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COVER NOTE

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Delegations will find attached document SWD(2023) 1 final - PART 2/6.

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PART 2/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

JRC technical report on "Assessment of the potential for energy efficiency in electricity generation, transmission and storage"

{COM(2023) 1 final}

Contents

2.2 Thermodynamics and thermal generation

As mentioned above, the two most important thermodynamic cycles used for electricity generation are:

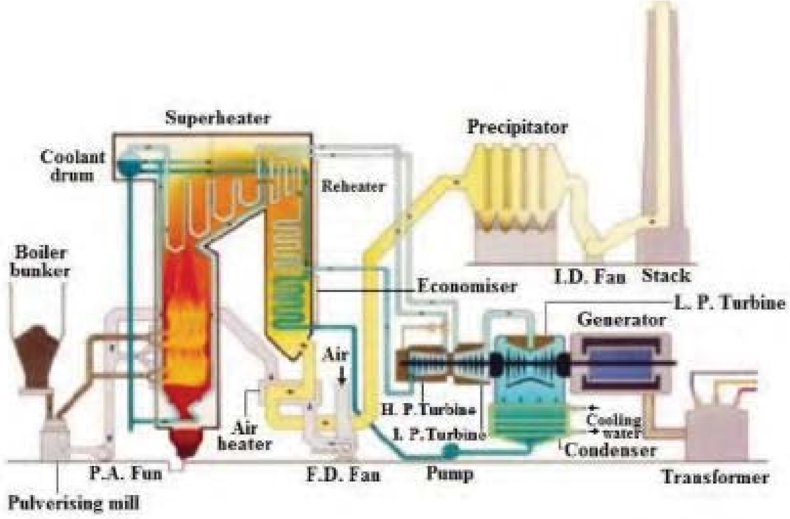
- Rankine cycle, used in conventional thermal plant (fuelled by coal, oil, gas or other fuels) as well as in nuclear power stations;
- Brayton cycle, used in Gas Turbines (GT).

2.2.1 The Rankine cycle

The Rankine cycle (Figure 5) makes it possible to generate electric power by means of an electric generator moved by a steam turbine. The steam to be expanded in the turbine is produced by a boiler where the combustion of the fuel (coal, oil or gas, typically) takes place, thus providing the necessary heat to transform the feeding water into steam at suitable pressure and temperature conditions.

After the expansion in turbine, the steam is discharged to a condenser where it is condensed to water at low pressure. This water is then pumped to higher pressure and sent back to the boiler to close the cycle.

Figure 5. Simplified scheme of thermal plant [7].



From a thermodynamical point of view, the Rankine cycle has the same basic properties independent of the fuel adopted to generate the steam (gas, coal, oils, waste, nuclear, etc.). Its main components are:

- The boiler: the boiler furnace is surrounded by high-pressure pipes belonging to evaporation circuit. They are hit by the thermal radiation of the ignited fuel. The feedwater, previously heated into the boiler convective part, circulates inside the pipes, absorbs the heat and changes into steam; saturated steam is collected in the drum. Different types of boiler are currently available:
  - Natural circulation boiler: here the circulation is achieved thanks to the density difference of the water. The circulation of the feedwater is simply guaranteed by convection.
  - Controlled circulation boiler: the natural circulation takes place helped by pumps.
  - Forced circulation boiler or once through boiler. In this type of boiler, drum is not required since there is not a distinct evaporation circuit and circulation is guaranteed by feedwater pumps suitably sized.

  The saturated steam is introduced into superheaters and then sent to the high pressure (HP) steam turbine; back from the HP turbine, it is then reheated in the boiler and resent back to the medium and low pressure turbines (MP and LP respectively); finally, it is discharged to the condenser.
- The steam turbine: the axial steam turbine is placed on the same shaft as the electrical generator and it is usually made by two or three sections (HP, MP, LP). The boiler reheater placed between the first two sections of the turbine increases the plant efficiency. Other arrangements are possible, depending on the power, on the amount of available steam, etc. The solution described is the standard one, called tandem

compound, but in some cases two different shafts are used, at different angular speed, and that solution is called cross compound.

- The cooling system: after the steam is discharged by the LP steam turbine, it has to be converted back to water by cooling. When cooling water is available (sea or river water), condensers are typically used, as they are more efficient; however, when cooling water is not available (because the power station is far from any sea or river) or its use is subject to restrictions or it is too expensive, cooling towers or air-cooled condensers are used.
    - Condenser: the condenser is installed at the outlet of the steam turbine. The cooling water, flowing through the pipes, condensates the steam, that enters from the shell side and drops down into the hotwell. The cooling water is usually provided by either large rivers or the sea: that water is hence pumped into the condenser. The condenser, along with the drums and the deaerator, is also important from the operational point of view, because it is a reserve of condensate to compensate load variations and transients.
    - In cooling towers, the heat is ejected into the atmosphere by the partial evaporation of the water into a tower. Cooling towers are less efficient than condensers, but more efficient than air cooled condensers.
    - Air cooled condensers are made up of modules are arranged in parallel rows. Each module contains a number of fin tube bundles. An axial flow forces the cooling air across the heat exchange area of the fin tubes.
- Feedwater pumps: needed to increase the pressure of the feedwater and to pump it into the boiled and the turbines.

In order to increase the efficiency of the Rankine cycle, it is important to make use of suitable materials, because all the following measures require it:

- Increase the vaporization temperature and pressure;
- Decrease the condensation pressure;
- Increase maximum temperature in superheaters;
- Introduction of feedwater heaters (6-7 heaters at both LP and HP) for the feedwater, that make use of steam extracted from the turbine to heat feedwater;
- One or more superheating;
- Pre-heating of combusting air;
- Optimization of consumption of auxiliaries.

All such measures are always implemented in modern thermal power stations, as the Rankine cycle is a very mature technology. Nowadays, most actions are addressed to the control of emissions and improvement of dynamic performances to be more effective in modern electricity markets, rather than increasing of efficiency. It is worth noticing that Rankine cycles typically have a very high consumption of electrical energy to supply all auxiliary systems: pumps, fans, but also the more and more requiring system to limit emissions and pollutants. This makes the difference between gross and net electricity production very significant.

As mentioned, the basic Rankine cycle can be fuelled by different types of fuels: coal, oil and gas are the most used. The efficiency is basically the same, but due to the low cost of coal, currently coal Rankine cycles are the only power plants competitive on the electricity markets. The use of gas and particularly oil for Rankine cycles is nowadays almost abandoned.

2.2.1.1 Coal power plants

As previously mentioned, most coal power stations are based on the Rankine cycle. In such cases, the boiler is a pulverized coal-fired boiler, where the pulverized coal is burnt easily and efficiently. Pulverized coal plants can present subcritical, supercritical or ultra-supercritical boilers; these boilers can operate with different types of coal (hard coal, lignite, bituminous coal), but biomass or other materials may be added to the fuel mixture (where usually a Circulating Fluidized Bed boiler is preferred [8][9]).

The raw coal is crushed into small pieces and then pulverized, by coal mills, into fine powder and sent to the combustion chamber. The required air flow is guaranteed by proper fans; the fuel-air mixture is hence introduced as a vortex fluid in different points of the combustion chamber though suitable burners and ignited. Fluidized bed combustion is another common technology used for boilers, as it is able to provide higher efficiency and it can also combust mixtures of fuels.

Among the huge variety of coal types, anthracite, also known as hard coal, presents the highest carbon content and fewer impurities; its energy value ranges from 7000 to 8000 kcal/kg. The most used type of coal for electricity generation is the bituminous coal. The emissions generated by the combustion of solid fuels are the sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO) and dust. SO_2, CO, dust and NO_x can be nowadays managed and reduced with specific technologies (primary and secondary measures) while the handling of CO_2 is still an open issue. Carbon capture storage is not yet a technology ready for a real implementation [10][11][12].

Coal plants, in general, are not very suited to provide fast dynamics and ancillary services for the system. The flexibility allowed can be increased but it is not available in the basic structure of the plant. Regarding the start-up procedure, as a general indication, a 320 MW plant requires 6/8 hours of preheating operations before its synchronization with the grid, depending on the initial conditions, the most binding constraint being the heating of the steam turbine. On the contrary, in case of emergency conditions in the power system, the dynamic response to large load ramps can be very good in the first second after a significant transient, and this is a very important point for the security of the power system.

The overall plant efficiency has been increasing over the years and modern coal power plants are characterised by efficiencies described in Table 1:

Table 1. Boiler types and main features

Type	Main steam pressure [bar]	Main steam temperature [°C]	Reheat steam temperature [°C]	Gross efficiency [%]
Subcritical	166	538	538	36
Supercritical	241	550	550	40-42
Ultra-supercritical	> 276	> 580	> 580	47

The size of a steam turbine can vary between 320 and 1300 MW; this last value can be reached with supercritical and ultra-supercritical boilers with double reheater system and cross, or also tandem, compound turbines.

The efficiency of the entire plant is affected by the energy losses along the described elements and depends on the loading level. The maximum efficiency is achieved usually at the maximum generated power: lower loading implies lower efficiency due to the lower pressure and temperature compared to nominal values. Figure 6 and Figure 7 show the required developments of the material, processes and components required to increase the plant efficiency up to a theoretical 50 % efficiency. It is worth noticing that the gross power produced should be decreased by the power of auxiliary services, necessary to run the power station. Such services are particularly significant for coal plants. For example, a 660 MW group can require up to 27 MW for its continuous operation. This of course makes the overall (net) efficiency lower.

The combination of a good efficiency and the low cost of the fuel makes this type of power plant still competitive in the electricity market. Its main drawbacks are a somehow low flexibility and the decrease of efficiency as the loading in not at its optimal values.

Figure 6. Efficiency improvement of different steam boilers [13].

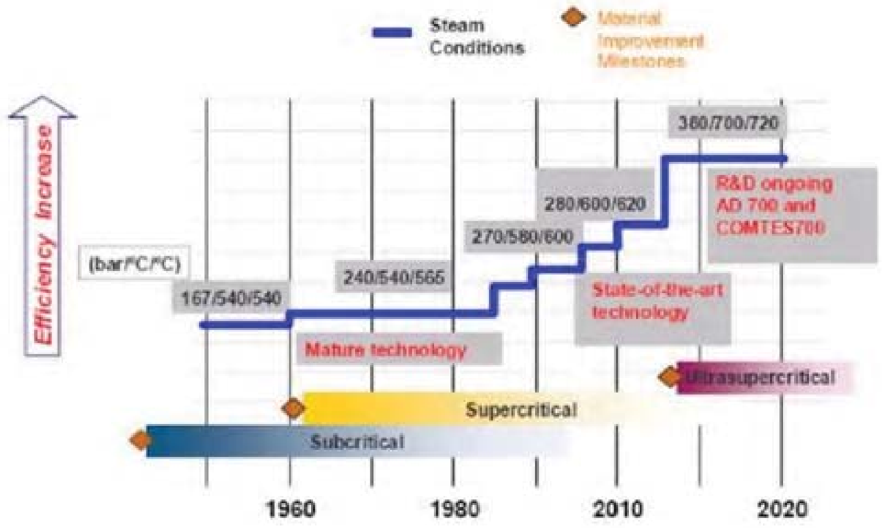
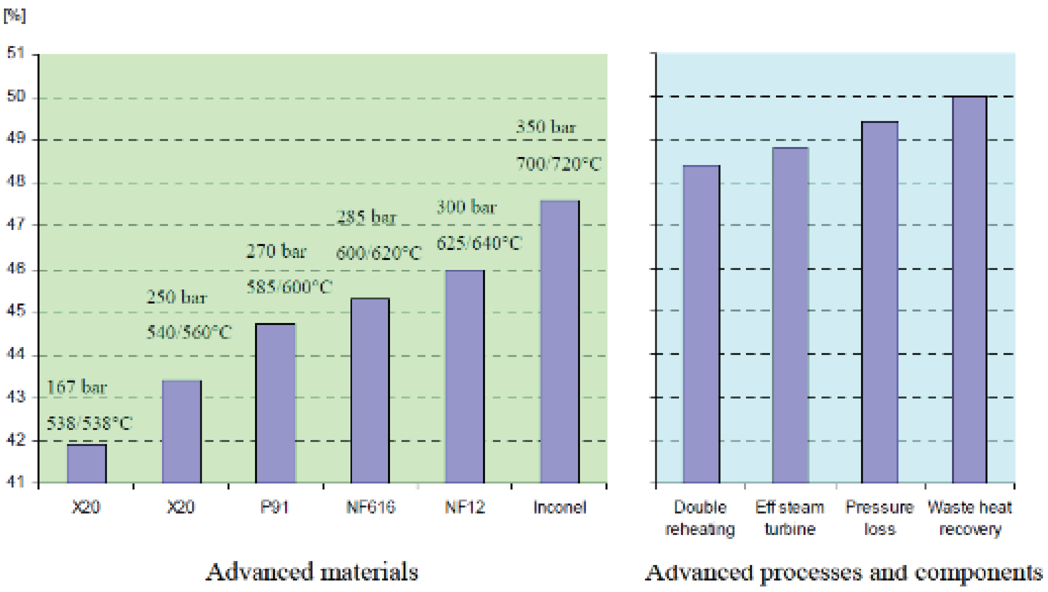


Figure 7. Efficiency improvements of pulverised coal power plants [14].



Appendix I shows the EU annual Production of electricity from coal (1985-2019), from 41.8% to 15.2%, which is expected to be zeroed out due to the EU coal phase-out. Also the classification of pulverized coal combustion plants in terms of steam parameters is presented.

2.2.1.2 Oil power plants

The Rankine cycle described in Figure 5 can be fed by oil as well. The oil is usually kept warm around 40 °C into the storage tanks, is pumped to the boiler spray nozzles and then ignited.

Most of the liquid fuels used are derived from crude oil, characterized by 84 % of carbon, 12 % hydrogen and 2 % oxygen. The sulphur content may vary depending on the refinery treatment. Fuel oil type “bunker C” is usually adopted for the thermal generation, and it can be classified according to its sulphur content. Its energy value ranges from 9600 to 9800 kcal/kg. Emissions generated by the combustion of oil are the sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and they are generally managed in the same way as in coal power plants.

Oil power stations are currently out of the market, as their efficiency is low (about 38-40%) and the production costs are high. Few power stations of this type are still in operation, but they are typically used as reserve.

2.2.1.3 Gas power plants

Natural gas is the second most important fossil fuel for generating electricity after coal (Appendix I). In 2019, it covered the 23,3 % of the total global annual electricity production.

The situation in EU is very similar since (Appendix II) gas-fuelled power plants generate about 21,53 % of the overall produced electricity. This percentage is destined to grow more and more in the future due to coal phase-out.

In some power stations, boilers can burn natural gas combined with the fuel oil to supply a Rankine cycle. The natural gas is essentially a mixture of methane (95.8 %), ethane (3.0 %), propane (0.5 %), butane (0.1 %) and nitrogen (0.6 %). Its energy value is 8250 kcal/Sm^3 at 15 °C and 760 mmHg: the energy content of 1 m^3 of natural gas corresponds to 1.2 kg of coal and 0.85 kg of fuel oil. Since natural gas cannot be stored in huge amount, its provision is guaranteed by gas pipelines connected to the gas system (at 50/60 bar) and requires a very accurate schedule. The natural gas is hence decompressed and then finally sent to the boiler, where special burners enable a homogeneous combustion.

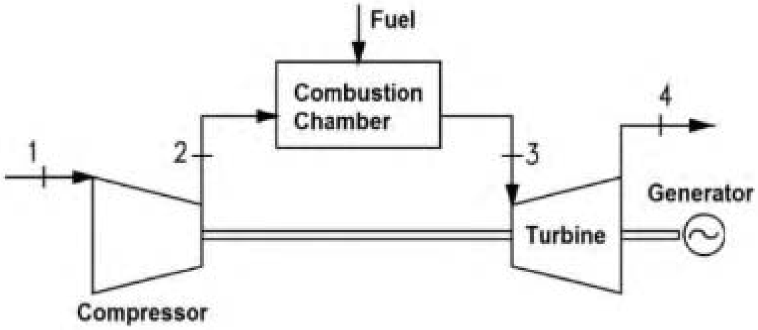
Like oil power stations, also gas-based Rankine cycles are currently out of the market, as generation costs are even higher than oil-based generation. Few power stations of this type are still in operation, but they are typically used as reserve.

2.2.1.4 The Brayton cycle

Natural gas can be used to fuel traditional Rankine power plants, as mentioned in previous subsections, or, alternatively, gas turbines (GT). GTs can be then used in open cycle plants (OCGT) or in combined cycle plants (CCGT).

A gas turbine is a fluid combustion machine which is the core of the Bryton cycle schematically depicted in Figure 8; air is the working fluid.

Figure 8. Gas turbine [15].



The basic Brayton cycle is made by a compression of the fluid (air), heating by means of gas combustion, expansion of hot exhaust gas and discharge. This is done arranging on the same shaft the compressor, the turbine, and the synchronous generator: the power available from the gas turbine is used to move the compressor, and the remaining power is converted to electricity. The OCGT power output and efficiency highly depend on the ambient conditions; in particular, the ambient temperature and pressure affect the maximum power, that can decrease during the summer period. So, a cooling system may be placed after the filtering stage.

Therefore, OCGTs for generation of electrical power have the following components.

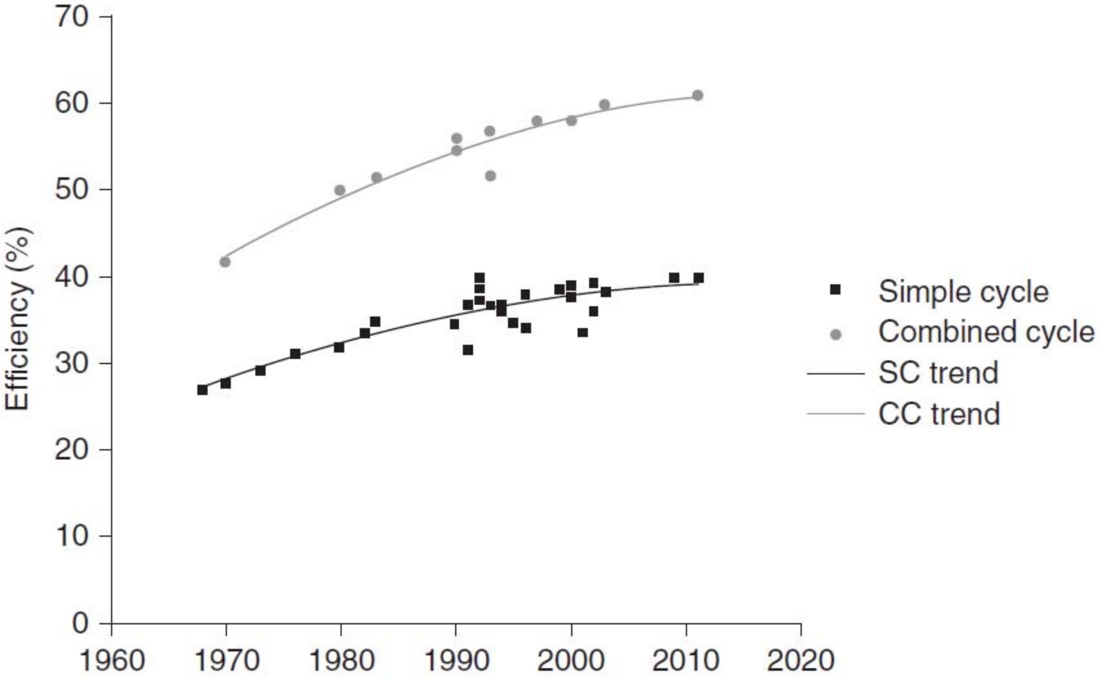
- Compressor: a multi-stage axial compressor that compresses the ambient air. An efficient multistage filter is always installed before the compressor, to avoid the turbine damage and deterioration. The compression ratio can vary between 16:1 and 30:1, depending on turbine requirements. Instabilities, like surging and stalling, that may affect the performance of the compressor and even damage it, can arise; hence, the fuel flow is controlled in an efficient way monitoring the air streams.
- Combustion chamber: here the fuel is injected and burnt. Special nozzles are used to increase the efficiency of the turbine and decrease the pollution emissions, mainly carbon dioxide, CO_2, and nitrogen oxides, NO_x, by suitably controlling the combustion.
- Gas turbine: it is a three/four stage turbine, where the pressurized air-fuel mixture expands. The air-fuel mixture can reach 1400-1500 °C. Therefore, special ceramic materials and cooling systems are applied (film cooling using air from the compressor) to overcome material damage and increase efficiency.

Nowadays, OCGT can reach an efficiency of 38 – 40 % (Figure 9); moreover, the generation costs are quite high, due to the high fuel costs. In order to improve efficiency of power generation GT, a few actions could be taken:

- Increasing of the pressure ratio;
- Increasing of the maximum temperature of the cycle;
- Decreasing of the air temperature (e.g., fogging or chillers);
- Pre-heating of the fuel.

The first two actions require significant improvements for what the materials are concerned. Inlet air cooling system and fuel heating are currently used.

Figure 9. Efficiency improvement of GT from 1960 [48]: Simple Cycle and Combined Cycle



Actually, GT technology is still showing significant improvements, and it is possible that in the next future the efficiency of OCGT can further increase above 40 %. For example, aeroderivative GT can reach efficiency of 44%; however, their cost per kW is such that lower efficiency heavy-duty GT are preferred today; moreover, aeroderivative GT have higher emissions, that make it necessary to install special and expensive abatement systems.

Notwithstanding such values of efficiency, OCGT are well on the market, because of their dynamic performances: OCGTs are quite compact, thanks to the reduced dimensions of the gas turbine, and they can be easily started up in few dozens of minutes. The turbine power can be adjusted controlling the gas stream or the air stream into the compressor. All such characteristics make OCGT suitable for keeping the power system security in modern power systems, and to promote the integration of renewables providing ancillary services like frequency control, fast start up, black-start capability, adding inertia and short-circuit power to the power system, etc.: they look complementary to the development of renewables, keeping power system security.

2.2.2 The Combined cycle

The best way to improve efficiency by means of a Brayton cycle, is actually obtained combining the two cycles above-described, namely the Brayton and the Rankine cycle. The first one is characterized by high temperatures for the introduction of heat (about 1500°C) on the cycle, but also discharges heat at high temperatures (about 600°C); the second one discharges heat to the ambient at low temperature (about 30°C), but the same holds for the introduction of heat (about 5-600°C). The basic idea of the combined cycle is to combine the two cycles, in order to have a single cycle with introduction of heat at high temperatures and discharge of heat at low temperatures, which guarantee higher efficiency.

Considering a GT like the one described in the previous subsection, its exhaust gases still have a high energy content at high temperature, around 600 °C: instead of discharging such energy to the ambient, like in OCGT, it is sent to a downstream Rankine cycle to produce steam to drive a steam turbine. That steam is therefore not produced by burning any additional fuel in a boiler but taking advantage of the heat recovered from the Brayton cycle. This arrangement is the Combined cycle (CCGT). Figure 10 shows a typical scheme of a CCGT, where a Heat Recovery Steam Generator (HRSG) is present to recover heat from the exhausted gas coming from the GT and produce steam for the Rankine cycle downstream.

The HRSG consists of three major components, placed downstream to the exhaust gas flow: the economizer, that works as a preheater, the evaporator and the superheater, that converts saturated steam into dry steam. The heat exchangers are simpler, compared to traditional boilers with combustion chamber, and made of finned tubes. HRSG can present horizontal or vertical displacement and multi-pressure steam levels (high, medium and low pressure) to increase efficiency, each one arranged with an economizer, an evaporator and a superheater; reheaters are commonly used, too. The evaporator bank may present different circulating systems: natural, controlled or forced. The remaining part of the plant is very similar to the traditional steam plants. The steam turbine approximately generates half of the electrical power generated by the gas turbine.

In Figure 10, bottom left, the temperature – entropy diagram of the entire cycle is shown. The global efficiency is very high, reaching the 55 – 60 %; some manufacturers have recently developed a combined cycle plant (using H-class GT Technology) with a net efficiency of 64 % [16]. Thanks to their efficiency and lower fuel consumption, compared to same-sized traditional thermal plants, in the past a lot of oil thermal plants have been dismantled and the steam turbine readapted: as a matter of fact, the pollution emissions are significantly lower, since gas fuel does not present any sulphur production (SO_2) and dust; moreover, the overall plant management is simpler. The average size of these plants is in the range 380-800 MW and they can also be built with a single generator (single-shaft). In some configuration, two gas turbines can be combined with a single steam turbine for a total power of 800-1600 MW.

Figure 10. Combined power plant [17].

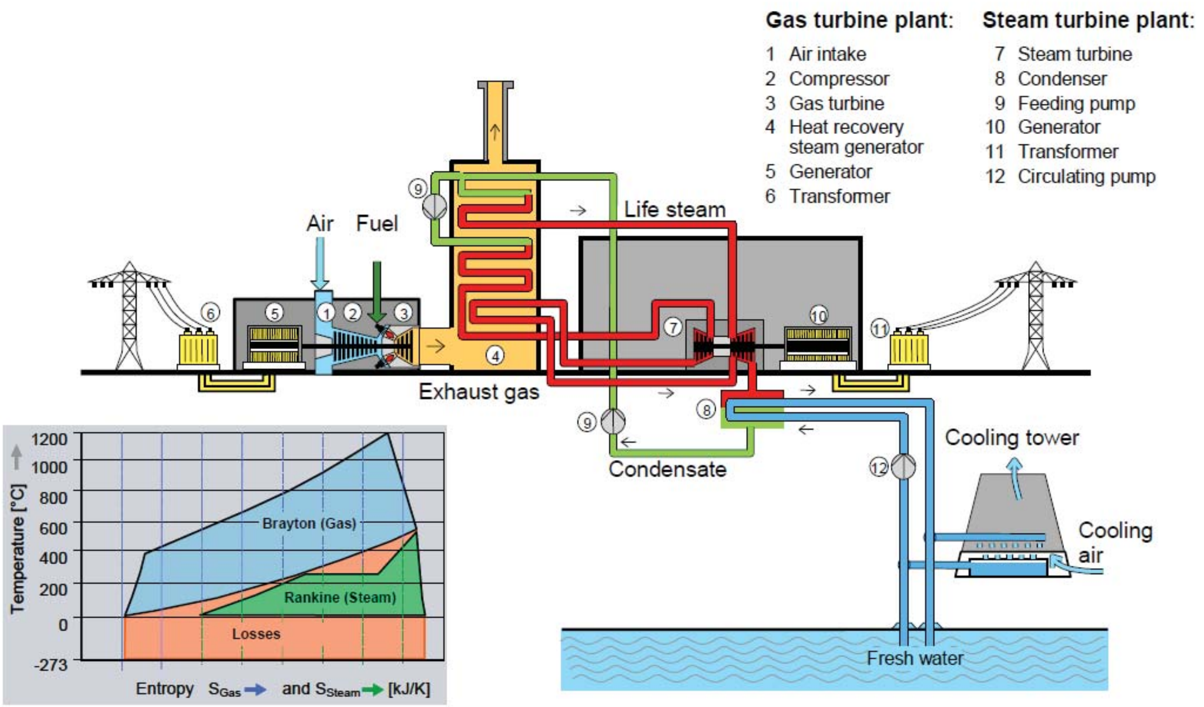
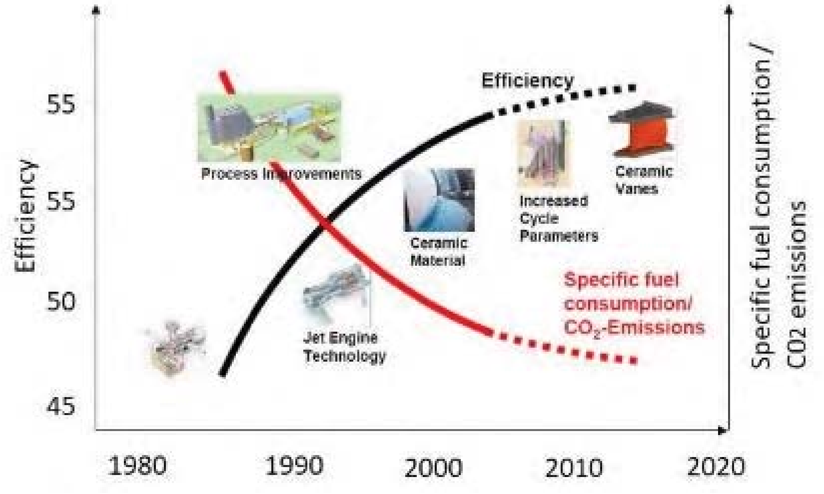


Figure 11 shows the evolution of the combined cycle efficiency over the years: the efficiency has been constantly increased thanks to the new technologies, especially in GT technology and the specific fuel consumption and CO_2 emissions have significantly decreased, making this type of plants very efficient and competitive in the electricity market.

Figure 11. Evolution of the combined cycle efficiency [17].



Gas turbine can be also fed by synthetic gas, generated by the coal gasification and combined with steam turbines. Such plants, called Integrated Gasification Combined Cycle (IGCC), can reach a higher efficiency rate than coal technologies: ICGG plants could achieve an efficiency rate higher than 45%. In a IGCC plant coal is first gasified by creating a 'shortage' of air/oxygen in a closed pressurised reactor, that creates a chemical reaction of the coal with the oxygen. The product from this process, a mixture of carbon and hydrogen (CO and H_2), called synthesis gas or syngas or fuel gas, is cleaned and burned in a gas turbine. SO_2 and NO_x emissions are significantly lower than a conventional coal plant [18].

Appendix II gives out more information on the specifications of GTs, in terms of manufacturers and possible modifications for the increase of its overall efficiency.