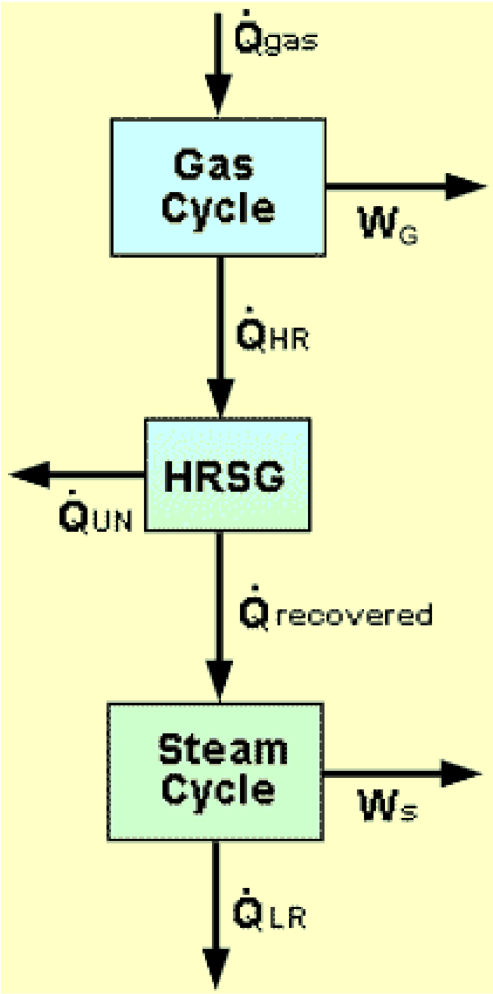


The combined cycle utilizes two proven technologies, however, the bottoming steam cycle needs to be adapted to the governing parameters and conditions, and often is relatively small.

The bottoming cycle delivers around 1/3 of the combined power output but takes 2/3 of the total investment cost!



Efficiency definition



There are two different power output points (from the gas and steam cycles), but only one fuel input - in the gas turbine. The overall efficiency of the combined cycle can be expressed as:

$$\eta_{CC} = \frac{W_G + W_S}{\dot{Q}_{gas}}$$

After developing and substituting the efficiencies of the gas and steam cycles:

$$\eta_G = \frac{W_G}{\dot{Q}_{gas}} \quad ; \quad \eta_S = \frac{W_S}{\dot{Q}_{recovered}}$$

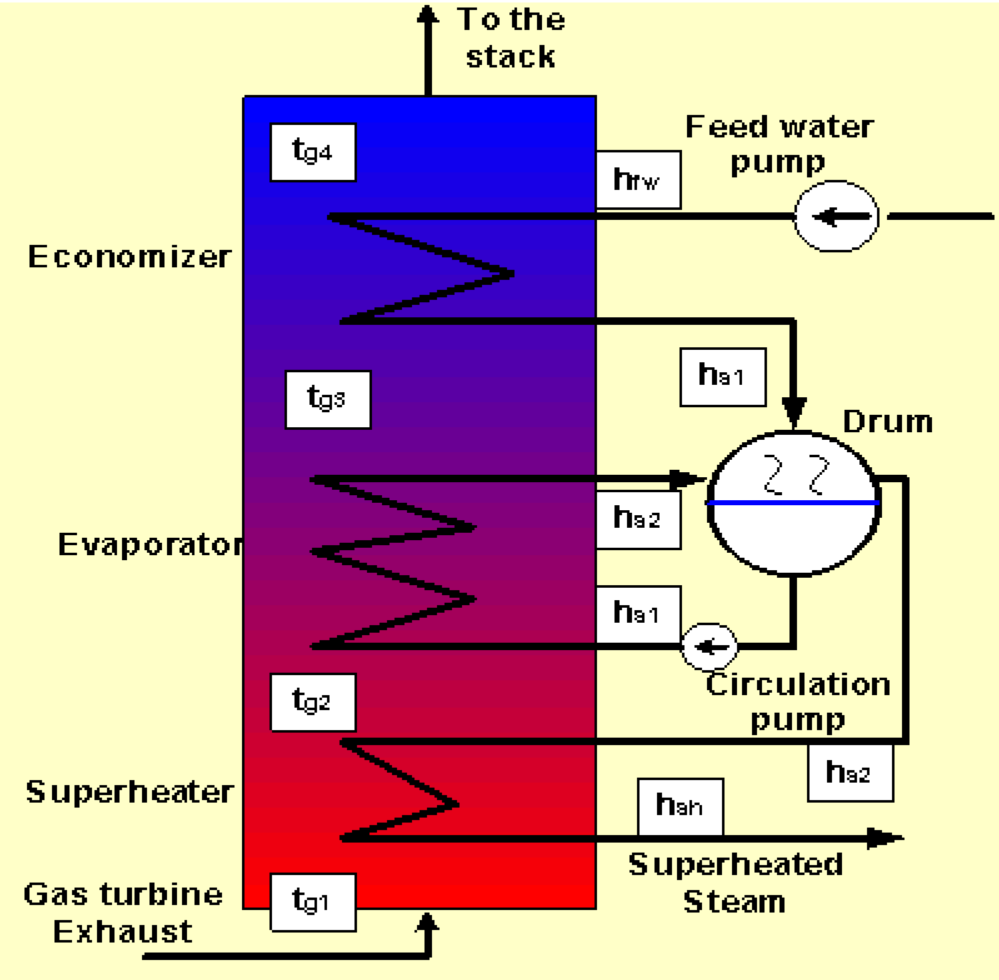
$$\dot{Q}_{recovered} = \dot{Q}_{HR} - \dot{Q}_{UN} = \dot{Q}_{gas}(1 - \eta_G) - \dot{Q}_{UN}$$

$$\eta_{CC} = \frac{\dot{Q}_{gas} \cdot \eta_{gas} + \eta_S \left[\dot{Q}_{gas}(1 - \eta_{gas}) - \dot{Q}_{UN}\right]}{\dot{Q}_{gas}}$$

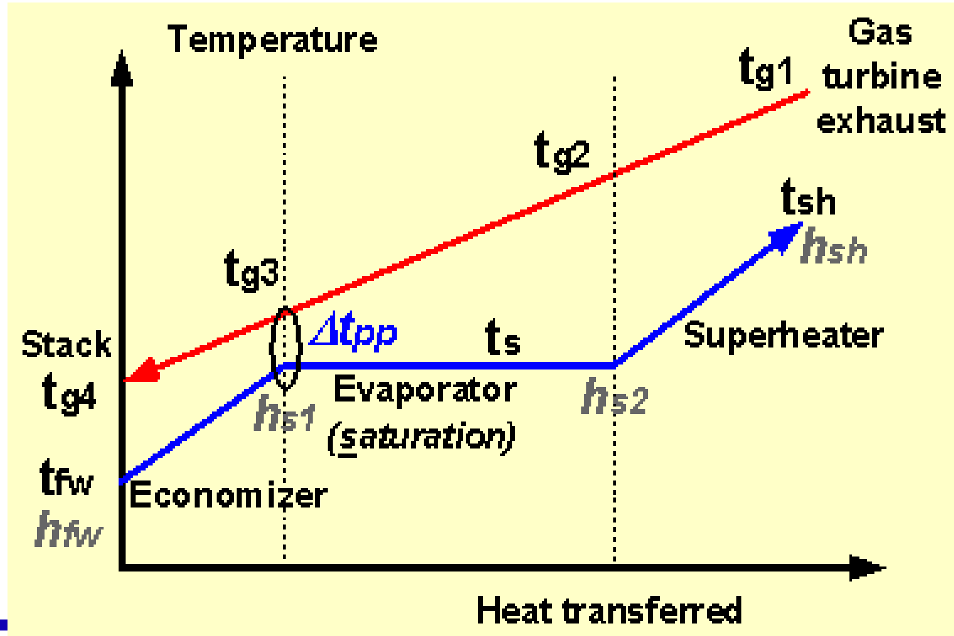
$$\eta_{CC} = \eta_{gas} + \eta_S - \eta_{gas} \cdot \eta_S - \eta_S \frac{\dot{Q}_{UN}}{\dot{Q}_{gas}}$$

Major component: The HRSG

Transfers the heat rejected from the gas turbine to the bottoming steam cycle. Suffers from two main types of inefficiencies: physical loss of heat that can't be recovered and goes to the stack; and the unavoidably large temperature difference between the gas and the boiling water in the evaporator, which triggers a substantial exergy loss.

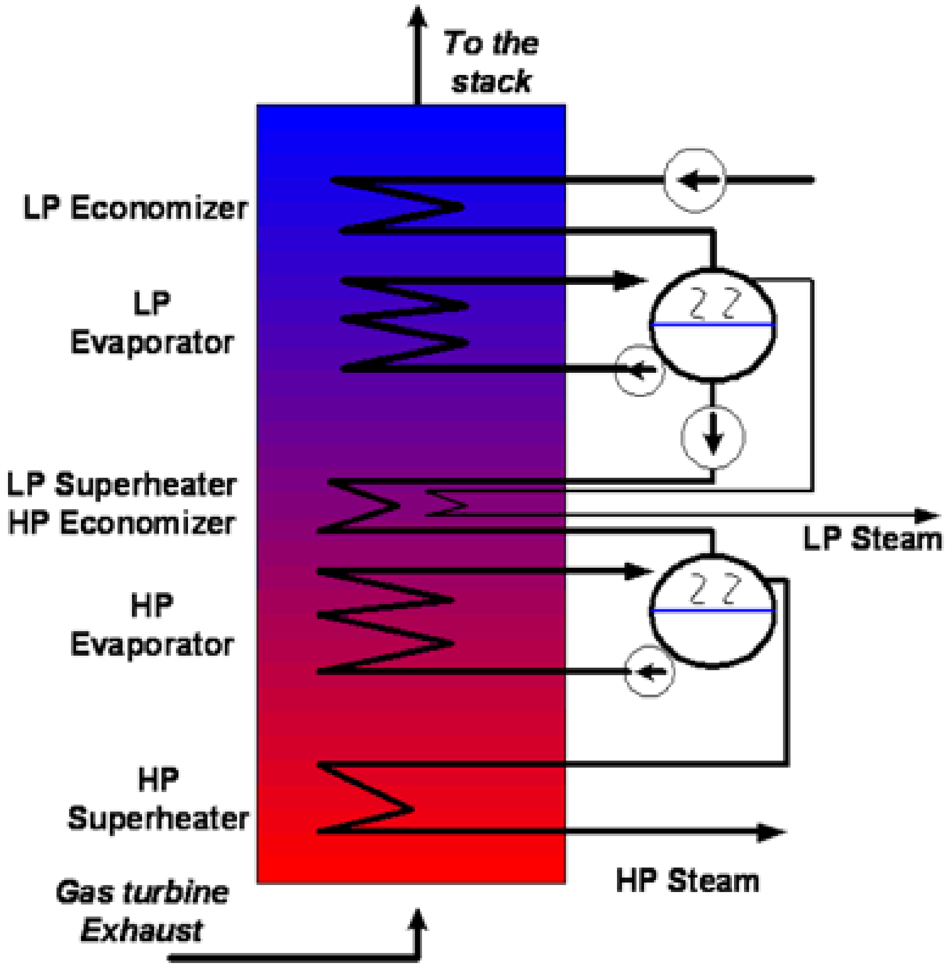


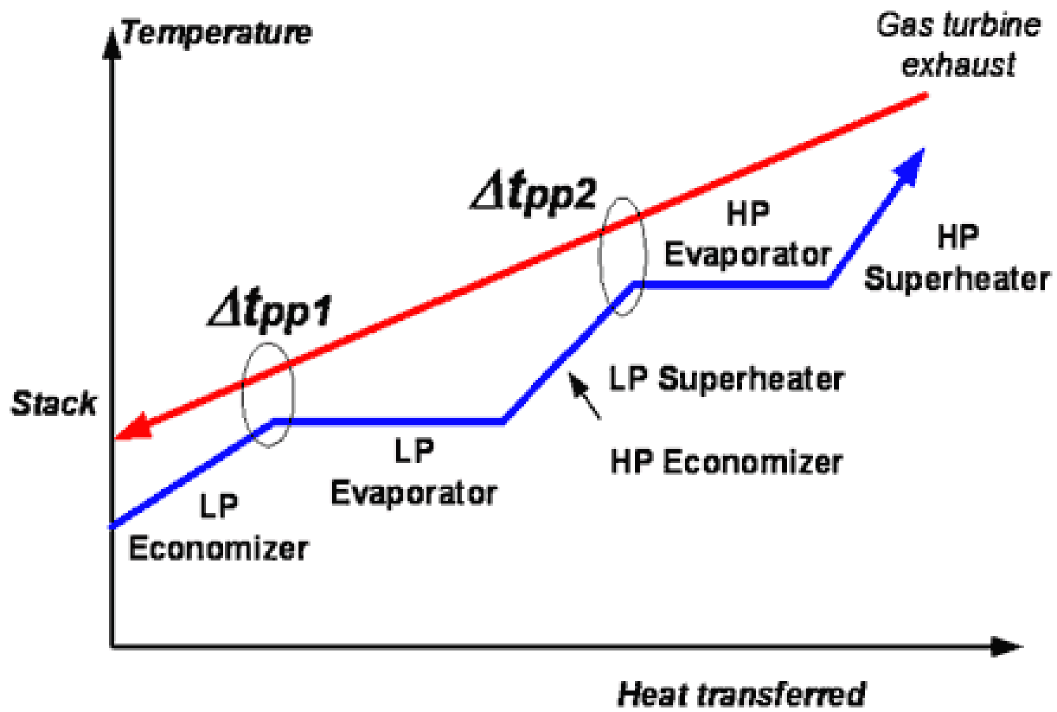
The water-steam side of the HRSG is divided in economizer, evaporator, superheater, similar to a common steam boiler. The governing parameter is the temperature difference at the so-called **pinch point**!



Improvements of the HRSG: multiple pressure levels of steam generation

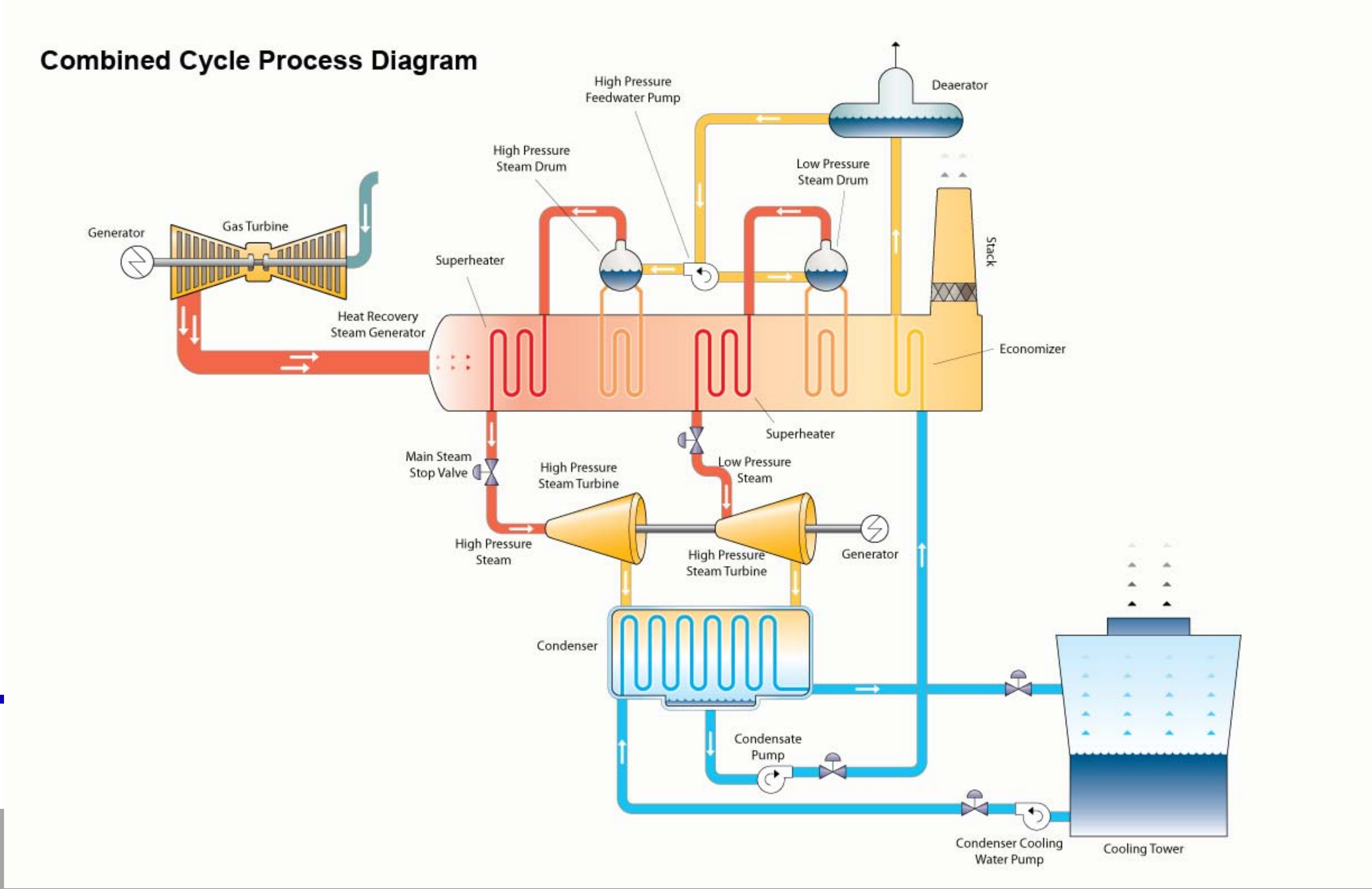
Many pressure levels in the HRSG would help decrease the exergy loss, resulting in higher thermal efficiency of the bottoming cycle. Practically limited to max 2 or 3 pressure levels, beyond which the advantage diminishes while costs and complexity grow.





Most common layout

A natural-gas fired gas turbine, 2 pressure levels in the HRSG and two sections of the steam turbine, simplified steam cycle with only a FWT.



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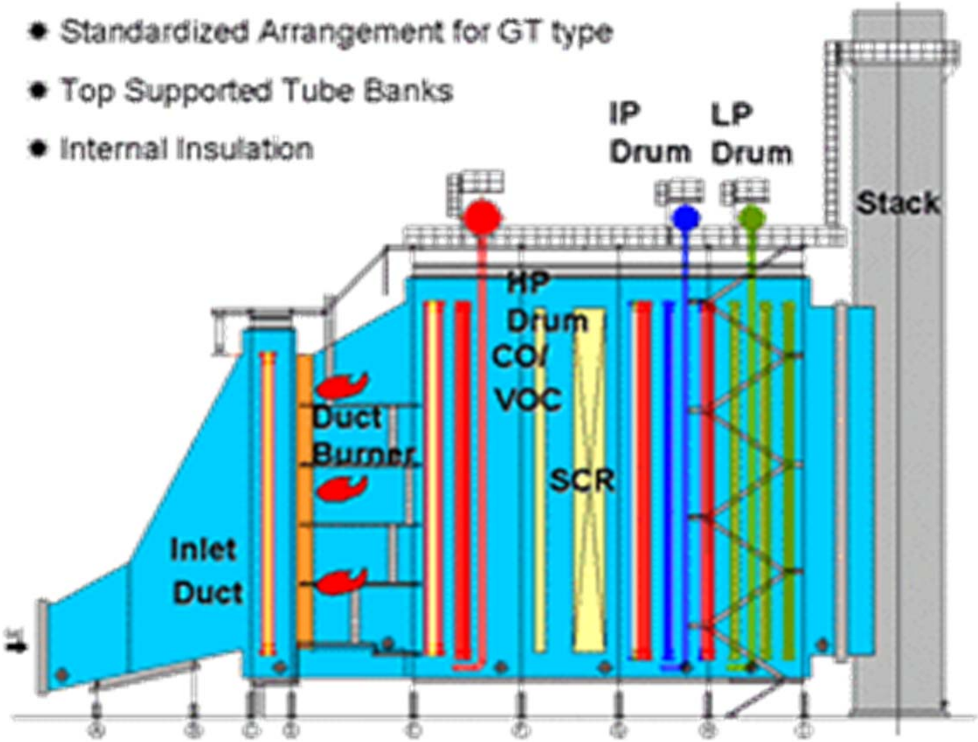
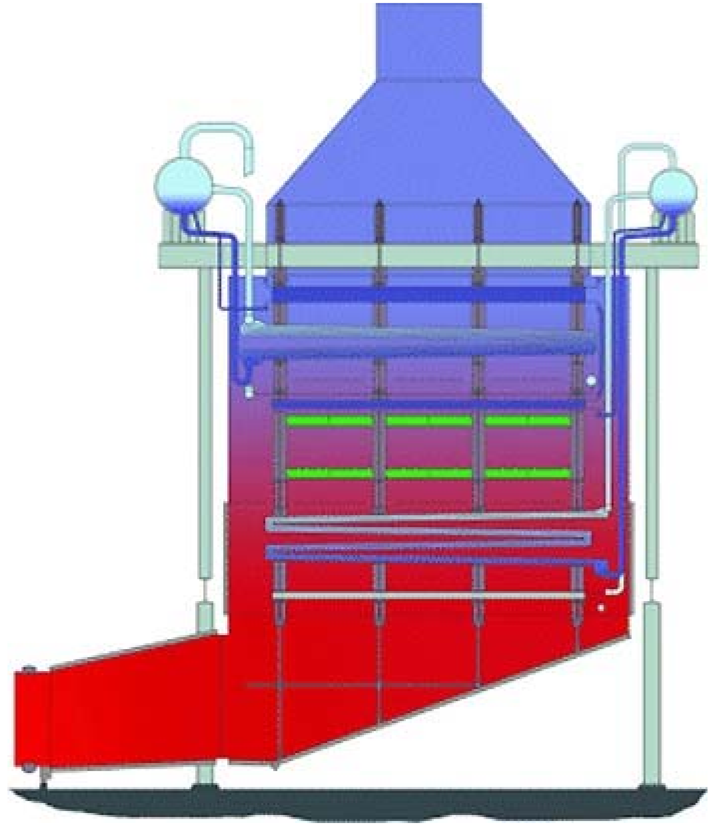
Main design types of HRSG

Horizontal or vertical, with 2 or 3 steam pressure levels, sometimes also with steam reheat





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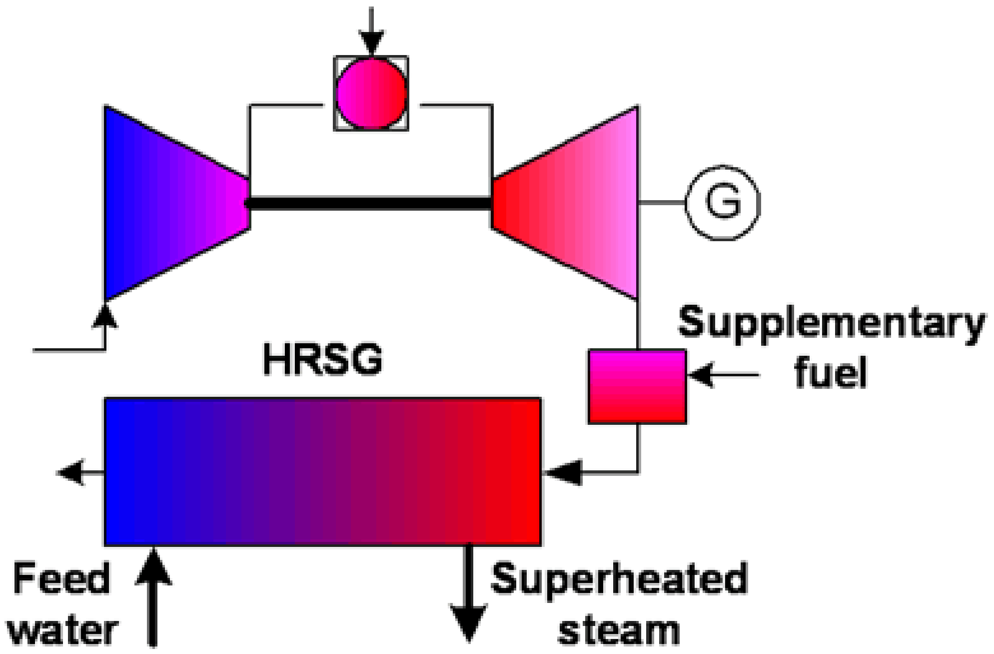
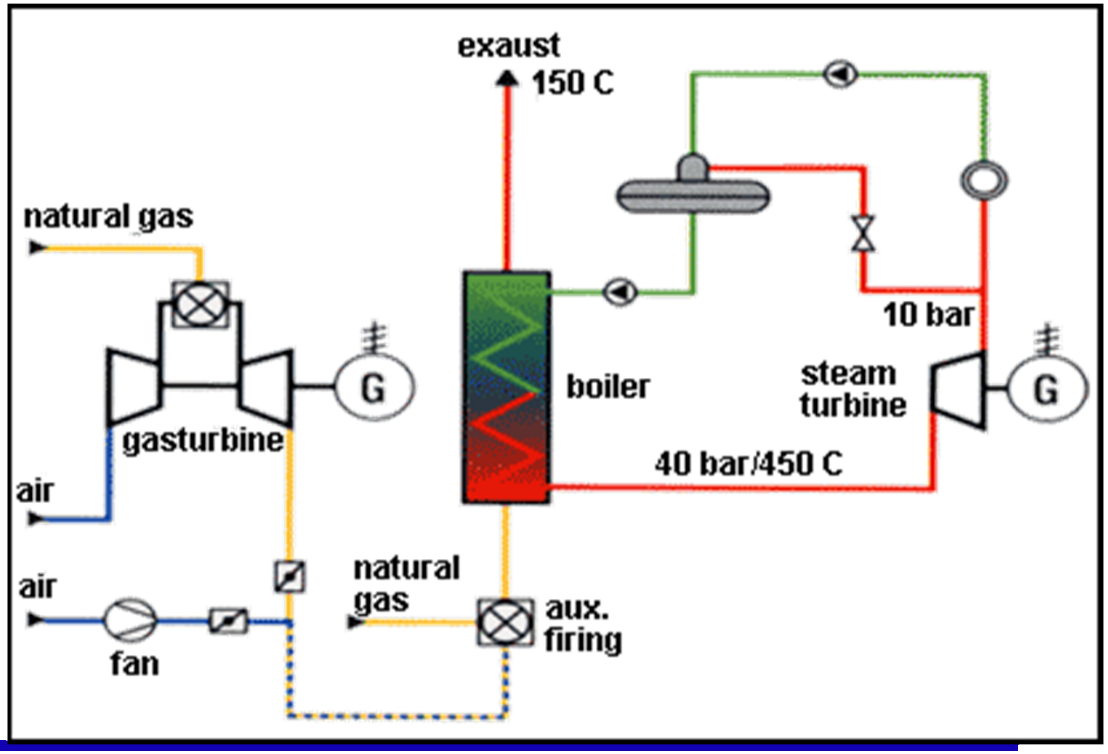
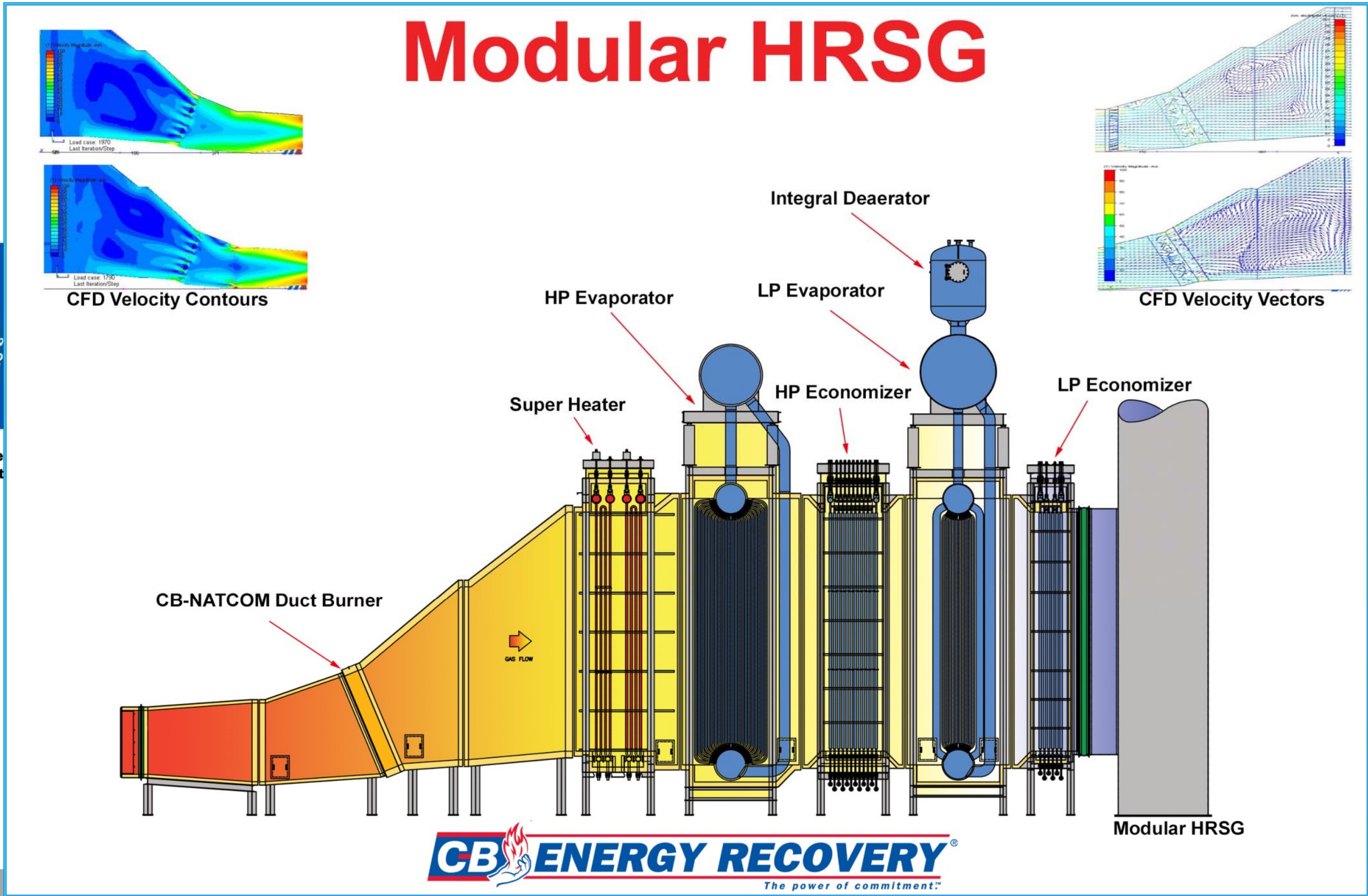
Supplementary Firing

Additional combustion of fuel (usully the same fuel as for the gas turbine) directly in the gas duct before the HRSG. Helps to increase the temperature of the GT exhaust gases and thus to generate more steam, also allows for independent operation of the HRSG and the steam cycle if the GT fails.





HRSG construction



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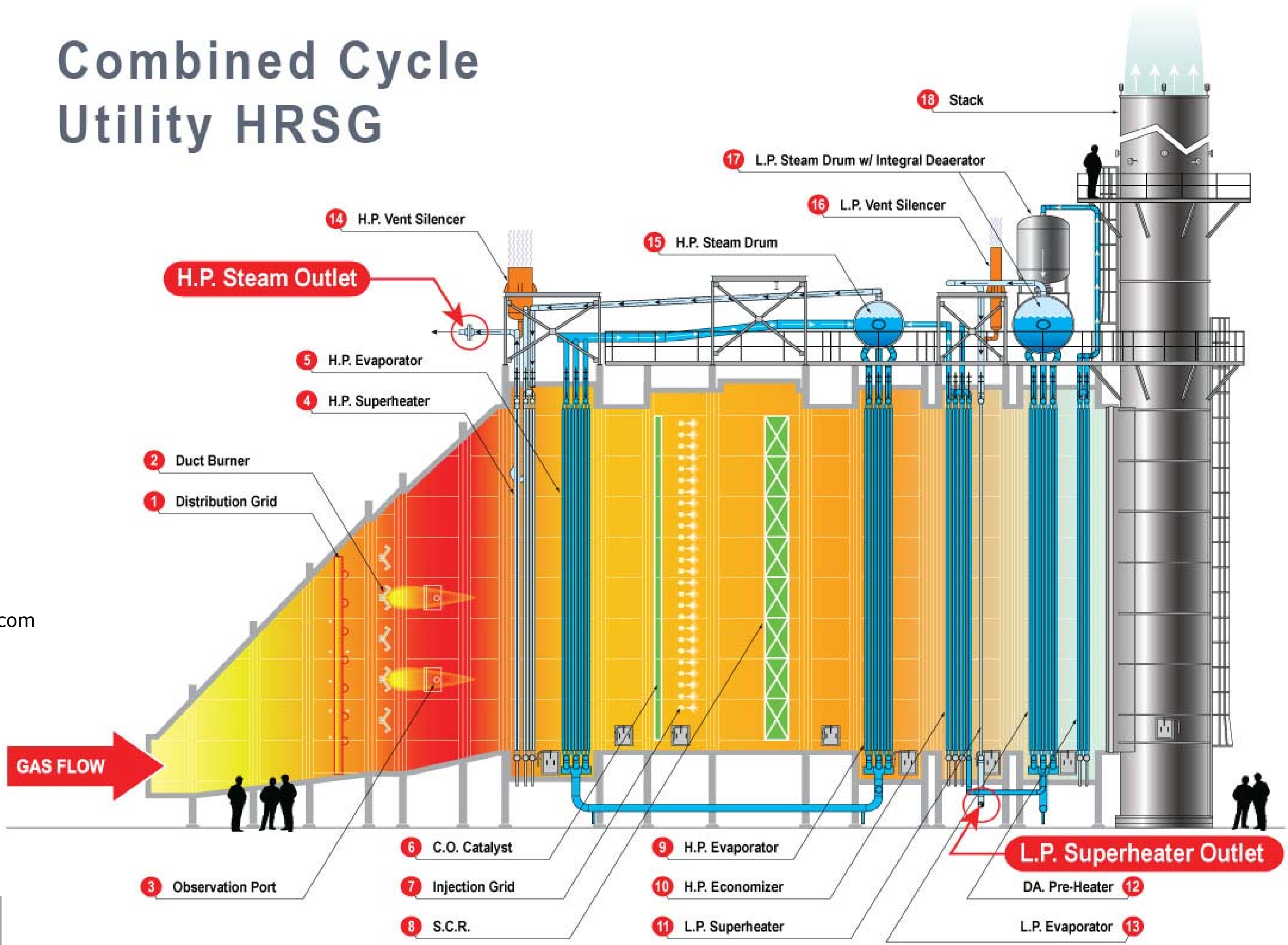
HRSG construction close-up



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Source: www.victoryenergy.com

Combined cycle plant layout

Source: www.cmigroupe.com

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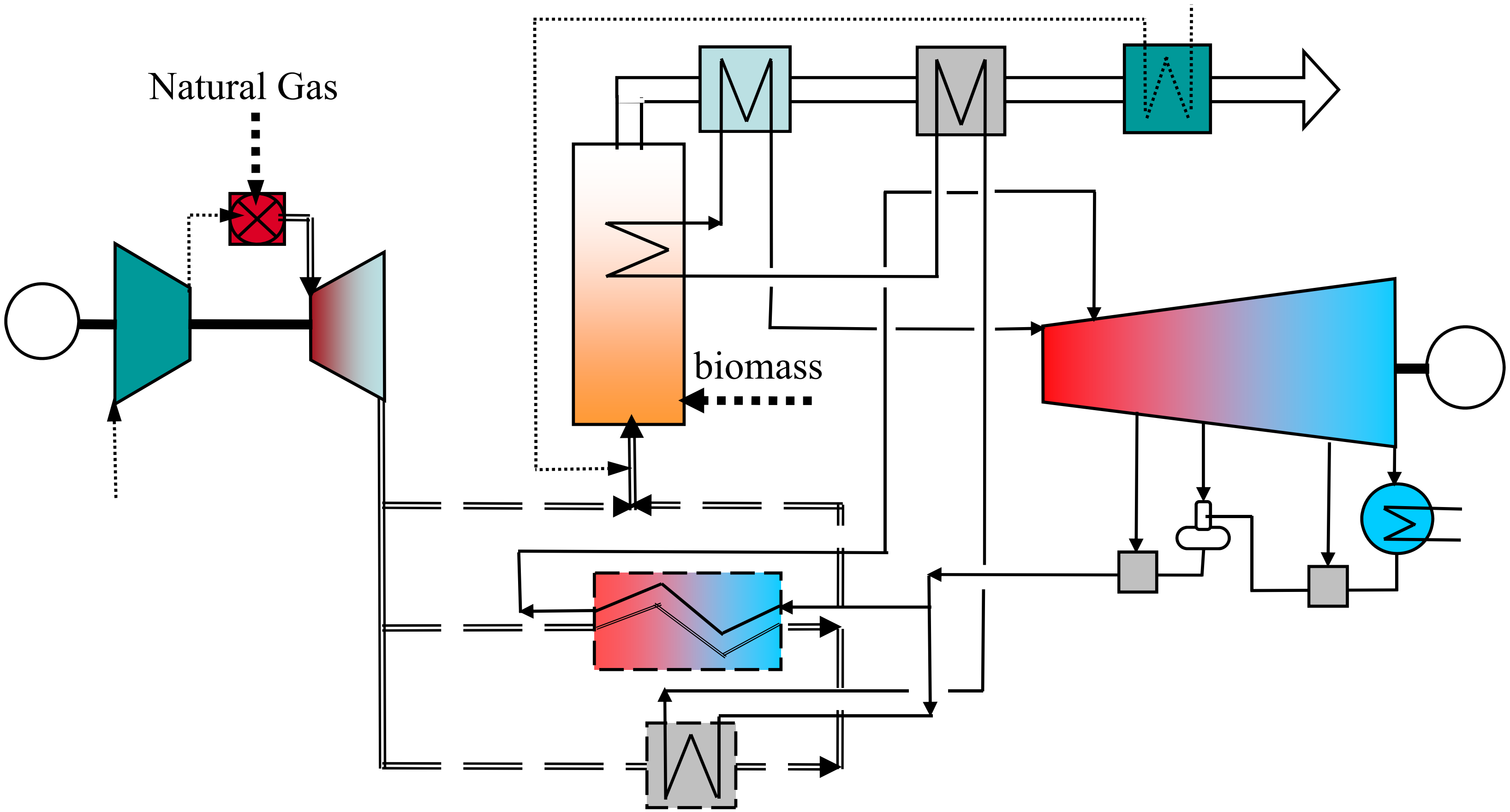
Hybrid combined cycles: Fully-fired (windbox) configurations



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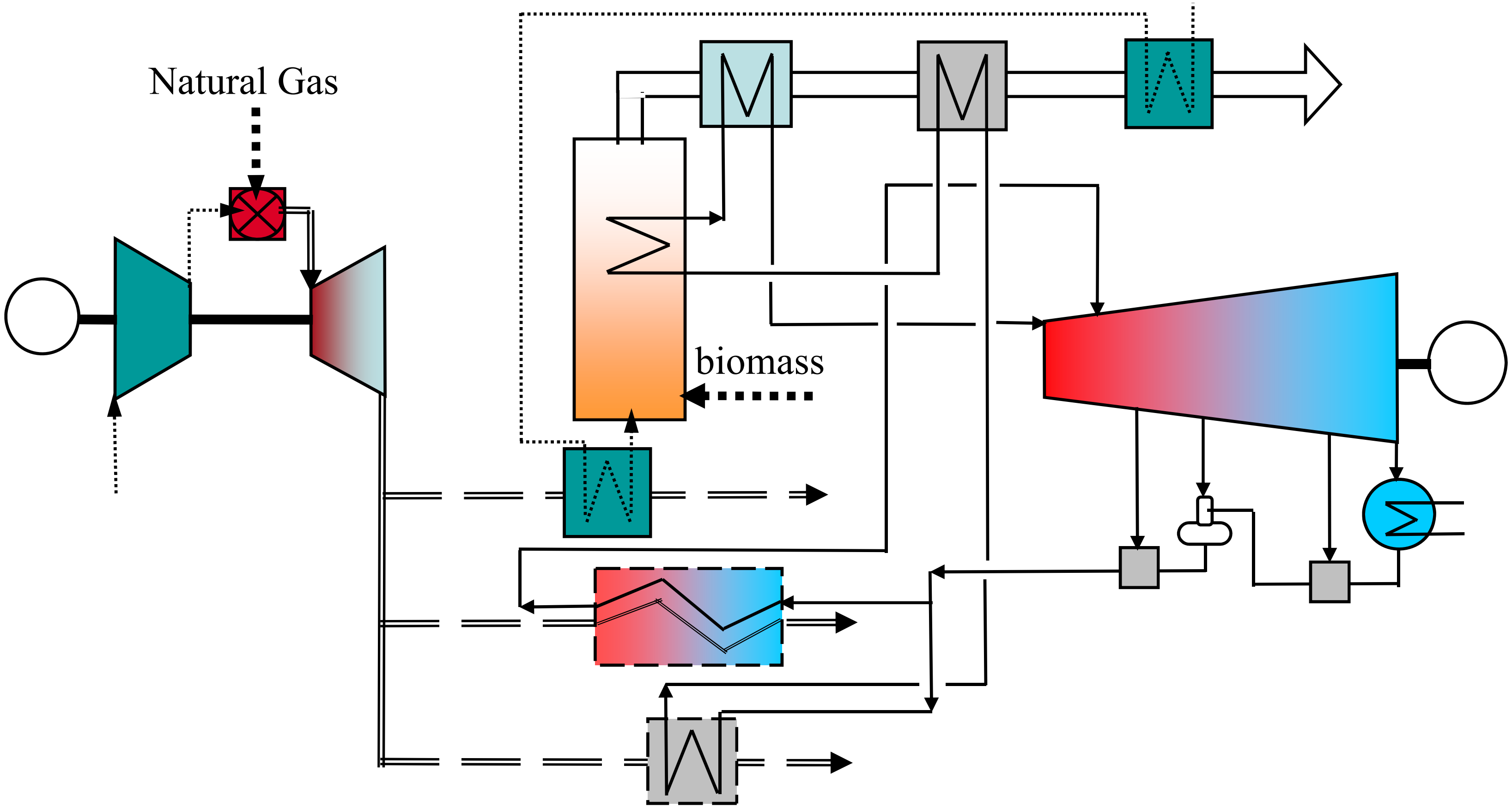
Hybrid combined cycles: Parallel-powered (compound) configurations



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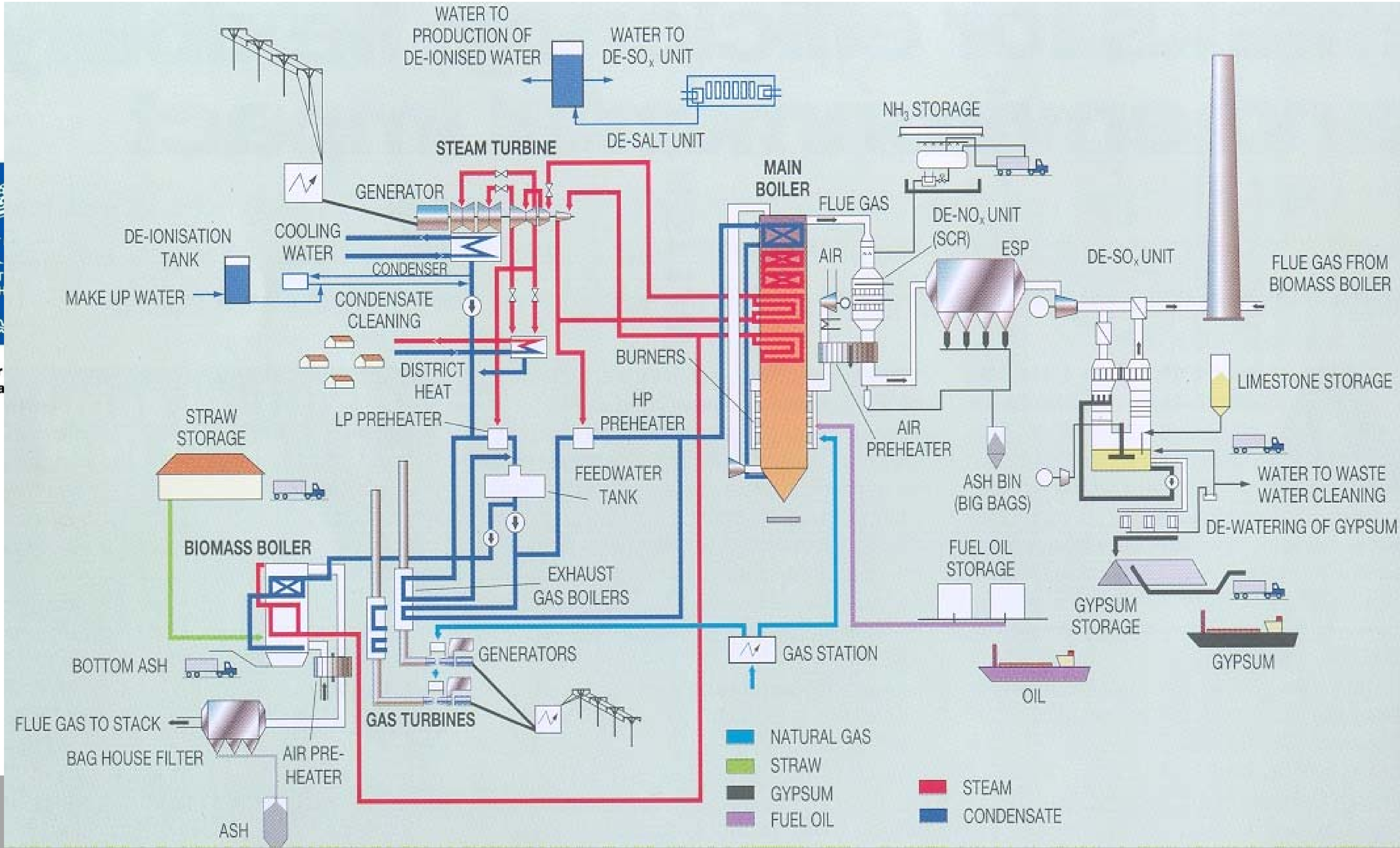
Hybrid Combined Cycle example

The Avedøre Power Plant near Copenhagen, Denmark; combining two gas turbines + a natural gas fired supercritical steam boiler + a biomass-fired steam boiler feeding the same steam turbine:



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Triple Hybrid Cycle

Geothermal + Solar CSP + Solar PV hybrid power plant near Fallon (Stillwater), Nevada:

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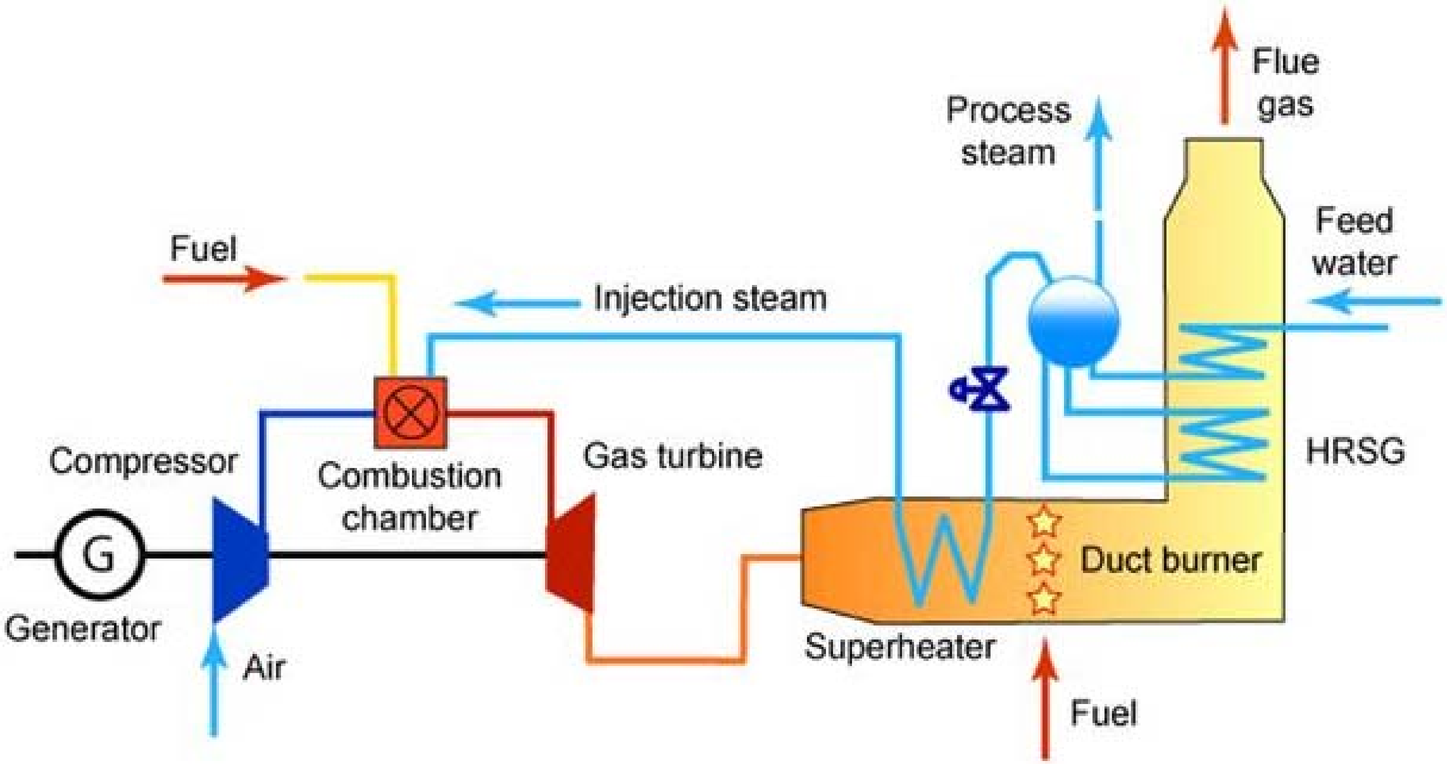
Peculiar combined cycle configurations

1. The steam-injected gas turbine:



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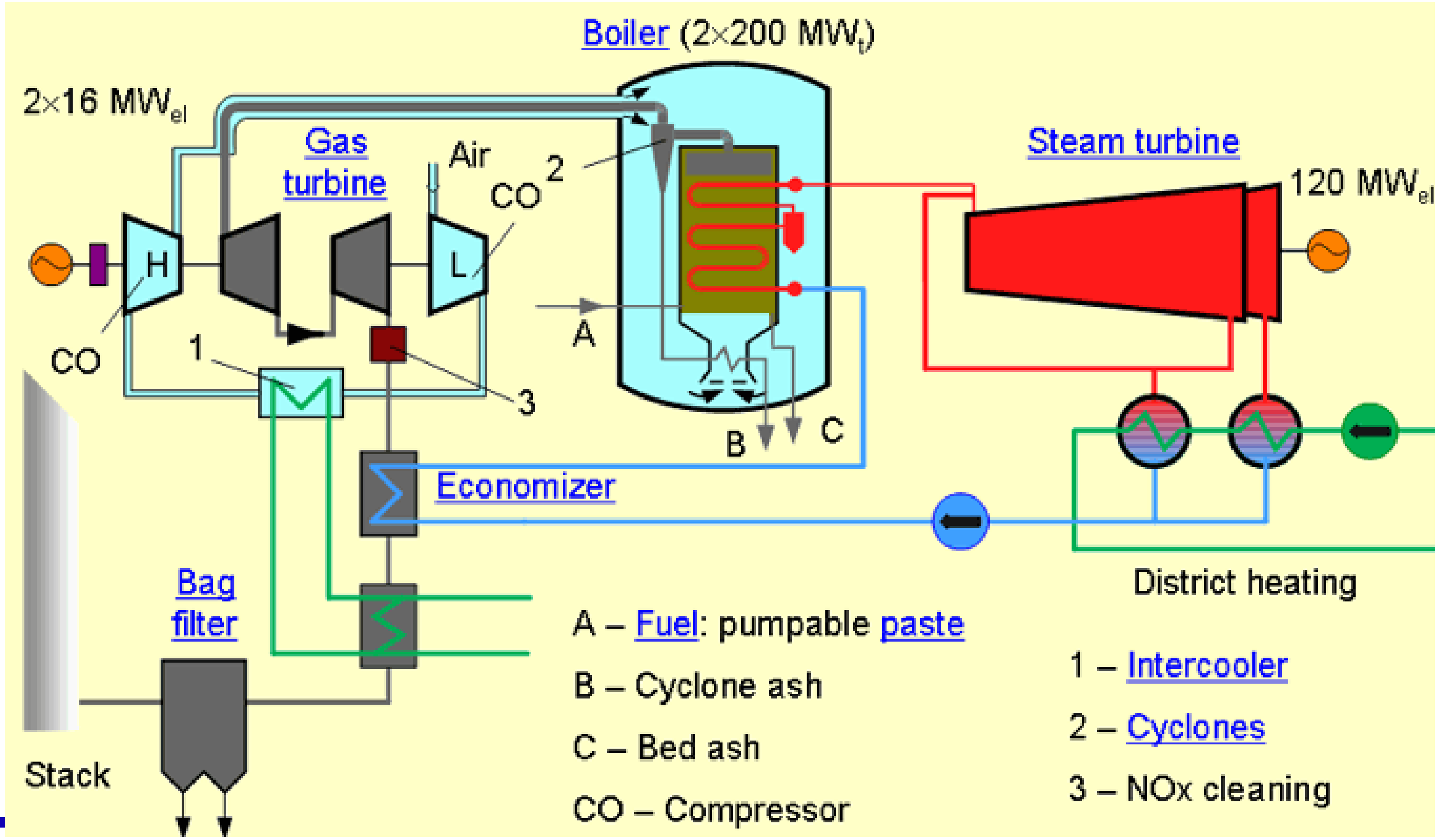
Peculiar combined cycle configurations

2. The pressurized fluidized bed combustion (PFBC):



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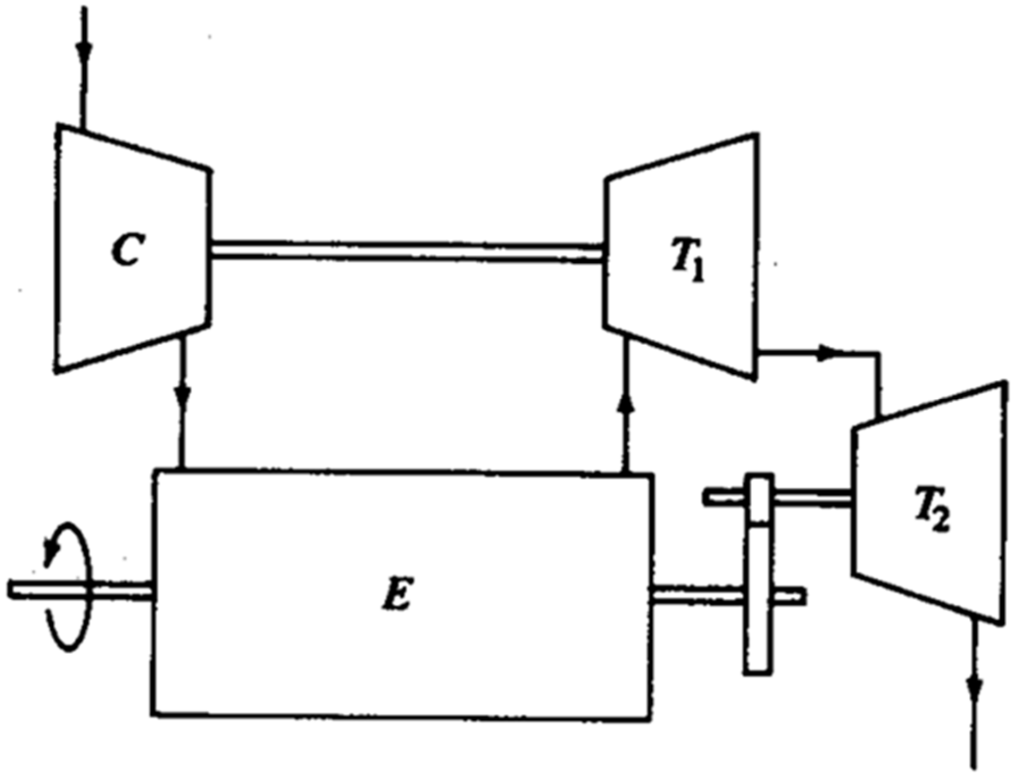
Peculiar combined cycle configurations

3. **The turbocompound system for internal combustion engines:**



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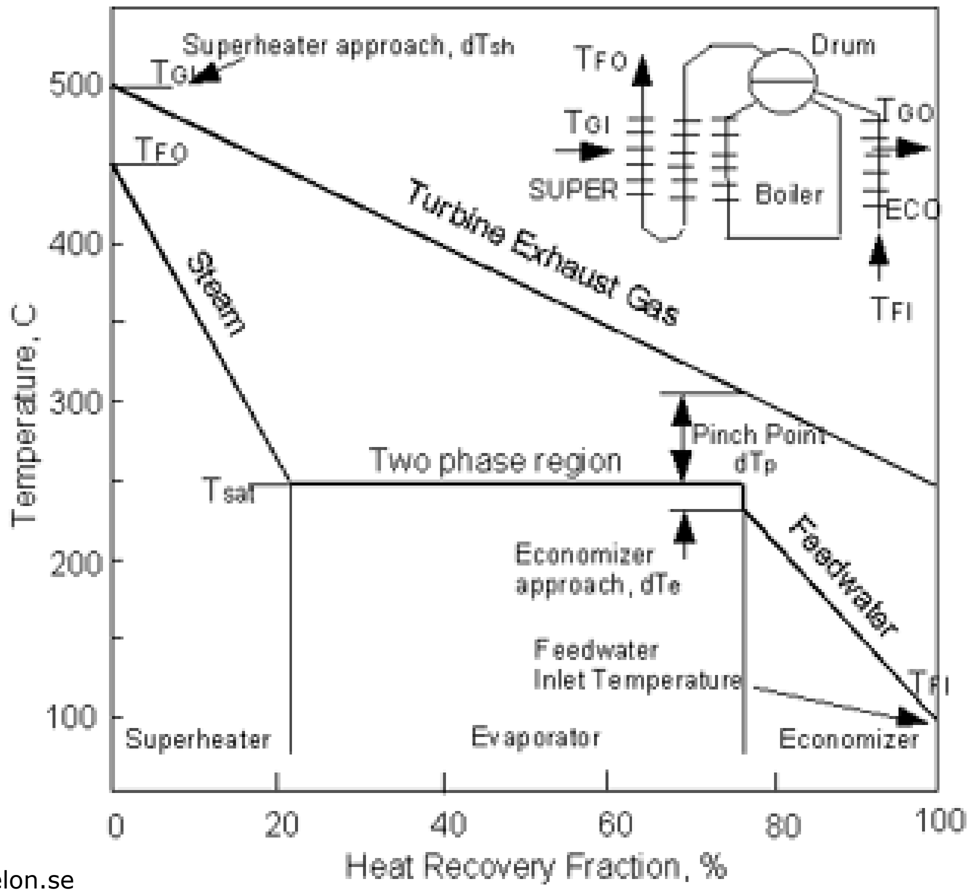
Optimizing the HRSG



Source: www.modelon.se

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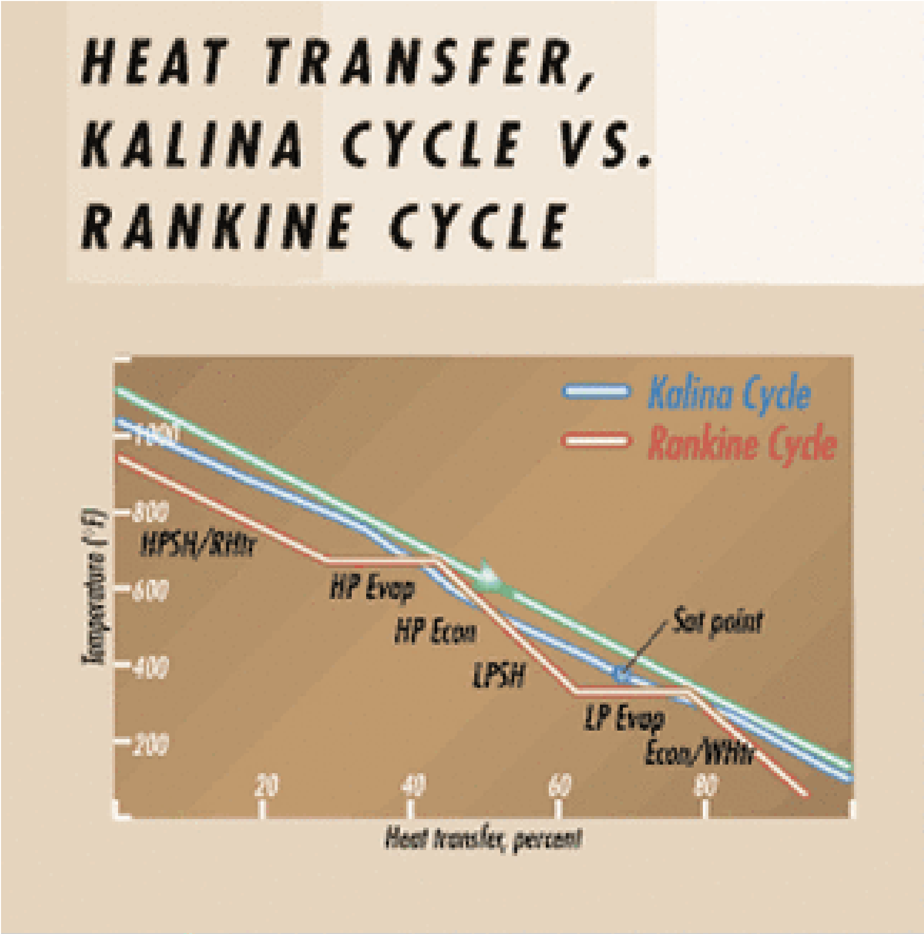
There is an optimum steam pressure in the HRSG, a function of the actual exhaust gas parameters, the losses, and the pinch point ΔT.

The practical limit for the number of steam pressure levels is 3, beyond which the HRSG becomes complicated and too expensive.

Advanced fluids for bottoming cycles



Mixtures (fluid blends) instead of pure fluids can be applied for better utilization of available heat in a HRSG.

A blend of ammonia and water has been suggested as a very efficient bottoming fluid:
➔ the Kalina cycle.

Source: www.powergenworldwide.com

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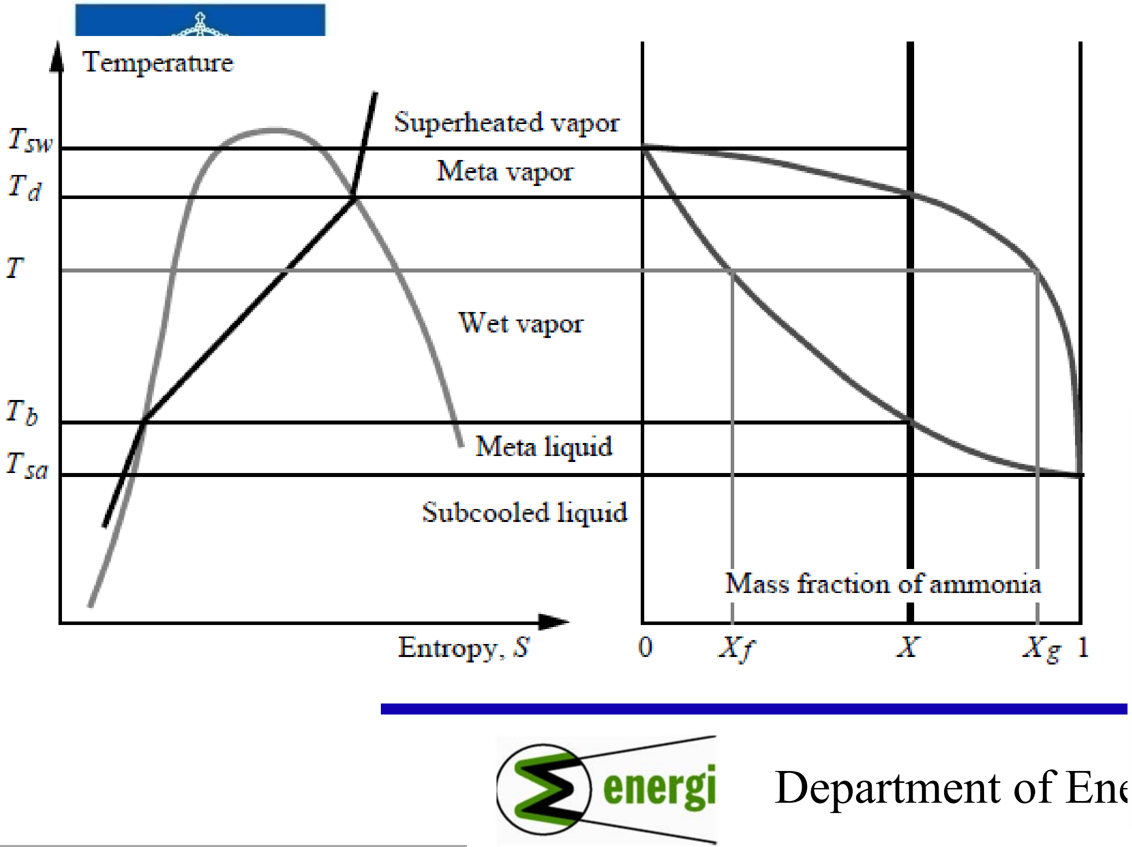
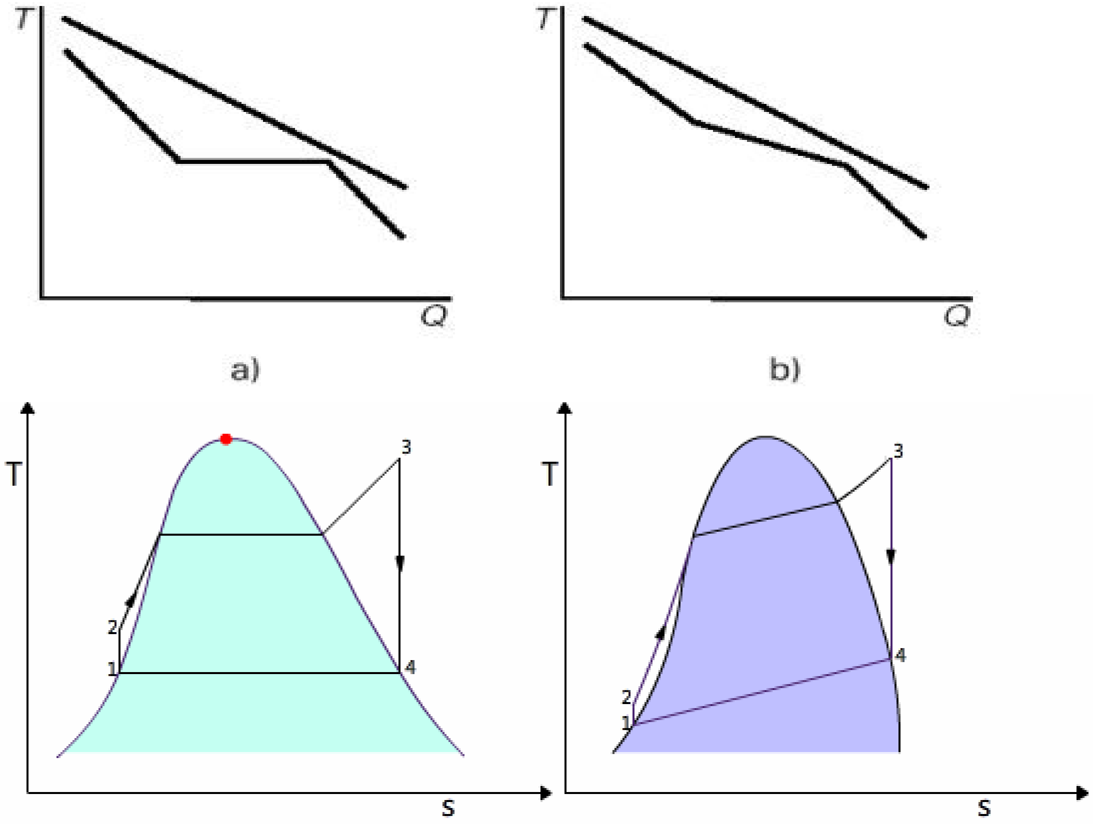
The Kalina cycle

Working fluid in the bottoming cycle: **water + ammonia**!
A mixture of two fluids doesn't have a constant temperature of evaporation but rather sliding between the saturated temperatures of the constituents at any given constant pressure!
This phenomenon offers a way to decrease the exergy loss in the HRSG, at least in theory, with a simple low-cost arrangement if compared to the multiple-pressure single-fluid system.





Polygeneration Combined Cycles

Al Taweelah plant in Abu Dhabi – combining gas turbines, steam turbines, and water desalination units.

Source:
Modern Power Systems,
January 2004

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