MASTER MEIM 2023-2024

Low carbon energy technologies

GREEN MANAGEMENT

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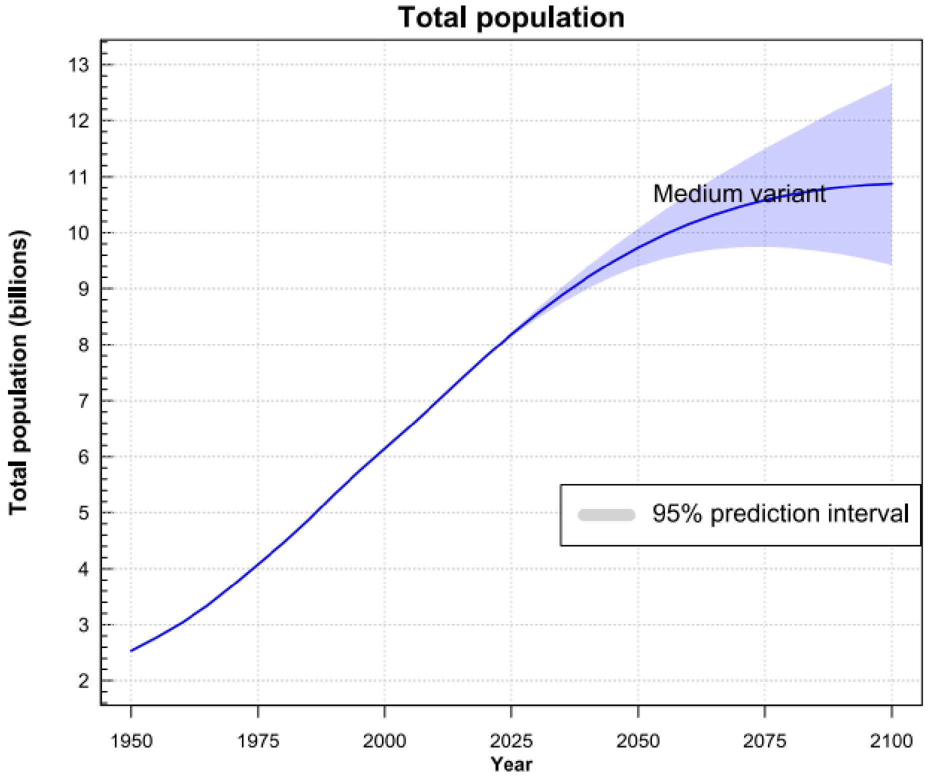
Introduction

Energy, **environment**, and **sustainable development** are three important and interrelated topics confronted by the modern world. Energy directly affects economic development and generation of wealth.

World population continuously increases, with more than 9 billion people projected for 2050. Population increase necessarily implies increasing demand for commodities such as energy.

Projections of world energy demand by resource type are of crucial importance to energy planning and environmental management.

Electricity demand represents the major component of energy consumption worldwide, and the demand is in such close correlation with human population that the projected increase of global population implies an unavoidable increase in consumption.



United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019, Volume II: Demographic Profiles (ST/ESA/SER.A/427). https://population.un.org/

Introduction

It is predicted that the increase of electrical energy consumption is not linearly related to the increase of population. Instead, the consumption of electricity per capita grows more quickly relative to population, given societal development and the diversification of needs over time.

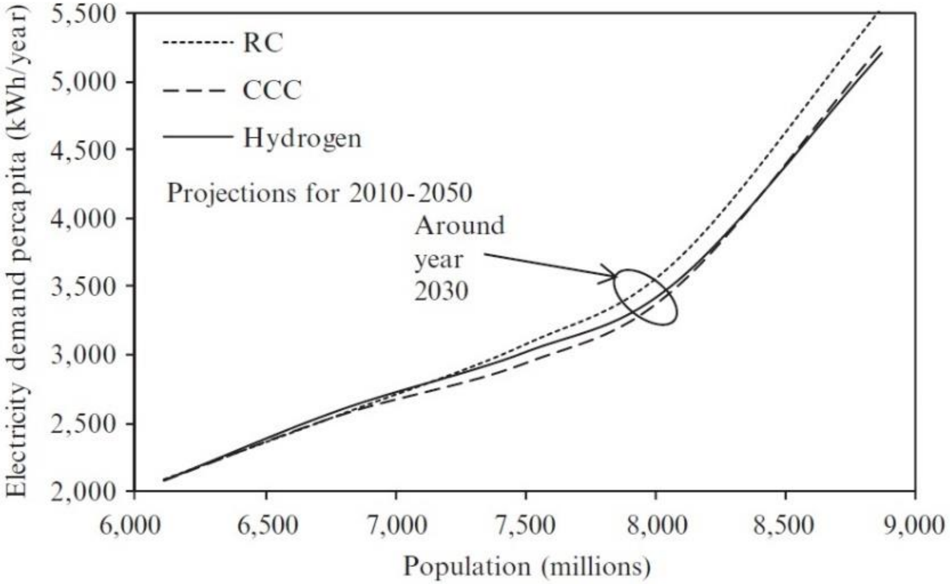
The European Commission formulated projections of world population increase vs power demand until 2050, by defining three scenarios. as follows:

- **Reference Case** (RC) scenario: Nations exhibit a minimum degree of political initiative toward sustainable development.
- **Carbon Constraint Case** (CCC) scenario: Nations impose severe political limits on CO_2 emissions up to 2050.
- **Hydrogen Case** (H2) scenario: Most countries implement policies to facilitate the development of a hydrogen economy.

The curve has a knee by year 2030 after which the electricity consumption increases more sharply.

Developing countries, with a population of around four billion, represent about 77% of the global population, but their electricity consumption represents only 25% of global consumption.

Given the extra energy demand that should occur in developing countries due to population growth, diversification of services, and increases in standard of living, electricity consumption per capita will likely be 1.5–1.8 times higher than population growth rate after around 2030.



European Commission, World Energy Technology Outlook – 2050, WETO-H2 report.

Introduction

There are six essential factors that have to be addressed with sustainable energy solutions:

1. **Efficiency**. There is a strong connection between energy efficiency, environmental impact, and energy resource depletion. Less consumption and less pollution are associated with increased energy efficiency.

2. **Cost effectiveness**. The cost effectiveness of energy solutions is crucial to make them feasible and to promote their spread into the market/society. Costs are related directly and indirectly to sustainability. Cost effectiveness means more savings or reduced expenses for the same services or products.

3. **Resources use**. Better resource utilization is related to energy conservation and refers to the assembly of measures leading to the rational use of resources and energy conservation. Energy conservation leads to the stabilization of energy demand, reduced resource consumption, and decreased environmental impact, enhancing sustainability.

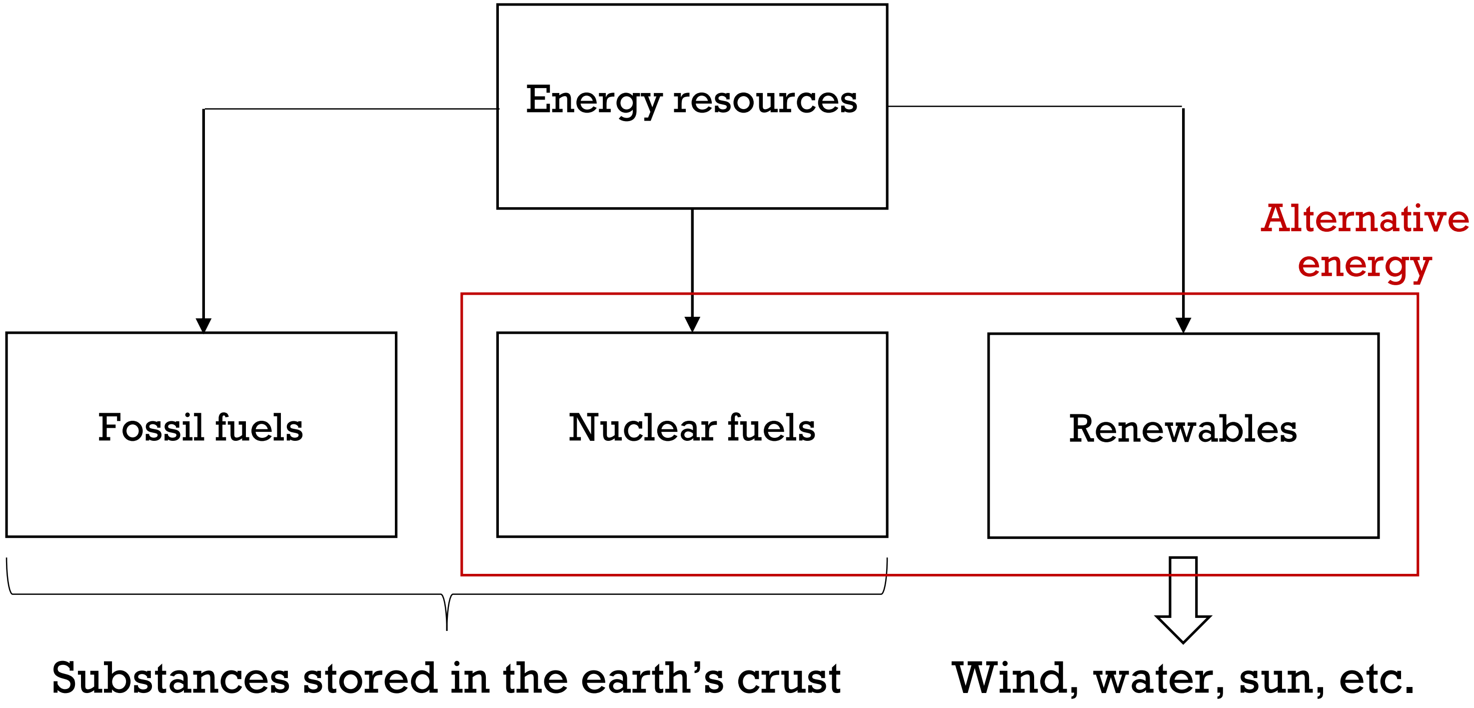
4. **Design and analysis**. These have a direct impact on technology development, innovation, and knowledge enhancement. Systems optimization leads to a better exploitation of energy processes and resources.

5. **Energy security**. Security implies development of energy policies and geopolitical strategies that will eventually assure equitable access to energy resources and therefore increased sustainability and a cleaner environment.

6. **Environmental impact**. Better environment is a basic human desire. Development of energy systems must take into account environmental protection. This stimulates the development of advanced power generation systems capable of producing multiple outputs with lower environmental impact than conventional processes.

Energy resources

An energy resource is any form of energy available on Earth which can be converted into a useful form such as electrical power, mechanical power, or heat.



Energy resources

Alternative energy

Fossil fuels

Nuclear fuels

Renewables

Substances stored in the earth's crust

Wind, water, sun, etc.

Alternative energy refers to energy sources other than fossil fuels. This includes all renewable sources and nuclear. Nuclear is not classified as a renewable energy source, because it is produced from mined elements like uranium and thorium which cannot be replenished.

Energy resources

Any energy resource that naturally occurs and is non-exhaustible is referred to as **renewable energy**.

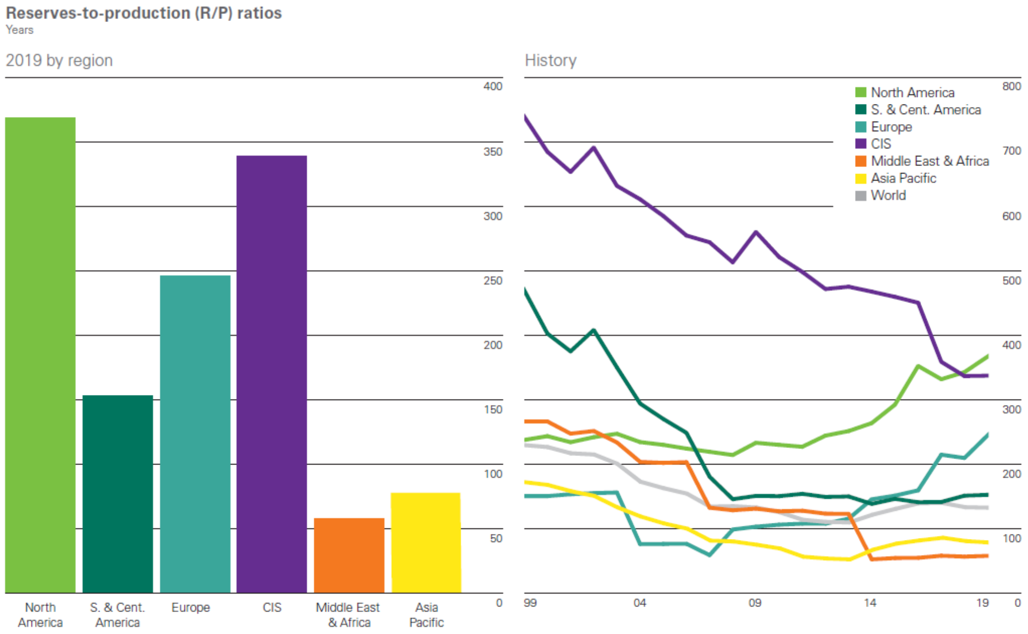
The use of renewable energies therefore does not affect the availability of natural resources for future generations.

Energy resources

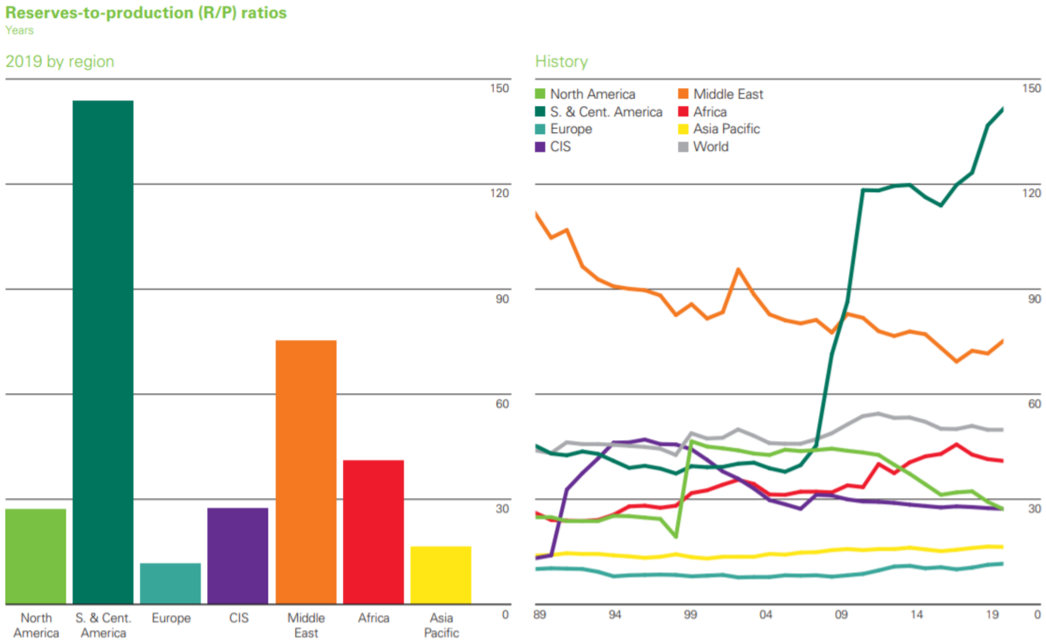
Fossil fuel: any of a class of hydrocarbon-containing materials of biological origin occurring within Earth’s crust that can be used as a source of energy. Fossil fuels are non-renewable resources. This means that we use them much more quickly than nature makes them.

Fossil fuels are mainly used for direct combustion with air in various systems such as furnaces, gas turbines, and internal combustion engines.

Conventional fossil fuels encompass three classes of materials: *coal*, *petroleum* and *natural gas*.

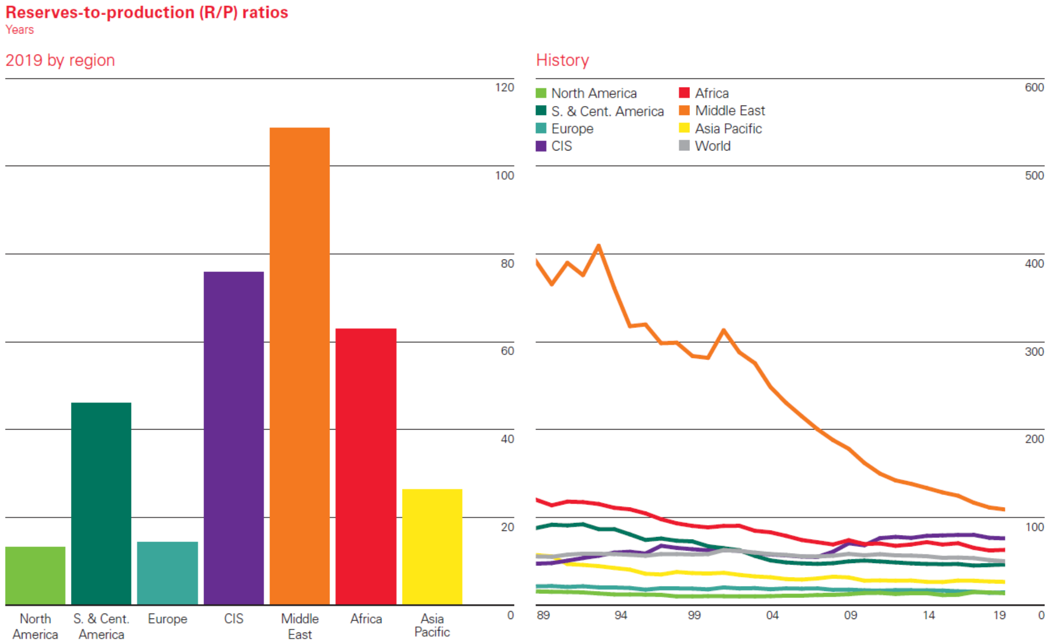


COAL ~ 130 years



PRETOLEUM ~ 50 years

NATURAL GAS ~ 50 years



British Petroleum Statistical Review of World Energy 2020

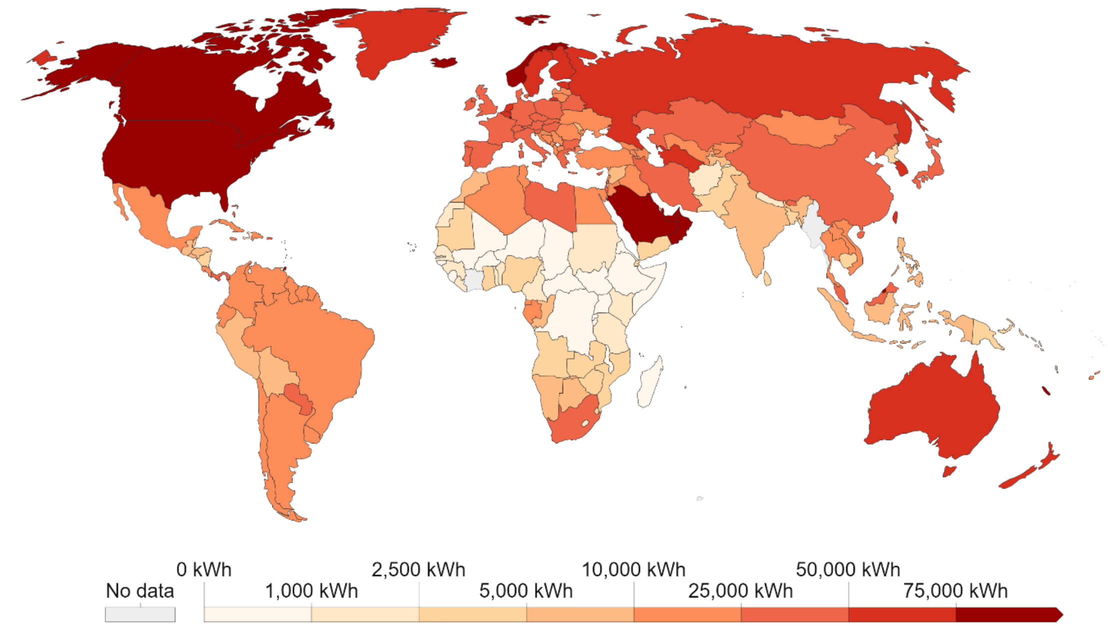
Energy resources

Conventional **nuclear fuel** is represented by fissile Uranium-235, which naturally occurs in form of U_3O_8 ore. One ton of ore yields about 6 kg of fissile uranium, which is equivalent to 144 TJ of electrical energy (or 40 GWh), whereas 1 ton of coal can be used to generate 14000 times less electricity.

Many more non-conventional nuclear fuel resources do exist, mainly in the form of thorium, as well as spent fuel material that might be used in the breeder reactors of next generation nuclear power plants.

Global comparison: how much energy do people consume?

There are vast differences in energy consumption across the world. The ratio between the US and India for example is around 12. This means that the average American consumes about the same amount of energy in one month as the average Indian consumes in an entire year. The average Brit consumes double that of the average Brazilian.



Energy use per person, 2019

Energy use not only includes electricity, but also other areas of consumption including transport, heating and cooking.

Source: Our World in Data based on BP & Shift Data Portal
OurWorldInData.org/energy • CC BY
Note: Energy refers to primary energy – the energy input before the transformation to forms of energy for end-use (such as electricity or petrol for transport).

This metric captures the amount of domestic energy used in each country. It doesn't include the energy used to produce goods that we import from overseas.

Different ways of measuring energy

Understanding the breakdown of energy systems – how much energy we get from coal, oil, gas, nuclear, solar, wind, etc. is crucial. It allows us to compare energy mixes across the world; track whether we are making progress on decarbonizing our energy systems; and plan and manage demands for natural resources.

Evaluating the produced energy from all the different sources is in fact not straightforward at all. These difficulties result in different approaches for "energy accounting" and present a different picture of the energy mix.

There are mainly two key methodologies to account for primary energy: "**direct**" and "**substitution**" methods.

Primary energy refers to energy in its raw form, before it has been converted into other forms of energy (e.g. coal, oil or gas before they are burnt, or solar or wind energy before they are converted into electricity).

When we are asking how much energy is consumed or what the breakdown of the sources of energy is we are asking about primary energy.

Direct primary energy *does not* take account of the energy lost in the conversion of fossil fuels to usable energy. The substitution method *does* attempt to correct for this loss.

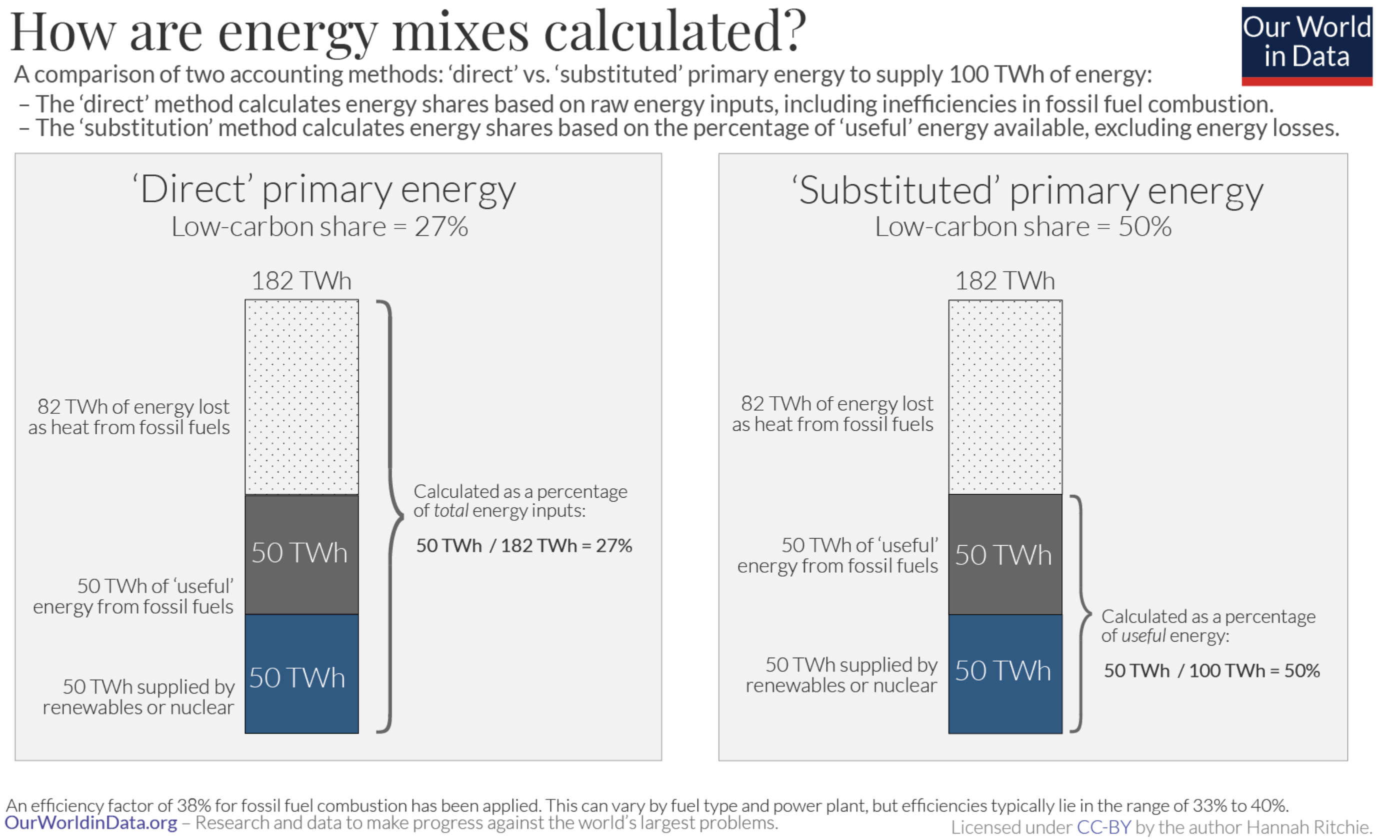
Different ways of measuring energy

When we burn fuel in a thermal power plant most of the energy we put into the process is lost, primarily in the form of heat. Most fossil fuel plants run with an efficiency of around 30-40%. The remaining 70-60% is wasted as heat. This means for every unit of energy that we can use, another two are wasted.

When we measure electricity generation from renewables or nuclear power, we're measuring the direct output, with no losses or waste to consider.

- Low-carbon's share in **direct primary energy** = % of **total primary energy** consumption (including all of the inefficiencies of fossil fuel production)

- Low-carbon's share in **substituted primary energy =** % of **useful energy** (once we subtract all of the wasted energy in the burning of fossil fuels)

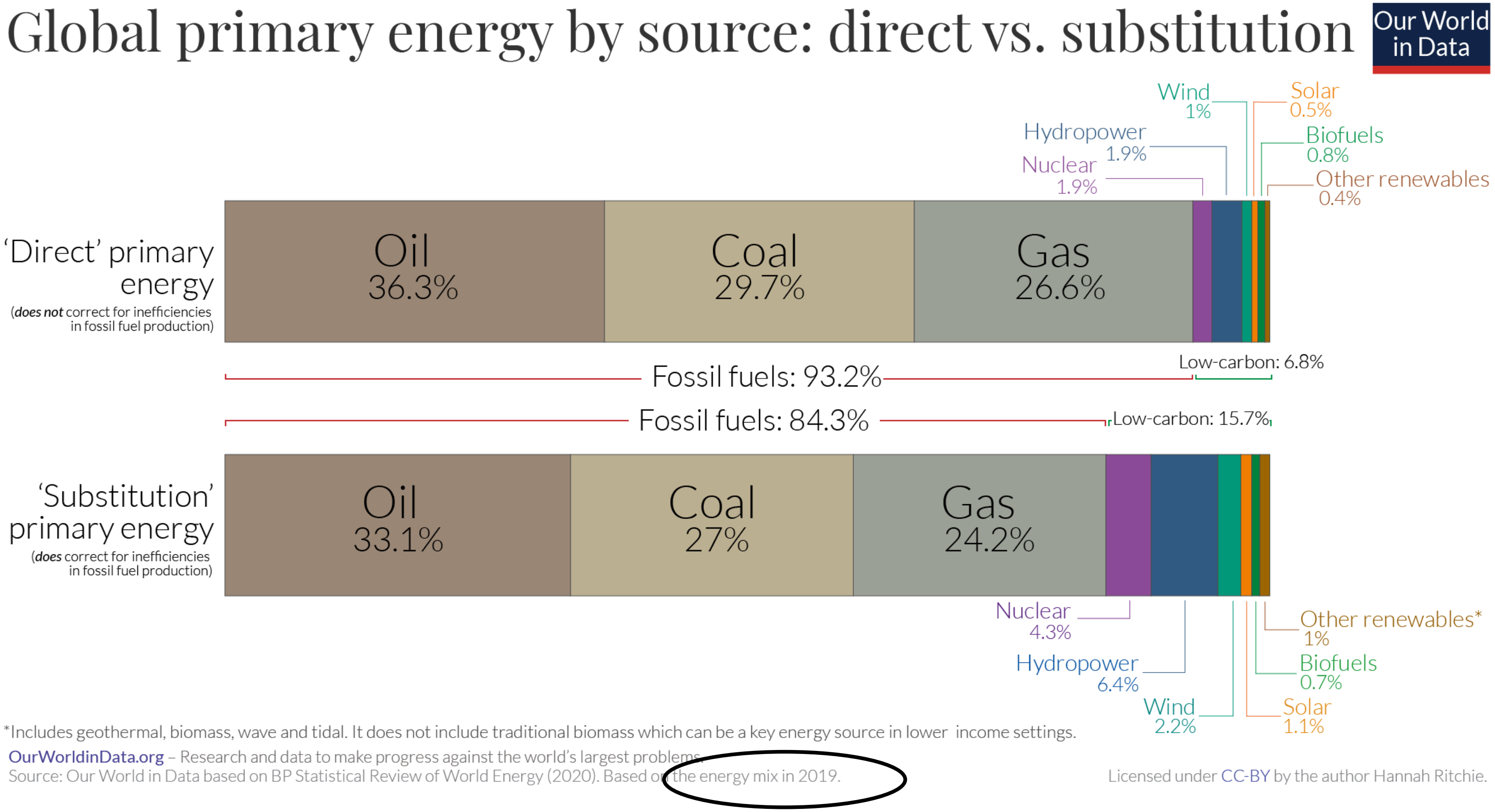


How are energy mixes calculated?

A comparison of two accounting methods: 'direct' vs. 'substituted' primary energy to supply 100 TWh of energy:
– The 'direct' method calculates energy shares based on raw energy inputs, including inefficiencies in fossil fuel combustion.
– The 'substitution' method calculates energy shares based on the percentage of 'useful' energy available, excluding energy losses.

An efficiency factor of 38% for fossil fuel combustion has been applied. This can vary by fuel type and power plant, but efficiencies typically lie in the range of 33% to 40%.
OurWorldinData.org – Research and data to make progress against the world's largest problems.
Licensed under CC-BY by the author Hannah Ritchie.

Different ways of measuring energy



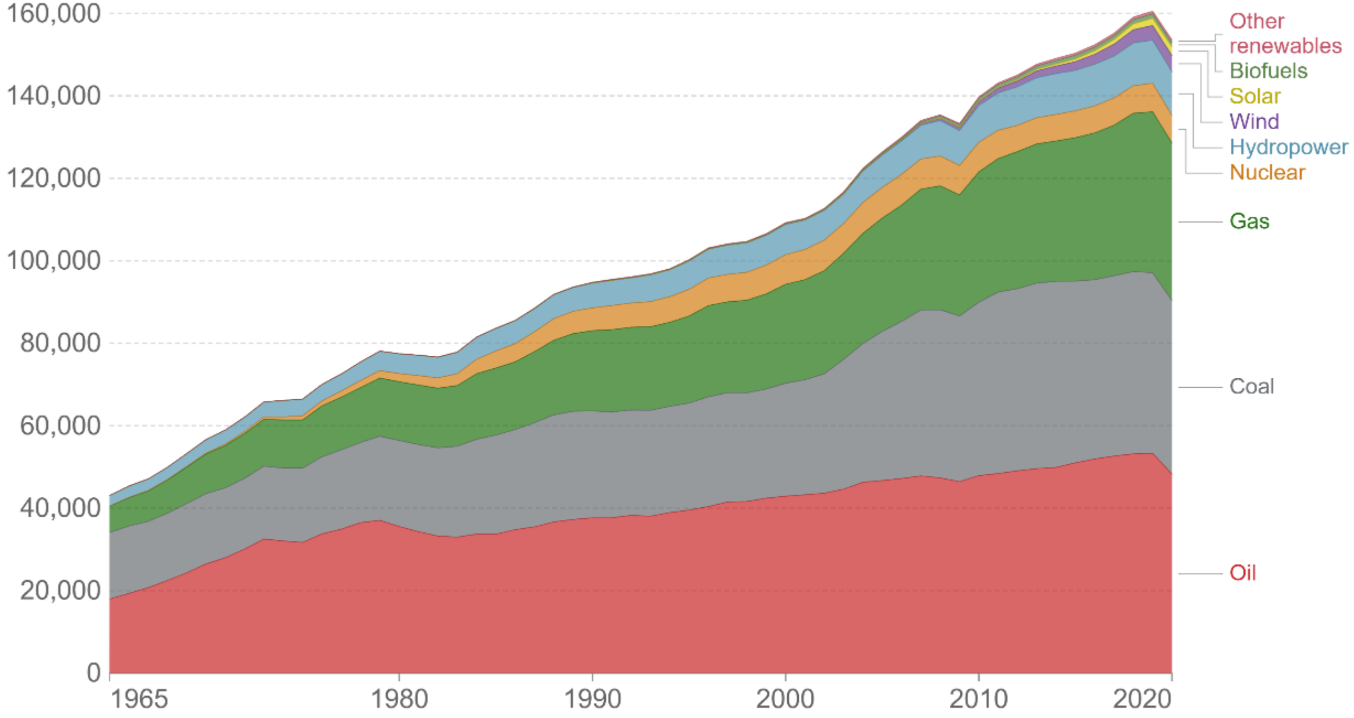
*Includes geothermal, biomass, wave and tidal. It does not include traditional biomass which can be a key energy source in lower income settings.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Our World in Data based on BP Statistical Review of World Energy (2020). Based on the energy mix in 2019.

Primary energy consumption

Energy consumption by source, World

Primary energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor (the 'substitution' method) has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.



Source: BP Statistical Review of World Energy
Note: 'Other renewables' includes geothermal, biomass and waste energy.

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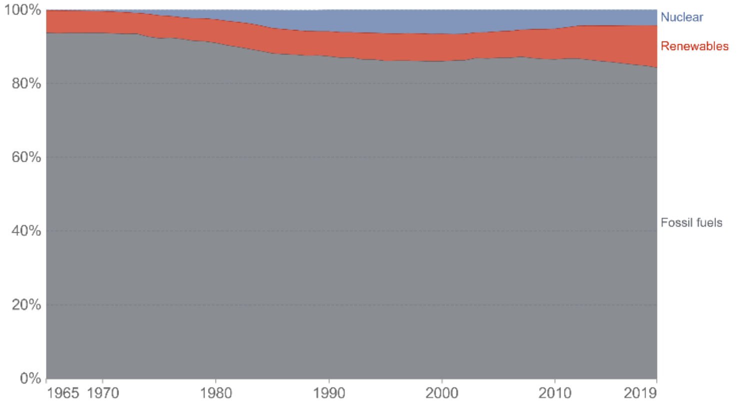
Primary energy consumption from fossil fuels, nuclear and renewables, World

The breakdown of primary energy is shown based on the 'substitution' method which takes account of inefficiencies in energy production from fossil fuels.

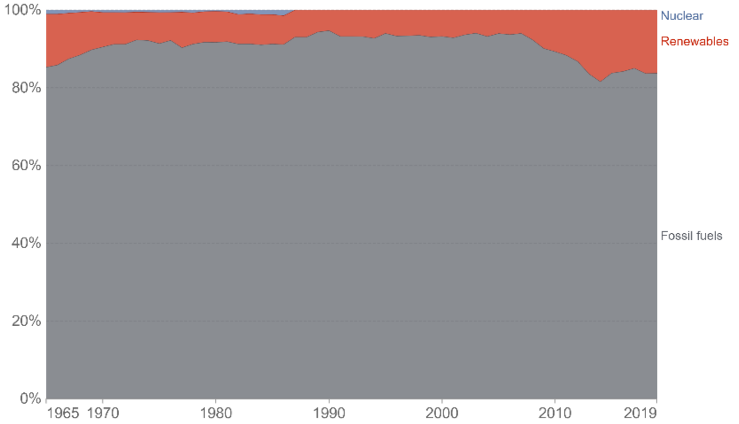


Source: Our World in Data based on BP Statistical Review of World Energy (2020)
Note: Renewables includes hydropower, solar, wind, geothermal, wave and tidal and bioenergy. It does not include traditional biofuels.

OurWorldInData.org/energy • CC BY

Primary energy consumption from fossil fuels, nuclear and renewables, Italy

The breakdown of primary energy is shown based on the 'substitution' method which takes account of inefficiencies in energy production from fossil fuels.



Source: Our World in Data based on BP Statistical Review of World Energy (2020)
Note: Renewables includes hydropower, solar, wind, geothermal, wave and tidal and bioenergy. It does not include traditional biofuels.

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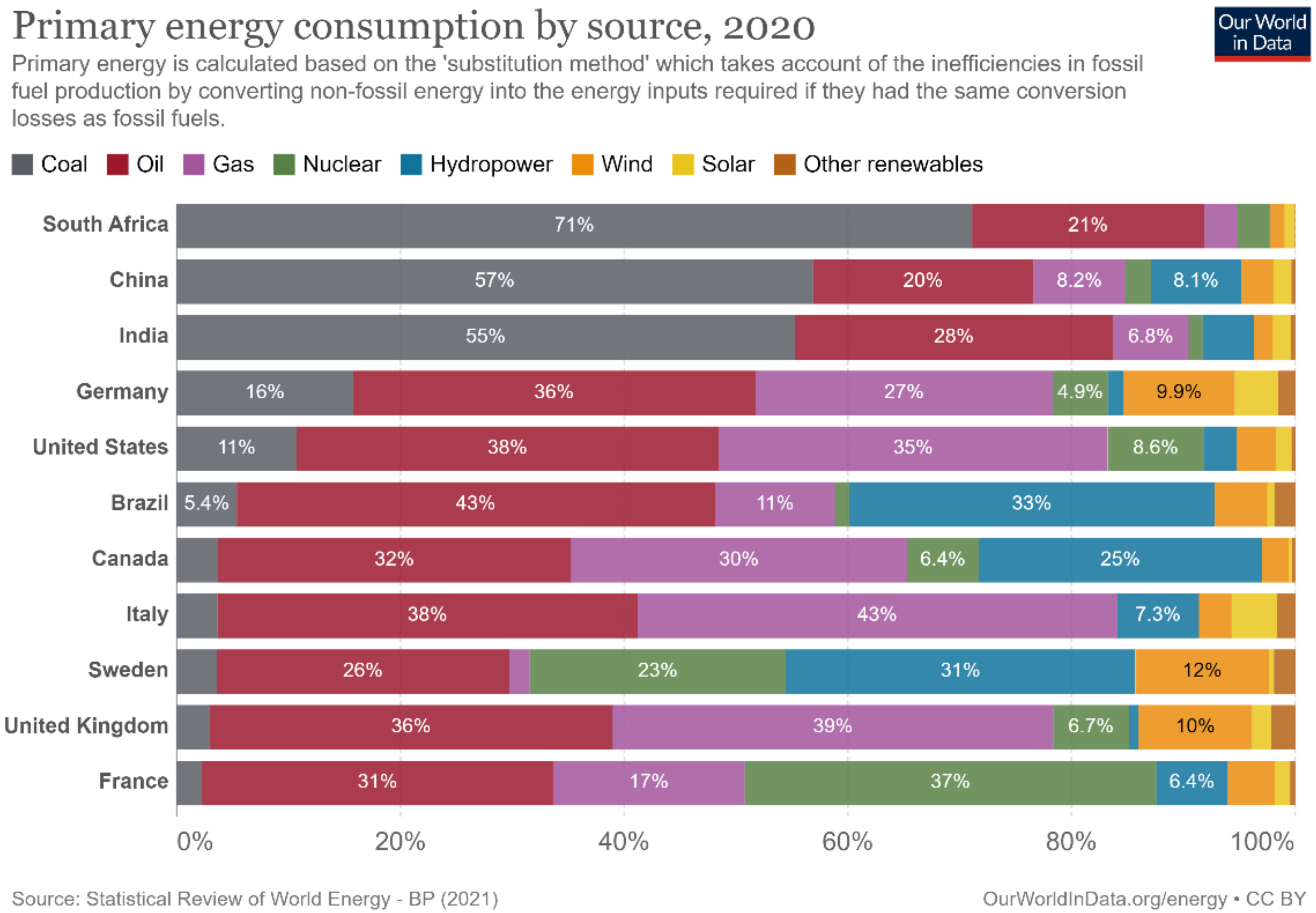
Primary energy consumption


Primary energy consumption by source, 2020

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

Source: Statistical Review of World Energy - BP (2021)

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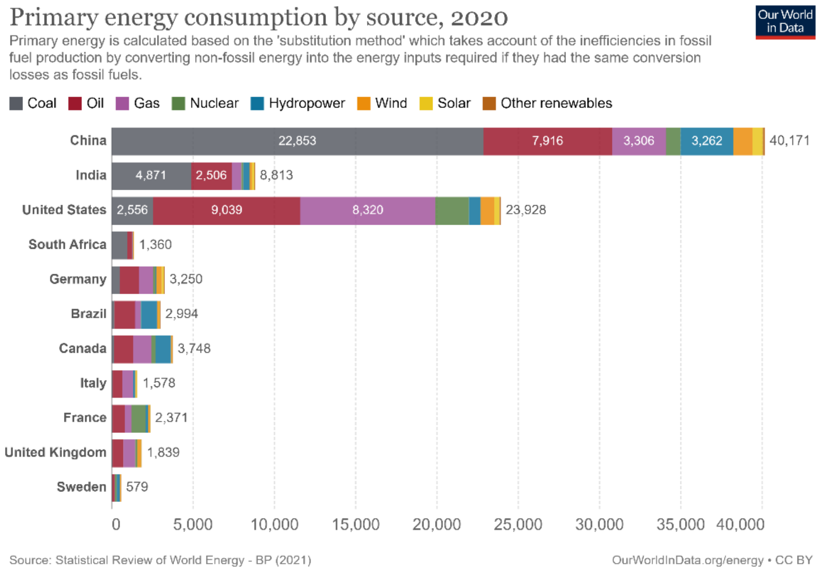
Primary energy consumption by source, 2020

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Source: Statistical Review of World Energy - BP (2021)

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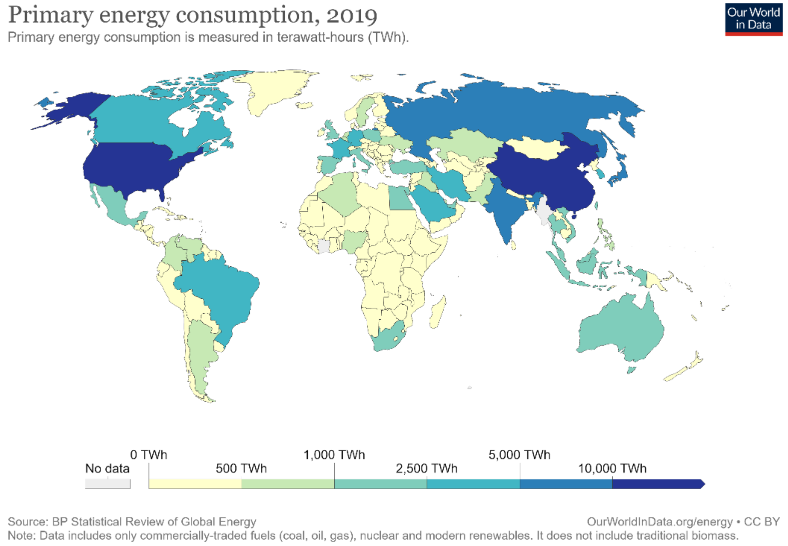

Primary energy consumption, 2019

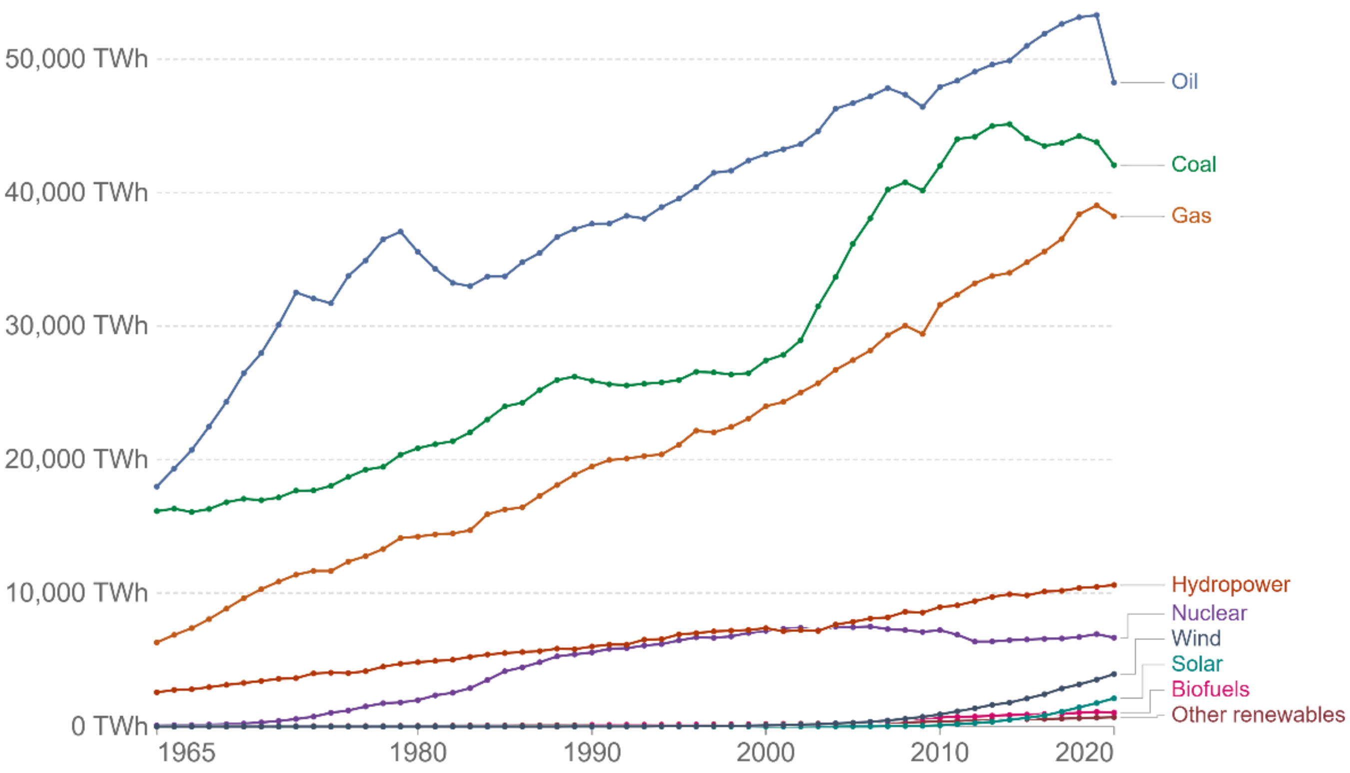
Primary energy consumption is measured in terawatt-hours (TWh).

Source: BP Statistical Review of Global Energy

OurWorldInData.org/energy • CC BY

Note: Data includes only commercially-traded fuels (coal, oil, gas), nuclear and modern renewables. It does not include traditional biomass.

Primary energy consumption



Primary energy consumption by source, World

Primary energy is shown based on the 'substitution' method which takes account of inefficiencies in energy production from fossil fuels.

Source: Our World in Data based on BP Statistical Review of World Energy

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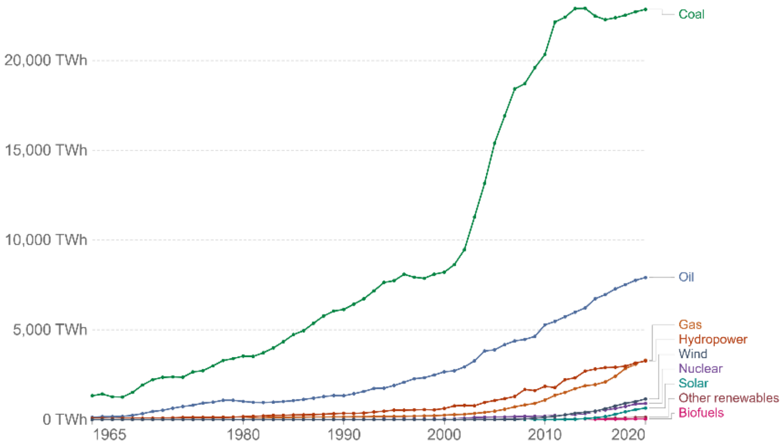

Primary energy consumption by source, China

Primary energy is shown based on the 'substitution' method which takes account of inefficiencies in energy production from fossil fuels.

Source: Our World in Data based on BP Statistical Review of World Energy

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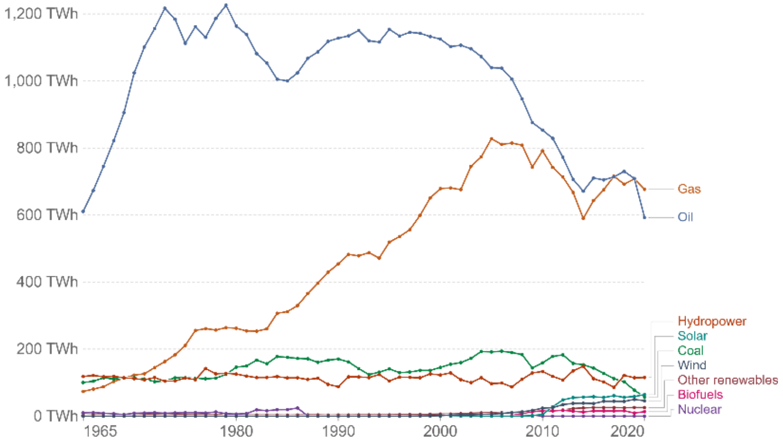

Primary energy consumption by source, Italy

Primary energy is shown based on the 'substitution' method which takes account of inefficiencies in energy production from fossil fuels.

Source: Our World in Data based on BP Statistical Review of World Energy

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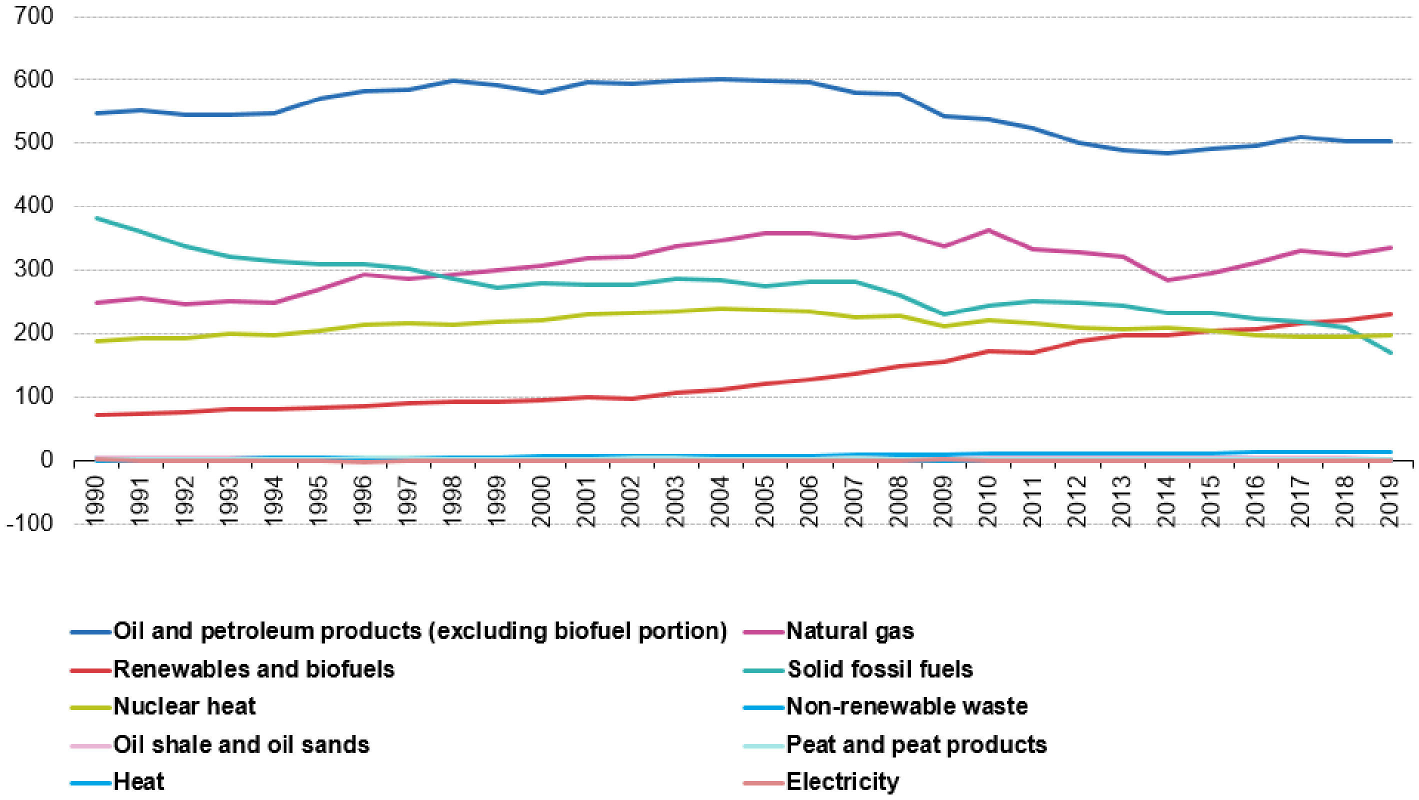
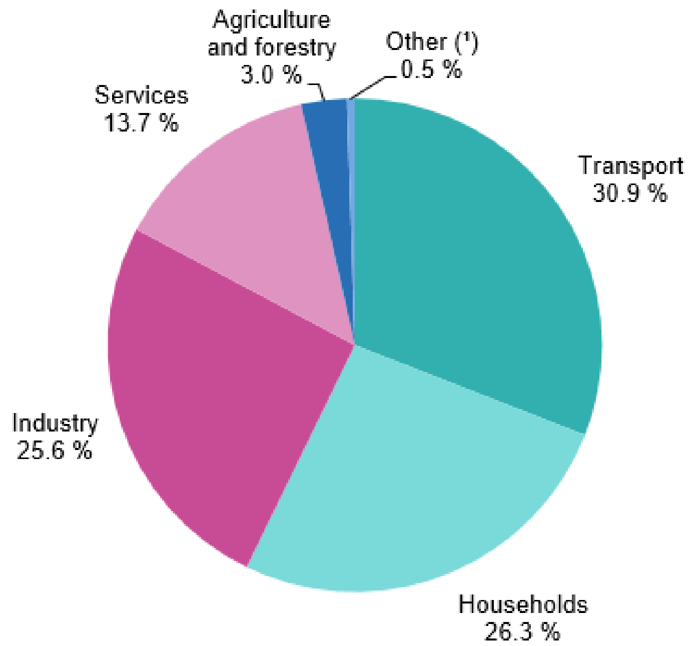
Primary energy consumption

Gross inland energy consumption by fuel, EU, 1990-2019
(million tonnes of oil equivalent)



Source: Eurostat (online data code: nrg_bal_c)

Final energy consumption by sector, EU, 2019
(% of total, based on tonnes of oil equivalent)

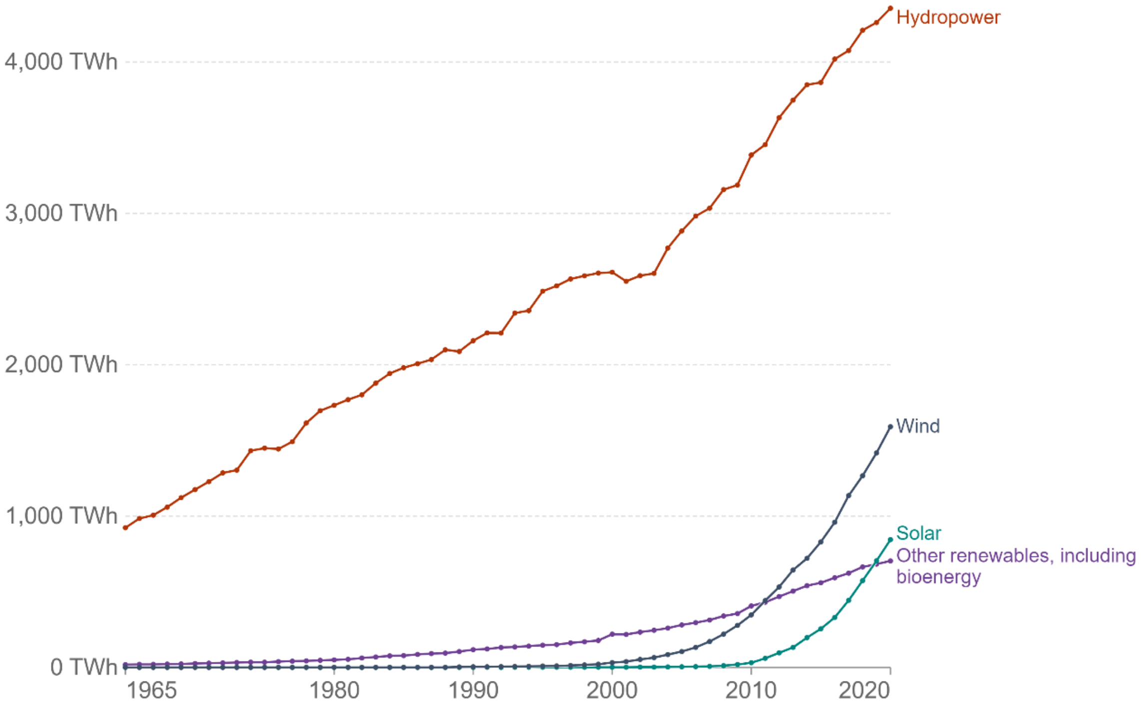


(¹) International aviation and maritime bunkers are excluded from category Transport.

Source: Eurostat (online data code: nrg_bal_s)

Renewable energy generation

Modern renewable energy generation by source, World



Source: Our World in Data based on BP Statistical Review of World Energy & Ember

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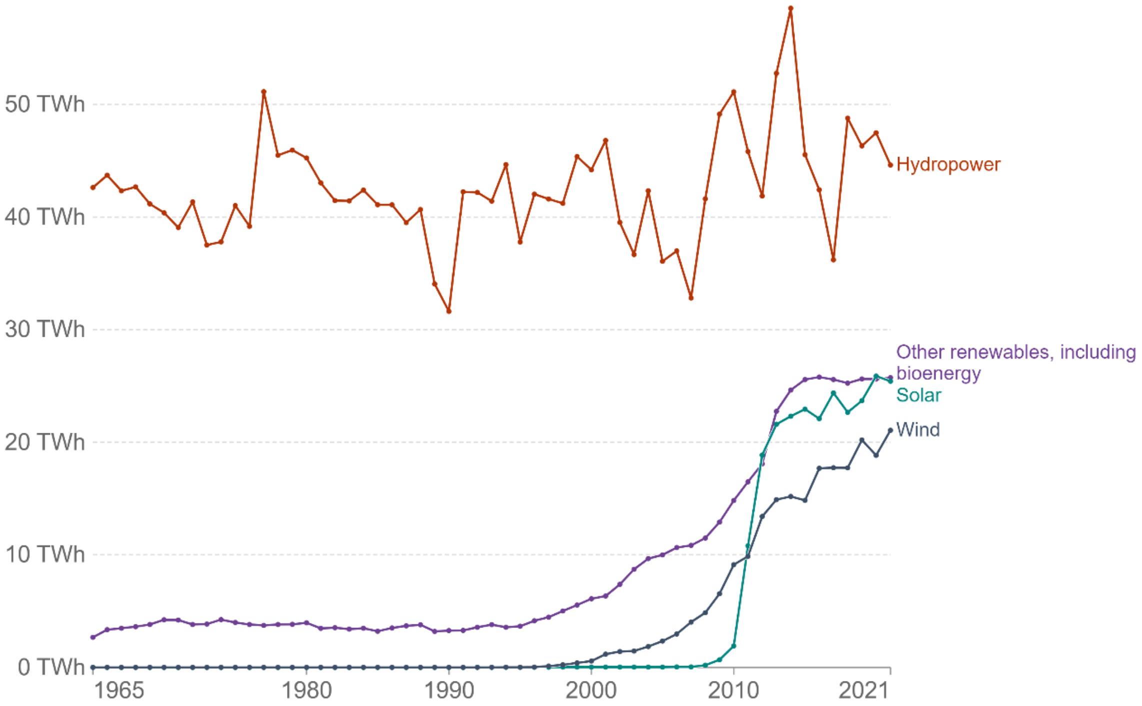
Modern renewable energy generation by source, Italy



Source: Our World in Data based on BP Statistical Review of World Energy & Ember

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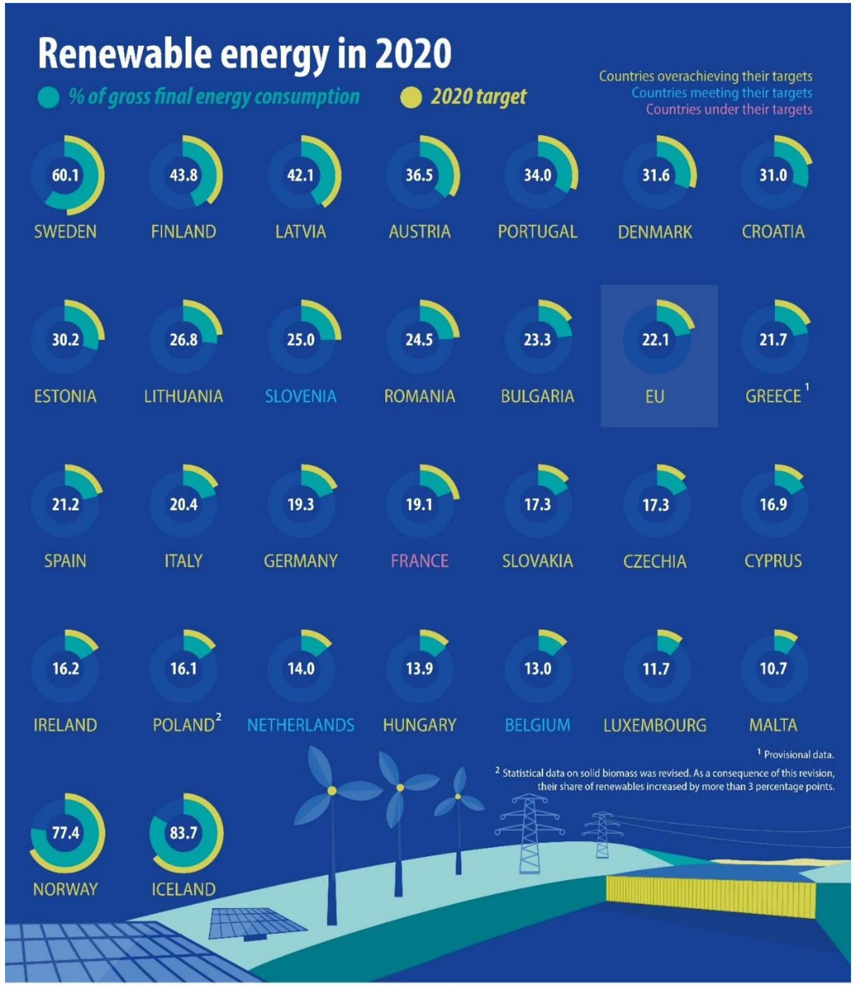
Renewable energy generation in the EU

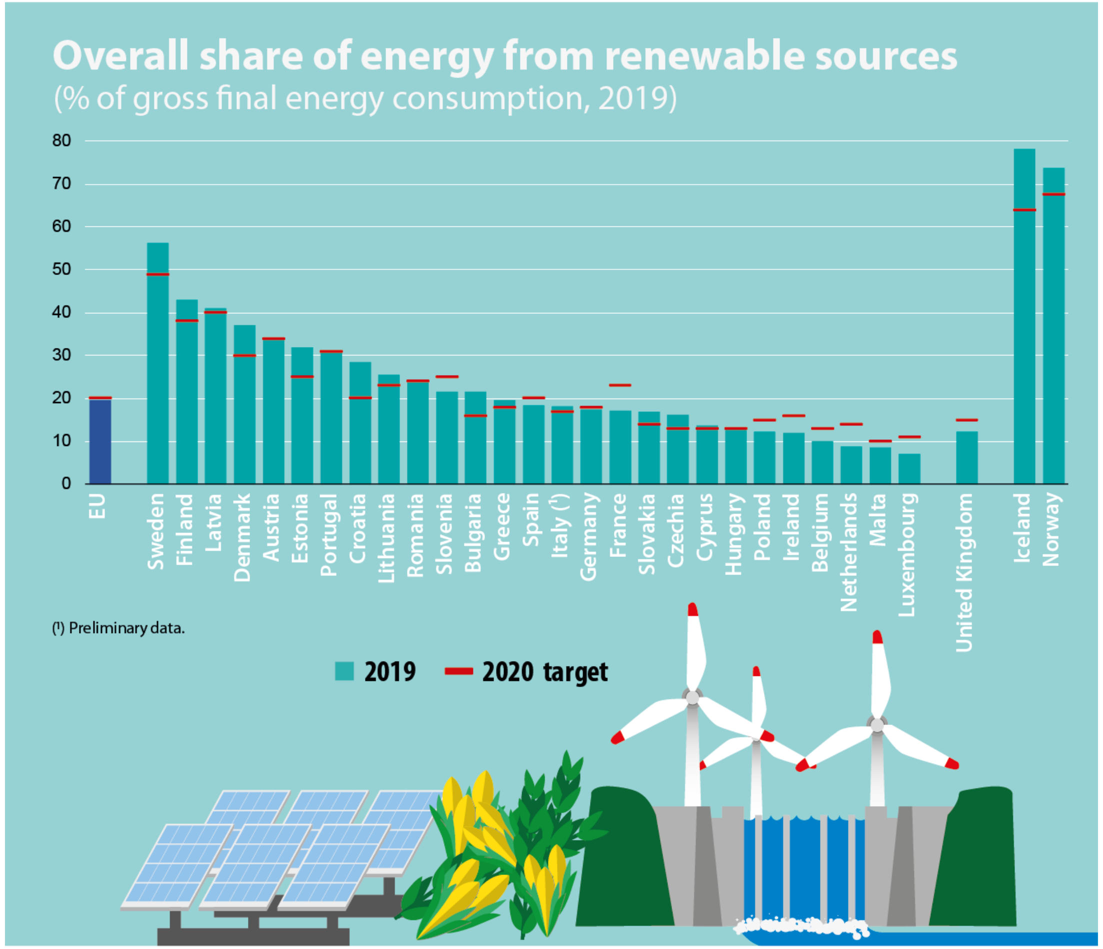


Renewable energy in 2020

[1] Provisional data.

[2] Statistical data on solid biomass was revised. As a consequence of this revision, their share of renewables increased by more than 3 percentage points.

ec.europa.eu/eurostat



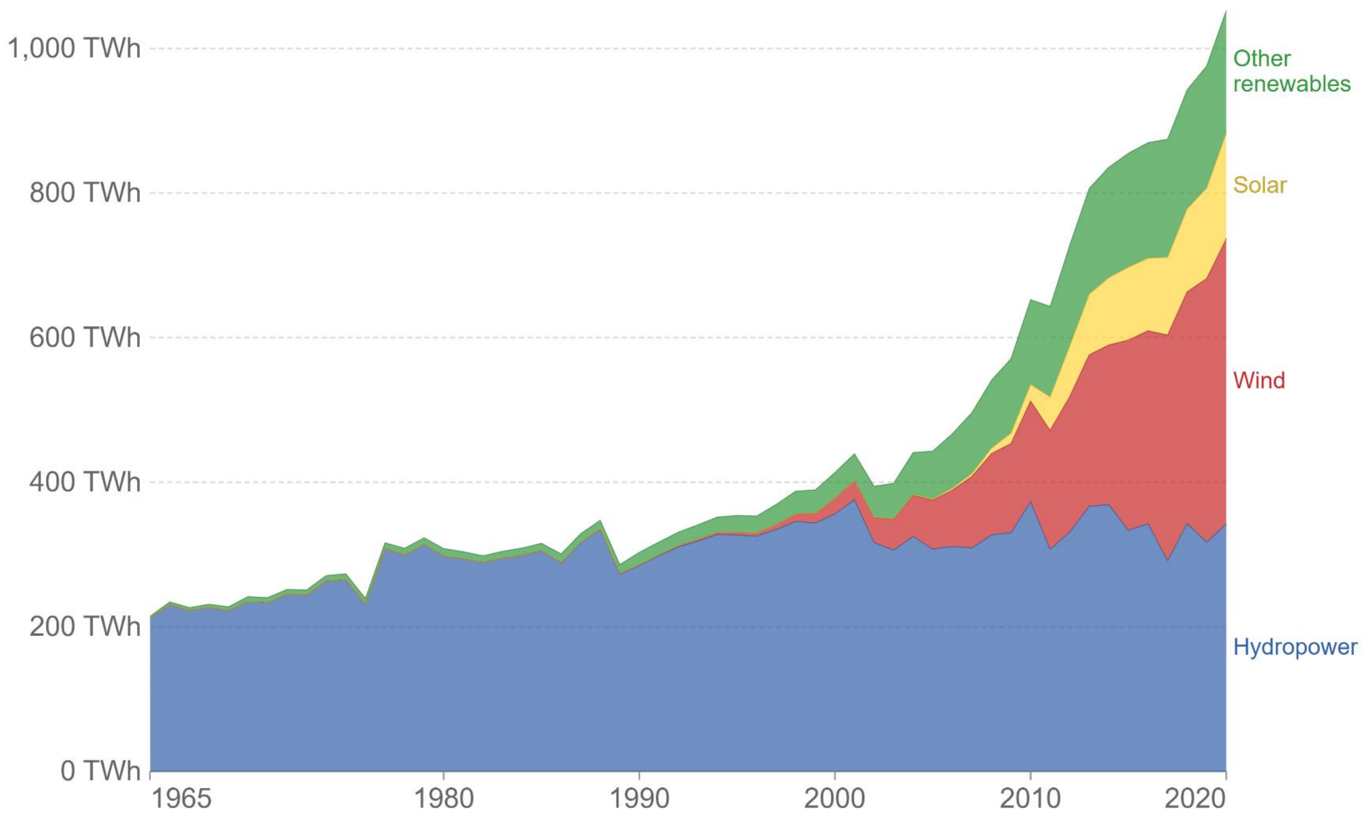
Overall share of energy from renewable sources

(% of gross final energy consumption, 2019)

(¹) Preliminary data.

ec.europa.eu/eurostat

Renewable energy generation in the EU



Renewable energy generation, European Union

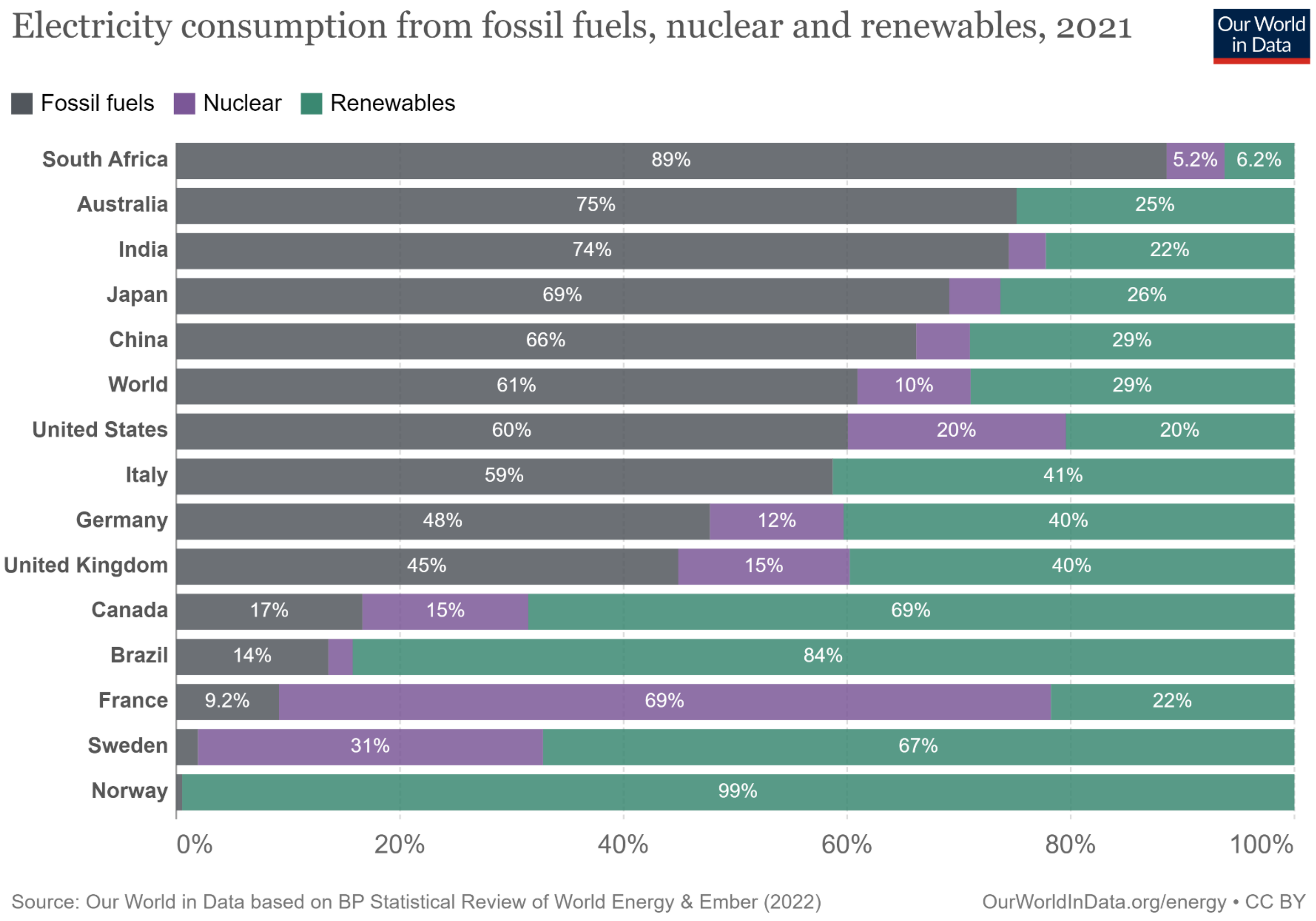
Our World in Data

Source: BP Statistical Review of Global Energy

OurWorldInData.org/renewable-energy • CC BY

Note: 'Other renewables' refers to renewable sources including geothermal, biomass, waste, wave and tidal. Traditional biomass is not included.

Electricity production



Electricity consumption from fossil fuels, nuclear and renewables, 2021

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022)

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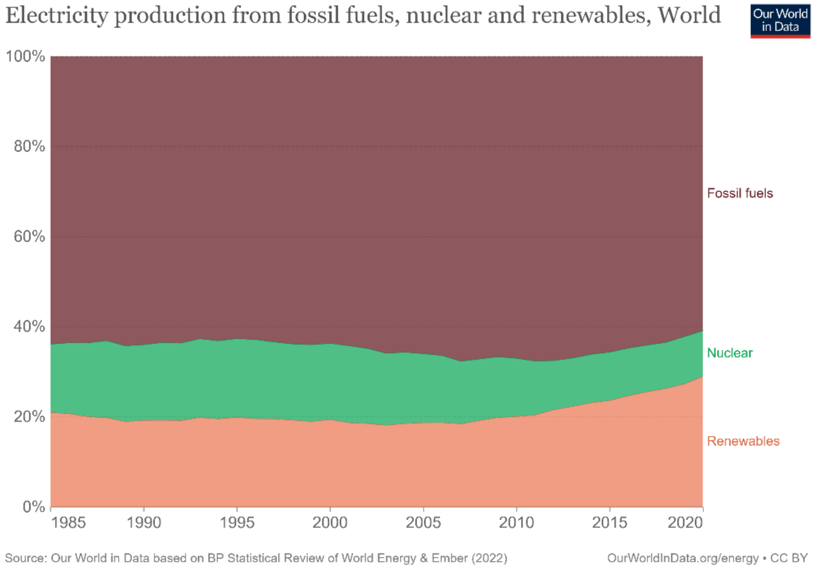
Electricity production



Electricity production from fossil fuels, nuclear and renewables, World

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022)

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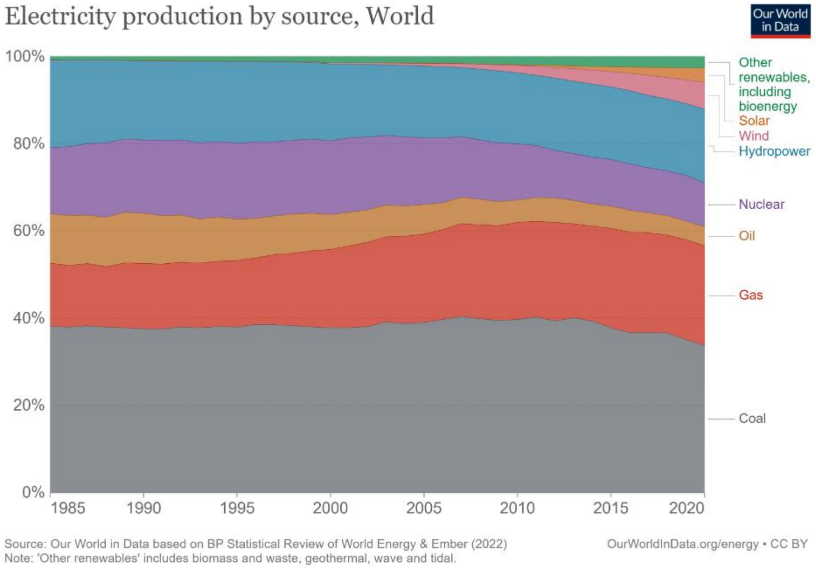

Electricity production by source, World

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022)

Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

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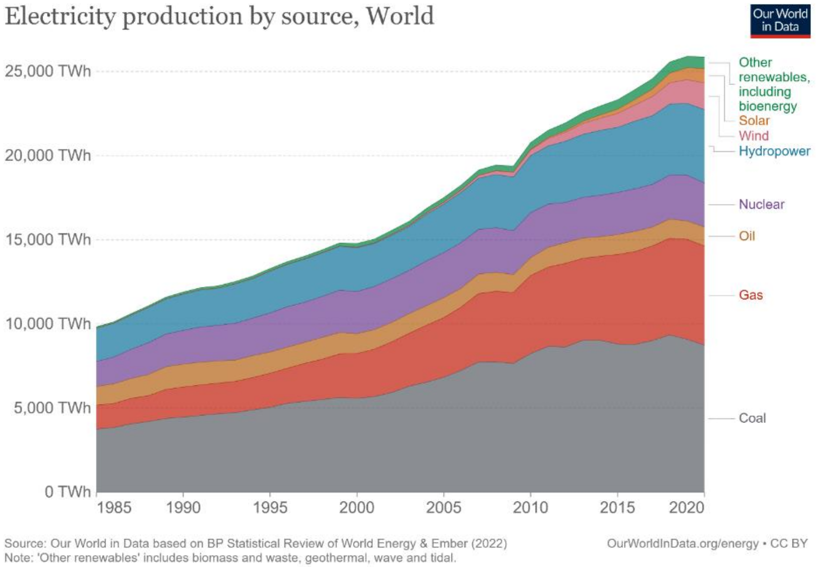

Electricity production by source, World

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022)

Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

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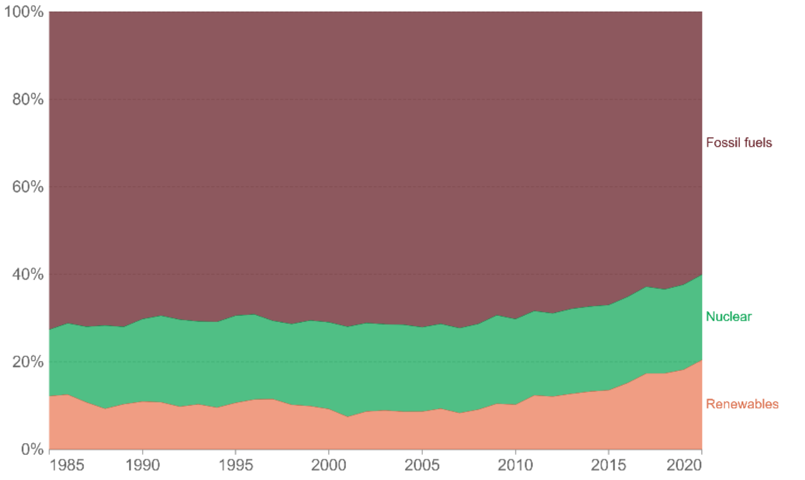
Electricity production from fossil fuels, nuclear and renewables, United States



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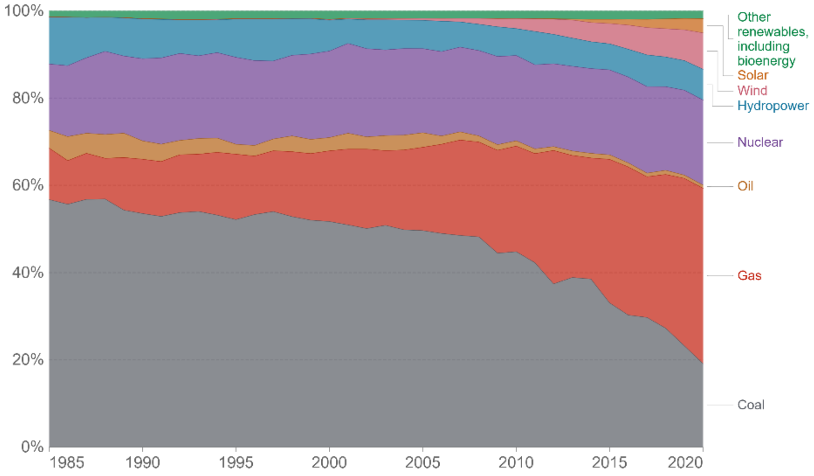
Electricity production by source, United States



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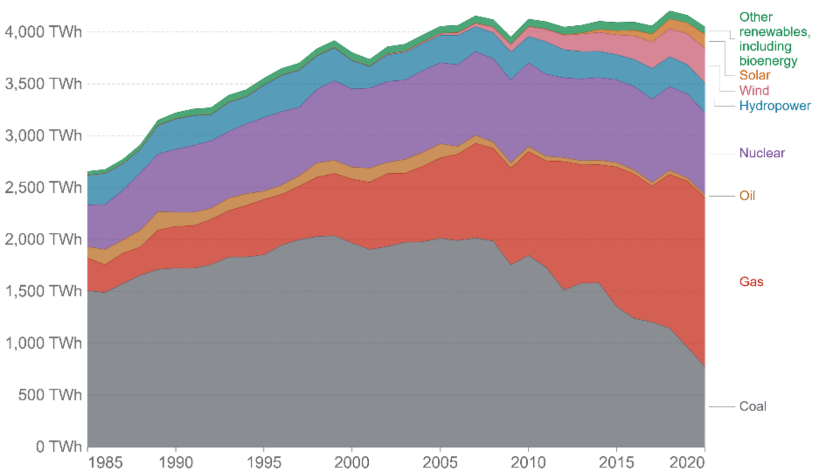
Electricity production by source, United States



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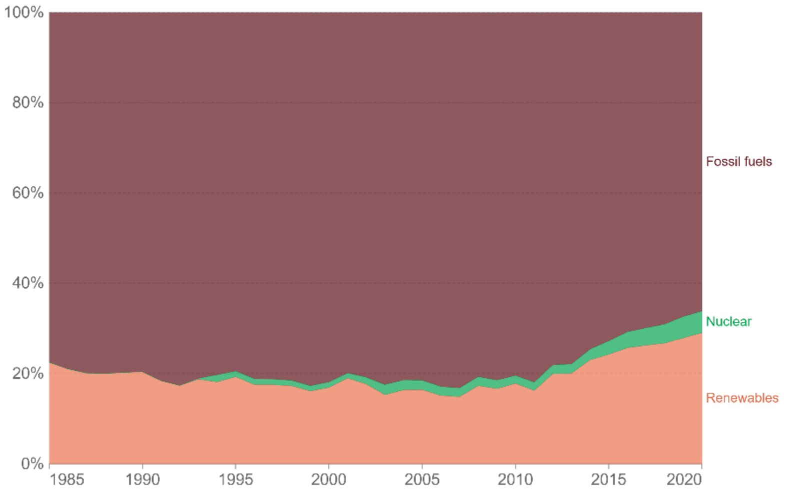
Electricity production from fossil fuels, nuclear and renewables, China



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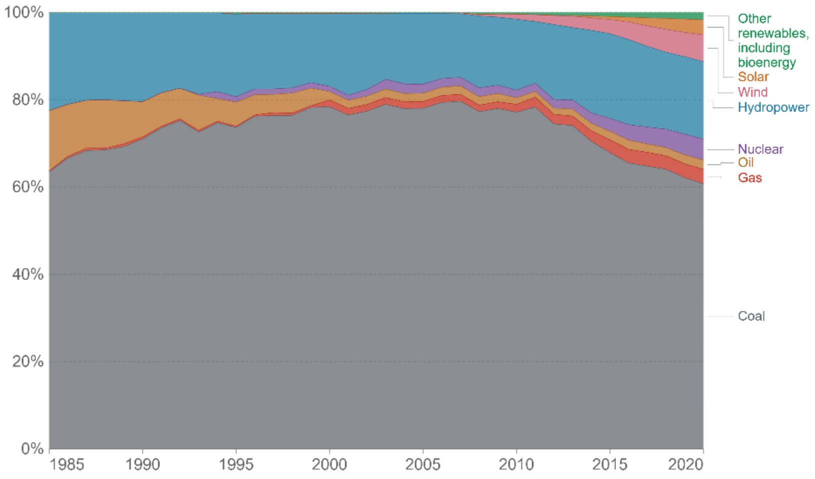
Electricity production by source, China



Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022) OurWorldInData.org/energy • CC BY
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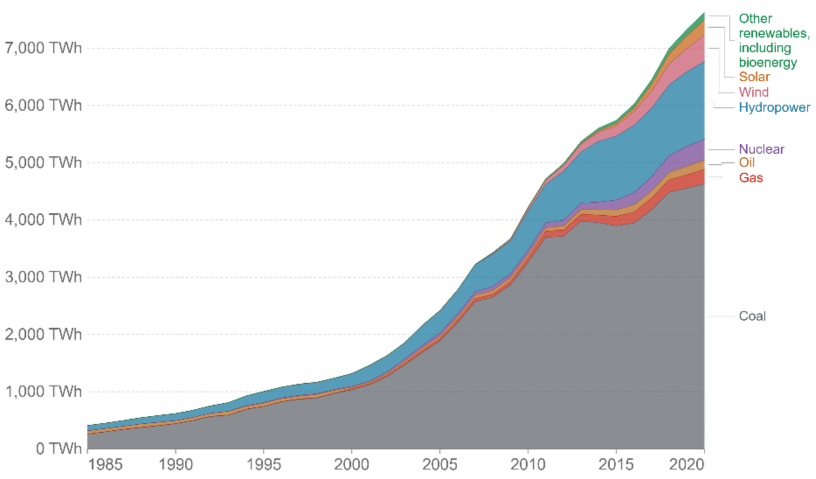
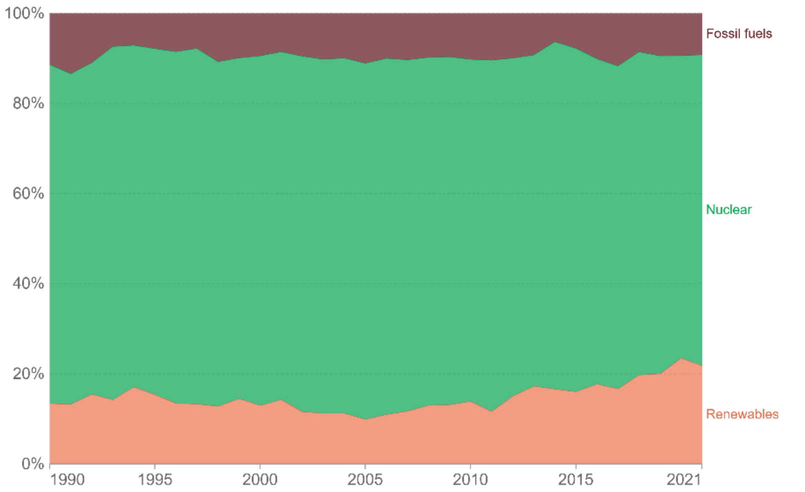
Electricity production by source, China



Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022) OurWorldInData.org/energy • CC BY
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

Electricity production from fossil fuels, nuclear and renewables, France



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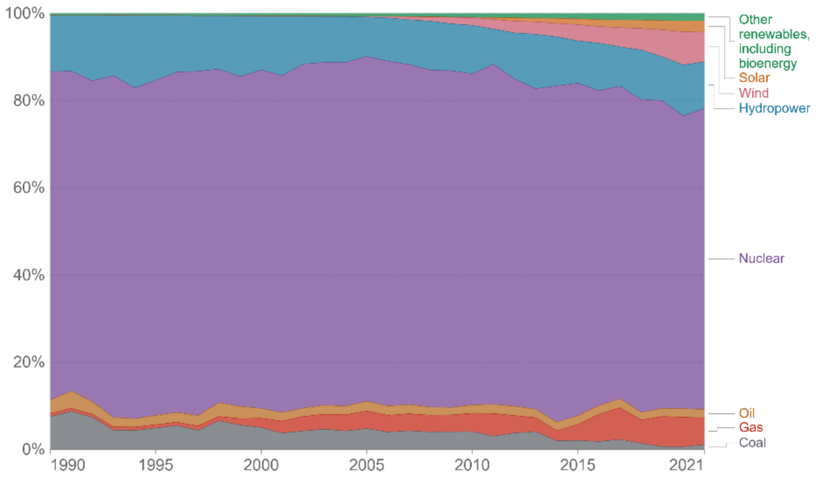
Electricity production by source, France



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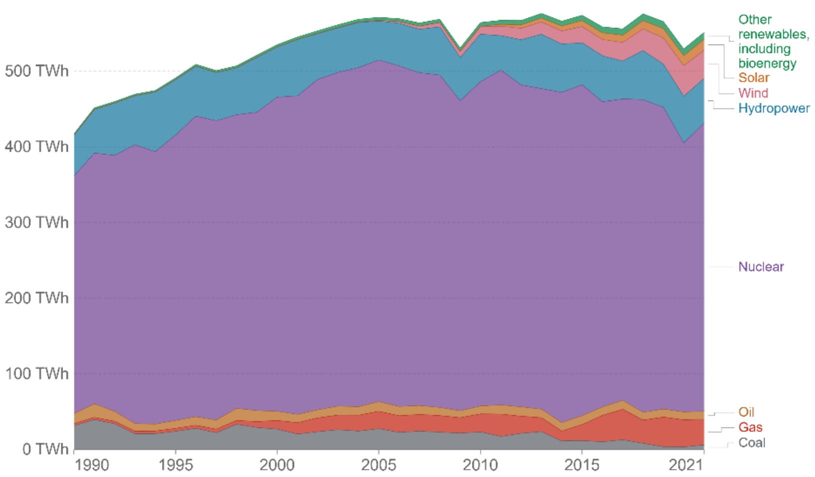
Electricity production by source, France



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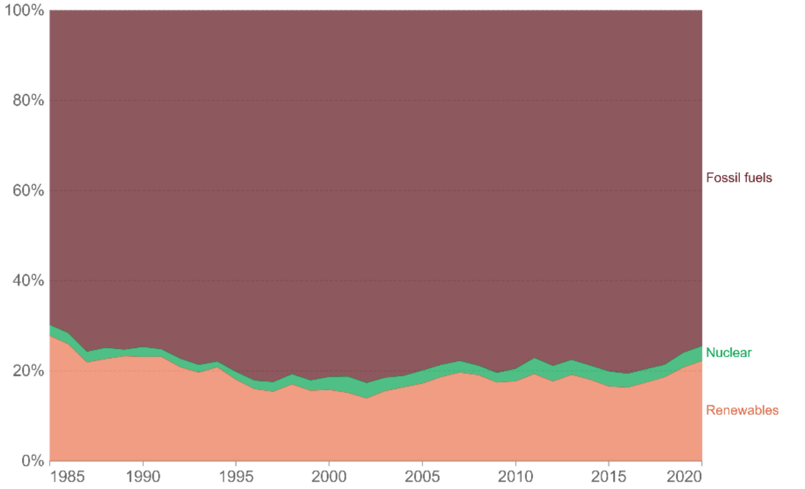
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

Electricity production from fossil fuels, nuclear and renewables, India



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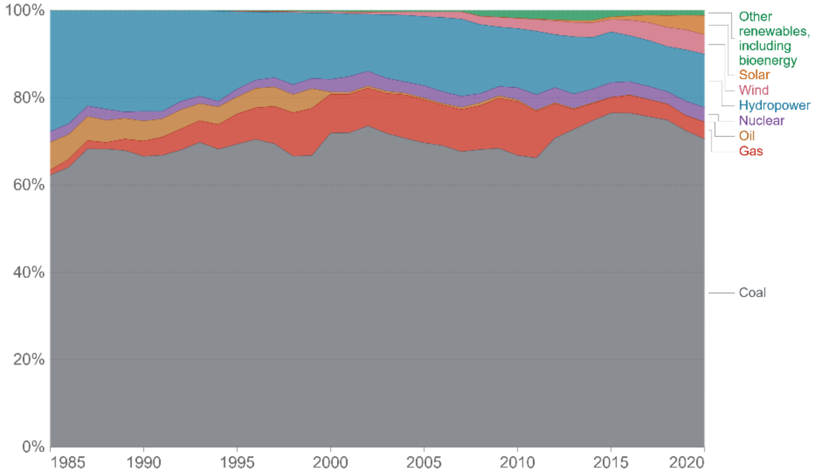
Electricity production by source, India



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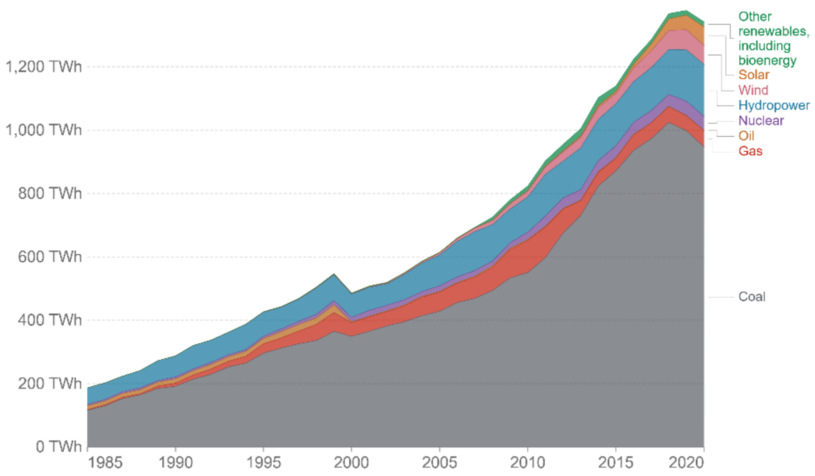
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

Electricity production by source, India



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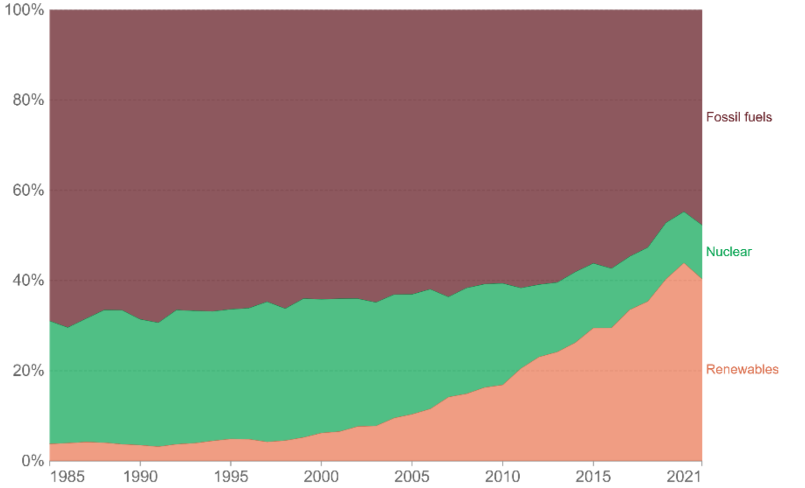
Electricity production from fossil fuels, nuclear and renewables, Germany

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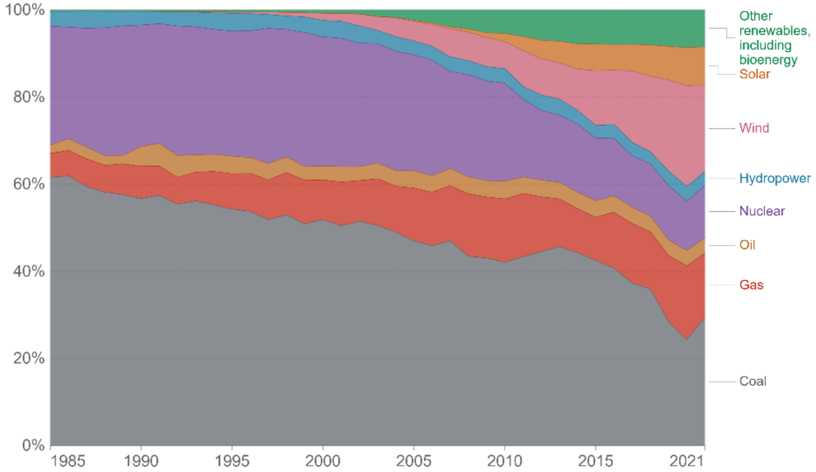
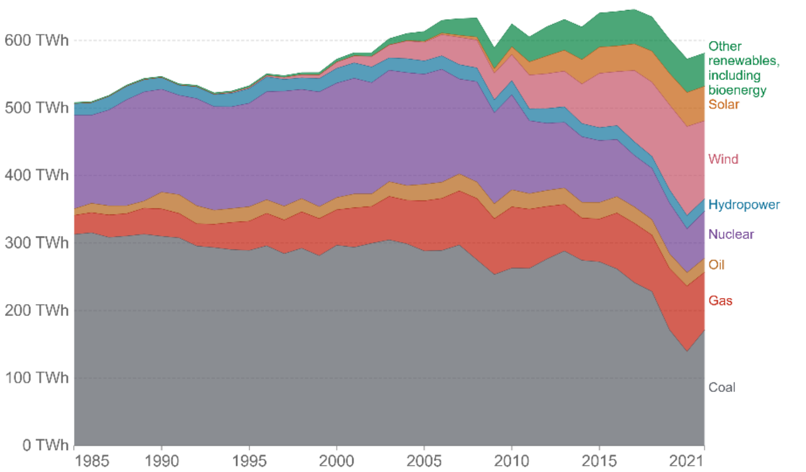

Electricity production by source, Germany

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022) OurWorldInData.org/energy • CC BY
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.


Electricity production by source, Germany

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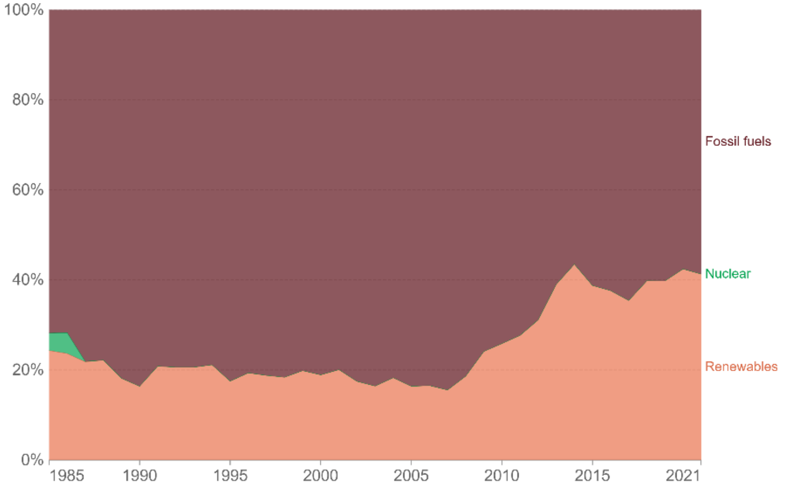
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.


Electricity production from fossil fuels, nuclear and renewables, Italy

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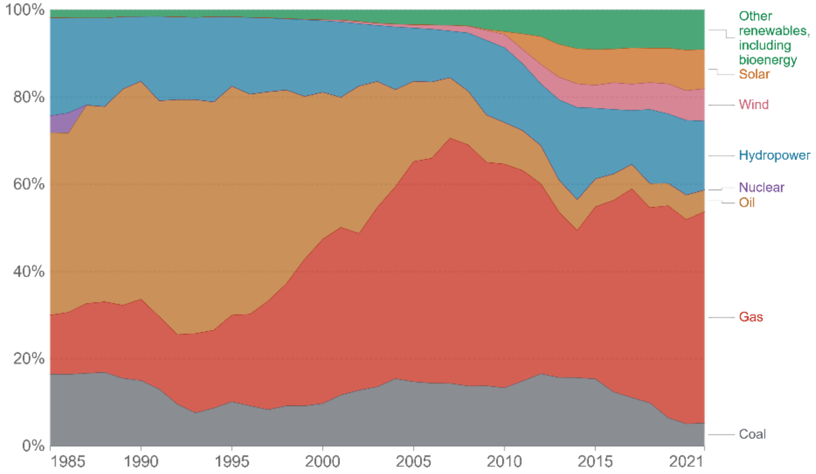
Electricity production by source, Italy

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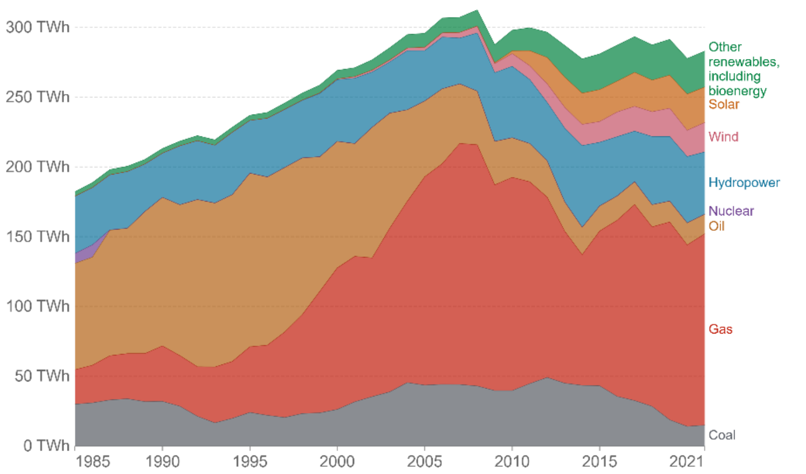
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.


Electricity production by source, Italy

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022) OurWorldInData.org/energy • CC BY
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

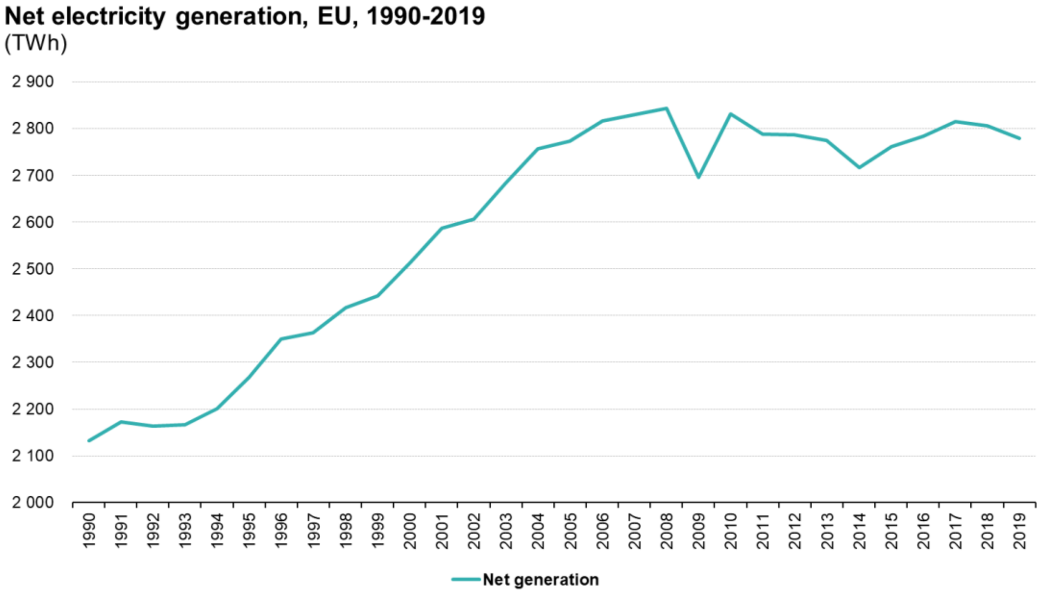
Electricity production in the EU

Total net electricity generation in the EU was 2778 Terawatt hours (TWh) in 2019. The level of net electricity generation in the EU in 2019 was 2.3 % lower than its relative peak of 2008, when total output stood at 2844 TWh.

Germany had the highest level of net electricity generation in 2019 among the EU Member States, accounting for 20.8 % of the EU total, just ahead of France (19.7 %); Italy (10.2 %) was the only other Member State with a double-digit share.

During the period covering 2009 to 2019, there was an overall increase of 3.1 % in the level of EU net electricity generation.

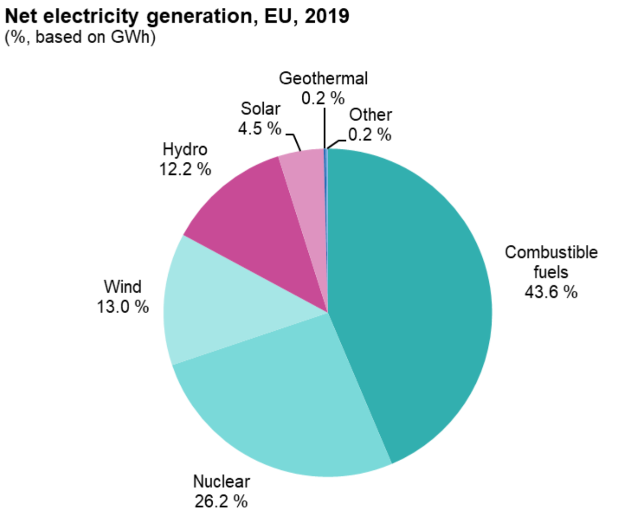
It should be noted that changes in electricity generation do not directly reflect changes in electricity consumption as they are also affected by changes in the different energy products used for energy production and by changes in electricity imports and exports.



Net electricity generation, EU, 1990-2019
(TWh)

Source: Eurostat (online data code: nrg_ind_peh)

eurostat



Net electricity generation, EU, 2019
(%, based on GWh)

Source: Eurostat (online data code: nrg_ind_peh)

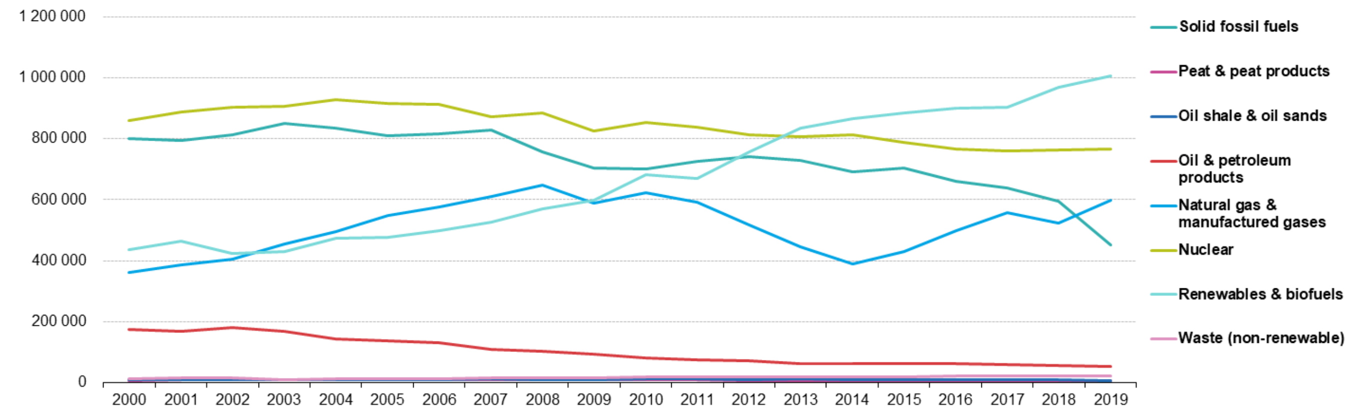
eurostat

Electricity production in the EU

Since 2000 **electricity generation from renewable energy sources has more than doubled** and it is the only source which continued to grow after 2008 (with only a small decrease in 2011).

The electricity production of coal fired power plants in 2019 was at its lowest level in the EU since 2000. Electricity generated from natural gas increased from 331 TWh in 2000 to its peak of 614 TWh in 2008. However, by 2014 the electricity generation from natural gas decreased to 357 TWh and began to increase once again from 2015 to 2017, followed by a small decrease in 2018, and an increase again in 2019, reaching 569 TWh. The trend of electricity production from nuclear power plants shows a peak in 2004, with a moderate increase from 2000 to 2004 (+8.0 %) and a decrease from 2004 to 2019 (-17.6 %).

Gross electricity production by fuel, EU, 2000-2019
(GWh)



Source: Eurostat (online data code: nrg_bal_peh)

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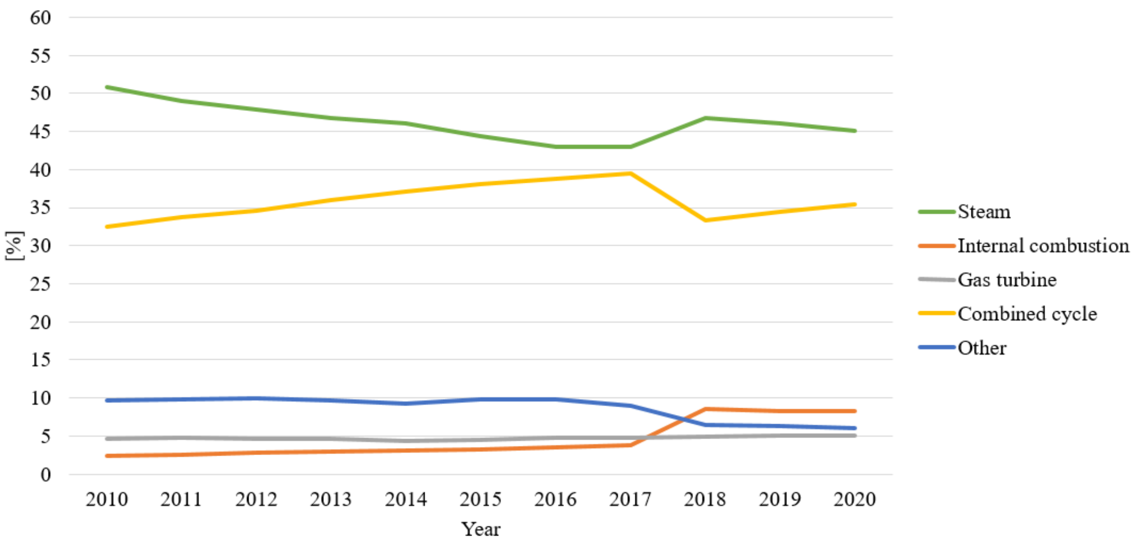
Electricity production capacities for combustible fuels by technology

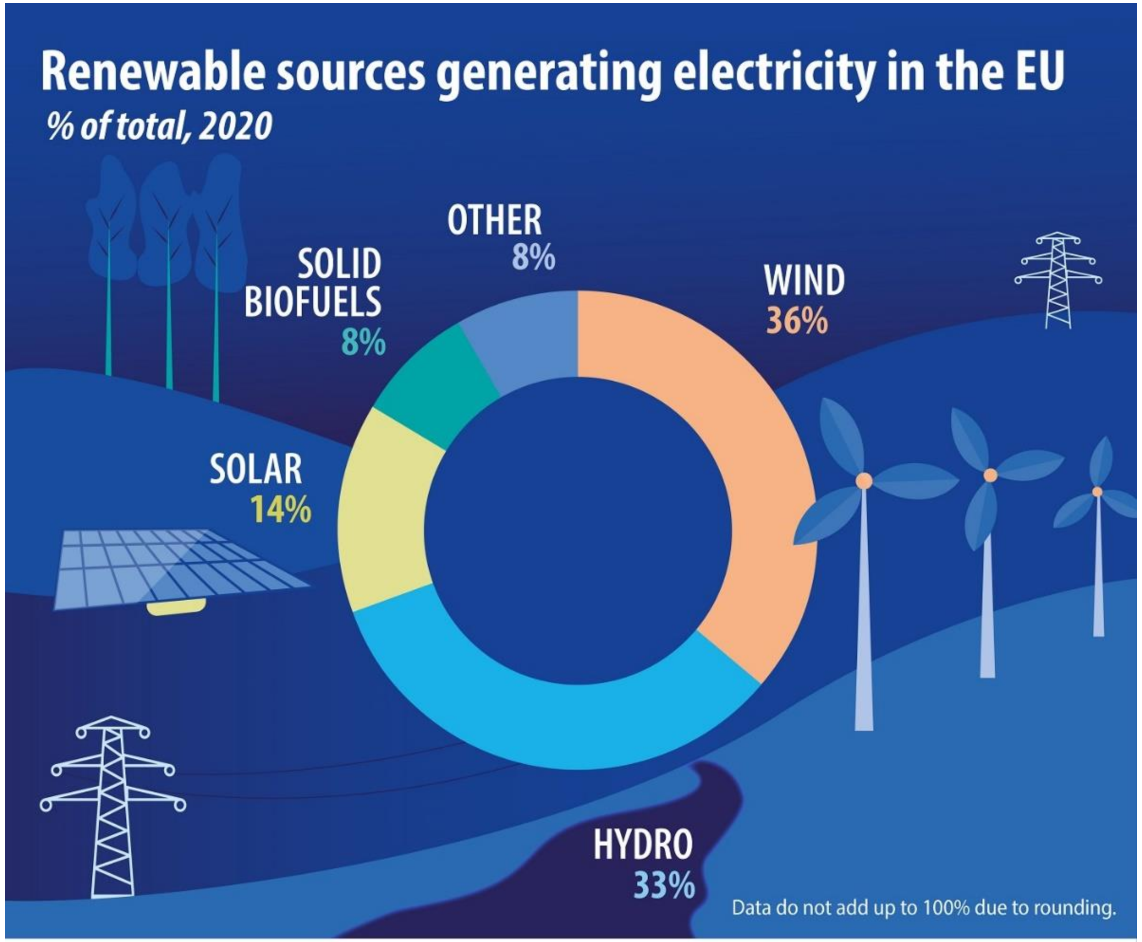


Electricity production in the EU

There have been significant changes in the contribution of the different renewable energy sources to electricity production over the last two decades.

In 2000, 87% of renewable electricity was produced from hydro energy, a share which dropped to 33% in 2020.

Other renewable energy sources with large shares in electricity production in 2020 were wind (36%), solar photo-voltaic (12%), primary solid biofuels (8%) and biogases (5%).



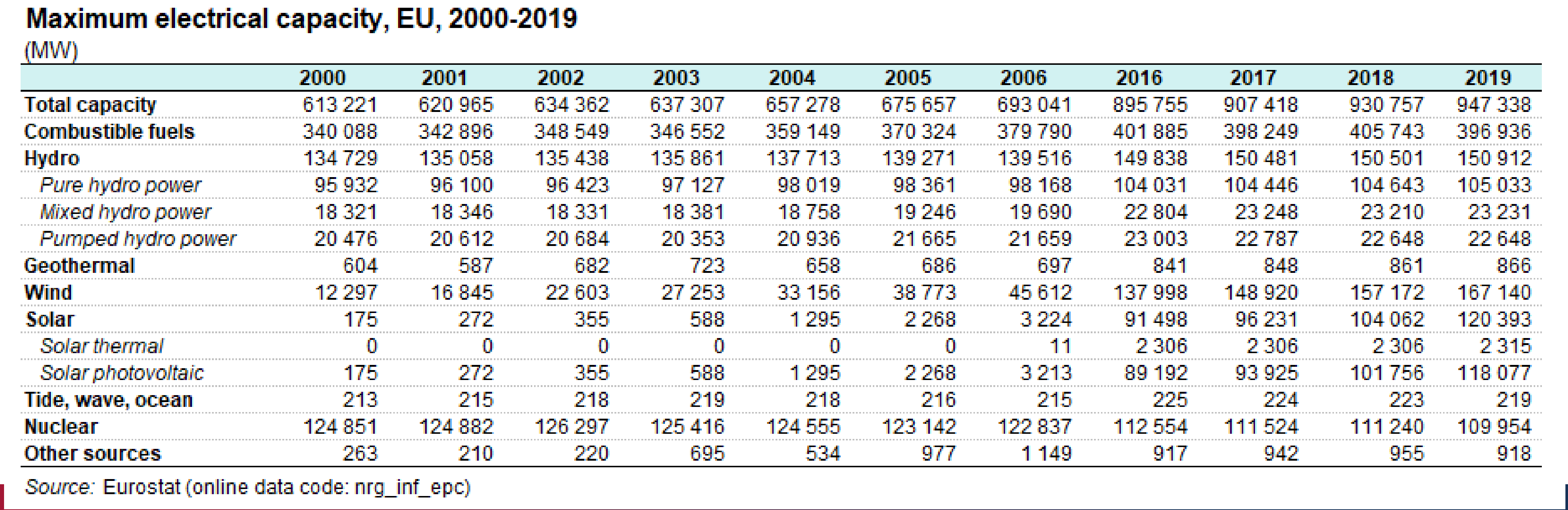
ec.europa.eu/eurostat

Installed electrical capacity in the EU

The installed electrical capacity in the EU increased by 54.5 % in the period from 2000 to 2019, and its structure changed significantly over this period.

In 2000, the highest share of installed capacity was accounted for combustible fuels (55.5 %), followed by hydro (22.0 %), nuclear (20.4 %) and wind (2.0 %), with all others at less than 2.0 %.

In 2019, the share of installed capacity of combustible fuels decreased to 41.9 %, the share of hydro to 15.9 % and the share of nuclear to 11.6 %. On the other hand, the share of wind increased to 17.6 % and the share of solar photovoltaic to 12.5 %, while geothermal and tide, wave and ocean remained negligible.



Maximum electrical capacity, EU, 2000-2019

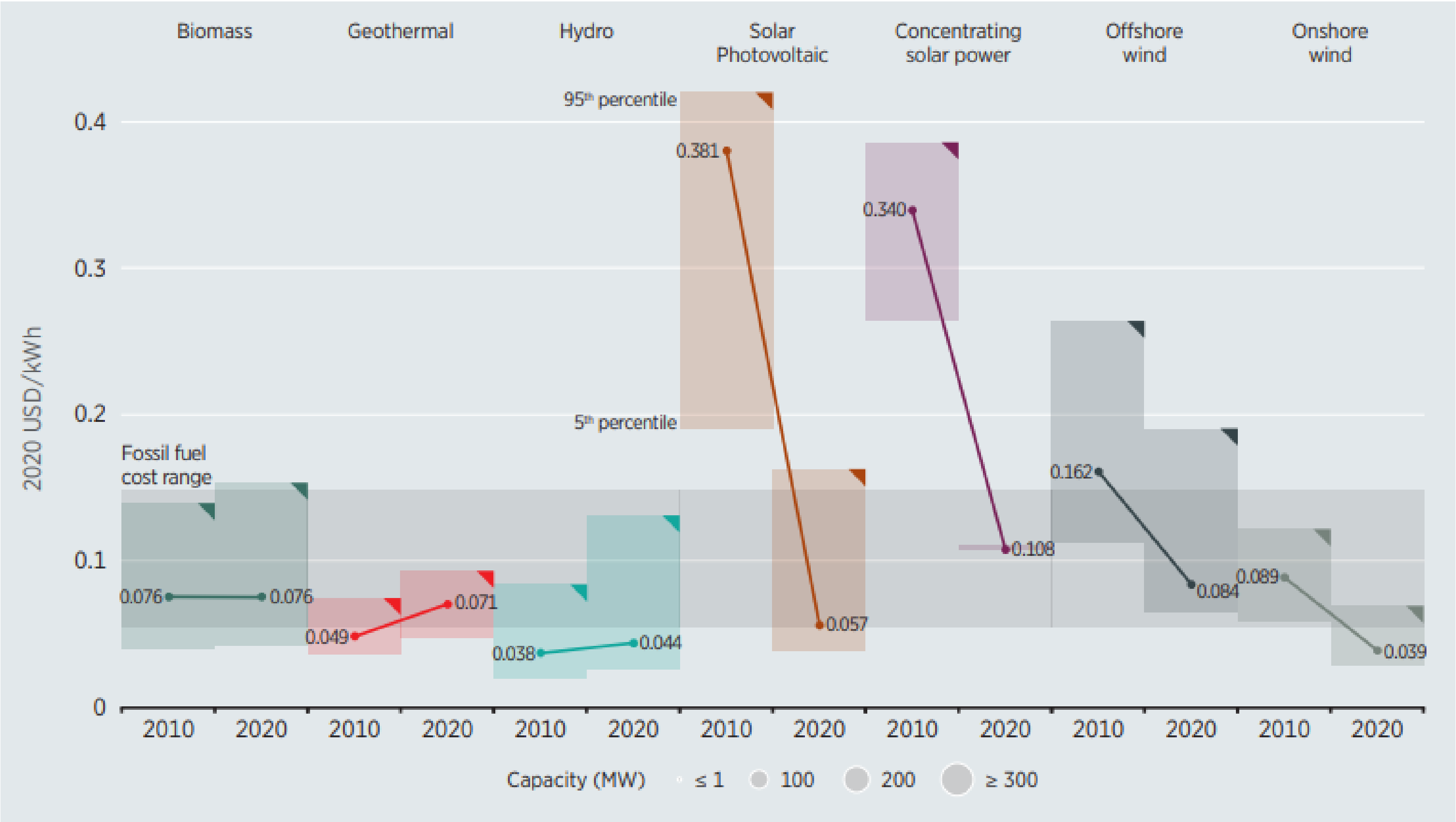
(MW)

	2000	2001	2002	2003	2004	2005	2006	2016	2017	2018	2019
Total capacity	613 221	620 965	634 362	637 307	657 278	675 657	693 041	895 755	907 418	930 757	947 338
Combustible fuels	340 088	342 896	348 549	346 552	359 149	370 324	379 790	401 885	398 249	405 743	396 936
Hydro	134 729	135 058	135 438	135 861	137 713	139 271	139 516	149 838	150 481	150 501	150 912
Pure hydro power	95 932	96 100	96 423	97 127	98 019	98 361	98 168	104 031	104 446	104 643	105 033
Mixed hydro power	18 321	18 346	18 331	18 381	18 758	19 246	19 690	22 804	23 248	23 210	23 231
Pumped hydro power	20 476	20 612	20 684	20 353	20 936	21 665	21 659	23 003	22 787	22 648	22 648
Geothermal	604	587	682	723	658	686	697	841	848	861	866
Wind	12 297	16 845	22 603	27 253	33 156	38 773	45 612	137 998	148 920	157 172	167 140
Solar	175	272	355	588	1 295	2 268	3 224	91 498	96 231	104 062	120 393
Solar thermal	0	0	0	0	0	0	11	2 306	2 306	2 306	2 315
Solar photovoltaic	175	272	355	588	1 295	2 268	3 213	89 192	93 925	101 756	118 077
Tide, wave, ocean	213	215	218	219	218	216	215	225	224	223	219
Nuclear	124 851	124 882	126 297	125 416	124 555	123 142	122 837	112 554	111 524	111 240	109 954
Other sources	263	210	220	695	534	977	1 149	917	942	955	918

Source: Eurostat (online data code: nrg_inf_epc)

Cost of renewable power generation technologies

Figure ES.2 Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020



Source: IRENA Renewable Cost Database

Thermodynamic principles

The **Zeroth Law of Thermodynamics** is a statement about thermodynamic equilibrium expressed as follows:

"If two thermodynamic systems are in thermal equilibrium with a third, they are also in thermal equilibrium with each other."

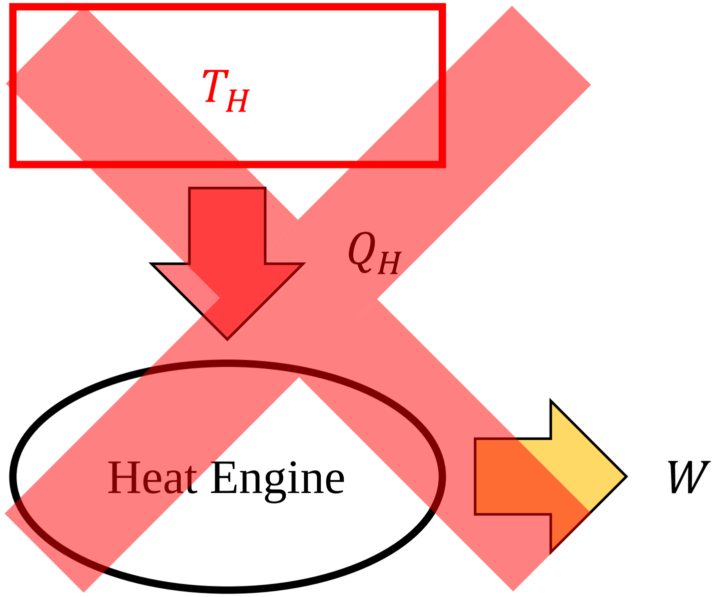
One of the statements of the **First Law of Thermodynamics** (FLT), which is known as the energy conservation principle, is:

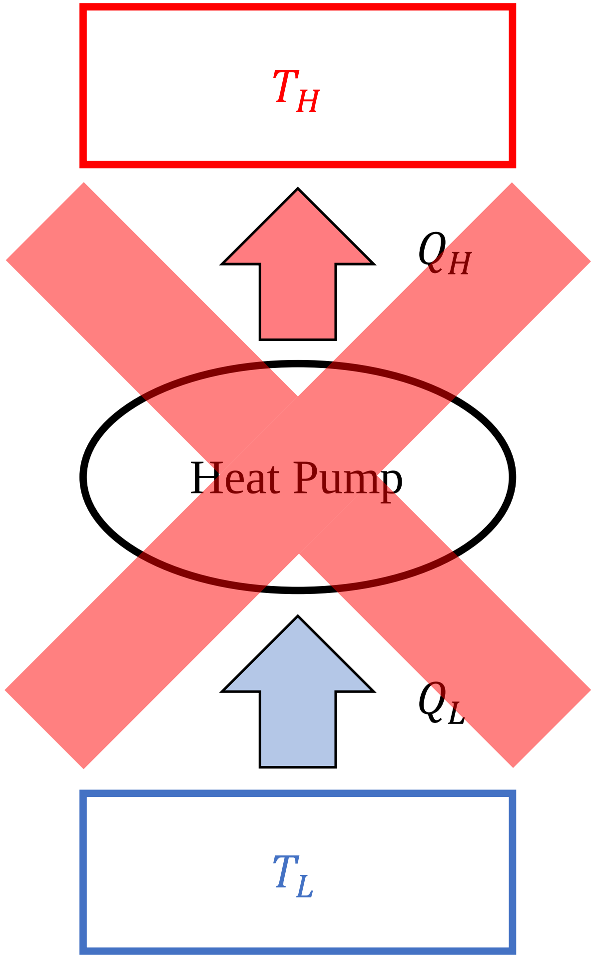
"*Energy is neither created nor destroyed*." The FLT can be phrased also as "you can't get something from nothing."

Second Law of Thermodynamics:

*"It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work" (**Kelvin–Planck statement**)*

*"It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body" (**Clausius statement**)*





Thermodynamic principles

Work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices. These devices are called **heat engines**.

Heat engines differ considerably from one another, but all can be characterized by the following:

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. They convert part of this heat to work (usually in the form of a rotating shaft).
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4. They operate on a cycle.

Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**.

Thermodynamic principles

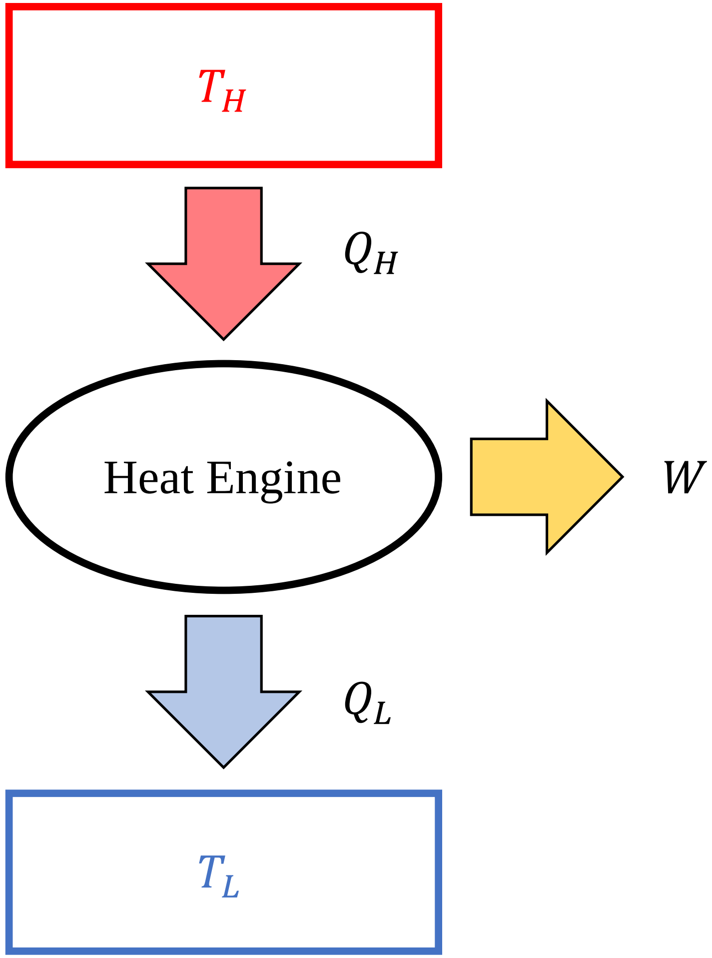
- Let us provide heat (Q_H) to a system (Heat Engine) from a high temperature heat source at T_H
- Thermodynamic processes: a fraction of Q_H is converted into useful work (W)
- The fraction of Q_H that is not converted into W (Q_L) is rejected to a low temperature heat sink at T_L

Q_L is never zero. Thus, the net work output of a heat engine is always less than the amount of heat input.

That is, only part of the heat transferred to the heat engine is converted to work. The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine and is called the thermal efficiency.

For heat engines, the desired output is the net work output, and the required input is the amount of heat supplied to the working fluid. Then the thermal efficiency of a heat engine can be expressed as:

$$\eta_{th} = \frac{\text{Net work output}}{\text{Total heat input}}$$



Thermodynamic principles

Thermal efficiency is a measure of how efficiently a heat engine converts the heat that it receives to work.

- Heat engines are built for the purpose of converting heat to work, and engineers are constantly trying to improve the efficiencies of these devices since increased efficiency means less fuel consumption and thus lower fuel bills and less pollution.
- The thermal efficiencies of work-producing devices are relatively low.
- Ordinary spark-ignition automobile engines have a thermal efficiency of about 25%. That is, an automobile engine converts about 25% of the chemical energy of the gasoline to mechanical work.
- This number is as high as 40% for diesel engines and large gas-turbine plants and as high as 60% for large combined gas-steam power plants.
- Thus, even with the most efficient heat engines available today, almost one-half of the energy supplied ends up in the rivers, lakes, or the atmosphere as waste or useless energy.

Thermodynamic principles

Most heat engines in operation today have efficiencies under 40%, which appear low relative to 100%.

However, when the performance of actual heat engines is assessed, the efficiencies should not be compared to 100%; instead, they should be compared to the efficiency of a **reversible** heat engine operating between the same temperature limits - because this is the true theoretical upper limit for the efficiency, not 100%.

The thermal efficiency of actual heat engines can be maximized by supplying heat to the engine at the highest possible temperature (limited by material strength) *and rejecting heat from the engine at the lowest possible temperature* (limited by the temperature of the cooling medium such as rivers, lakes, or the atmosphere).

Energy has **quality** as well as quantity. The higher the temperature, the higher the quality of the energy.

High efficiency → Heat addition at the highest temperature possible

High efficiency → Heat rejection at the lowest temperature possible

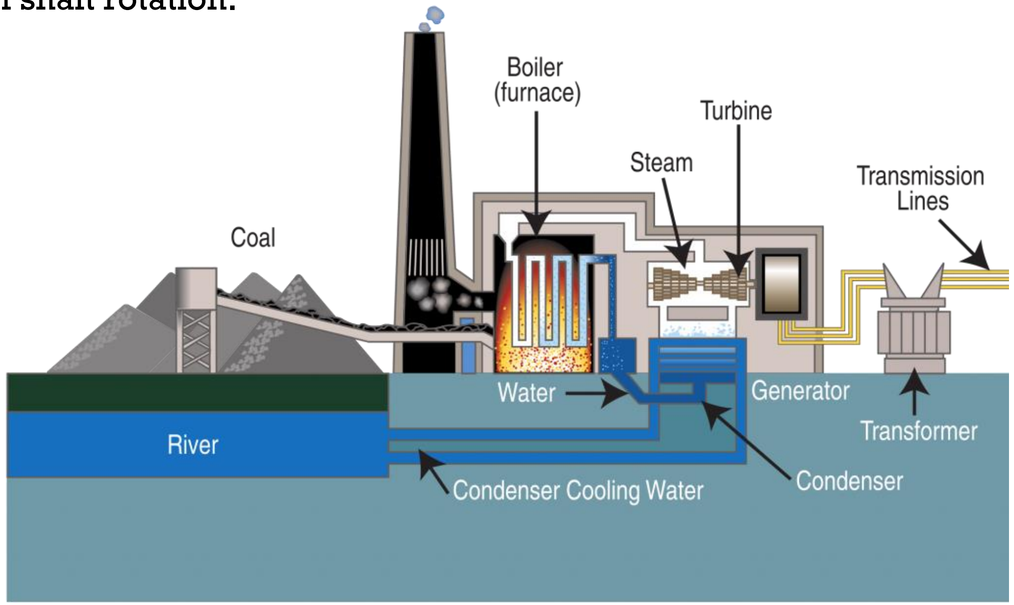
Overview on power generating systems

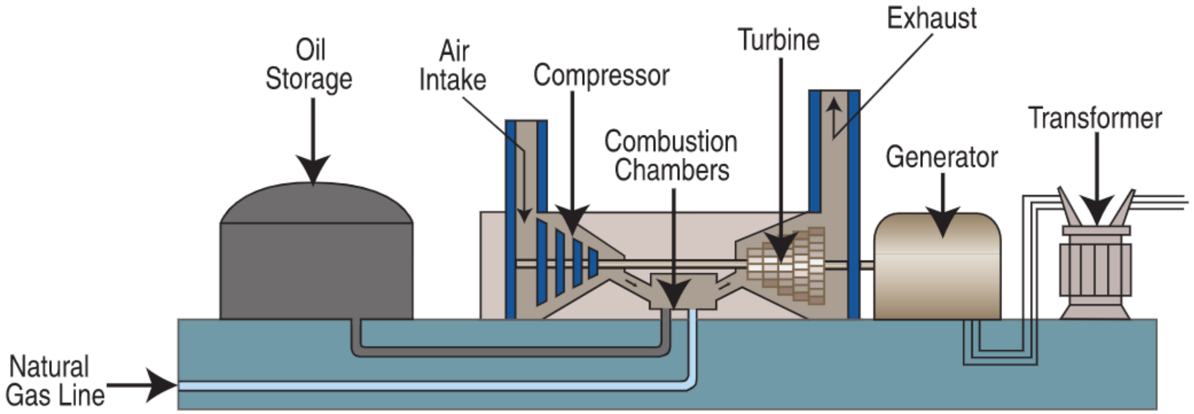
Power generating systems are treated as heat engines to convert heat input into work, hence to produce electricity at a sustained rate.

Heat input is typically supplied by burning fossil fuels (coal, oil and natural) and biomass. In particular, the chemical energy of a fuel is converted in thermal energy by means of a combustion reaction and eventually it is converted into mechanical energy.

Conventional power generating systems: internal combustion engines, steam-turbine power plants and gas-turbine power plants.

All these conventional power generating systems primarily produce mechanical work which is transferred to subsequent systems in the form of shaft rotation.





Overview on power generating systems

In vehicles, shaft power developed by engines is transferred to the traction system for propulsion. In stationary power plants the shaft power developed by the prime mover is used to rotate an electrical generator which converts the rotational mechanical power to electrical power.

The key component of conventional power generating systems is the **prime mover** or the organ that produces shaft power:

- positive displacement machines (e.g., reciprocating engines)
- turbomachines.

Reciprocating machines generally consist of piston-and-cylinder assemblies where the pressure force of an expanding gas is transformed in a reciprocating movement which subsequently is converted into shaft rotation.

Turbomachines (turbines) instead are devices that convert continuously the kinetic energy of a moving fluid directly into shaft rotation.

Overview on power generating systems

Small-scale power plants use in general **reciprocating prime movers** (spark ignition engines and compression-ignition engines).

Large-scale power plants use **turbines as prime movers**.

Available technologies for large scale power generation (>100 MWe)

- Steam turbines → coal, nuclear, CSP, biomass, geothermal
- Gas turbines → natural gas, fuel oil

All power plants represent thermomechanical converters and operate based on a specific thermodynamic cycle:

- the **Rankine cycle** is the base-cycle used in steam-turbine power plants.
- the **Brayton-Joule cycle** is the base-cycle used in gas-turbine power plants.
- a **Diesel cycle** is specific to compression-ignition engines, whereas the spark ignition engine operates based on the **Otto cycle**.

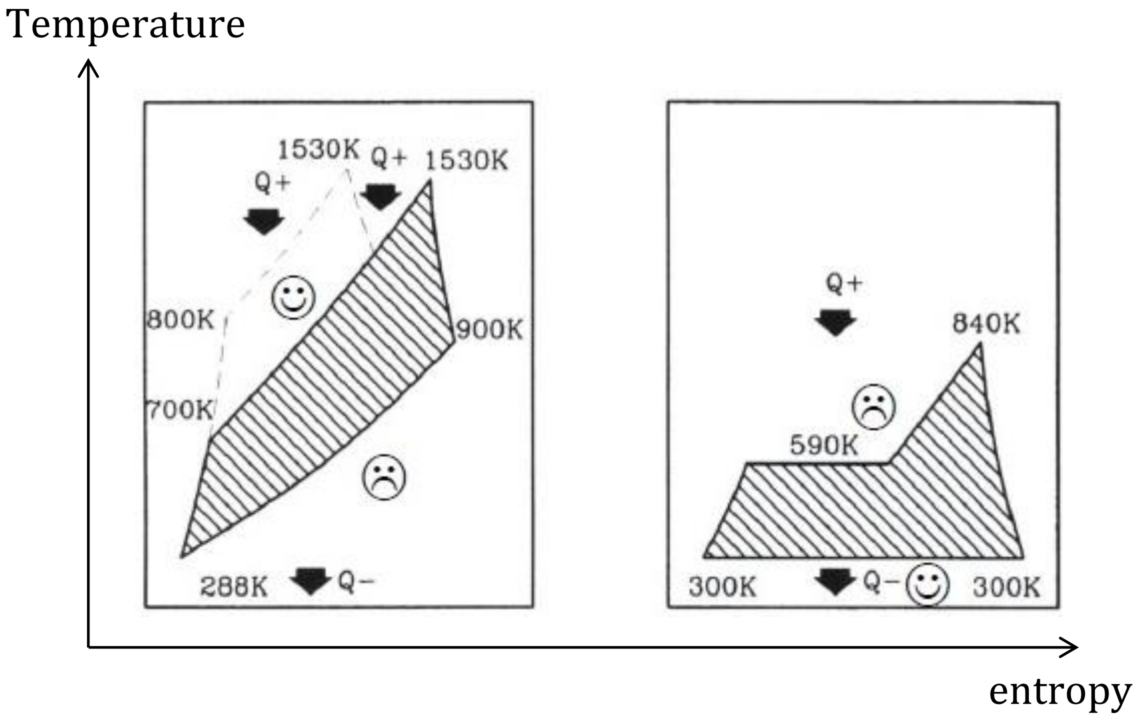
Overview on power generating systems

Comparison of average heat addition & rejection temperatures

	Gas turbine	**Steam turbine**
T_H [°C]	750 - 1200	350 - 450
T_L [°C]	270 - 450	30 – 80
$\eta_{\text{Carnot,eq}}$[%]	45-50	45-55

None of the engines have both T_H ↑ and T_L ↓

It is possible to hold the best features of each one?



Overview on power generating systems

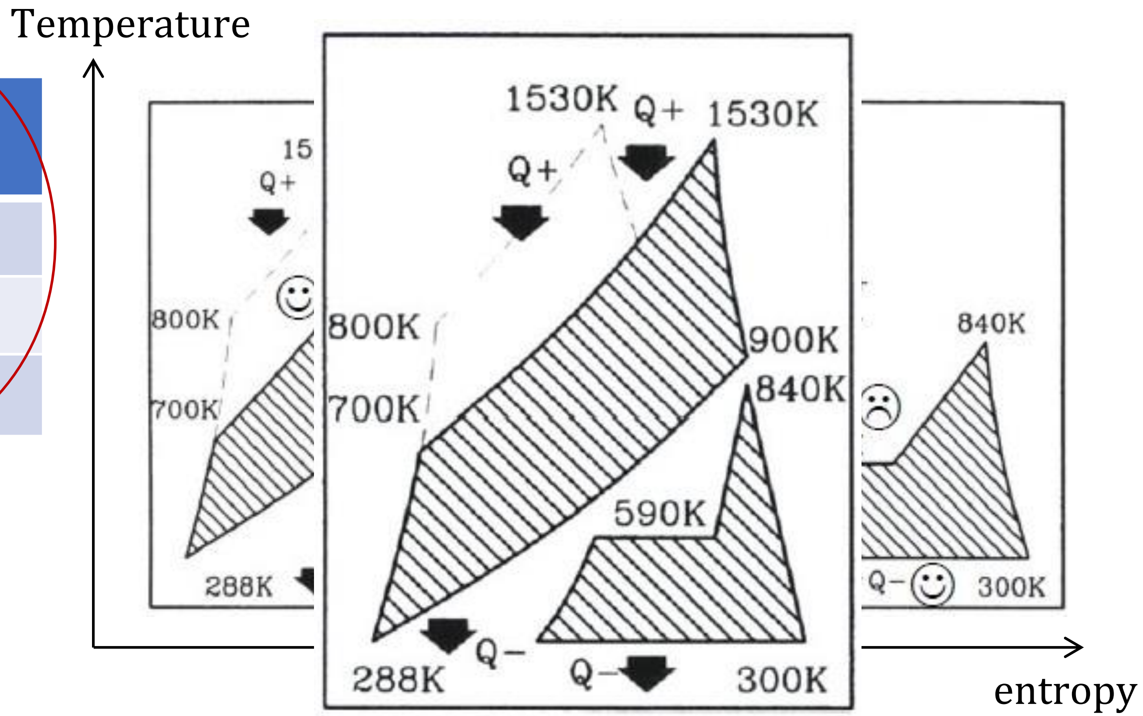
Comparison of average heat addition & rejection temperatures

	Gas turbine	Steam turbine	Combined cycle
T_H $[°C]$	750 - 1200	350 - 450	750 - 1200
T_L $[°C]$	270 - 450	30 – 80	30 – 80
$\eta_{\text{Carnot,eq}}[\%]$	45-50	45-55	65-75

None of the engines have both T_H ↑ and T_L ↓

It is possible to hold the best features of each one?

Yes. Gas & Steam Combined Cycles.



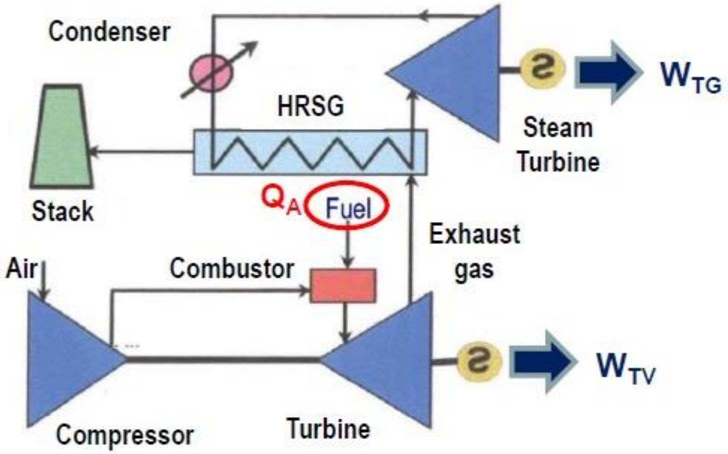
Overview on power generating systems

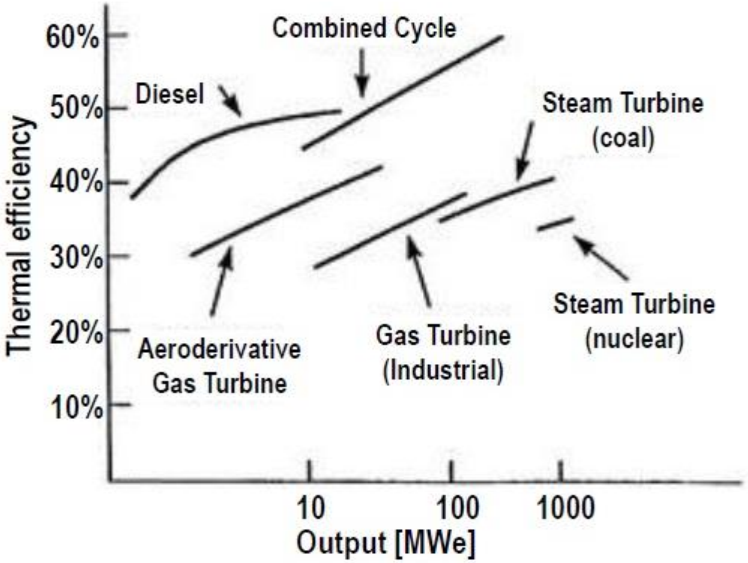
A Gas & Steam Combined Cycle is based on three principles:

i. **Add heat** (thermal energy) to the gas turbine engine
ii. **Transfer waste heat** from the gas turbine engine exhaust to the steam cycle
iii. **Reject heat** (thermal energy) from the steam turbine engine to the enivronment

Conclusions about T_H and T_L still valid:

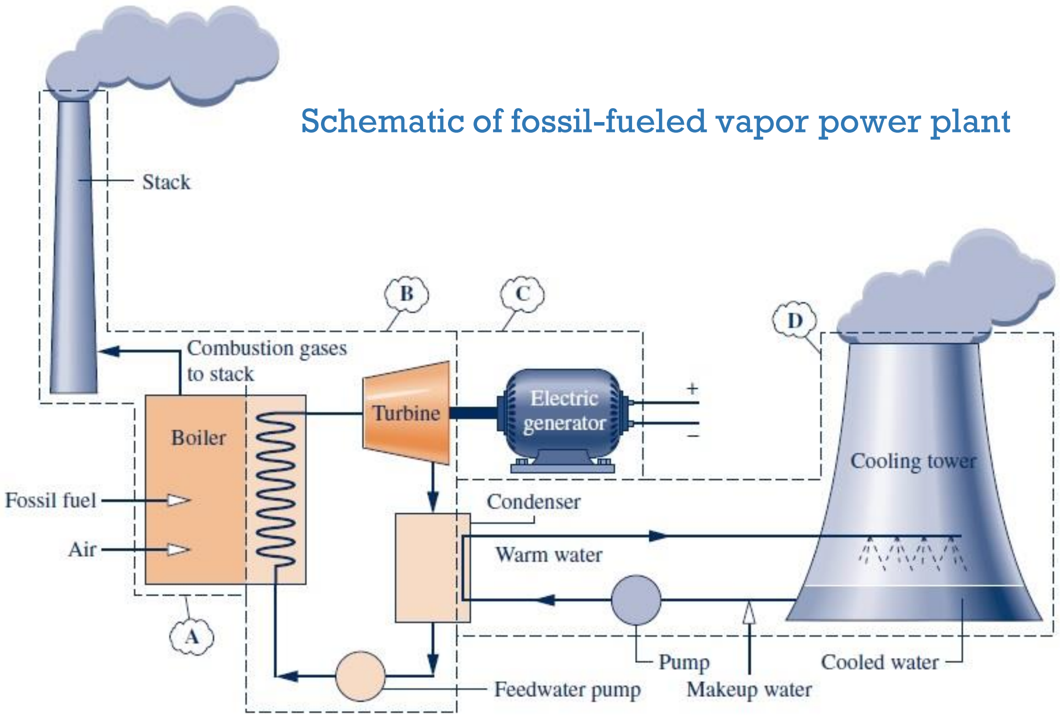
i. Highest efficiency for large-scale heat engine – based power generation
ii. Currently higher than 60%
iii. Output up to 800 MWe





Vapor power plants

- Used in coal-fueled, oil-fueled, biomass-fueled, geothermal, solar-concentrating and conventional nuclear power plants.
- The **Rankine cycle** is the basic building block of vapor power plants.
- A specific version of Rankine cycle is the **Organic Rankine Cycle (ORC)**, a technology that has been developed to commercial level in the last few decades and is used now in some specific applications, especially in renewable energy systems.


Schematic of fossil-fueled vapor power plant

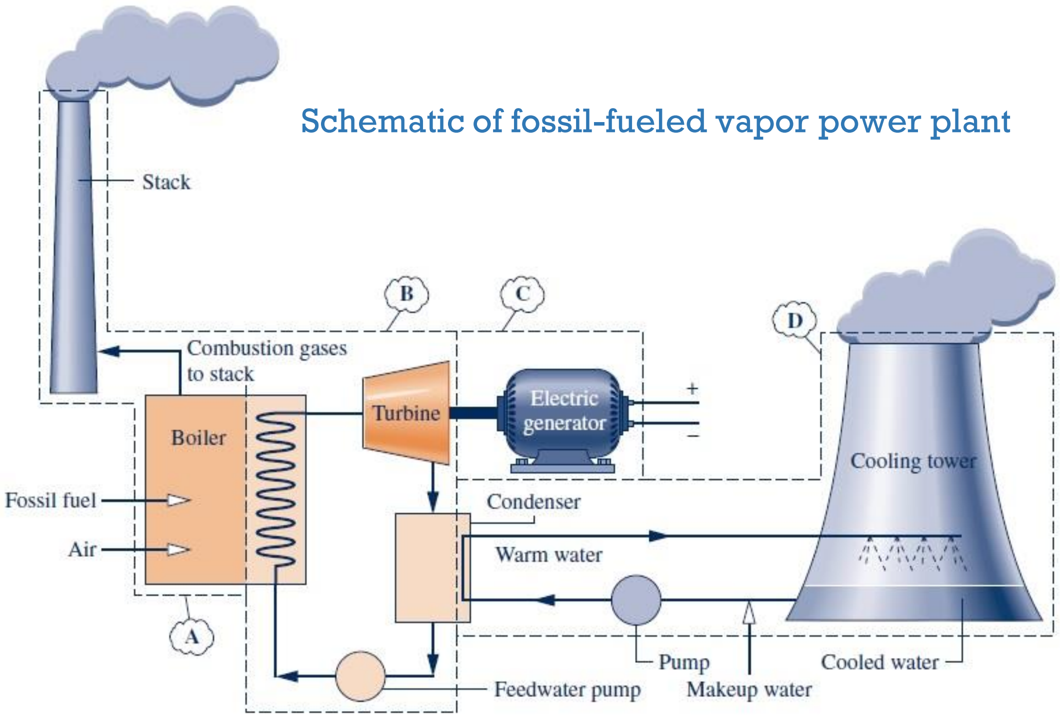

Fossil-fueled vapor power plant

Vapor power plants

In a conventional vapor power plant, fuel is burnt in a boiler which produces steam at high pressure and temperature.

This steam is passed through a steam turbine which converts steam's heat energy into mechanical energy. The steam turbine acts as a prime mover and it is coupled to an alternator.

The alternator collects the mechanical energy from the steam turbine and convert into electrical energy.



Schematic of fossil-fueled vapor power plant

Four major subsystems:

A. The energy needed to vaporize the working fluid is supplied.

B. The energy conversion from heat to work occurs.

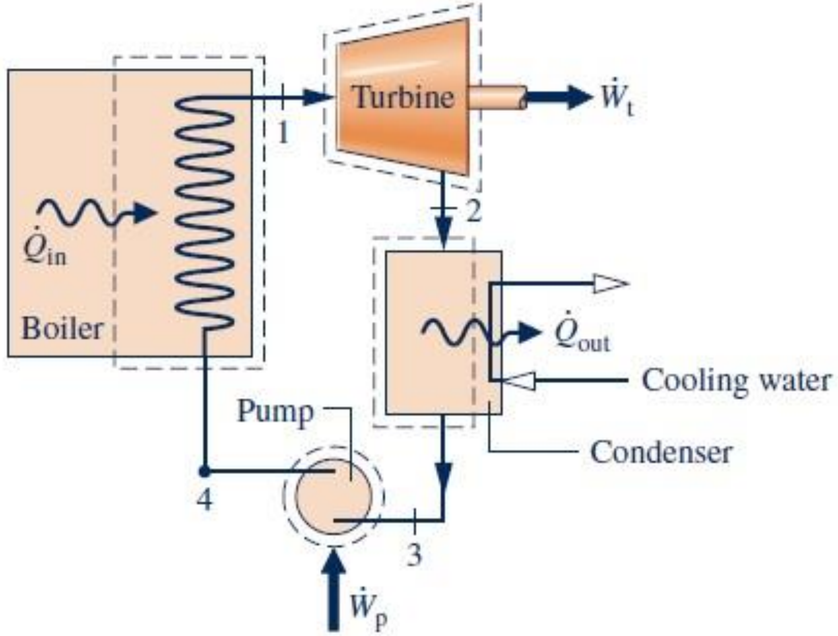
C. Mechanical energy is converted in electrical energy.

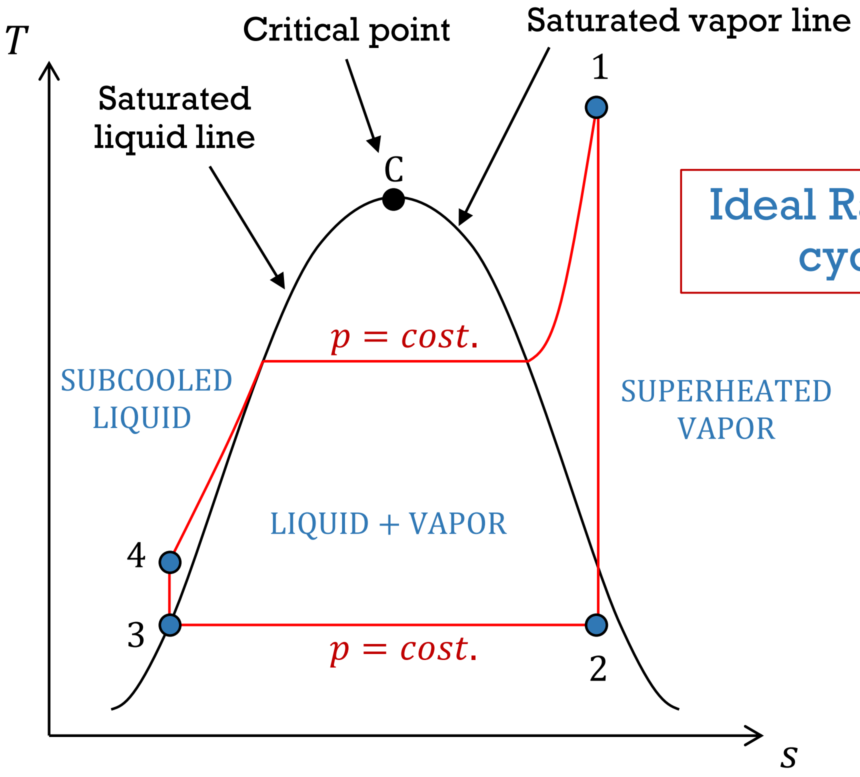
D. The energy received from steam condensing in the condenser is rejected into the atmosphere.

Vapor power plants

Referring to subsystem B, each unit of mass of working fluid periodically undergoes a thermodynamic cycle as it circulates through the series of interconnected components. This cycle is the Rankine cycle.

The Rankine cycle is described by four consecutive processes. This cycle is executed with a machine comprising the following four principal components: turbine, condenser, pump, and boiler/vapor generator.





Ideal Rankine cycle

Steam Rankine power stations

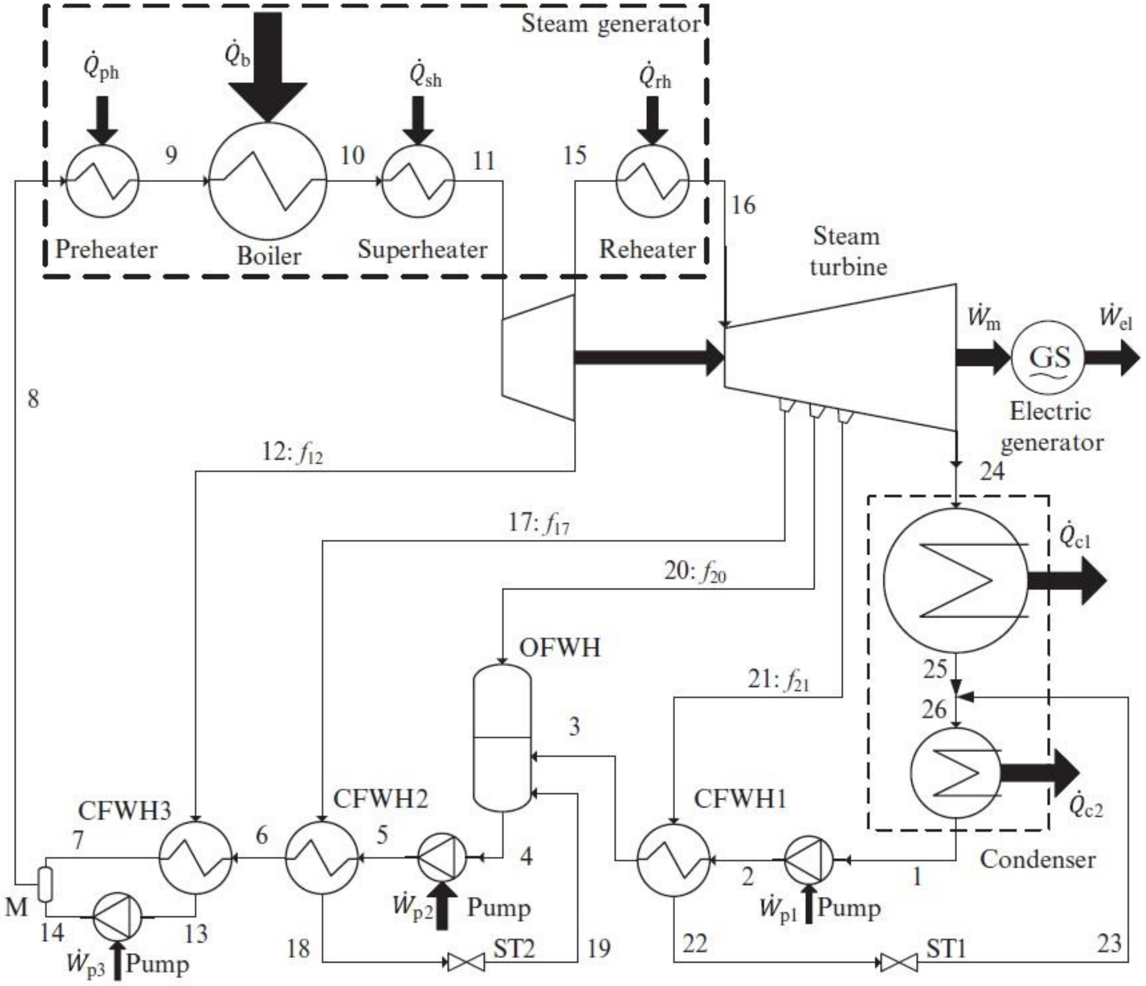
The vast majority of steam power stations are based on **reheating-regenerative Rankine cycles**.

These types of cycles are very complex as they comprise many types of components, including:

- preheater, boiler, superheater, reheater
- closed (CFWH) and open (OFWH) feedwater heaters
- condenser
- mixer, deaerator, steam traps (ST)
- pumps, turbines

Multiple feedwater heaters of closed type can be cascaded using steam traps and a single pump.

Power plants with multiple feedwater heaters ordinarily have *at least one open feedwater heater* operating at a pressure greater than atmospheric pressure so that oxygen and other dissolved gases can be vented from the cycle.



Vapor power plant with single reheating and multiple feedwater heaters (M – mixer, CFWH – closed feedwater heater, OWFH – open feedwater heater, ST – steamtrap).

Organic Rankine Cycles

Water is the choice working fluid for large-scale Rankine cycles operating with high temperature energy sources in a wide variety of cycle configurations, from the cycles of nuclear power plants to those for coal-fired power plants.

However, the thermodynamic properties of steam lead to complex plant schemes and to liquid formation during the expansion process. These constraints make steam a working fluid not suitable for *low temperature/low power output* applications.

Organic Rankine Cycles (ORCs) employ organic substances as working fluids.

ORC systems are typically used for power production from low/medium temperature heat sources (below 400°C) and for low/medium power applications.

This technology allows for exploitation of low-grade heat that otherwise would be wasted.

This is obtained by selecting a proper working fluid, capable of obtaining a simple plant arrangement and a low-cost turbine without liquid formation during the expansion.

The possibility of selecting the proper working fluid is the most important degree of freedom in ORC design.

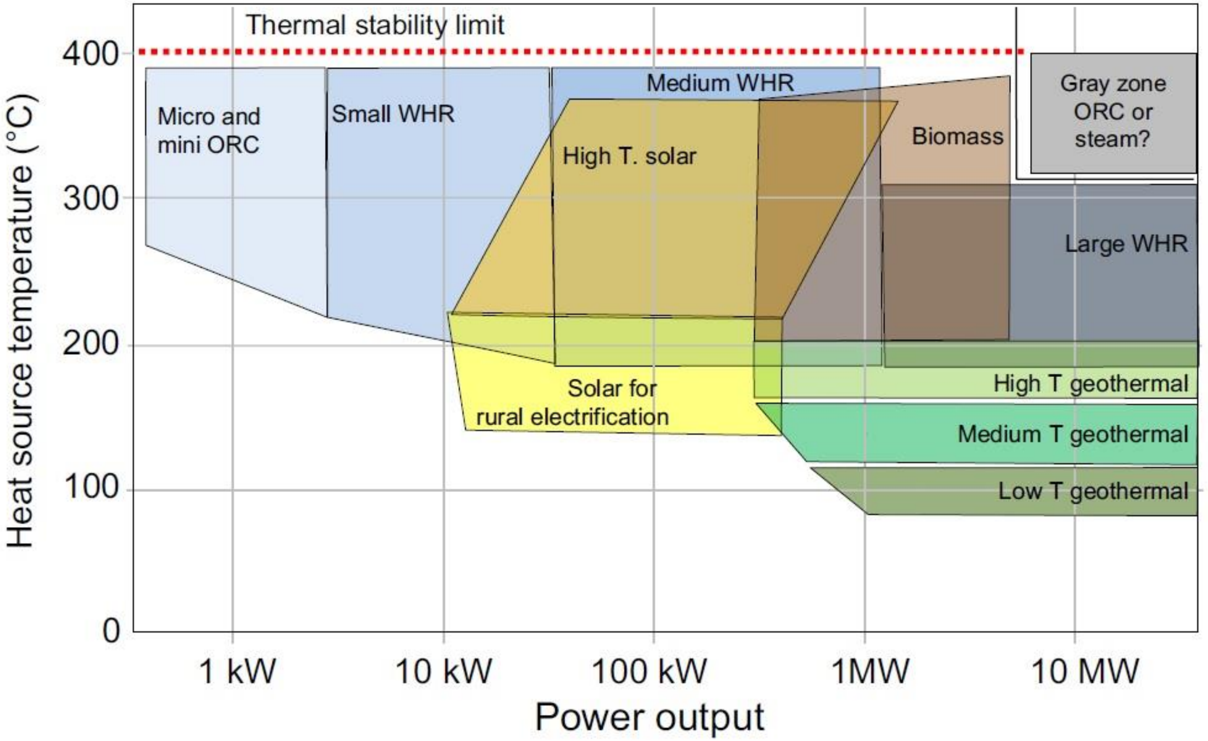
There is a wide choice for the working fluid. This affects the thermodynamic cycle, the performance and cost of components, the plant layout and the safety requirements.

Organic Rankine Cycles

Local and small-scale power generation as well as *renewable energy systems* and *low-grade heat recovery systems* are the best applications for ORC technology.

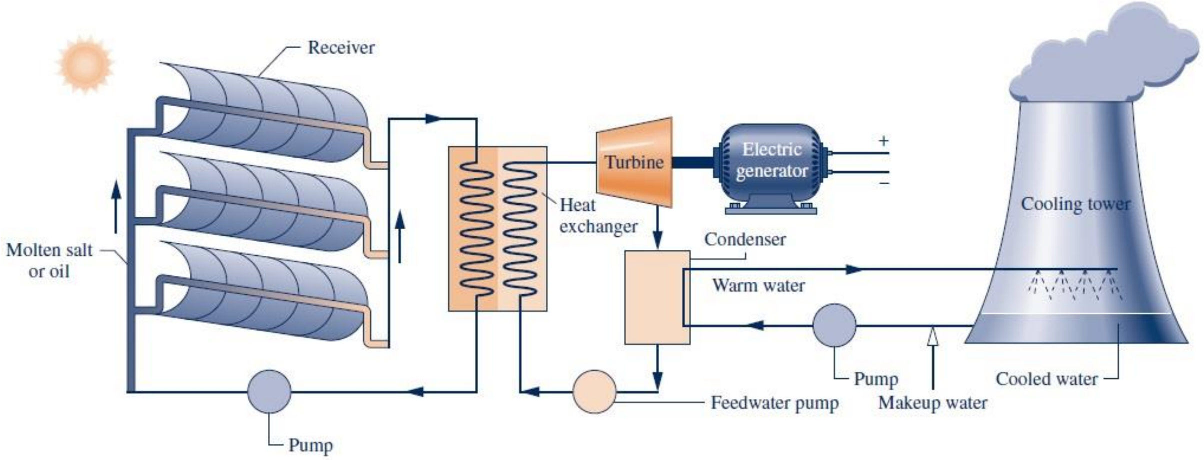
ORCs are suitable for a wide range of applications. Some examples of low-temperature heat sources from renewable sources:

- geothermal energy
- biomass combustion systems
- concentrated solar power (CSP)
- waste heat recovery (WHR) systems
- heat recovery systems from engine/gas turbine exhaust gases

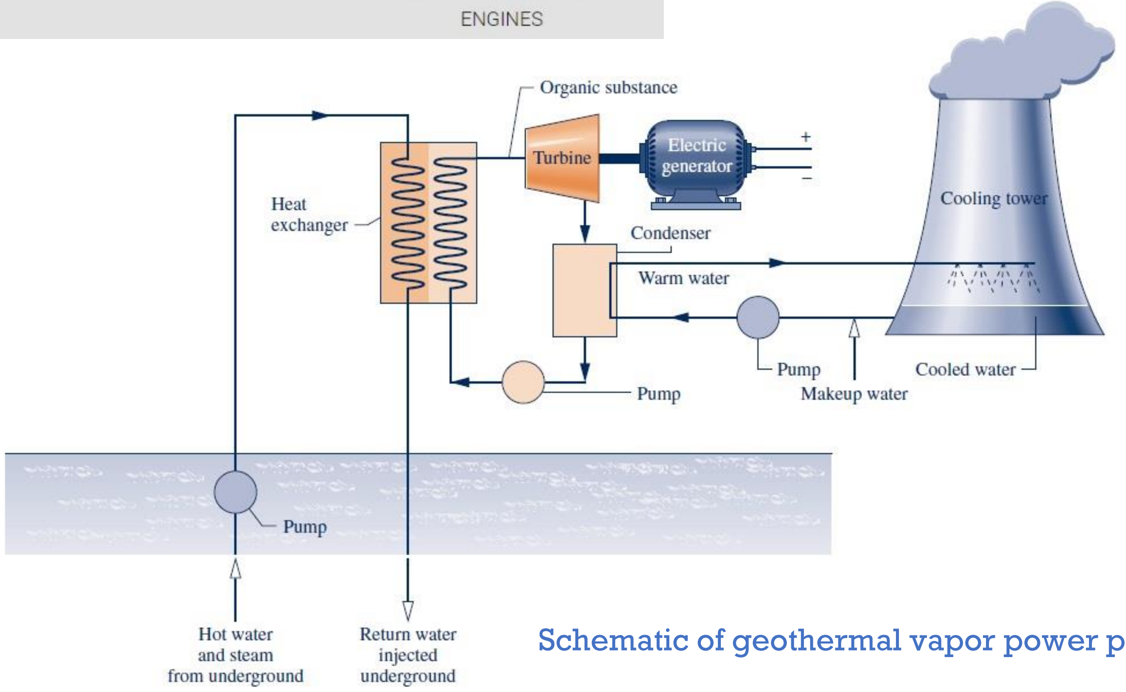


Organic Rankine Cycles

- GEOTHERMAL
- BIOMASS
- CONCENTRATED SOLAR POWER (CSP)
- POWER GENERATION FROM WASTE HEAT IN INDUSTRIAL PROCESSES
- POWER GENERATION INCREASING EFFICIENCY OF SYSTEMS BASED ON DIESEL AND GAS TURBINES AND RECIPROCATING ENGINES



Schematic of concentrated solar thermal vapor power plant



Schematic of geothermal vapor power plant

Organic Rankine Cycles

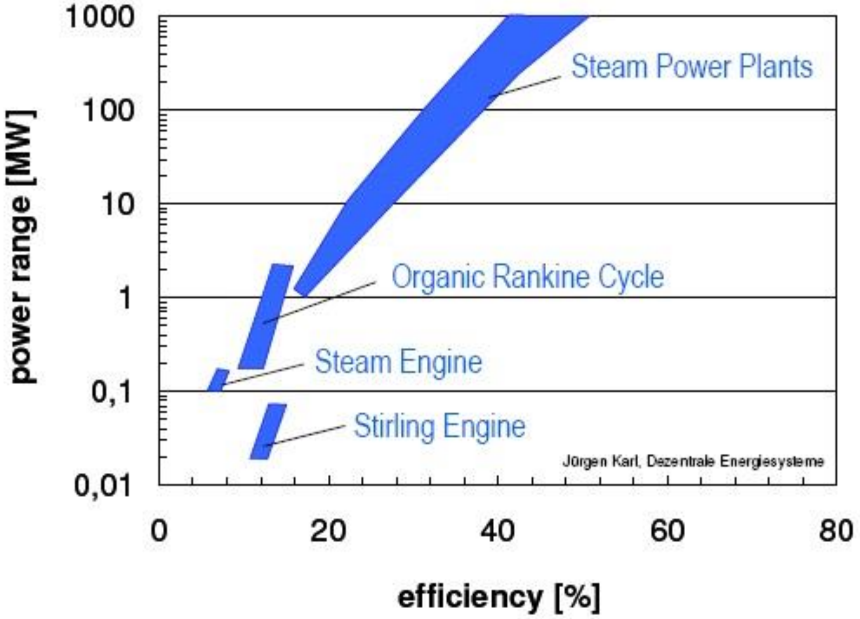
The efficiency of ORCs is limited: for medium/low temperature heat sources because of the Carnot effect; for medium/low power output because of the limited efficiency of some key components, which are penalized by miniaturization.

However, due to their limited power output, ORCs are realized by means of plant layouts less complex than those for common steam Rankine cycles.

Compared to large recuperative steam cycles, two or three pressure levels cycles are rarely proposed on the market, with the exception of the geothermal field, where the high cost of the heat source (exploration and drilling are capital intensive activities) makes profitable the use of more expensive but also more efficient plants.

Intrinsically simpler plant layout:

- limited number of components
- easy operation
- small thermal inertia
- great flexibility in off-design conditions



Jürgen Karl, Dezentrale Energiesysteme

Organic Rankine Cycles

ORC technology has received increased attention in the last decades.

The manufacturers of ORC provide a wide range of solutions, based on the temperature level and sources.

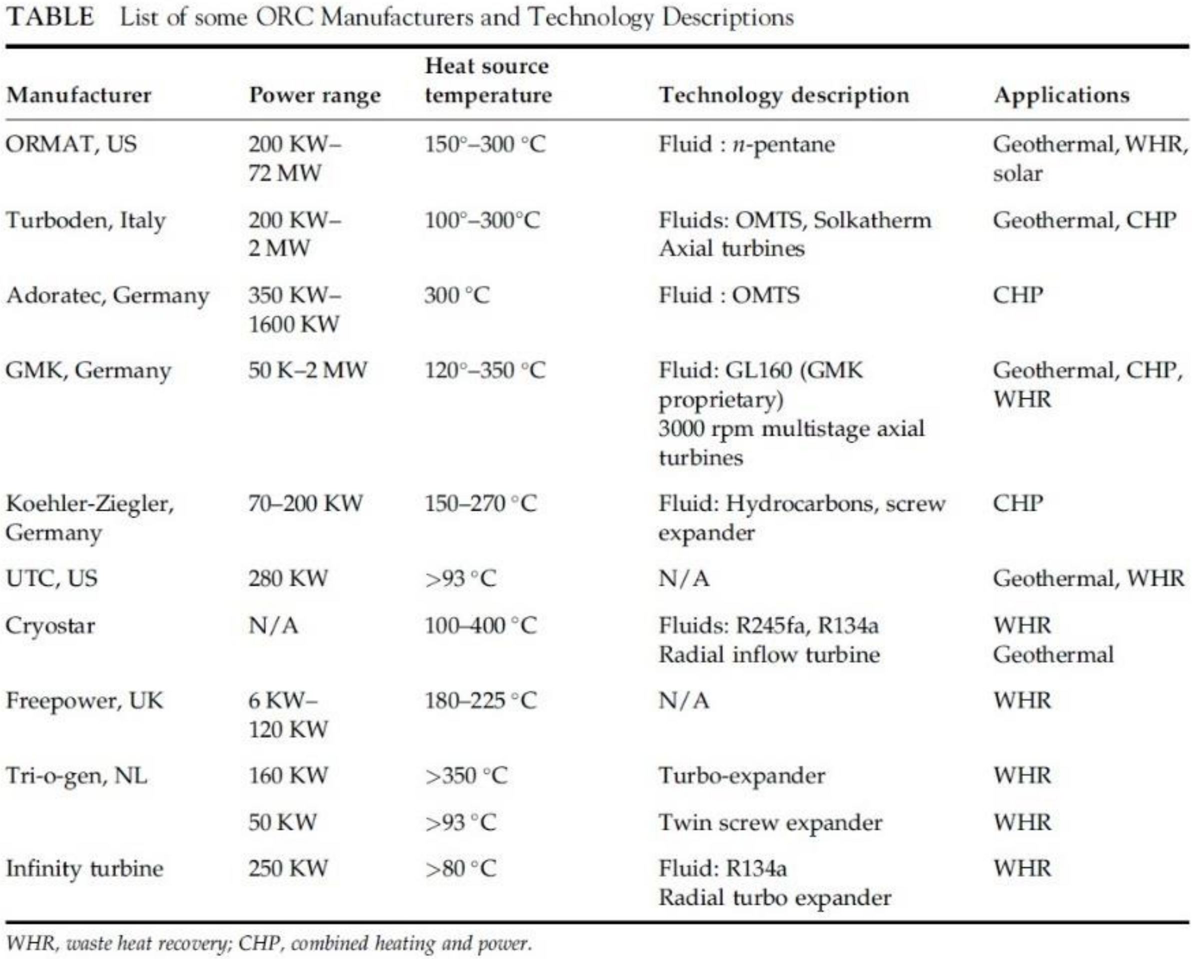


TABLE List of some ORC Manufacturers and Technology Descriptions

Manufacturer	Power range	Heat source temperature	Technology description	Applications
ORMAT, US	200 KW–72 MW	150°–300 °C	Fluid : *n*-pentane	Geothermal, WHR, solar
Turboden, Italy	200 KW–2 MW	100°–300°C	Fluids: OMTS, Solkatherm Axial turbines	Geothermal, CHP
Adoratec, Germany	350 KW–1600 KW	300 °C	Fluid : OMTS	CHP
GMK, Germany	50 K–2 MW	120°–350 °C	Fluid: GL160 (GMK proprietary) 3000 rpm multistage axial turbines	Geothermal, CHP, WHR
Koehler-Ziegler, Germany	70–200 KW	150–270 °C	Fluid: Hydrocarbons, screw expander	CHP
UTC, US	280 KW	>93 °C	N/A	Geothermal, WHR
Cryostar	N/A	100–400 °C	Fluids: R245fa, R134a Radial inflow turbine	WHR Geothermal
Freepower, UK	6 KW–120 KW	180–225 °C	N/A	WHR
Tri-o-gen, NL	160 KW	>350 °C	Turbo-expander	WHR
	50 KW	>93 °C	Twin screw expander	WHR
Infinity turbine	250 KW	>80 °C	Fluid: R134a Radial turbo expander	WHR

WHR, waste heat recovery; CHP, combined heating and power.

Organic Rankine Cycles

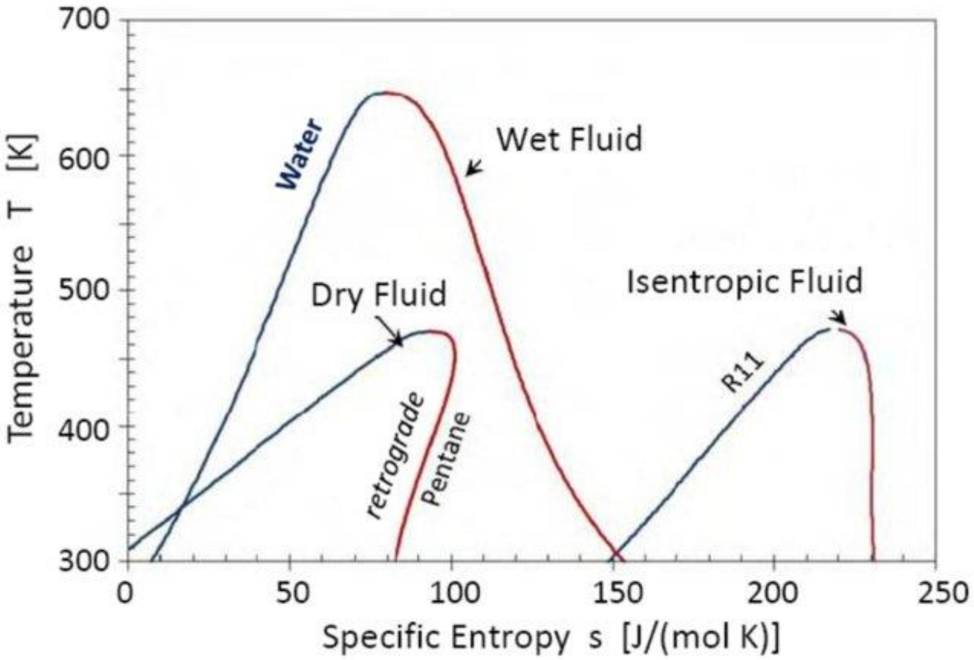
Working fluid characteristics have great influence in determining the cycle configuration.

Selection of the working fluid must be done in compliance with the ORC application, which is influenced by the type of heat source, level of temperature, modes of heat transfer, and scale of the application.

The retrograde characteristic of the working fluid plays a crucial role in determining the cycle configuration.

Organic working fluid selection criteria:

- *Thermodynamic and physical properties.* Organic working fluids has lower boiling point than water. This is way they are able to use low temperature heat sources to produce electricity.
- *Compatibility with materials*. Organic working fluids must be non corrosive.
- *Thermochemical stability at high temperatures*. Most ORC applications require the working fluid to withstand relatively high temperatures in cyclic conditions.
- *Cost effectiveness*. Maintenance costs are related to fluid degradation.
- *Commercial availability*.



Organic Rankine Cycles

Organic working fluid characterization

Several indexes account for the environmental impact and safety of the fluid:

ODP – Ozone Depletion Potential. Ozone destruction rate per unit mass released in the atmosphere. Reference: R11 (or CFC-11), having ODP = 1.0. That is, the ratio of global loss of ozone due to given substance over the global loss of ozone due to the release of the same mass of R11.

GWP – Global Worming Potential. It is the heat absorbed by the gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide. Reference: CO_2, having GWP = 1.0.

TOX – Toxicity. Average concentration after 8 h operation.

ALT – Atmospheric lifetime. Lifetime in the atmosphere based on the reaction rate and affinity with other reactants.

Flammability. Ability to ignite in the presence of an ignition source.

Organic Rankine Cycles

It is practically impossible to satisfy all the requirements with an organic fluid suitable for ORC applications. The problem is still unsolved and in most cases, the ORC manufacturers must renounce to some of the requirements.

Typical organic working fluid: pentane, mixtures of hydrocarbons, commonly used refrigerants, ammonia, and silicon oil.

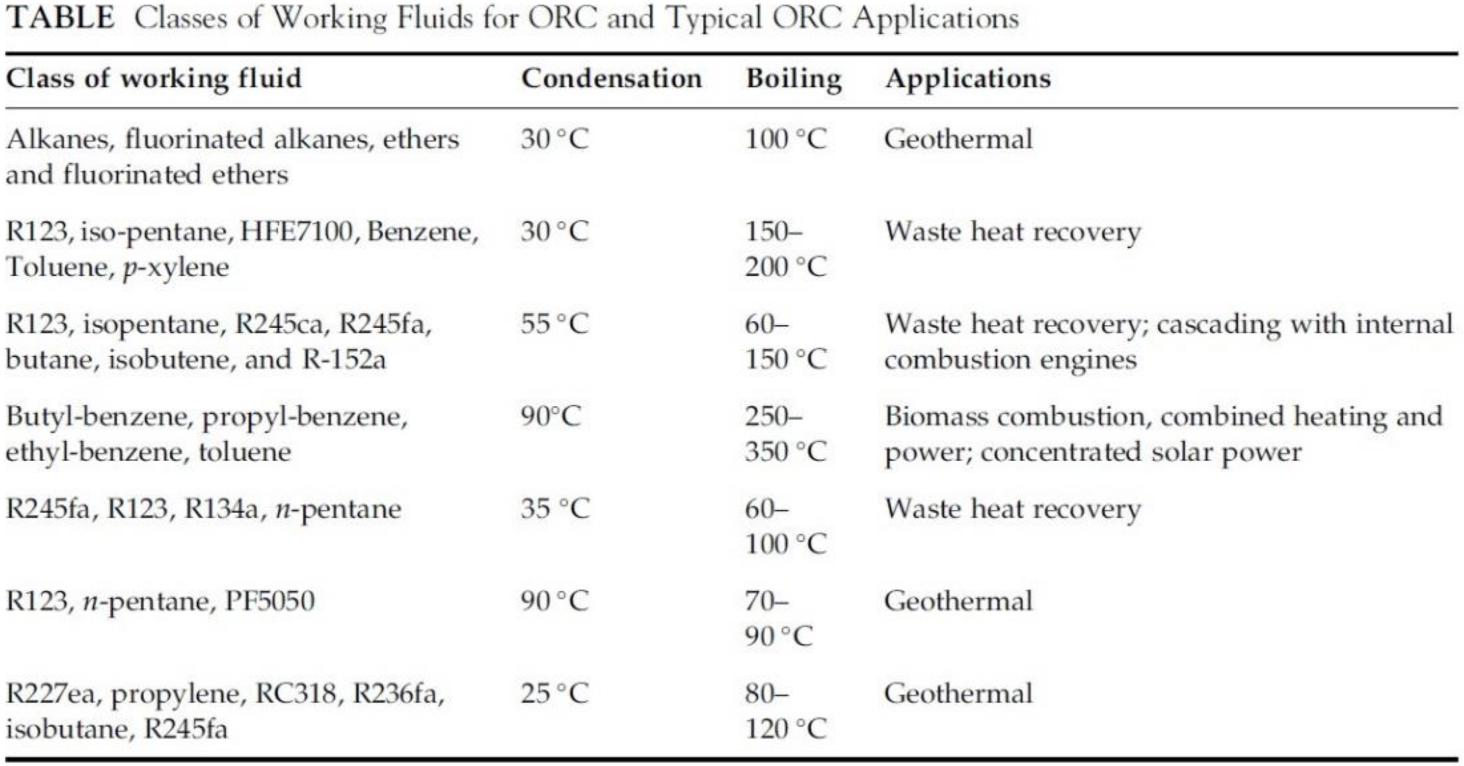


TABLE Classes of Working Fluids for ORC and Typical ORC Applications

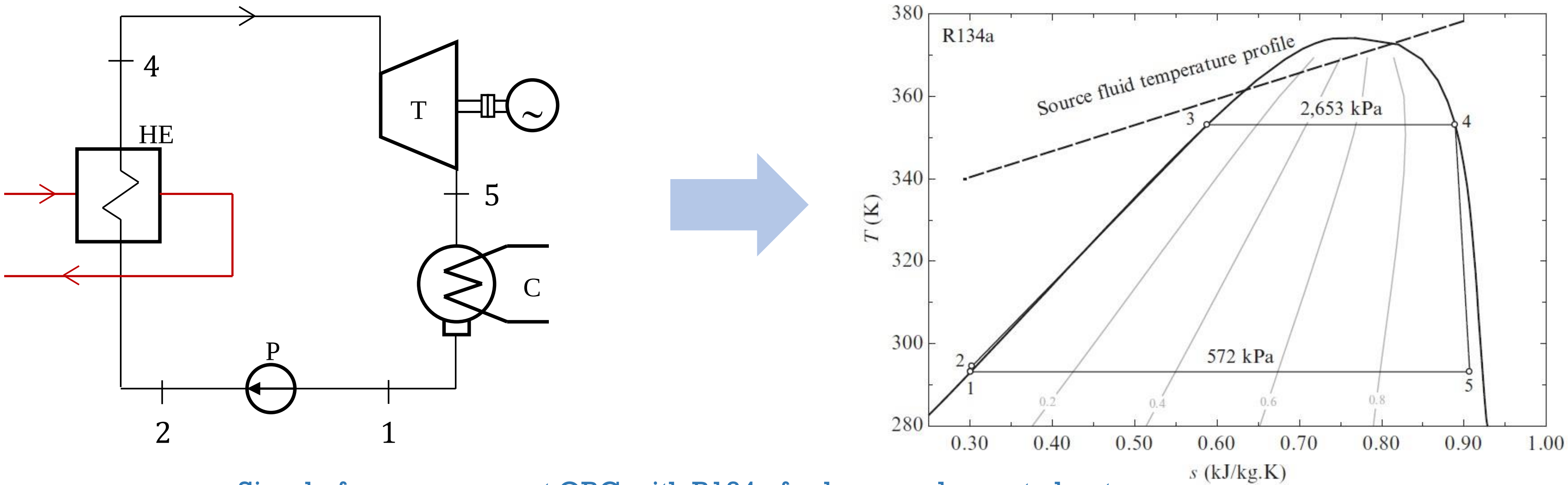
Class of working fluid	Condensation	Boiling	Applications
Alkanes, fluorinated alkanes, ethers and fluorinated ethers	30 °C	100 °C	Geothermal
R123, iso-pentane, HFE7100, Benzene, Toluene, *p*-xylene	30 °C	150–200 °C	Waste heat recovery
R123, isopentane, R245ca, R245fa, butane, isobutene, and R-152a	55 °C	60–150 °C	Waste heat recovery; cascading with internal combustion engines
Butyl-benzene, propyl-benzene, ethyl-benzene, toluene	90°C	250–350 °C	Biomass combustion, combined heating and power; concentrated solar power
R245fa, R123, R134a, *n*-pentane	35 °C	60–100 °C	Waste heat recovery
R123, *n*-pentane, PF5050	90 °C	70–90 °C	Geothermal
R227ea, propylene, RC318, R236fa, isobutane, R245fa	25 °C	80–120 °C	Geothermal

Organic Rankine Cycles – power plant configurations

There are many configurations of the ORC which differ from the typical reheat-regenerative steam cycle configuration that normally uses steam extraction.

Both turbines and positive displacement expanders are considered prime movers for ORCs. The choice depends on the scale of the application, the working fluid, pressure differentials, and pressure and volume ratios. Turbines are the preferred choice for large-scale applications, because of their higher efficiency.

ORC with retrograde fluids can operate without superheating, which makes them better suited for applications that involve heat recovery or solar energy.



Simple four-component ORC with R134a for low-grade waste heat recovery

Organic Rankine Cycles – power plant configurations

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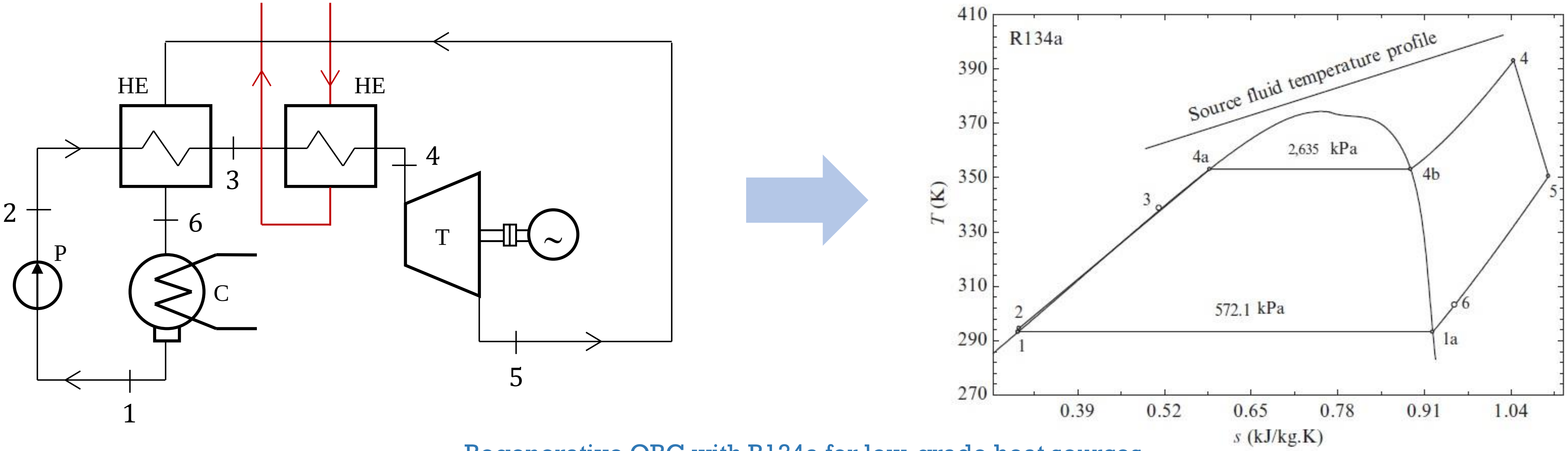


Regenerative ORC with R134a for low-grade heat sources.

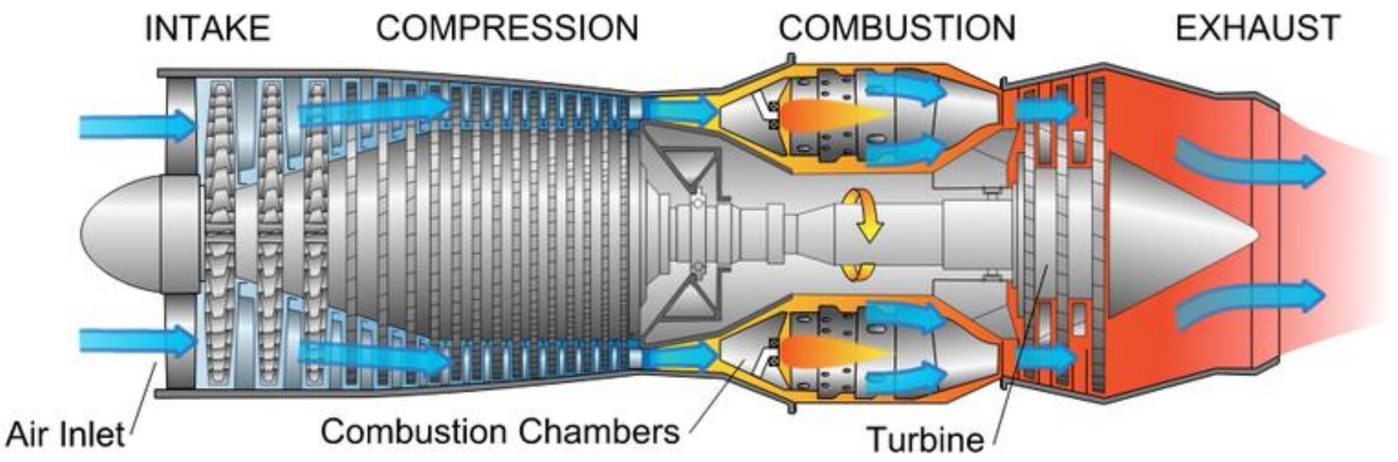
Gas turbine power plants

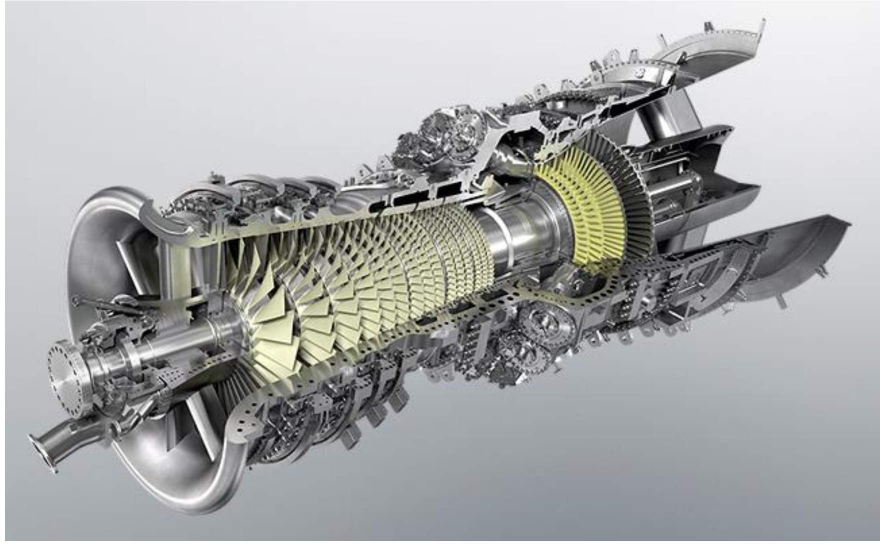
Gas turbine power plants started to be developed commercially in the 1930s based on a simple Brayton cycle of open type that includes a compressor, a combustion chamber, and a gas turbine.

Further technological developments led to commercialization of advanced power generators with enhanced efficiency due to use of a regenerator, gas-reheater, and compressor intercooler, as well as turbine-blade cooling, which allowed for a higher operating temperature.

The favourable power-output-to-weight ratio of gas turbines makes them well suited for transportation applications (aircraft propulsion, marine power plants, etc.).

Today's electric power-producing gas turbines are almost exclusively fueled by **natural gas**. However, depending on the application, other fuels can be used by gas turbines, including syngas (synthesis gas) obtained by gasification of coal.





Gas turbine power plants

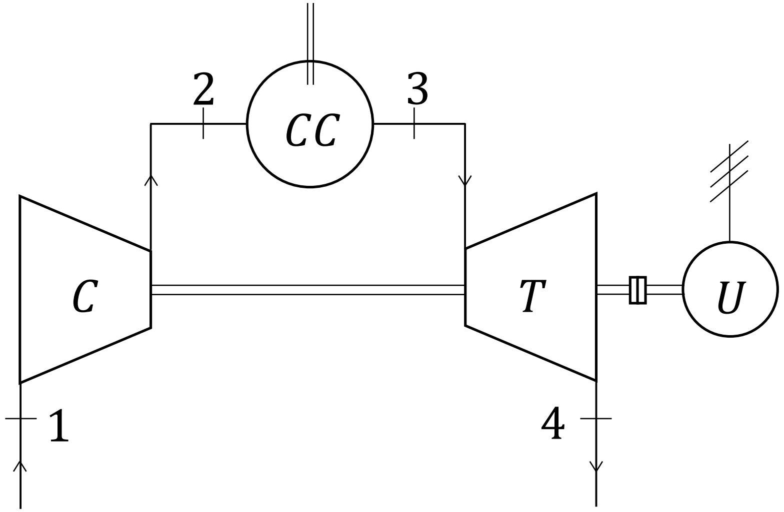
Large power generation plants reach up to 500 MW of power output, with efficiencies ranging from 30% to 48%, and above 60% in a combined-cycle mode.

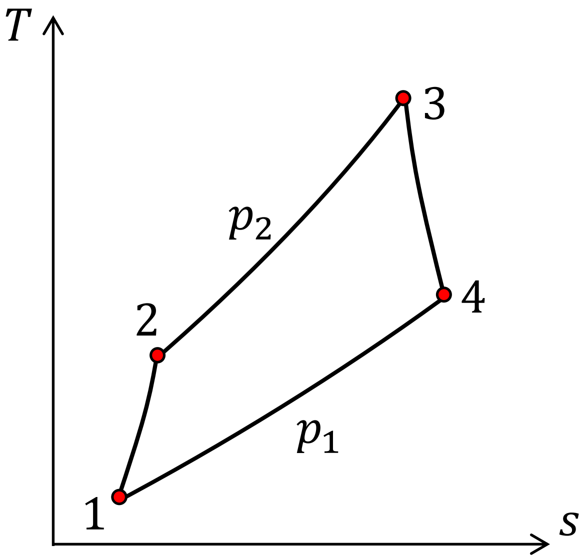
The overall pressure ratio of these units is up to 35:1. Turbine inlet temperatures run as high as 1500 °C.

There are three major components of gas-turbine power plants:

- Compressor
- Turbine
- Combustor

The frame type heavy-duty gas turbines employ *multistage axial-flow compressors and turbines*, with multiple *can-annular combustors* each connected to the other by crossover tubes, or single large *annular combustors* with multiple nozzles.





Gas turbine power plants operate on an open cycle, as follows:

- 12 – fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised.
- 23 – the high pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure.
- 34 – the high-temperature gases then enter the turbine, where they expand to the atmospheric pressure while producing power.
- 41 – the exhaust gases leaving the turbine are thrown out.

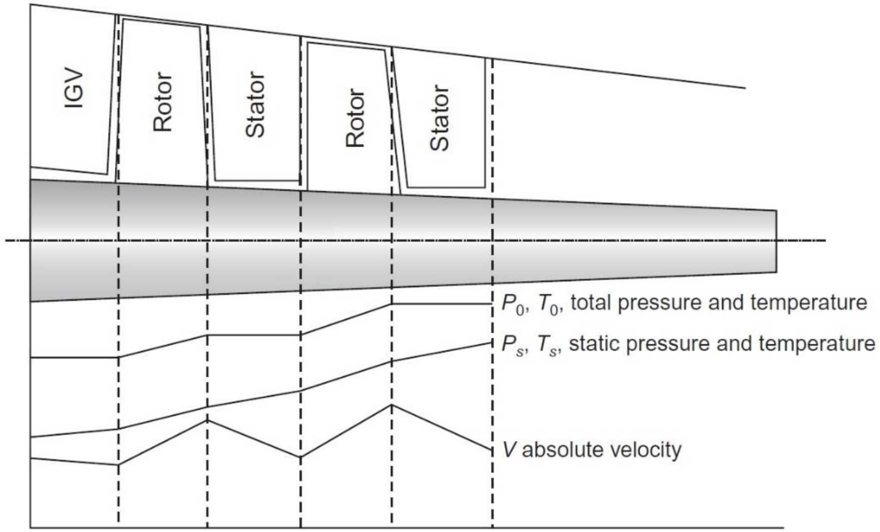
Gas turbine power plants

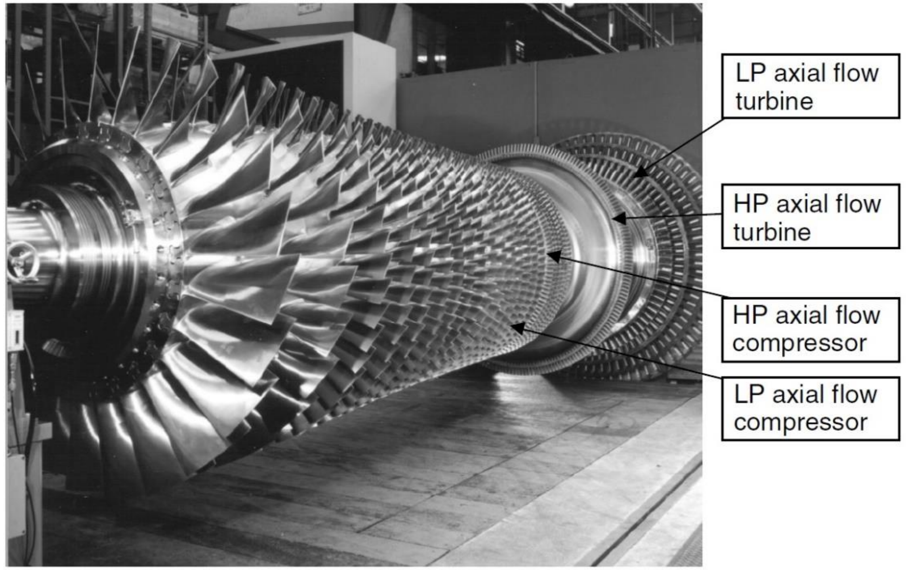
An axial-flow compressor is one in which the flow enters the compressor in an axial direction (parallel with the axis of rotation), and exits from the gas turbine also in an axial direction.

The axial-flow compressor compresses its working fluid by first accelerating the fluid and then diffusing it to obtain a pressure increase.

The fluid is accelerated by a row of rotating airfoils (blades) called the **rotor**, and then diffused in a row of stationary blades (the **stator**). The diffusion in the stator converts the velocity increase gained in the rotor to a pressure increase.

A compressor consists of several stages. A combination of a rotor followed by a stator make up a stage in a compressor.



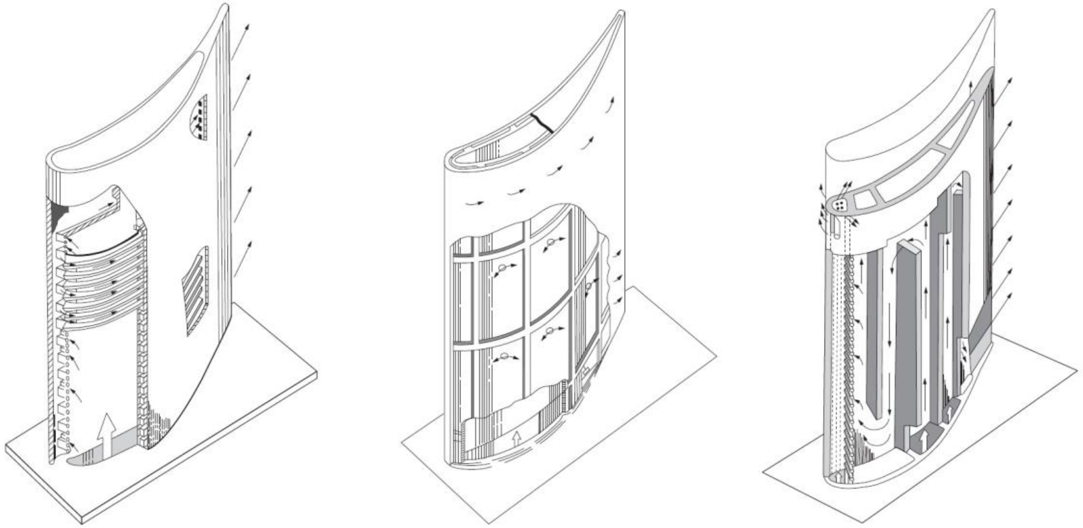


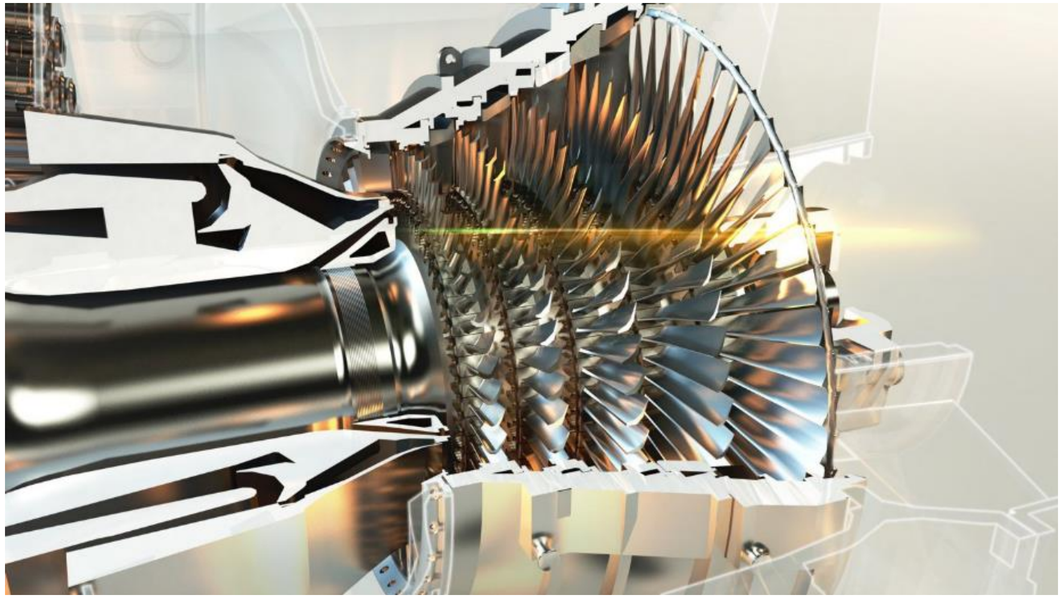
Gas turbine power plants

Axial-flow turbines are the most widely employed turbines using a compressible fluid.

The axial-flow turbine, similar to its counterpart, the axial-flow compressor, has flow that enters and leaves in the axial direction.

The turbine inlet temperatures of gas turbines have increased considerably over the past years. This trend has been made possible by advancement in materials, technology and the use of advanced turbine blade cooling techniques. These developments led to high turbine efficiencies.



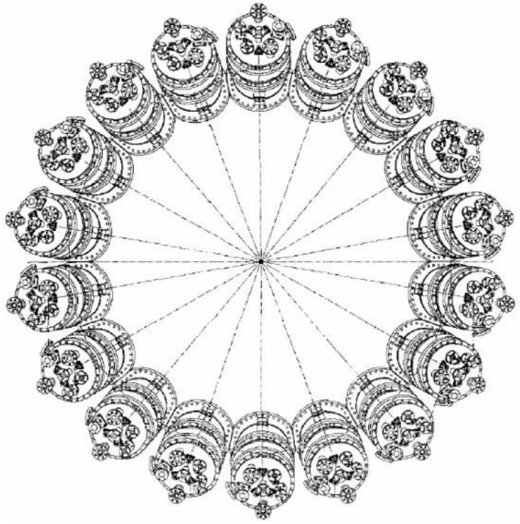


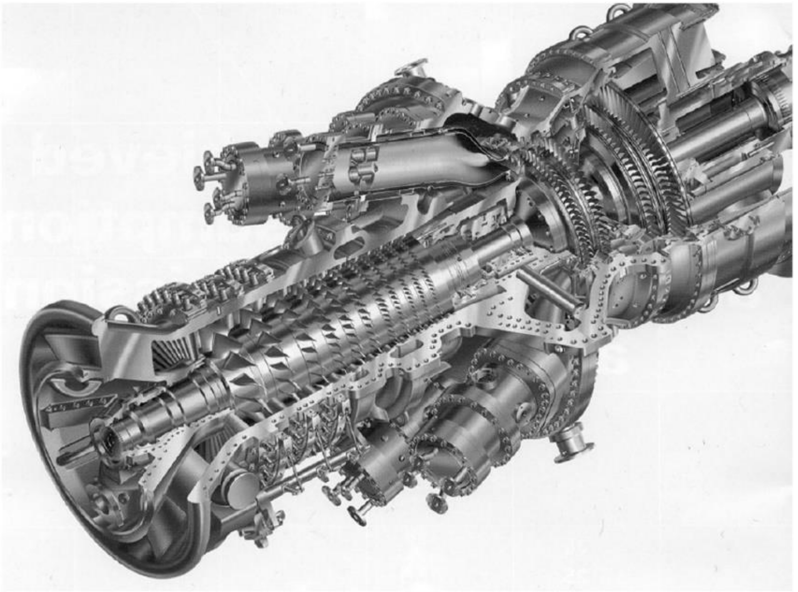
Gas turbine power plants

Heat input to the gas turbine cycle is provided by a combustor. The combustor accepts air from the compressor and delivers it, at an elevated temperature, to the turbine (ideally with no pressure loss).

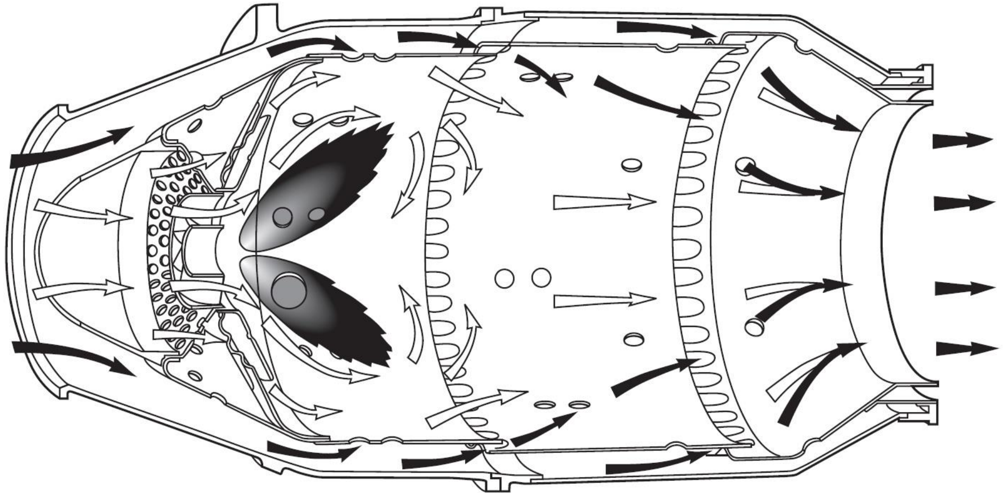
All gas turbine combustors perform the same function; they increase the temperature of the high-pressure gas.

Combustion efficiency is a measure of combustion completeness. Combustion completeness affects fuel consumption directly, since the heating value of any unburned fuel is not used to increase the turbine inlet temperature.





Can-Annular combustors



Gas turbine power plants

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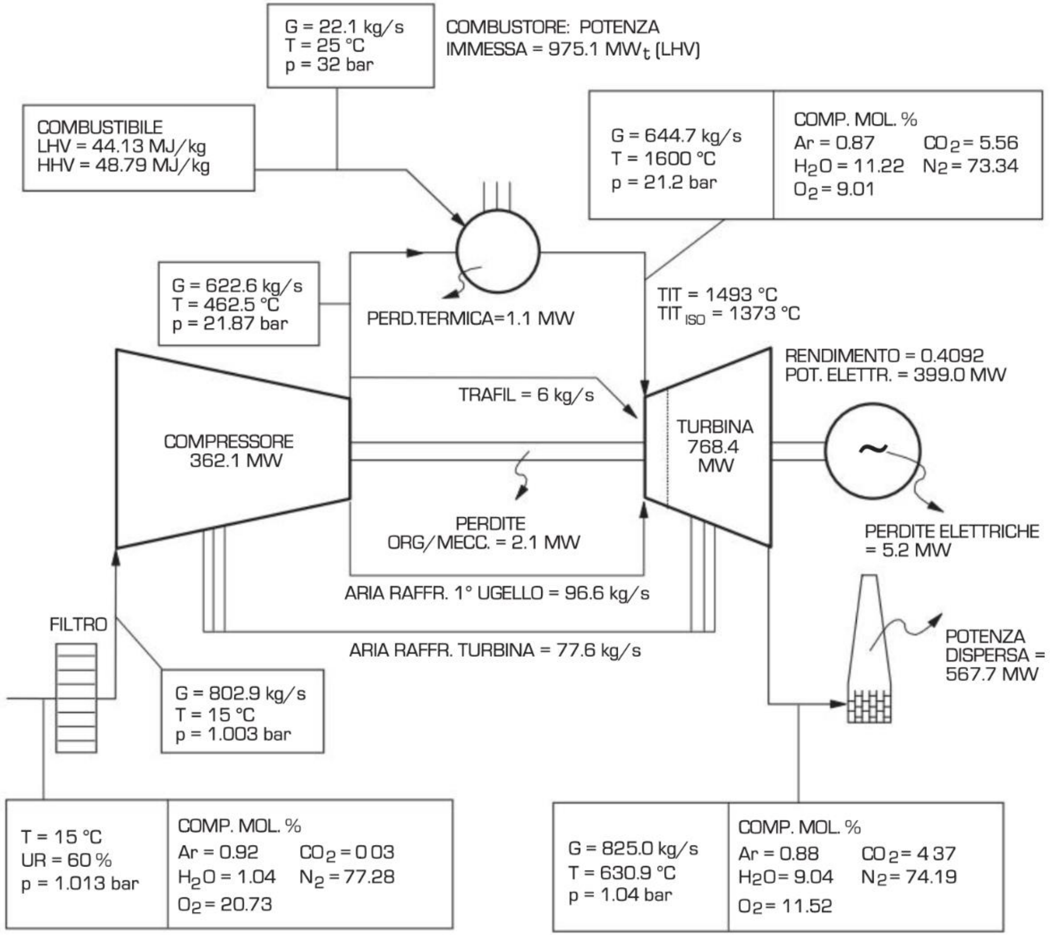
https://www.youtube.com/watch?v=zcWkEKNvqCA

https://www.youtube.com/watch?v=NQPIWitFq3Q

Gas turbine power plants



G = 22.1 kg/s
T = 25 °C
p = 32 bar

COMBUSTORE: POTENZA
IMMESSA = 975.1 MW_t (LHV)

COMBUSTIBILE
LHV = 44.13 MJ/kg
HHV = 48.79 MJ/kg

G = 644.7 kg/s
T = 1600 °C
p = 21.2 bar

COMP. MOL. %
Ar = 0.87
CO_2 = 5.56
H_2O = 11.22
N_2 = 73.34
O_2 = 9.01

G = 622.6 kg/s
T = 462.5 °C
p = 21.87 bar

PERD.TERMICA=1.1 MW

TIT = 1493 °C
TIT_{ISO} = 1373 °C

RENDIMENTO = 0.4092
POT. ELETTR. = 399.0 MW

TRAFIL = 6 kg/s

COMPRESSORE
362.1 MW

TURBINA
768.4
MW

PERDITE
ORG/MECC. = 2.1 MW

PERDITE ELETTRICHE
= 5.2 MW

ARIA RAFFR. 1° UGELLO = 96.6 kg/s

FILTRO

ARIA RAFFR. TURBINA = 77.6 kg/s

POTENZA
DISPERSA =
567.7 MW

G = 802.9 kg/s
T = 15 °C
p = 1.003 bar

T = 15 °C
UR = 60 %
p = 1.013 bar

COMP. MOL. %
Ar = 0.92
CO_2 = 0 03
H_2O = 1.04
N_2 = 77.28
O_2 = 20.73

G = 825.0 kg/s
T = 630.9 °C
p = 1.04 bar

COMP. MOL. %
Ar = 0.88
CO_2 = 4 37
H_2O = 9.04
N_2 = 74.19
O_2 = 11.52

Gas turbine technologies

There is a wide range of industrial gas turbines for electric power generation with ratings from a few megawatts up to 500 MW. In that entire range, there are many Original Equipment Manufacturers (OEMs) with diverse products. The four major OEMs are:

1. Siemens (formerly Siemens-Westinghouse)
2. GE (including former Alstom, acquired at the end of 2015)
3. MHPS (formerly Mitsubishi Heavy Industries)
4. Ansaldo Energia

which serve two markets:

- 60-Hz market, i.e. most of the Americas, South Korea, Saudi Arabia
- 50-Hz market, i.e., Europe, Africa, most of Asia, and part of South America

At the pinnacle of the gas turbine technology are four "families" of products by these four major OEMs:

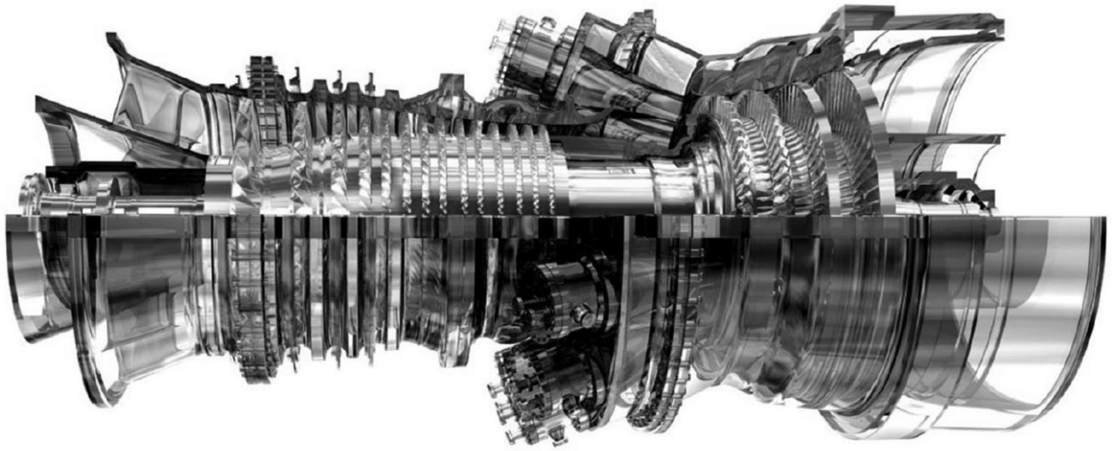
- Siemens' H/HL class
- GE's HA class
- Mitsubishi Hitachi Power Systems' (MHPS) J/JAC class
- Ansaldo Energia's GT36

Those four product families incorporate each OEM's best technologies in compressor, combustor, and turbine design as well as packaging and auxiliary systems.

Gas turbine technologies

Top technologies:

OEM	SGT5-9000HL	9HA.01	9HA.02	GT36-S5	M701J	M701JAC
	Siemens	GE		Ansaldo	MHPS	MHPS
Output, MW	545	446	544	500	478	493
Efficiency	42.0%	43.1%	43.9%	41.5%	42.3%	42.9%
Cycle Pressure Ratio	24.0	23.5	23.8	25.0	25 (?)	25 (?)
Exhaust Temperature, °F (°C)	1,256 (680)	1,164 (629)	1,177 (636)	1,155 (624)	1,166 (630)	1,186 (641)
Exhaust Flow, lb/s (kg/s)	2,205 (1,000)	1,862 (845)	2,168 (983)	2,227 (1,010)	1,975 (896)	1,975 (896)

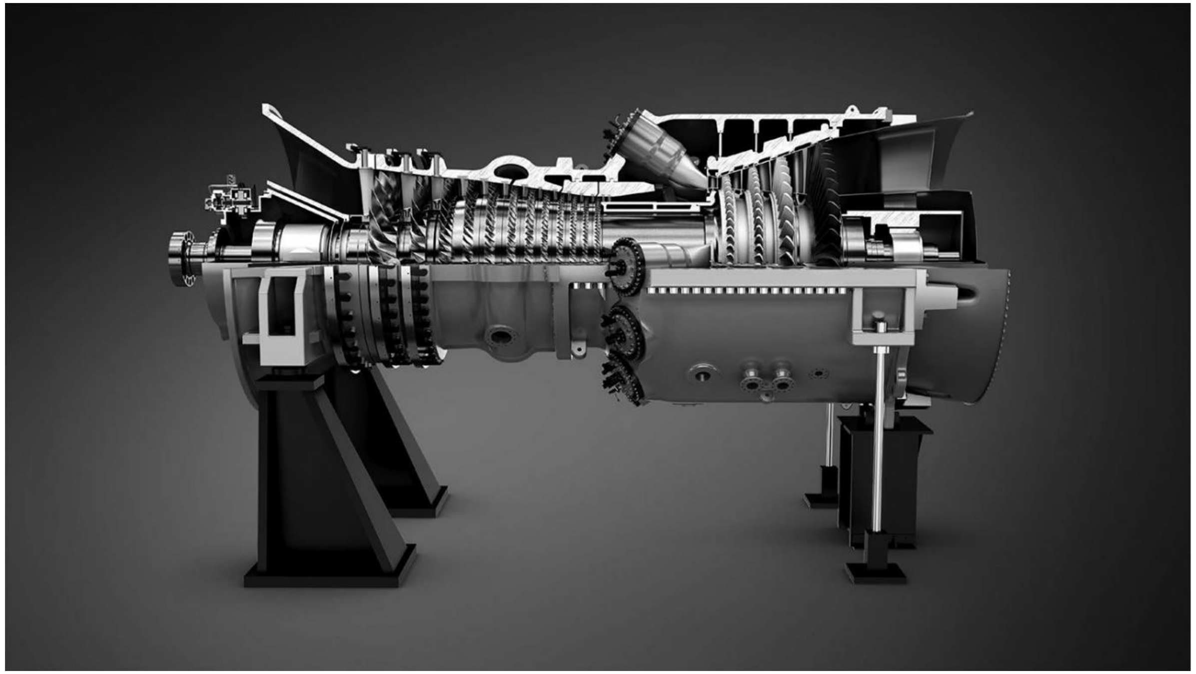


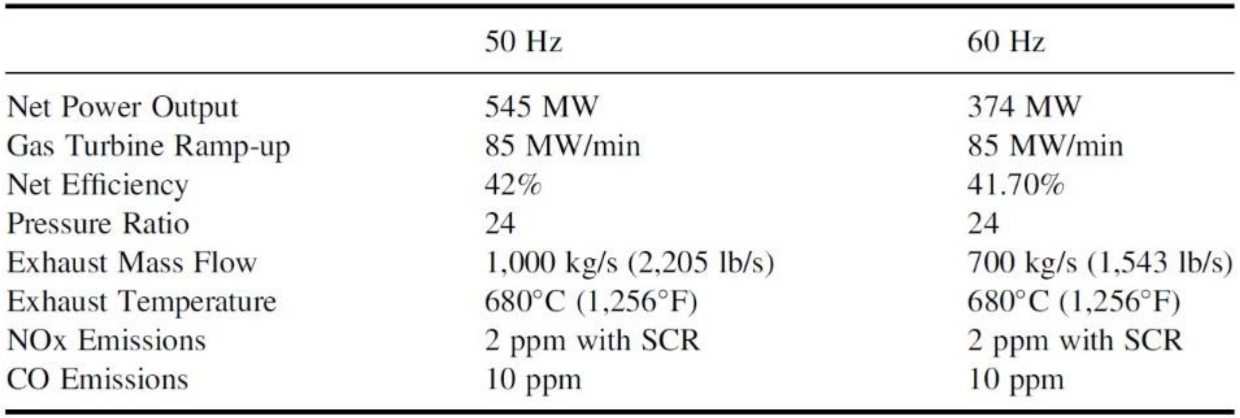
GE HA-class gas turbine

Gas turbine technologies

Siemens HL Class

- Four-stage air-cooled turbine, twelve-stage compressor with two variable stator vanes, can-annular combustor.
- Capable of about 63% net combined-cycle efficiency.
- The turbine inlet temperature for the HL class is estimated as 1757 °C.



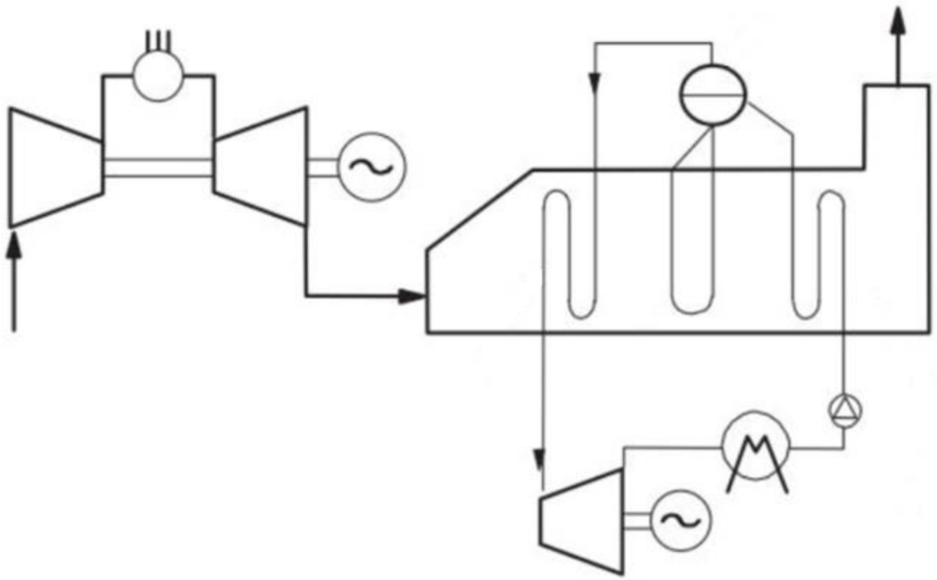


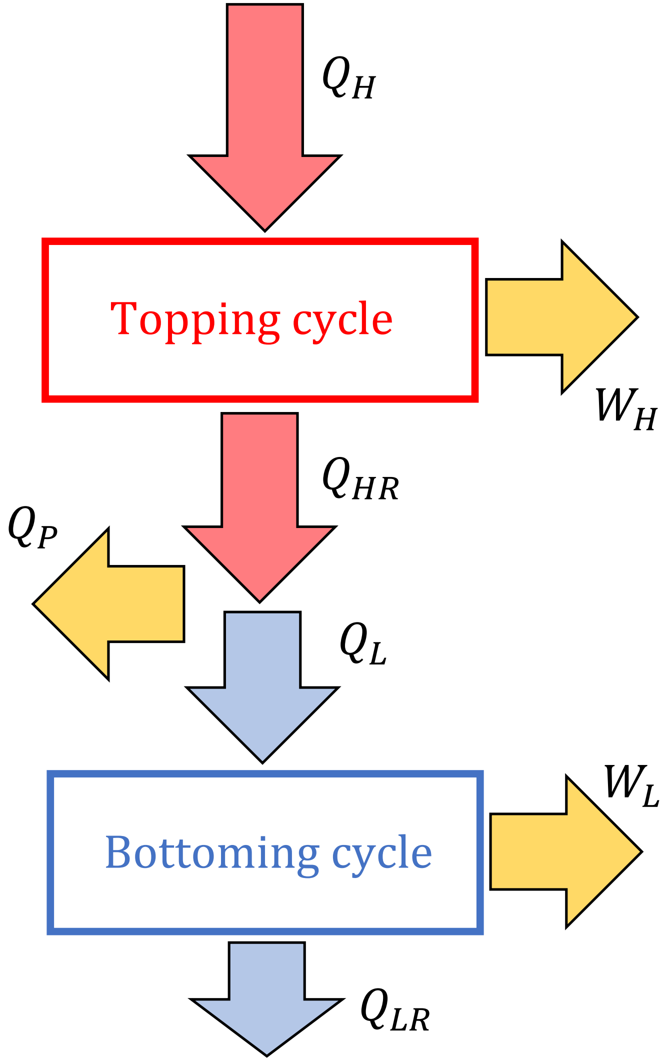
	50 Hz	60 Hz
Net Power Output	545 MW	374 MW
Gas Turbine Ramp-up	85 MW/min	85 MW/min
Net Efficiency	42%	41.70%
Pressure Ratio	24	24
Exhaust Mass Flow	1,000 kg/s (2,205 lb/s)	700 kg/s (1,543 lb/s)
Exhaust Temperature	680°C (1,256°F)	680°C (1,256°F)
NOx Emissions	2 ppm with SCR	2 ppm with SCR
CO Emissions	10 ppm	10 ppm

Siemens HL class gas turbine

Combined cycles

- Gas-steam combined cycle is the most widely used technology for electrical energy production at industrial level.
- It is the most efficient and less polluting kind of power plant.
- Gas and vapor follow separate paths.
- The primary energy is supplied to the gas turbine power plant (topping cycle).
- The vapor power plant (bottoming cycle) receives the heat lost by the topping cycle.





Q_H

Topping cycle

W_H

Q_{HR}

Q_P

Q_L

Bottoming cycle

W_L

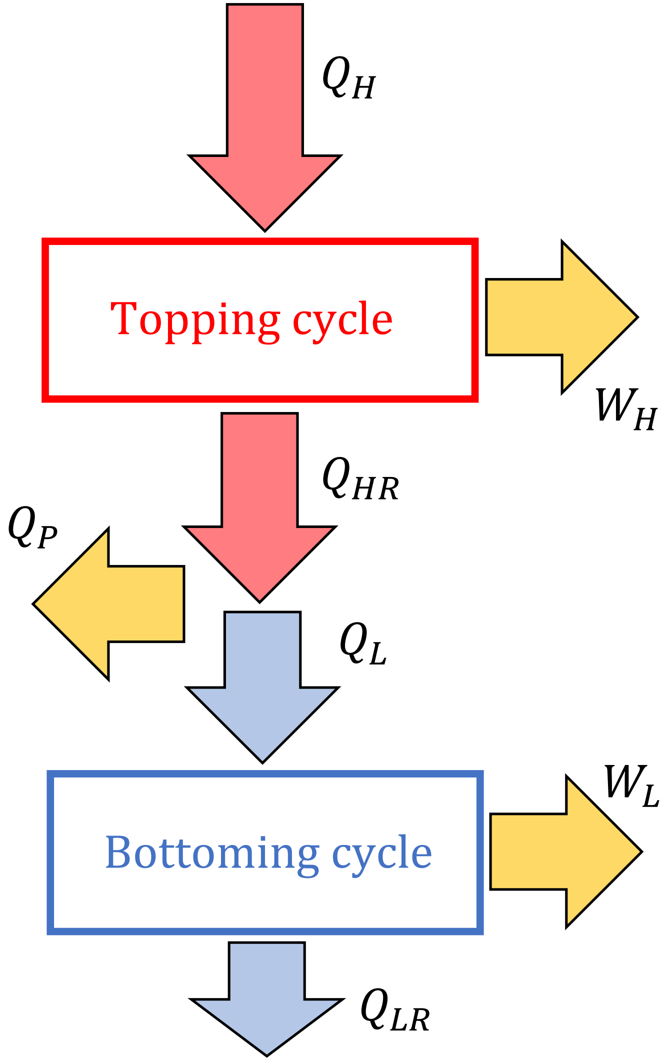
Q_{LR}

Combined cycles

The efficiency of a combined cycle can be calculated from those of its components:

$$\boxed{\eta_{CC} = \frac{W_H + W_L}{Q_H}} \; ; \quad \eta_H = \frac{W_H}{Q_H} \rightarrow W_H = Q_H \eta_H \quad ; \quad \eta_L = \frac{W_L}{Q_L} \rightarrow W_L = Q_L \eta_L$$

Q_H : heat added to the topping cycle
W_H : work done by the topping cycle
Q_{HR} : heat rejected from the topping cycle
Q_P : heat losses from the topping cycle
Q_L : heat added to the bottoming cycle
W_L : work done by the bottoming cycle
Q_{LR} : heat rejected from the bottoming cycle



Combined cycles

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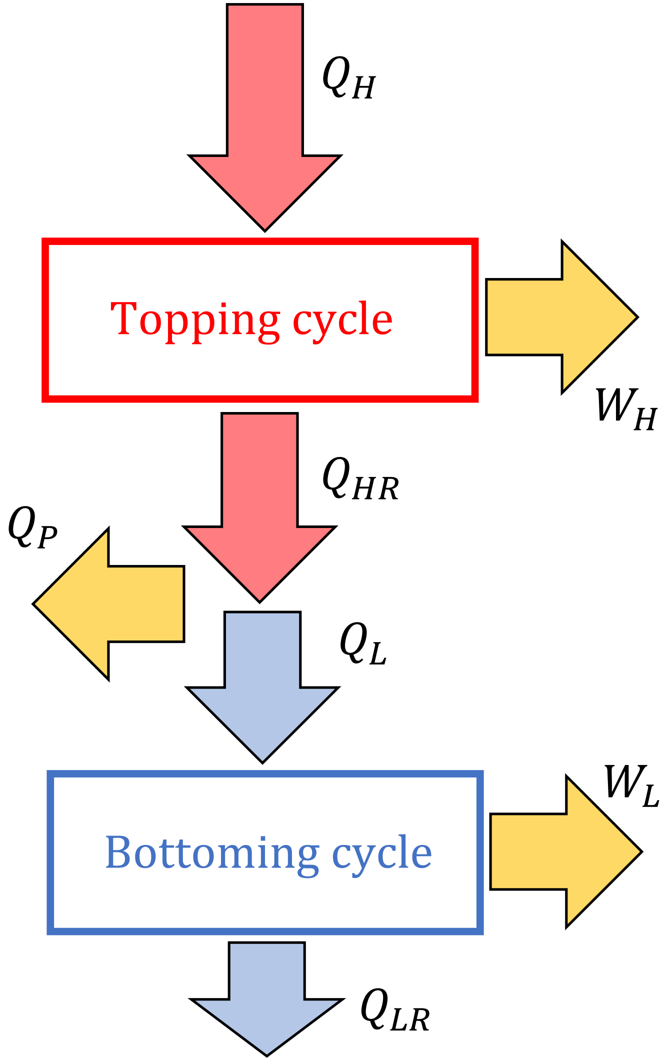
$$f_P = \frac{Q_P}{Q_H}$$

$$Q_{HR} = Q_H - W_H = Q_H - Q_H \eta_H = Q_H (1 - \eta_H)$$

$$Q_L = Q_{HR} - Q_P = Q_H (1 - \eta_H) - Q_H f_P = Q_H (1 - \eta_H - f_P)$$

$$\eta_{CC} = \frac{Q_H \eta_H + Q_L \eta_L}{Q_H} = \frac{Q_H \eta_H + Q_H (1 - \eta_H - f_P) \eta_L}{Q_H} = \frac{\cancel{Q_H}[\eta_H + (1 - \eta_H - f_P)\eta_L]}{\cancel{Q_H}}$$

$$\Longrightarrow \boxed{\eta_{CC} = \eta_H + \eta_L - \eta_H \eta_L - f_P \eta_L}$$



Combined cycles

The efficiency of a combined cycle can be calculated from those of its components:

$$\eta_{CC} = \eta_H + \eta_L - \eta_H \eta_L - f_P \eta_L$$

Let η_B be the heat transfer efficiency from the topping to the bottoming cycle:

$$\eta_B = \frac{Q_L}{Q_{HR}} = \frac{Q_{HR} - Q_P}{Q_{HR}} = 1 - \frac{Q_P / Q_H}{Q_{HR} / Q_H} = 1 - \frac{f_P}{1 - \eta_H} \rightarrow f_P = (1 - \eta_B)(1 - \eta_H)$$

$$\eta_{CC} = \eta_H + \eta_L - \eta_H \eta_L - (1 - \eta_B)(1 - \eta_H)\eta_L = \eta_H + \eta_B \eta_L - \eta_B \eta_H \eta_L$$

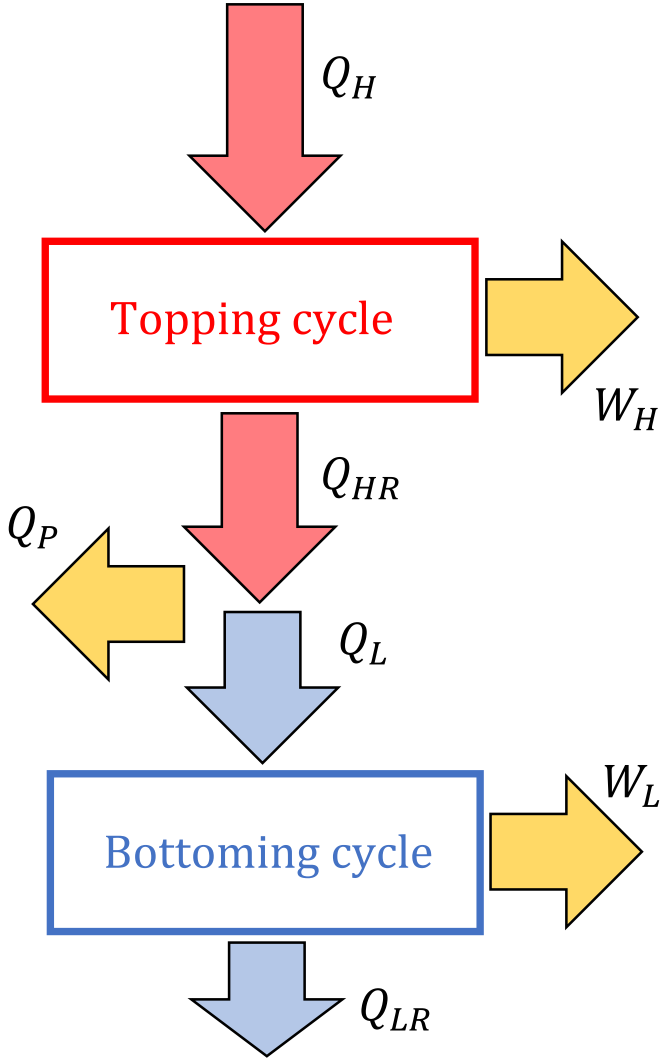
Let η_{OL} be the global heat transfer efficiency of the bottoming cycle (including top to bottoming heat transfer):

$$\eta_{OL} = \frac{W_L}{Q_{HR}} = \eta_B \eta_L$$

then:

$$\boxed{\eta_{CC} = \eta_H + \eta_{OL} - \eta_H \eta_{OL}}$$

$$\begin{cases} \eta_{CC} = \eta_H + \eta_{OL}(1 - \eta_H) > \eta_H \\ \eta_{CC} = \eta_{OL} + \eta_H(1 - \eta_{OL}) > \eta_{OL} \end{cases}$$



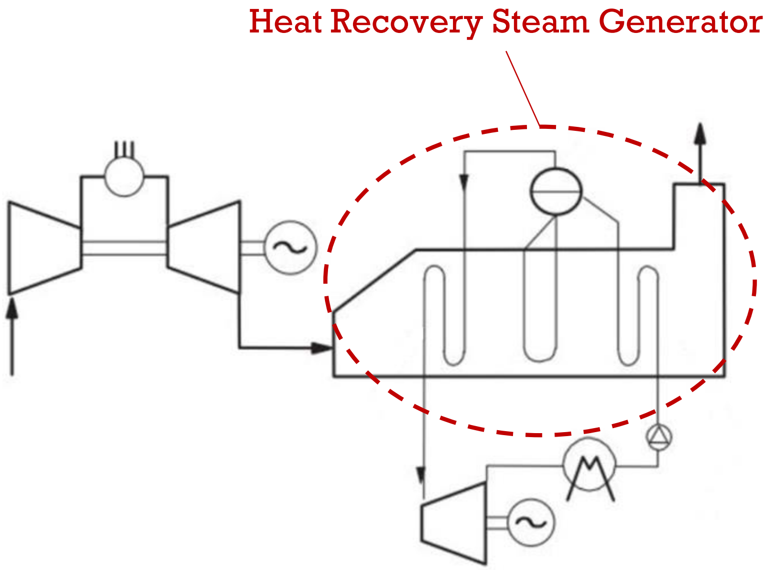
Combined cycles

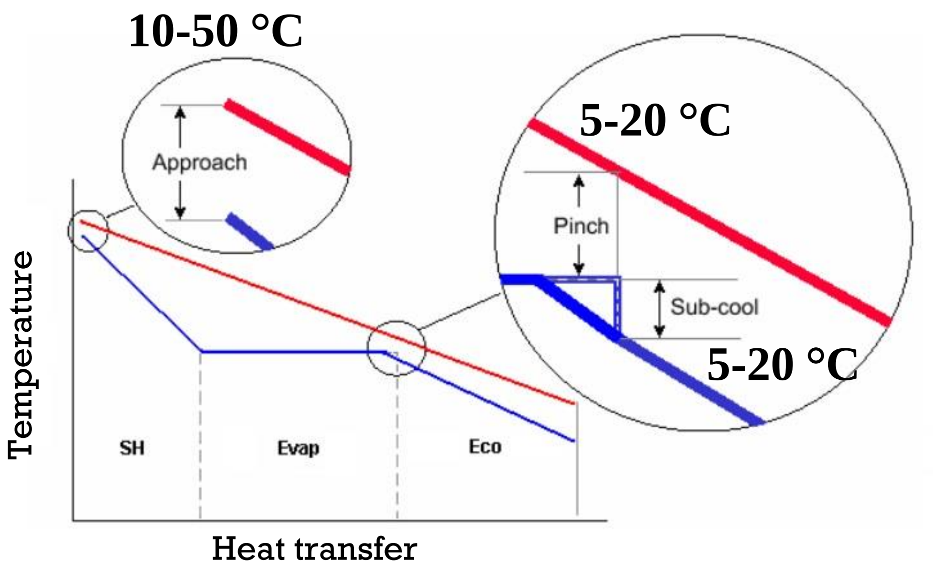
https://www.youtube.com/watch?v=eeiu-wcyEbs

Heat Recovery Steam Generator

Heat Recovery Steam Generator (HRSG):

1. **Economiser**: increases the feed-water temperature up to saturation temperature (almost)
2. **Evaporator**: closed evaporating circuit delivering saturated steam
3. **Superheater**: delivers superheated live steam





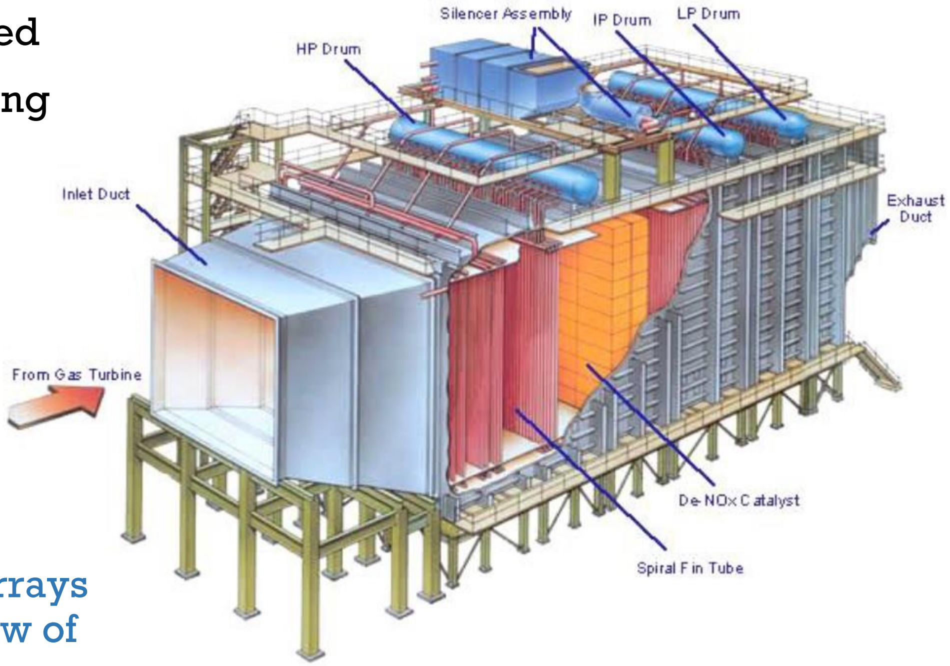
Pinch and approach points cannot take arbitrary values. They depends on techno-economic aspects.

Sub-cooling temperature is required to avoid the start of evaporation in the economizer.

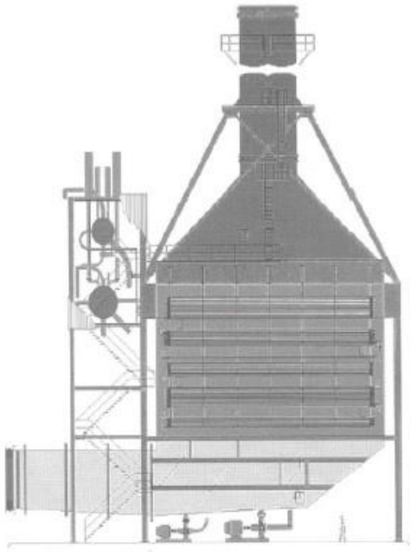
Heat Recovery Steam Generator

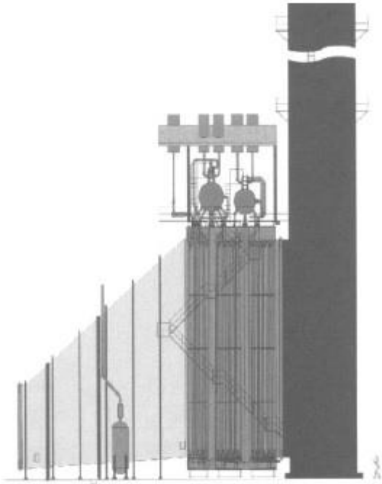
Heat Recovery Steam Generators can be classified according to:

1. Number of steam circuits/pressures
2. Layout: horizontal/vertical
3. Water circulation: natural/forced
4. With or w/o supplementary firing



Water/steam flows through arrays of pipes transversal to the flow of exhaust gas from the turbine

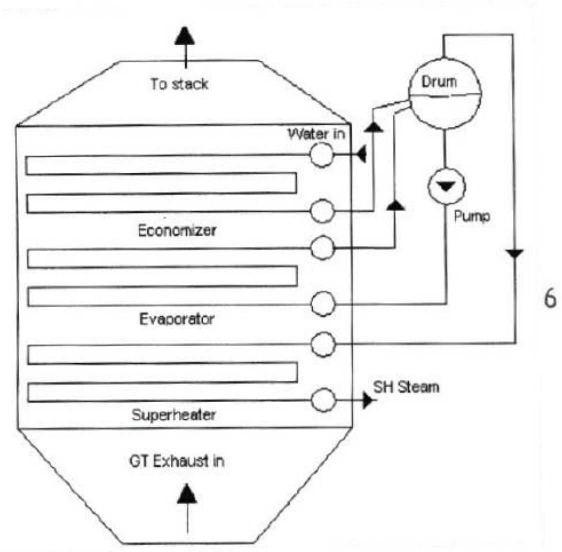

Vertical

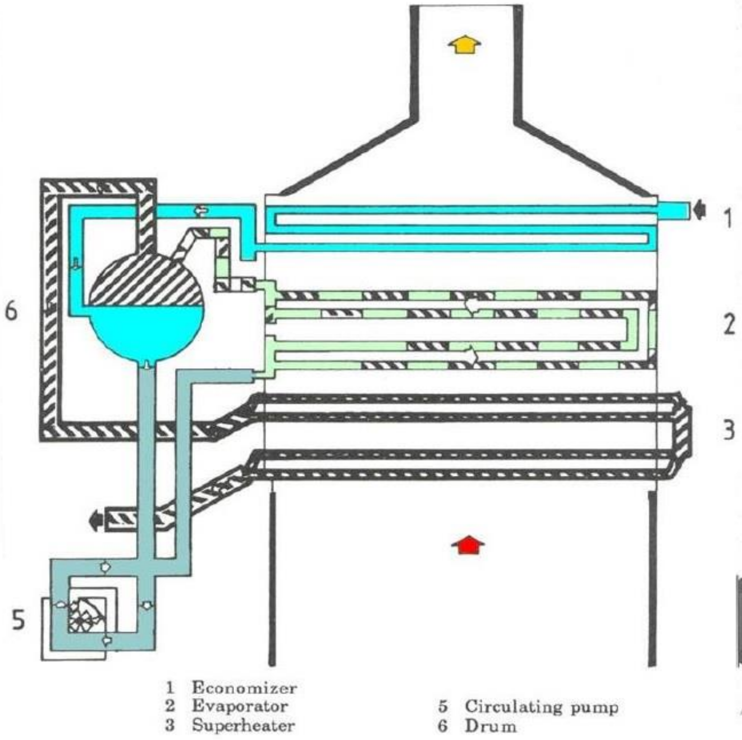

Horizontal

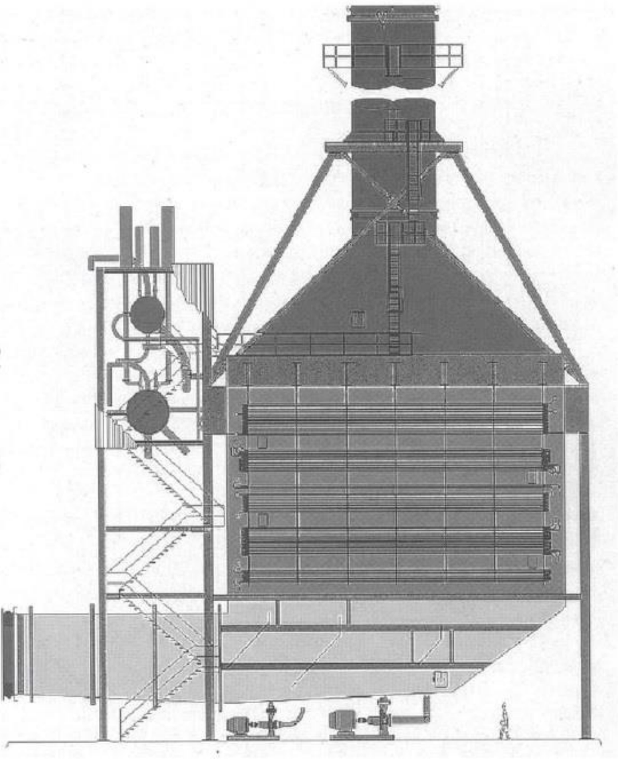
Heat Recovery Steam Generator

HRSG with vertical flow

- Usually make use of forced circulation
- Natural circulation sometimes possible if drum is at sufficient elevation and steam pressure is low







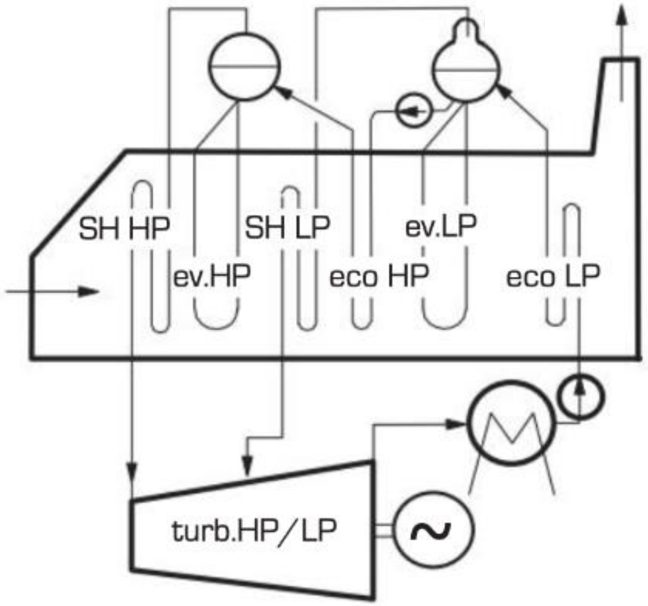
Heat Recovery Steam Generator

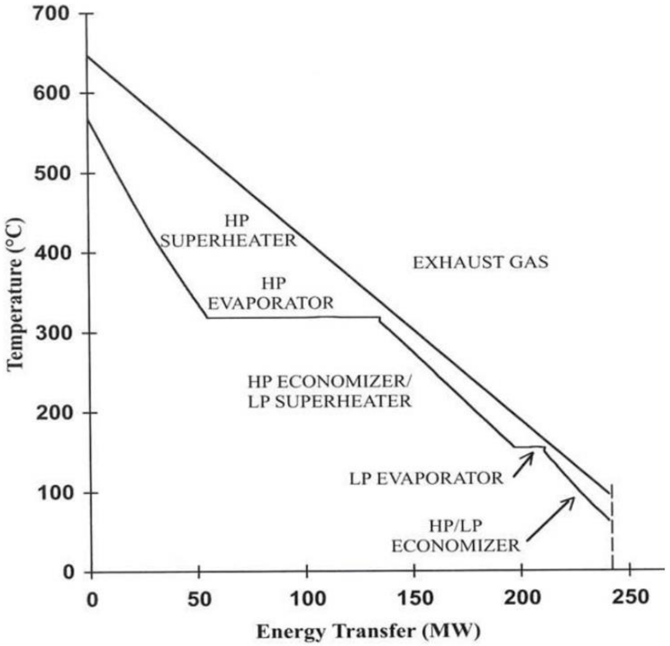
Depending on number of steam circuits, the HRSG can be:

- Single pressure
- Multiple pressure (2 or 3 levels)

This concept could be further exploited with the addition of reheat.

DUAL PRESSURE





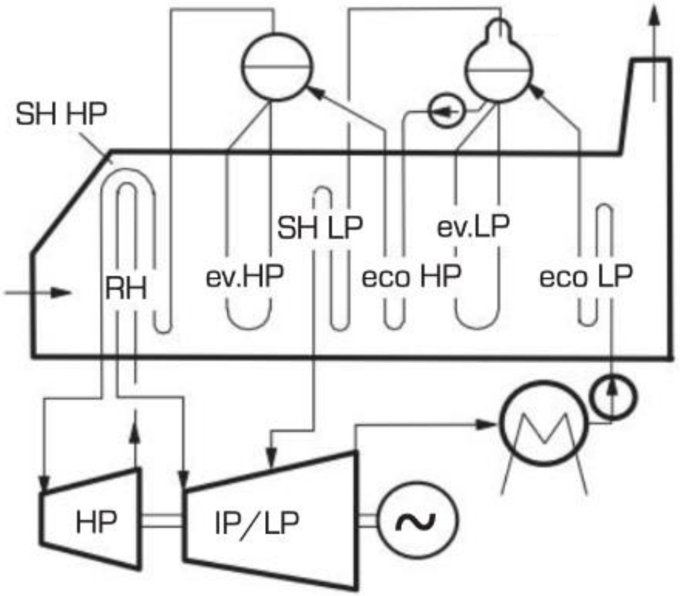
Heat Recovery Steam Generator

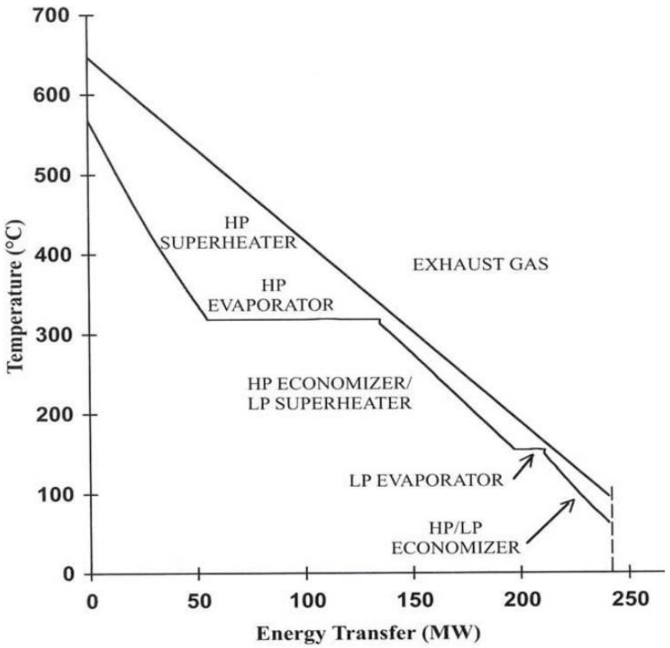
Depending on number of steam circuits, the HRSG can be:

- Single pressure
- Multiple pressure (2 or 3 levels)

This concept could be further exploited with the addition of reheat.

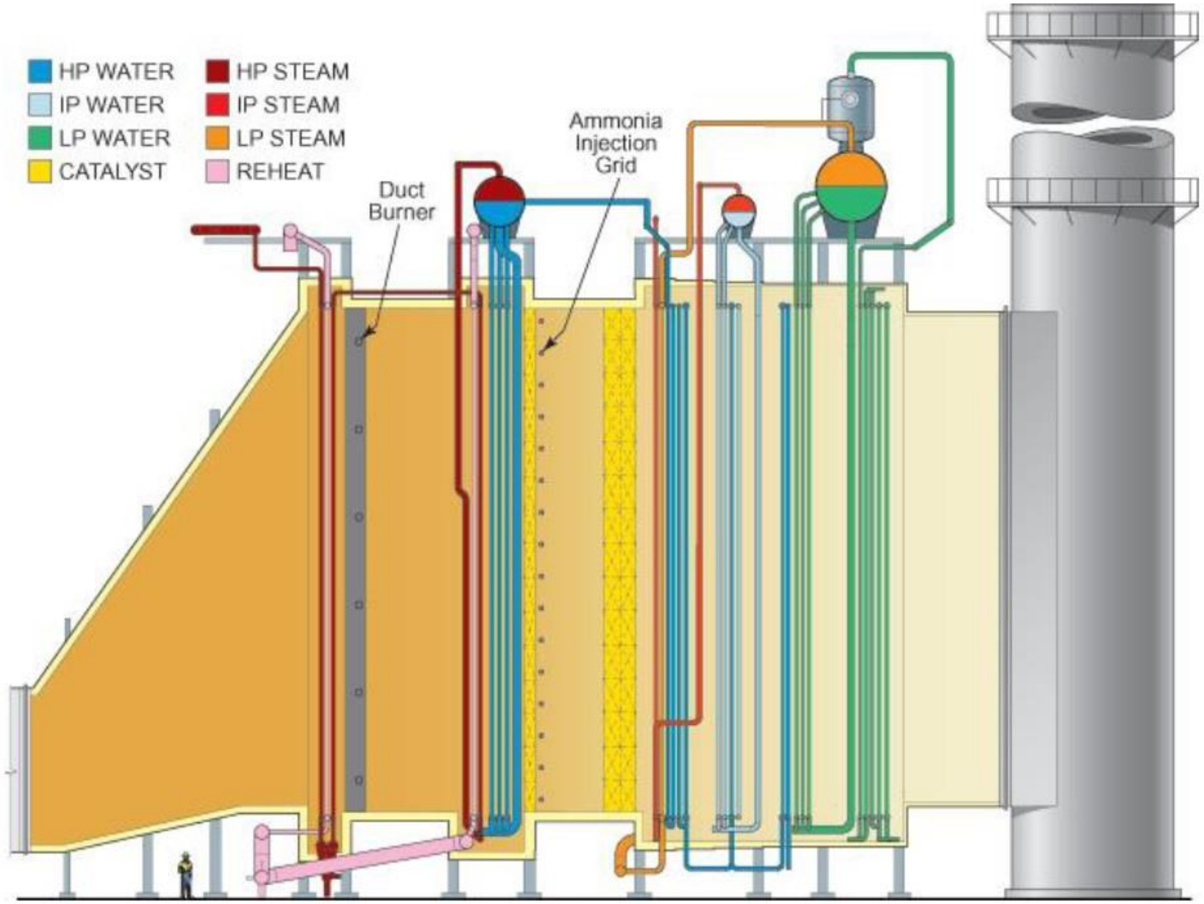
DUAL PRESSURE AND REHEAT





Heat Recovery Steam Generator

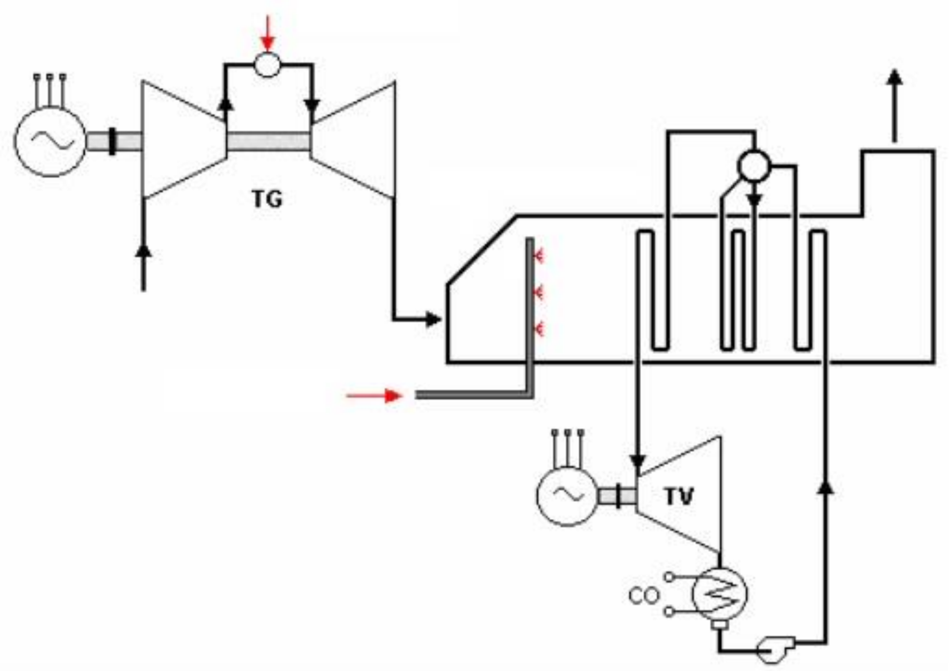
This is how a multiple-pressure and reheat horizontal HRSG looks like.

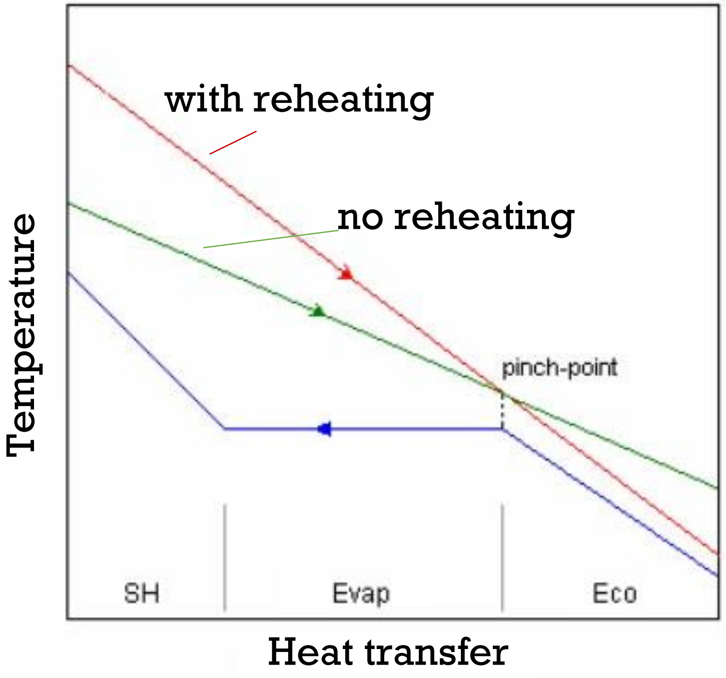


Combined cycle with reheating

The exhaust gases released by the gas-turbine can undergo a further combustion process, which is performed at the inlet of the HRSG by means of burners placed before the heat exchange section of the HRSG.

This new combustion process is possible given the still high oxygen content in the exhaust gases, which is due to the high excess air used in the first combustion.



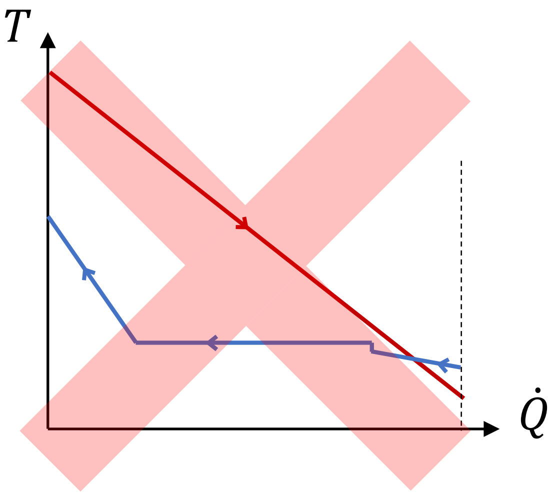


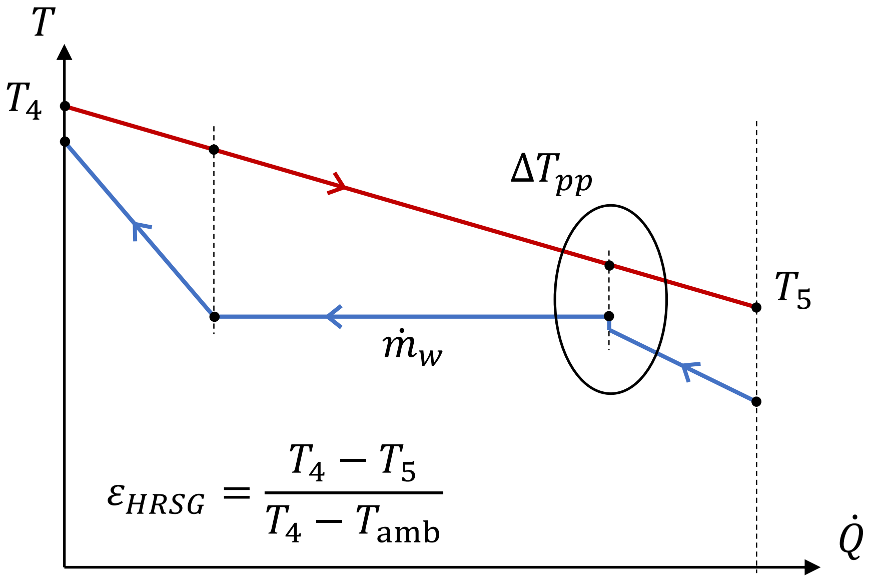
HRSG design

Pinch (ΔT_{pp}) and approach (ΔT_{ap}) points cannot take arbitrary values ⇒ risk of line crossing

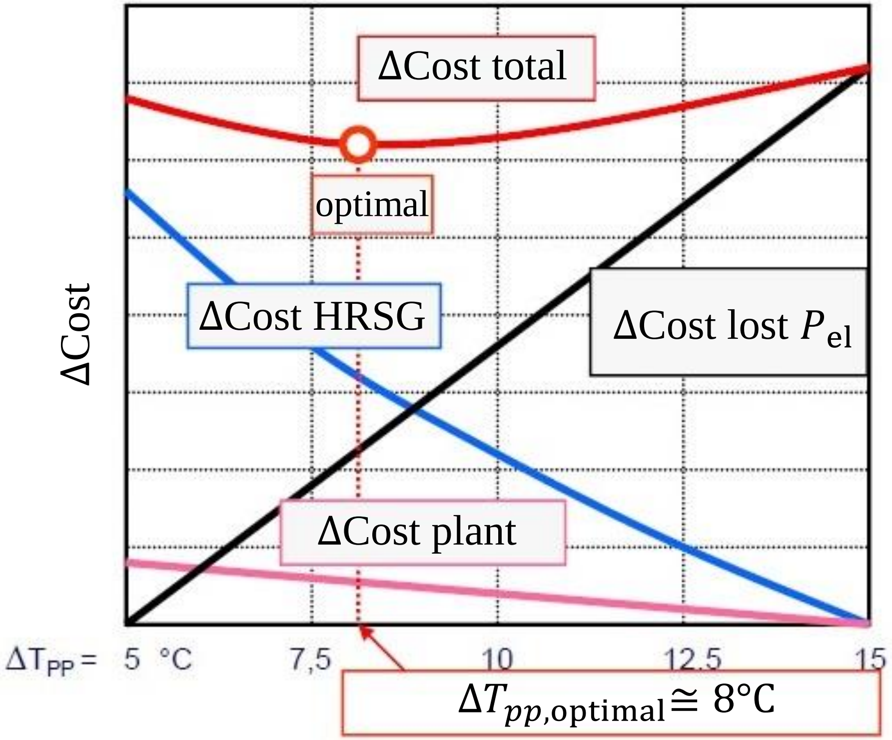
Pinch point selection criteria:

- if $\Delta T_{pp}\uparrow \;\Rightarrow\; T_5\uparrow \;\Rightarrow\; \varepsilon_{HRSG}\downarrow \;\Rightarrow\; \dot{m}_w\downarrow \;\Rightarrow$ HRSG size/cost ↓
- if $\Delta T_{pp}\downarrow \;\Rightarrow\; T_5\downarrow \;\Rightarrow\; \varepsilon_{HRSG}\uparrow \;\Rightarrow\; \dot{m}_w\uparrow \;\Rightarrow$ HRSG size/cost ↑

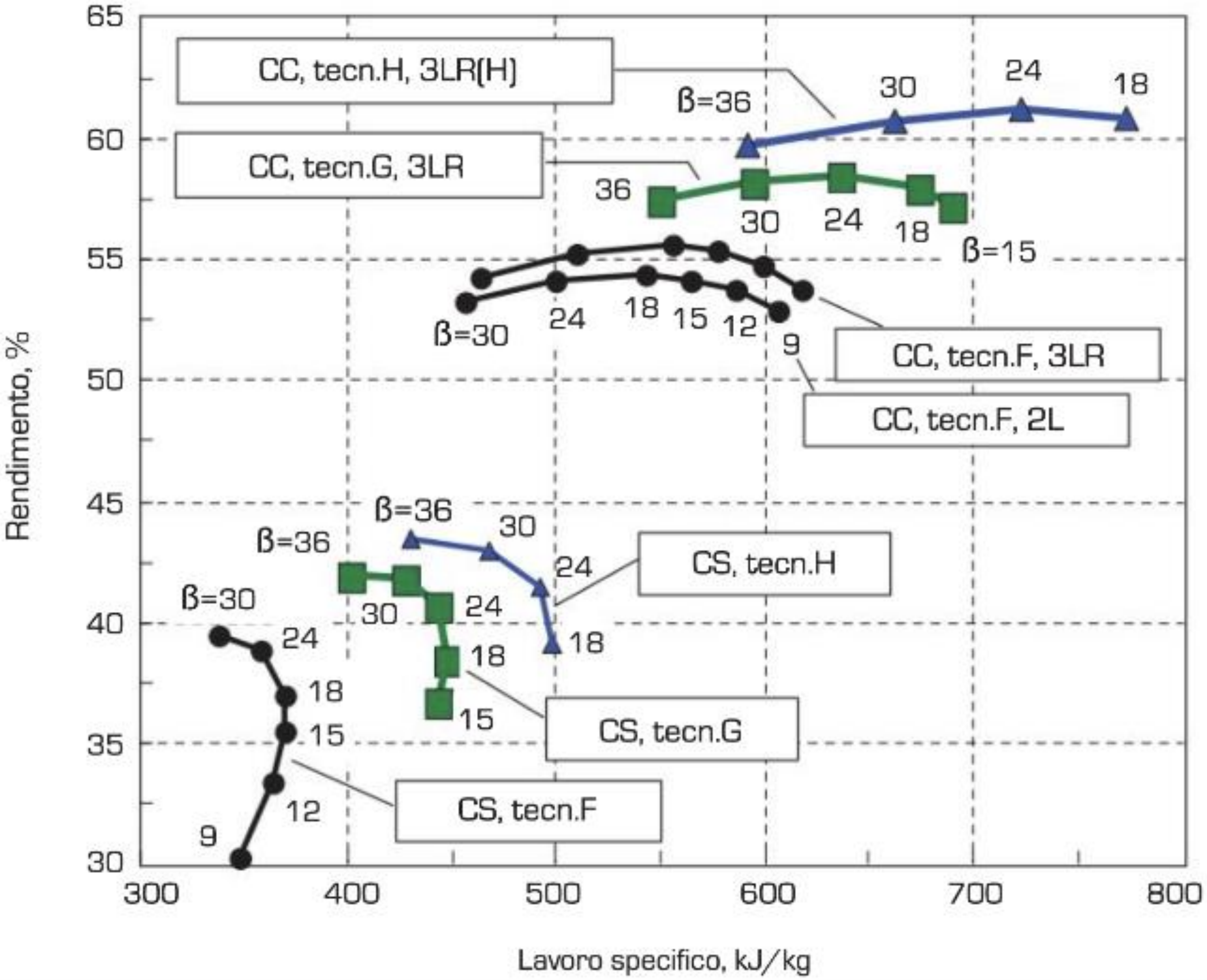




$$\varepsilon_{HRSG} = \frac{T_4 - T_5}{T_4 - T_{\mathrm{amb}}}$$



Combined cycle performance



Repowering

The gas turbine in conjunction with a heat recovery steam generator and a steam turbine, makes combined cycle power plants the most efficient power generation facilities.

Existing direct-fired plants can utilize this advanced cycle concept by adding a gas turbine and a HRSG. This so-called **repowering scheme** makes the existing power generation facility equally efficient as a modern combined cycle power plant. There are several alternatives to combine and integrate a gas turbine into an existing steam power plant.

Repowering schemes:

- Feed-Water Repowering (fired);
- Heat Recovery Repowering (fired);
- Hot Windbox Repowering (fired);
- Heat Recovery Repowering (unfired).

Parallel Repowering

In the parallel repowering concept, the original boiler will remain in operation. Additionally to the original steam source, a topping cycle will be added. Compared to the full repowering concept, this repowering scheme achieves slightly lower efficiency. Due to the two independent steam sources for the steam turbine, this concept provides a higher fuel flexibility and also greater flexibility in respect to load variations.

Full Repowering

Full repowering replaces the original boiler with a topping cycle consisting of one or more gas turbines and HRSGs. As the repowered cycle is similar to a modern combined cycle, this concept promises the best efficiency compared to all possible repowering schemes. It is widely used with old plants when the boiler has reached the end of its lifetime.

The choice about the most suitable repowering approach depends on:

- Size of the steam power plant to be repowered;
- Space availability;
- Installation and operating costs.

Repowering

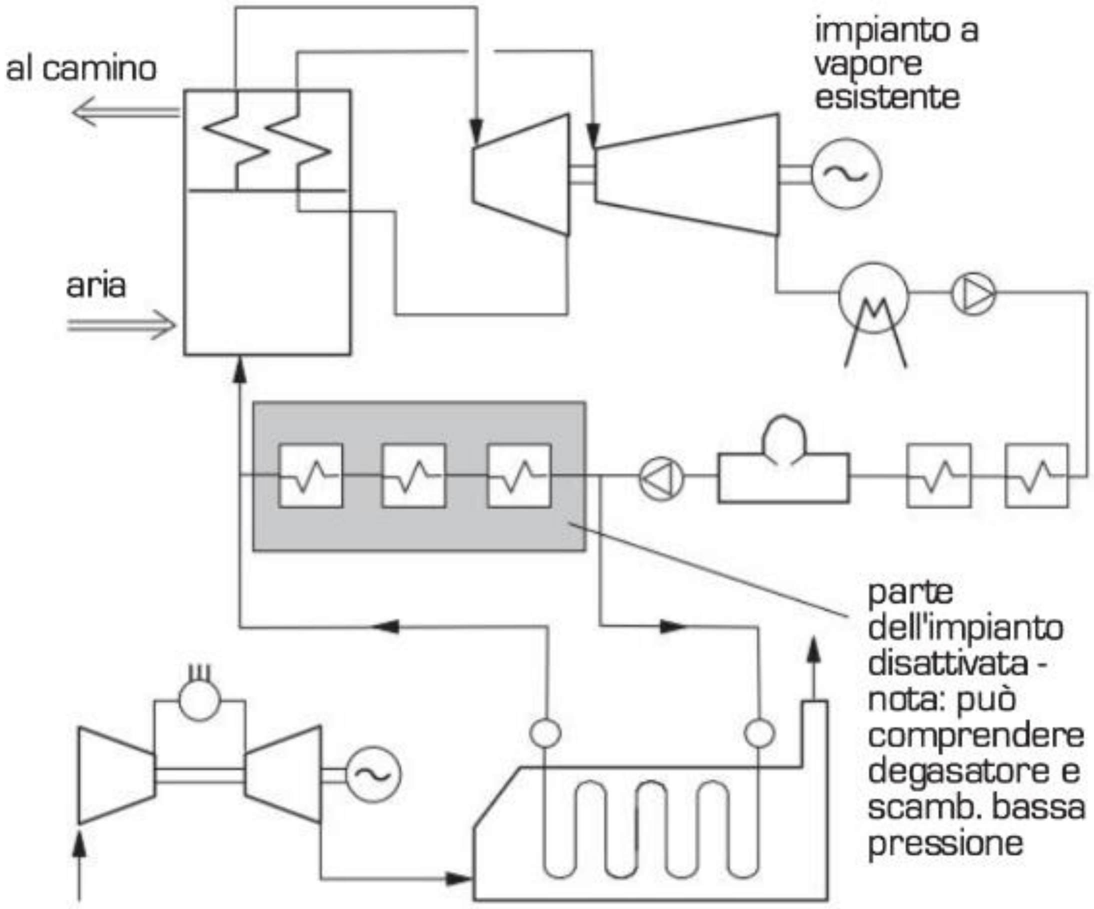
Feed-Water Repowering

The regenerative feedwater heaters are deactivated and the pre-heating of subcooled water occurs within the HRSG.

Increased steam mass flow in the steam turbine, which leads to an increased power output from the steam power plant.

Advantages:

- Minor modifications to the existing steam power plant.
- Short plant downtime for repowering.
- In case of gas turbine failure or downtime for maintenance, the steam power plant keeps operating by re-activating the regenerative line.



turbina a gas e caldaia a recupero aggiunte

Repowering

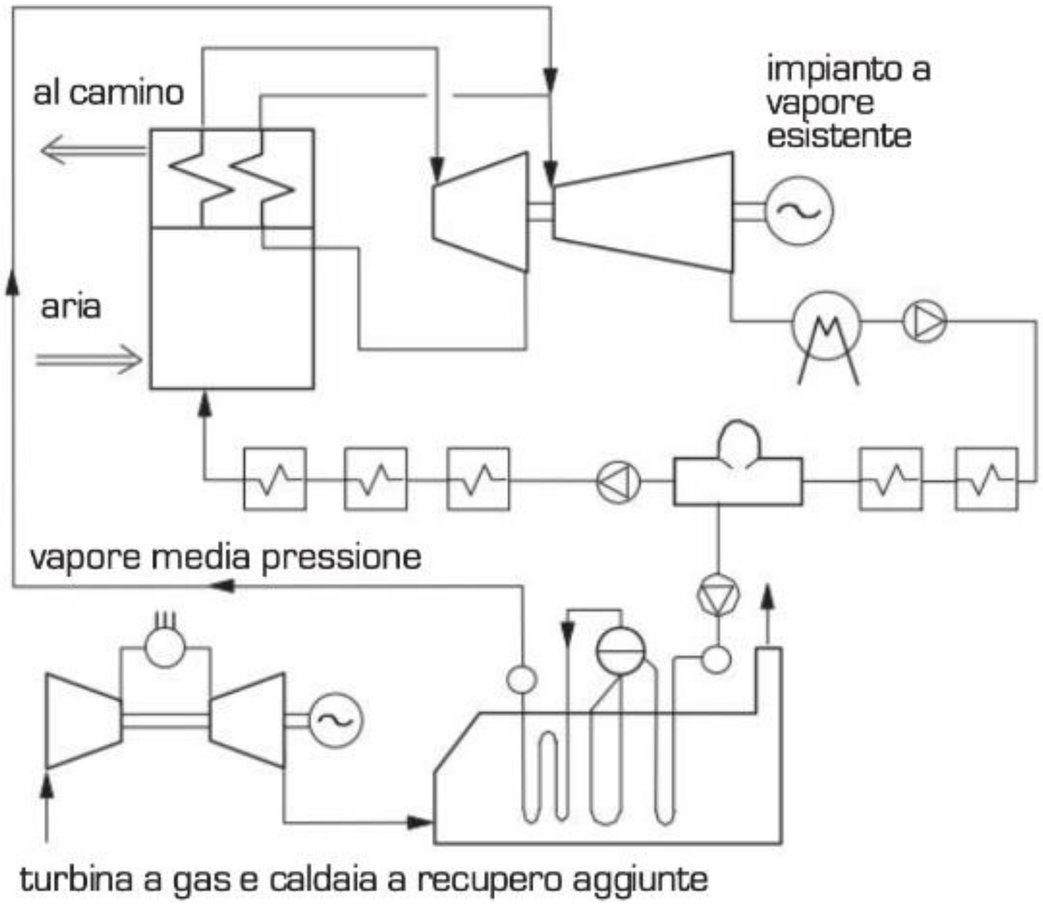
Heat Recovery Repowering (fired):

The steam generated by the HRSG feeds the medium- and low-pressure turbines, along with the reheated steam from the boiler.

Increased steam mass flow in the medium- and low-pressure steam turbines, which leads to an increased power output from the steam power plant.

Advantages (similar to Feed-Water repowering):

- Minor modifications to the existing steam power plant.
- Short plant downtime for repowering.
- In case of gas turbine failure or downtime for maintenance, the steam power plant keeps operating.



Repowering

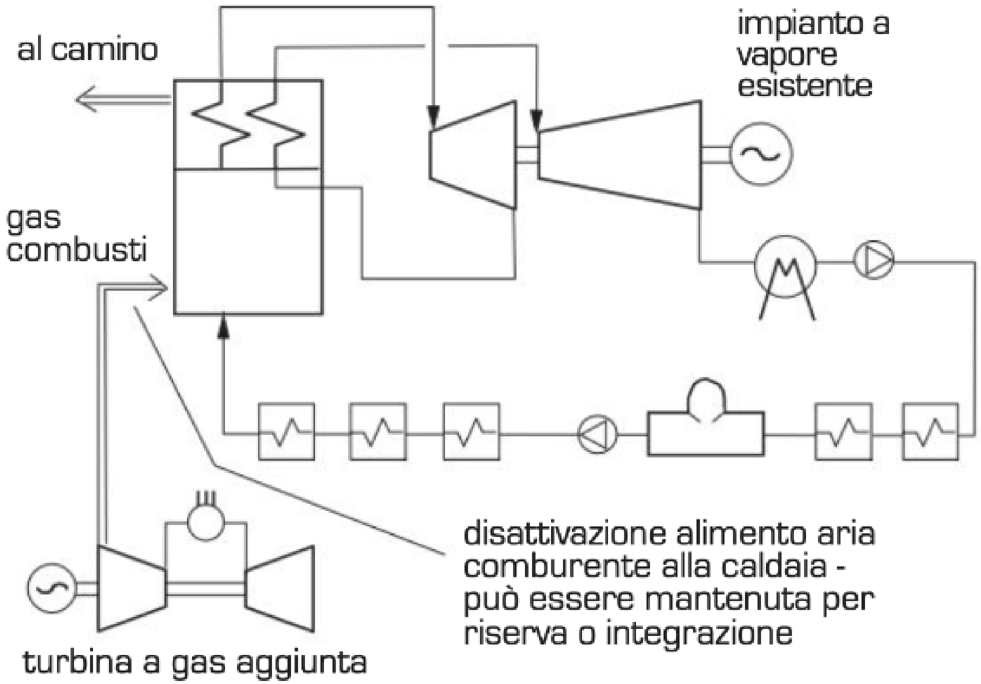
Hot Windbox Repowering (fired):

The exhaust gas from the gas turbine enters the boiler of the steam power plant. In fact, the high temperature of the exhaust gas allows to reduce the fuel consumption in the boiler.

The boiler requires substantial modifications to allow for a high mass flow of exhaust gas.

Excellent exhaust gas heat recovery, which leads to significant enhancement of power plant efficiency.

Repowering con utilizzo dei gas di scarico come comburente per la caldaia (hot windbox).



Repowering

Heat Recovery Repowering (unfired)

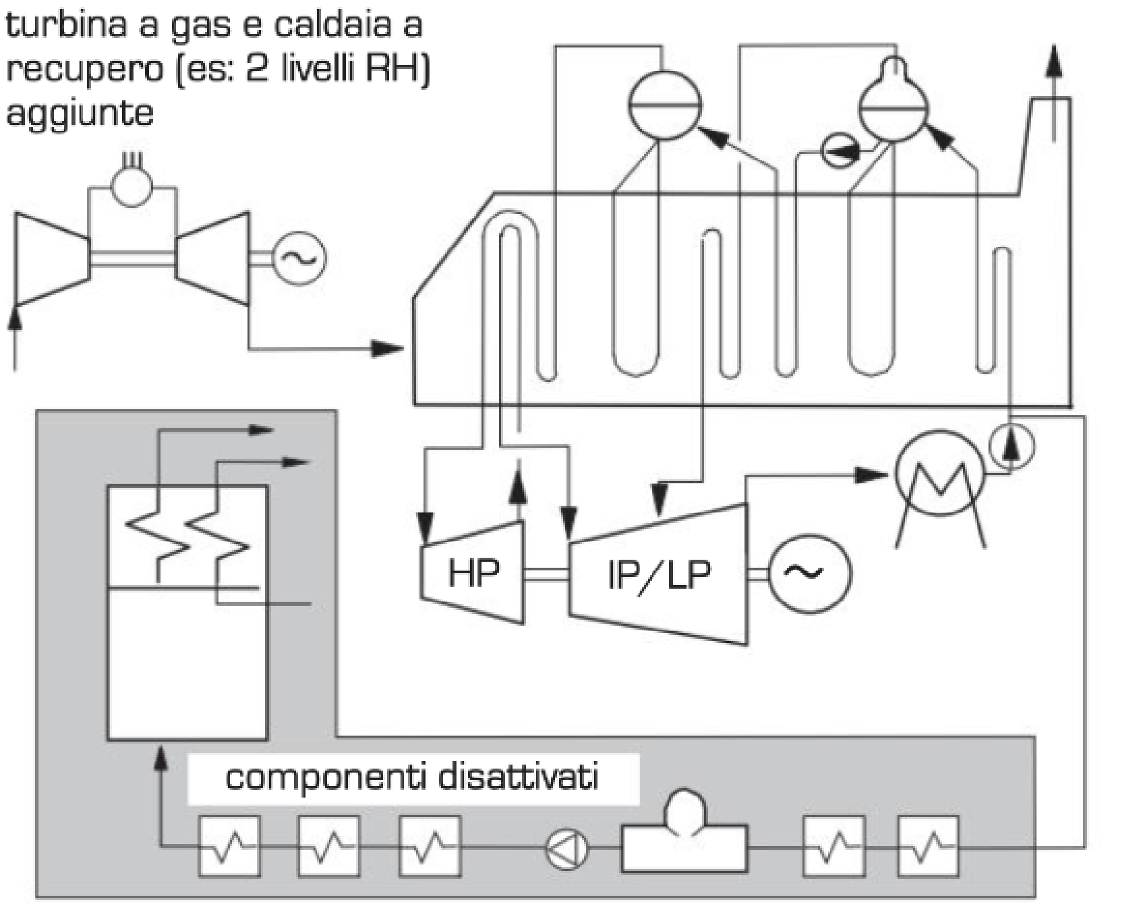
Full repowering: the boiler and the whole regenerative line (feedwater heaters, etc.) is replaced by a HRSG, which is fed by the exhaust gas from the gas turbine.

This repowering scheme requires a significant investment.

The main advantages are:

- Striking enhancement of efficiency;
- Significant reduction of emissions, due to the use of natural gas a fuel in the gas turbine power plant in place of another more harmful fuel (typically employed in a boiler).

Repowering con trasformazione in ciclo combinato.



Combined Heat and Power Generation

The electric and thermal loads at one site (building, industrial unit, etc.) are usually covered by means of a separate production, which means that the electricity is taken from the local distribution network, while heat is generated by burning a fuel in a boiler or a furnace located at the site.

However, the production of electricity in a power plant is accompanied by production of heat, which results in a huge waste of energy in case the heat is rejected to the environment via the exhaust gases and the cooling circuits of the plant.

Most of this heat can be recovered and used to cover thermal loads, thus converting the power plant to a **cogeneration system**, which increases the efficiency of fuel use from 40%–50% to 80%–90%.

Cogeneration, or ***Combined Heat and Power (CHP)****, is the simultaneous generation of work and useful heat (by means of steam or hot water) from the same primary energy source.*

Work shall mean either mechanical or electric energy. Mechanical energy, for example produced by a turbine or an internal combustion engine, is ultimately converted by a generator for electricity production. But it is also possible to have a direct conversion of the chemical energy stored in fuel into electricity by means of, for example, fuel cells.

The recovered thermal energy can be used for heating purposes and/or for cooling by means of additional equipment such as absorption chiller (Trigeneration, or Combined Cooling Heat and Power – CCHP).

Combined Heat and Power Generation

Cogeneration systems, due to efficient fuel utilization and the generation of several products, are one of the most promising methods in view of performance, economic, and environmental impacts for the optimal design of energy systems.

The primary goal of cogeneration is the increase of the primary energy utilization rate or, in other words, the **primary energy savings**. In particular, this technology offers the following benefits:

- **Increased energy efficiency**. Using a fuel to simultaneously generate heat and electricity with a single unit is up to 40% more efficient than the separate generation of heat and power.
- **Lower emissions**. Cogeneration saves every year about 200 million tonnes of CO2 in Europe thanks to being very efficient.
- **Reduced energy costs**. Users of cogeneration benefit from higher efficiencies and therefore need less fuel to cover their heating and electricity demand.
- **Empowered businesses and citizens**. Cogeneration comes in all sizes, from 1kW to nearly 1GW. It is fit to supply heat and electricity to all types of users, from a single household to a large industrial complex or entire town.
- **Reduced transmission and distribution losses/costs**. Cogeneration generates electricity and heat at the spot. Users of cogeneration rely less on electricity from the grid avoiding grid costs both at end-user and system level.

Combined Heat and Power Generation

Cogeneration systems, due to efficient fuel utilization and the generation of several products, are one of the most promising methods in view of performance, economic, and environmental impacts for the optimal design of energy systems.

The primary goal of cogeneration is the increase of the primary energy utilization rate or, in other words, the **primary energy savings**. In particular, this technology offers the following benefits:

- **Enhanced energy system reliability and flexibility**. Moving from large central power plants towards smaller local CHP plants also helps to improve the reliability and flexibility of energy systems. An uninterrupted supply of electricity is crucial: local electricity production systems that can operate independently from a central balancing system, if needed, can ensure the fulfilment of the energy demand even in case of interruptions in the central system.
- **Supporting renewable energy.** If the goals for a society with much-reduced greenhouse-gas emissions have to be reached, there is no other option than to implement a system that primarily uses renewable to produce electricity as the energy carrier.

Combined Heat and Power Generation

Since, today, it is still unfeasible to rely only on solar, wind or other options such as wave energy and geothermal, fuel-based energy (especially from natural gas) still plays an important role. Then, in all cases where fuel is used, cogeneration can be applied to maximise fuel efficiency and minimise emissions.

However, cogeneration installations should be an integral part of an energy supply system based on renewables, in order to improve energy efficiency, reliability and flexibility.

It is especially the volatile nature of solar- and wind-based energy that requires flexible and fast back-up. Modern cogeneration installations based on gas turbines and reciprocating engines can start and stop rapidly and frequently. Their response to a request for a sudden change in output is much higher than that of a large-size traditional power plant.

For instance, in case of a lack of sunshine and wind, such units can produce the required heat and electricity. In case of a high output from PV panels and wind turbines, the cogeneration units can be stopped, whereas any required heat can effectively be produced from electricity with a heat pump with a coefficient of performance of at least five.

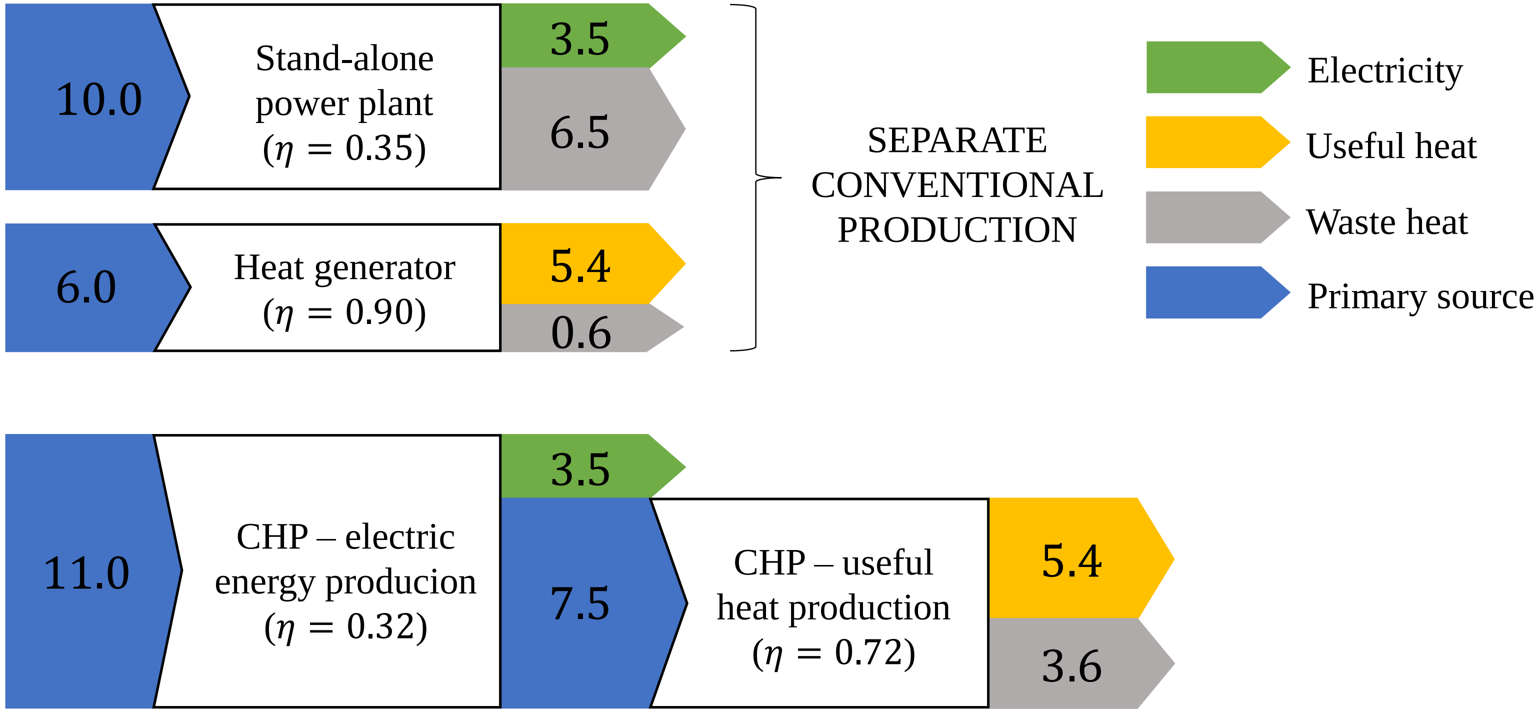
Heat storage can help for smoothing any discrepancies between heat production and demand.

Combined Heat and Power Generation

In a stand-alone power plant a large amount of heat is lost, mainly from exhaust gases. Let's assume that such a plant produce electricity with an overall efficiency of 35%. Consider also a heat generator (e.g. furnace, boiler) producing heat with a 90% efficiency.

Assuming a target electricity production of, say, 3.5 MWe, and a thermal power demand of 5.4 MWt, the primary energy consumption would be equal to about 16 MW, in case of separate production.

To obtain the same combined power output by a CHP plant, only 11 MW of primary energy would be required, also assuming lower electricity and heat production efficiencies (32% and 72%, respectively).



10.0 → Stand-alone power plant ($\eta = 0.35$) → 3.5 / 6.5

6.0 → Heat generator ($\eta = 0.90$) → 5.4 / 0.6

SEPARATE CONVENTIONAL PRODUCTION

11.0 → CHP – electric energy producion ($\eta = 0.32$) → 3.5 / 7.5

7.5 → CHP – useful heat production ($\eta = 0.72$) → 5.4 / 3.6

🟩 Electricity

🟨 Useful heat

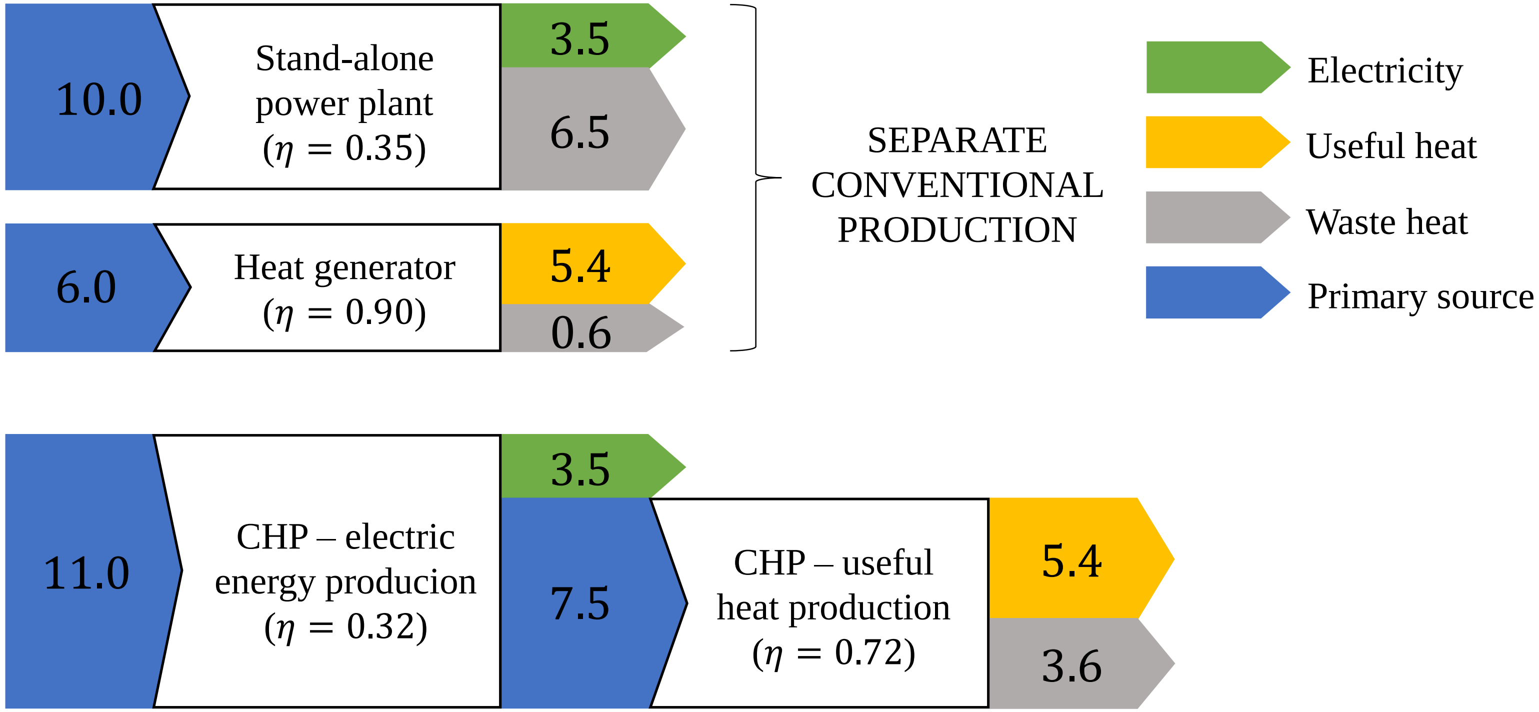
⬜ Waste heat

🟦 Primary source

Combined Heat and Power Generation

From this example, it can be readily seen that, even considering lower efficiencies for each sub-unit of the CHP plant, cogeneration allows to achieve a 30% of primary energy saving with respect to the total amount required by separate production from conventional plants.

This result is made possible since heat recovery in CHP plants is highly efficient, thus leading to a much higher overall efficiency than the one that can be achieved by separate production.



10.0
Stand-alone power plant ($\eta = 0.35$)
3.5
6.5

6.0
Heat generator ($\eta = 0.90$)
5.4
0.6

SEPARATE CONVENTIONAL PRODUCTION

🟩 Electricity
🟨 Useful heat
⬜ Waste heat
🟦 Primary source

11.0
CHP – electric energy producion ($\eta = 0.32$)
3.5
7.5
CHP – useful heat production ($\eta = 0.72$)
5.4
3.6

Combined Heat and Power Generation

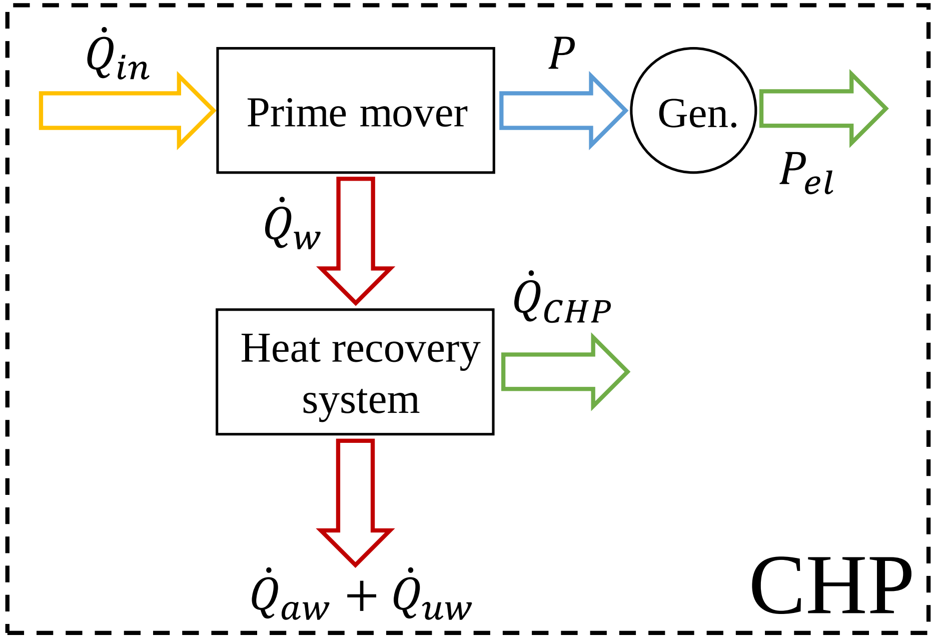
The input to the power plant is the power that can be potentially obtained from the combustion of the fuel, that is:

$$\dot{Q} = \dot{m}_f \mathrm{LHV}$$

where $\dot{m}_f$ is the mass flow rate of the fuel and LHV indicates its lower heating value. The thermal power actually transferred to the working fluid, that is, the thermal power that can be actually extracted from the combustion of the fuel is given by:

$$\dot{Q}_{in} = \dot{Q}\, \eta_b$$

where η_b is the *combustion efficiency*.



The net mechanical power output is a portion of such a thermal power, as follows:

$$P = \dot{Q}_{in}\, \eta_{th}$$

with η_{th} being the *thermal efficiency* of the power plant cycle. Finally, the net electric power output depends on the energy conversion at the generator, that is:

$$P_{el} = P\, \eta_m$$

where η_m is the *mechanical efficiency*, i.e. the efficiency of the generator.

Combined Heat and Power Generation

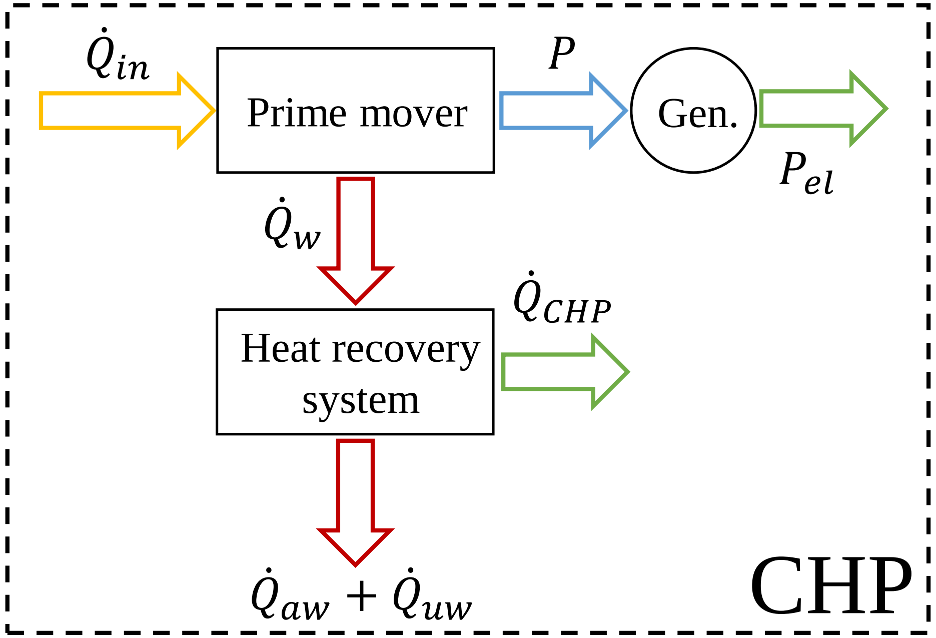
The net electric power output can be therefore expressed as a function of the total input thermal power:

$$P_{el} = \dot{Q}\,\eta_g = \dot{Q}\,\eta_m\,\eta_{th}\,\eta_b$$

where η_g refers to the *global efficiency* of the power plant, and is also named as electrical efficiency.

The difference between the actual input thermal power and the net mechanical power output corresponds to the maximum thermal power that can be theoretically recovered by cogeneration, that is, the waste heat:

$$\dot{Q}_w = \dot{Q}_{in} - P$$



This amount of thermal power is made available by the woking fluid after expansion in turbine (in case of heat engines). Therefore, it can be exploited by using a heat recovery system (i.e. heat exchanger of any kind, such as for instance a heat recovery steam generator) to produce useful heat.

The useful heat is typically recovered in the form of hot water or steam.

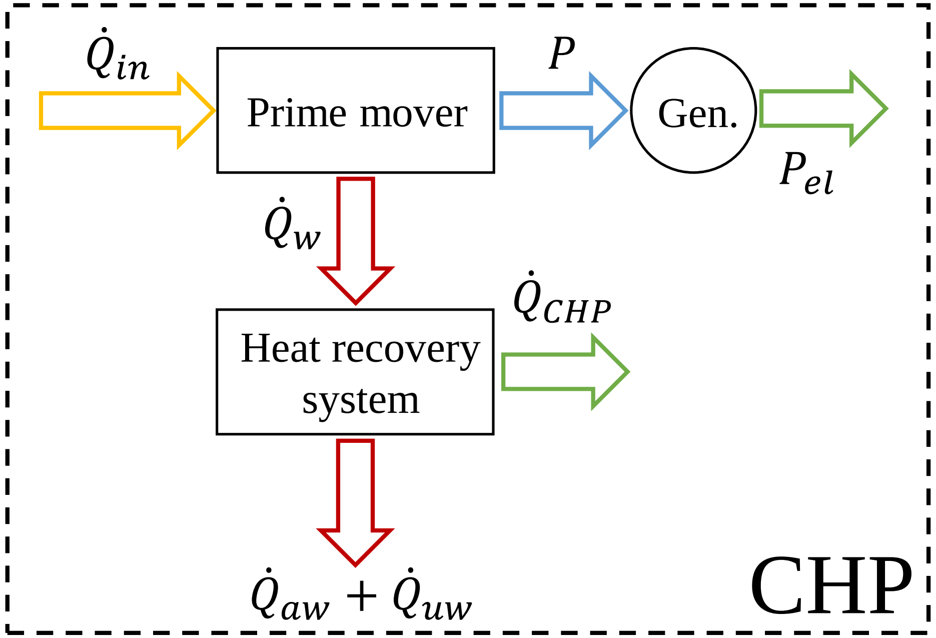
Combined Heat and Power Generation

The useful heat flow rate is a fraction of the available waste heat, as follows:

$$\dot{Q}_{CHP} = f\,\eta_{he}\dot{Q}_w$$

where η_{he} is the efficiency of the specific heat exchanger used to recovery the waste heat, while f is the *load factor*, which is a parameter taking into account that different fractions of the net available heat are recovered at different times during the power plant operation, depending on the instantaneous demand.

For instance, if the thermal power demand is lower than the recoverable heat, some of the net available heat will be lost.



On the light of these considerations, it is useful to see the waste heat as the sum of three contributions:

$$\dot{Q}_w = \dot{Q}_{CHP} + \dot{Q}_{aw} + \dot{Q}_{uw}$$

where:

$$\dot{Q}_{uw} = (1 - \eta_{he})\,\dot{Q}_w$$

is the unavoidable waste heat, and:

$$\dot{Q}_{aw} = (1 - f)\,\eta_{he}\dot{Q}_w$$

is the avoidable waste heat. In fact, no matter how efficient a system is, part of the input energy is an unavoidable loss to the environment, while another part that could be recovered in principle is loss if production and request are not aligned.

Combined Heat and Power Generation

Indexes of performance

A multitude of indexes (or figures of merit) have appeared in the literature for evaluation of the thermodynamic performance of cogeneration systems. The most important are:

- ***Electricity to heat ratio (R)*** →

$$R = \frac{P_{el}}{\dot{Q}_{CHP}}$$

- ***Energy Utilization Factor (EUF)*** →

$$\mathrm{EUF} = \frac{P_{el} + \dot{Q}_{CHP}}{\dot{Q}}$$

- ***Primary Energy Savings (PES)*** →

$$\mathrm{PES}_{\%} = \frac{\dot{Q}_{\mathrm{ref}} - \dot{Q}}{\dot{Q}_{\mathrm{ref}}} \cdot 100$$

These parameters cover different aspects of a CHP power plant and therefore all together provide a complete framework on the overall performance of the system.

Cogeneration technologies

Electricity and heat are both energy sources, but their properties are different.

Electricity can be delivered to every household and organization in a nation because it is relatively easy to transport swiftly and efficiently. In contrast, heat energy cannot conveniently and economically be transported with anywhere near the same ease.

The heat generated from cogeneration can be used for district heating or in process industries.

District heating includes a system in which the heat is centrally generated and sold to several customers. This is done using a distribution network that uses hot water or steam as a heat energy carrier.

Although it is possible to transport heat over long distances most heat is used locally, close to the point at which it is generated.

This dictates one of the key elements of CHP system design. A fundamental principle for optimum CHP efficiency is to identify a demand for heat and then design a plant with a heat output to meet this demand. Electricity from the plant can, in this sense, be considered as a valuable by-product.

However, while, ideally, a CHP system is designed around the heat demand in a particular location, in many cases a different approach can be followed and many designs are compromises that balance economic considerations with the optimum energy balance.

In same cases the main need may be for electricity and the use of heat is a secondary consideration. Even so, it is always the heat demand that will determine the location and outline of any CHP system. For without heat demand, there can be no CHP.

Cogeneration technologies

The heat demand around which the CHP plant is constructed must be *durable*.

So while CHP installations can range from single home heat-and-electricity units, to municipal power stations supplying heat and power to a city, or from paper mills burning their waste to provide steam and heat, to large chemical plants, they all share one theme:

Ideally, the heat and electricity from a CHP plant will be supplied to the same users.

While this is not an absolute requirement, it is a pragmatic principle for a successful CHP scheme.

If a heat and power plant is supplying both types of energy to the same users, be they an industrial plant or households, then the economics of the plant will remain sound so long as the customers remain.

In contrast, if a plant supplies electricity to one customer and heat to another, its economic viability can be undermined by the loss of either.

Part of this risk is mitigated if a plant can export electricity directly into the grid while selling its heat locally, but in general the economics of CHP will be most soundly based where the same customers take both.

Cogeneration technologies

Two different types of CHP system, depending on the sequence the energy is produced:

- **Topping cycle** or **upstream cycle**

  The fuel supplied to the system is used primarily to generate electricity while the heat that is left after electrical power has been generated is used in an ancillary application.

  Depending upon the type of generating system, the heat energy from the electricity generating system might be high grade heat that is suitable for raising steam or for use directly in an industrial process, or it might be lower grade heat that is only suitable for space heating and hot water production.

- **Bottoming cycle** or **downstream cycle**

  In this type of system the fuel is used first to produce heat.

  The heat will normally be exploited in an industrial process that requires very high temperatures or vast quantities of heat. Any energy not used in the process is then used to generate electricity.

  Bottoming cycle CHP is also called waste energy recovery or waste heat recovery.

  These kind of systems are particularly attractive because they can provide electricity without the need of consuming additional fuel.

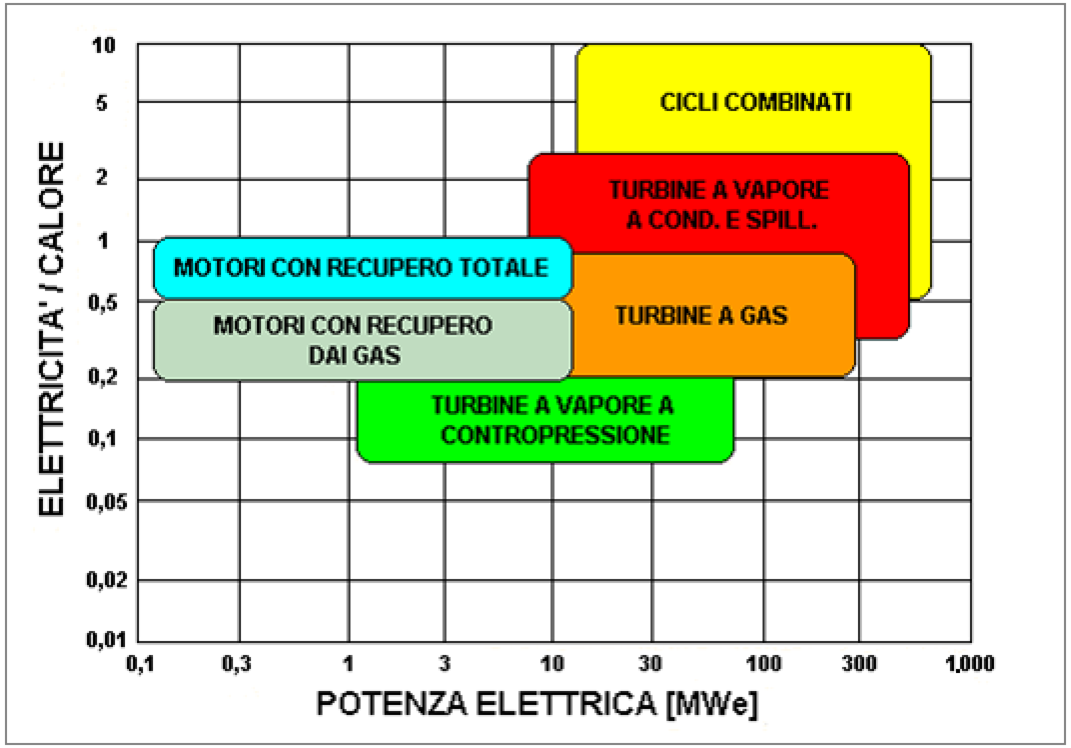
Cogeneration technologies

Common prime movers for CHP systems are:

- Gas-turbines
- Steam-turbines
- Combined cycles
- Reciprocating internal combustion engines
- Fuel cells

The key parameters that make some technology the preferred choice for a certain application include:

i) size of the plant,
ii) electricity to heat ratio,
iii) average temperature at which heat should be recovered, that is, the quality of useful heat,
iv) fuel type,
v) cycle efficiency,
vi) fixed and variable costs.



Cogeneration technologies

While the range of available technologies offers a wide choice for a CHP plant, the type of heat required from a CHP application will often narrow the choice of technology.

If heat at high **temperatures** is demanded, such as to produce high quality steam, the preferred choice would be a gas-turbine, since its exhaust gases can provide high grade heat, but also steam turbines and high-temperature fuel cells might be a suitable choice.

Reciprocating engines or low-temperature fuel cells are instead usually only capable of generating hot water or, at most, low quality steam, therefore they are typically used for small-size applications.

When the heat energy is available at a relatively low temperature, it may be possible to use an organic Rankine cycle which can convert lower grade heat into electricity.

However, also the **mode of operation** plays a role and it will determine the optimum choice of technology.

If the unit has to supply power to a particular consumer or group of consumers, with its output following their demand, then a generating unit that can operate efficiently at different load levels such as a reciprocating engine or fuel cell will probably be the best solution. In contrast, if it is going to provide base-load generation then part load efficiency will be of less significance.

Finally, **location** will be important too. It will not be possible to install some types of CHP plant in urban areas because of the emissions and the noise they generate. This will therefore limit the technologies available for use in this situation.

Gas-turbine CHP systems

In CHP applications, a gas turbine will almost always be used in a ***topping cycle*** configuration with heat being recovered from the exhaust gases.

There are a small number of situations in which a gas turbine could potentially be used in a bottoming cycle. These arise when there is a stream of high pressure/high temperature air that is exiting from an industrial process. In this case, a power turbine can extract energy from this gas stream.

The temperature of the exhaust gases exiting a gas turbine will be in the range 400 to 700 °C, depending on the pressure ratio and the turbine inlet temperature.

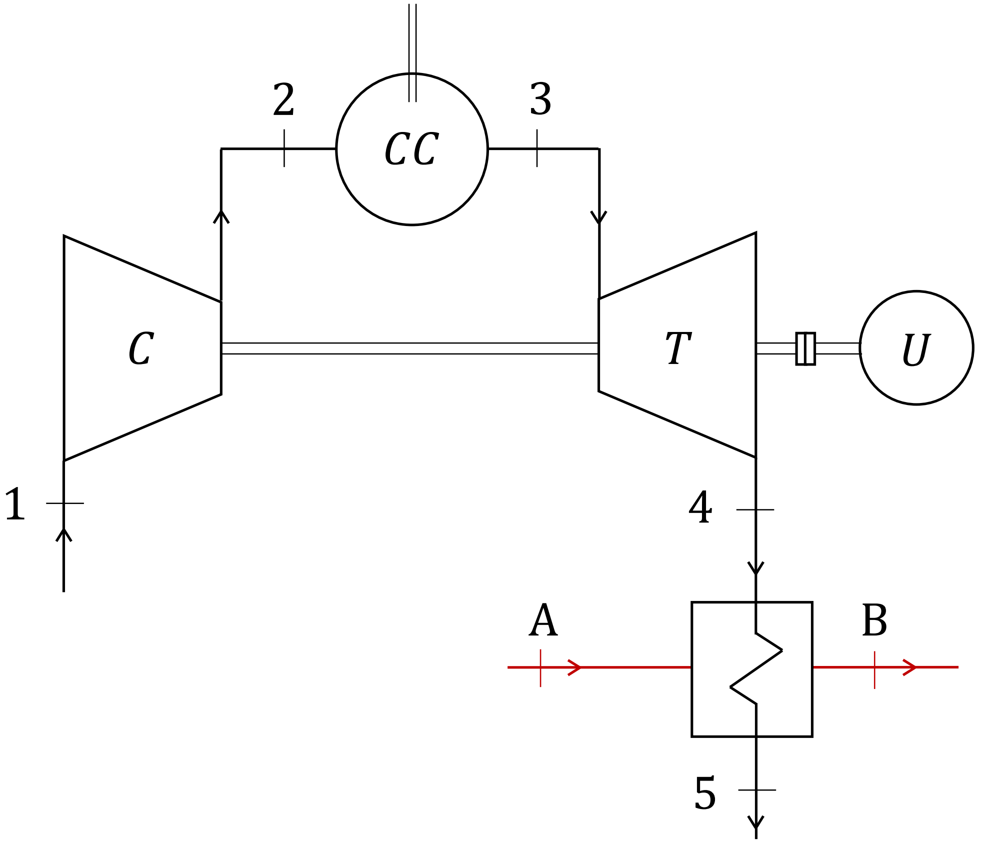
In general, heat recovery by gas-turbine CHP systems can be achieved by means of three ways:

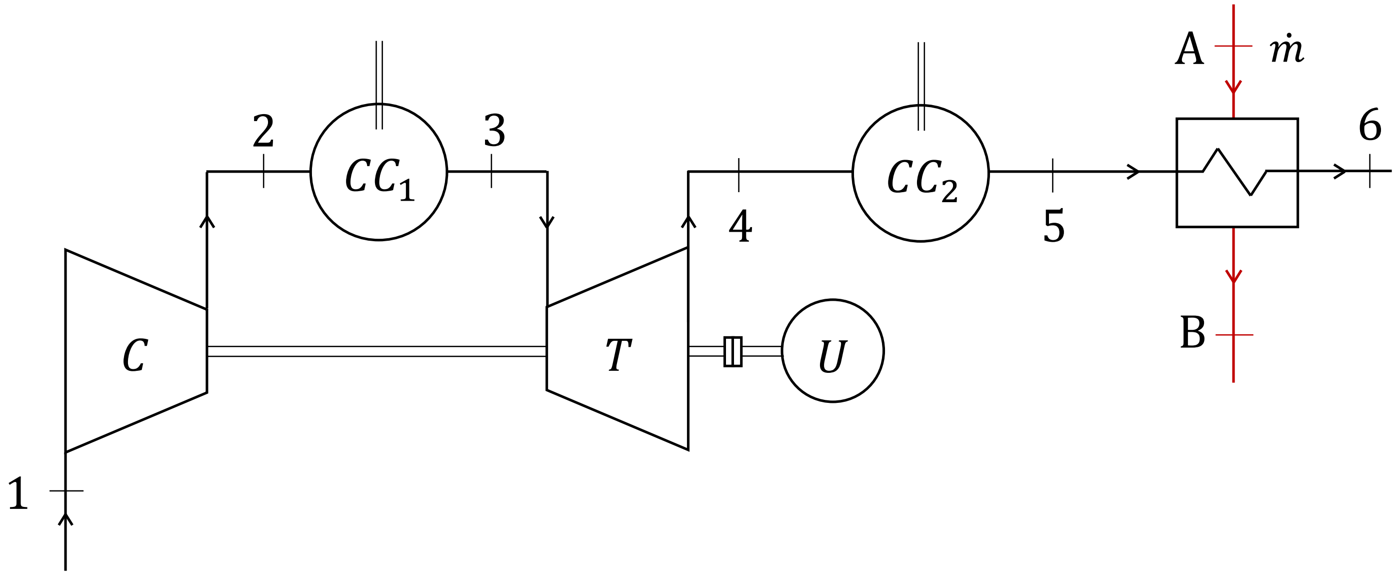
1. the hot exhaust gases are used directly. In some cases it is possible to use the exhaust gases in a kiln, for industrial processes. In other cases air-to-air heat exchangers are used to provide hot air.
2. the hot exhaust gases can be used to produce steam in a Heat Recovery Steam Generator (HRSG). The steam can be used to provide heat for an industrial process or for district heating.
3. heat from the hot exhaust gases is used to generate hot water.

The balance between electricity and heat demand will determine the exact configuration of the plant.

Gas-turbine CHP systems

Basic configurations – use of a heat exchanger for hot air or hot water production.





Gas-turbine CHP systems

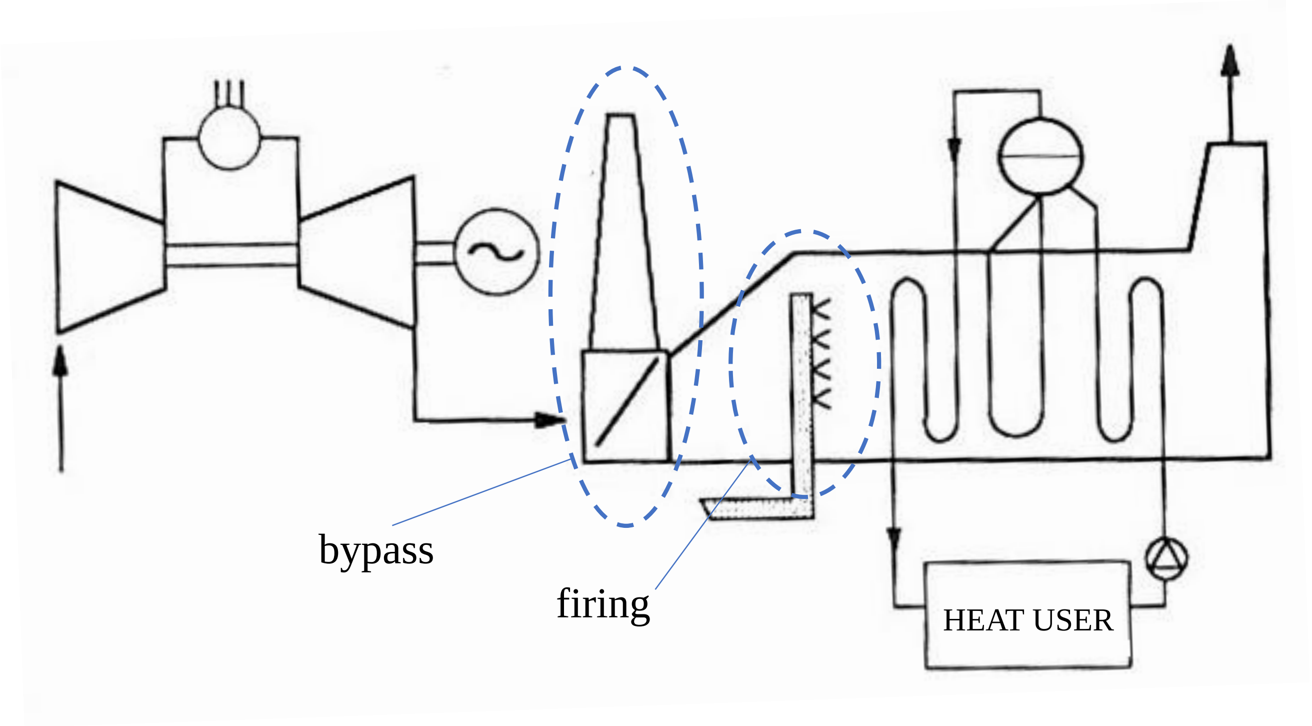
Steam production in a Heat Recovery Steam Generator

The need for power and heat/steam is rarely balanced so well that a CHP system can always provide for both.

Therefore, it can be necessary to control either the heat output or the electrical output or even both.

If the CHP system meets the electricity demand but the heat/steam demand is greater than the one that can be supplied, the solution may be to add supplementary firing burners upstream inside the HRSG to provide additional steam capacity.

Such a burners use the exhaust gas of the gas-turbine as its oxygen source. In fact, the exhaust gases contain a sufficient amount of oxygen for burning additional fuel.



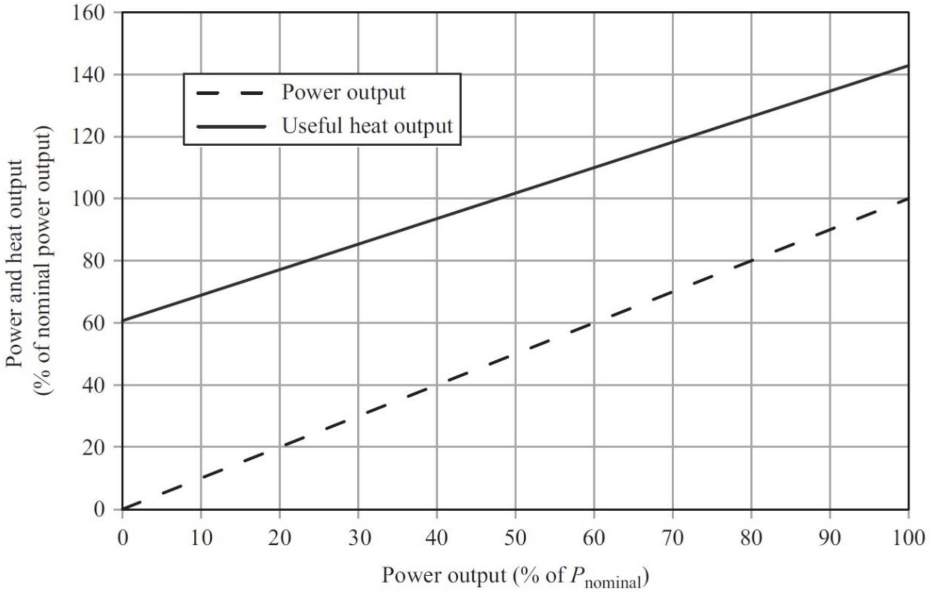
In contrast, if there is a surplus of heat, this might be dissipated by using a bypass system.

Viceversa, if the CHP system is sized to provide all the heat demand, it is likely that a lack or a surplus of electricity will occur. In this case, additional power can be imported/exported from/to the local grid, provided this is permitted by national regulations.

Gas-turbine CHP systems

In case no supplementary firing is available, the steam production can be varied by changing the power output of the gas turbine.

However, the heat released in the exhaust of the turbine does not decrease linearly with the power output. This is because the fuel efficiency of the turbine decreases with the power output, and therefore, the heat fraction increases with decreasing power output.



Example.

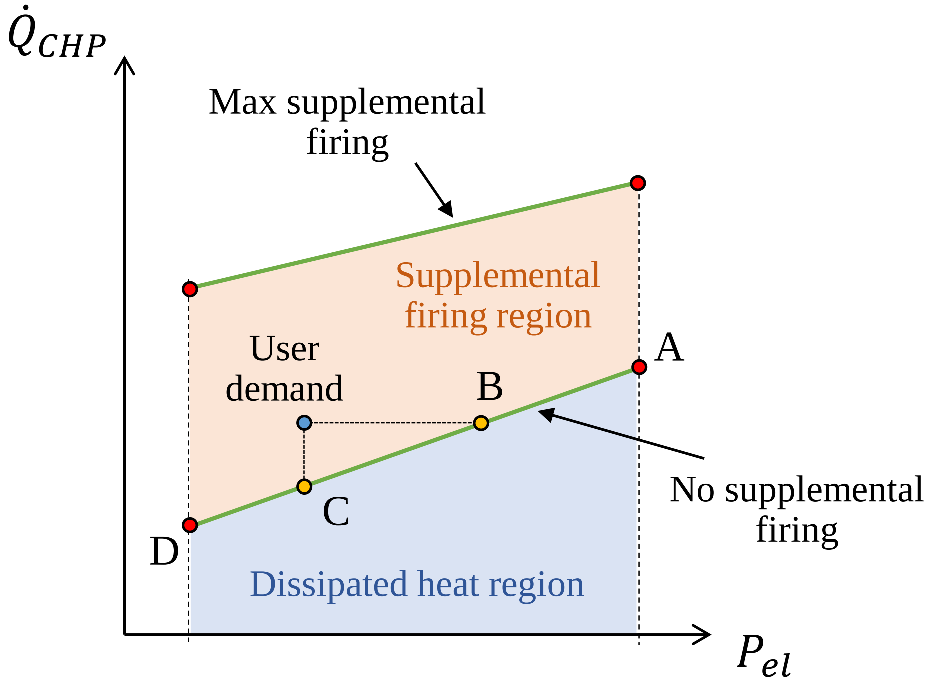
In case a constant combined efficiency of for example 85% is presumed, if the power output decreases from 100% to 60% of the nominal power, the useful heat output decreases from 143% to 110% of the nominal power, which is a reduction of only 23%.

This is the major reason why supplementary firing is preferred, if the steam production has to be changed in a wider range.

Gas-turbine CHP systems

CHP system operating points – control strategies

Point	Strategy	Electric power	Thermal power
A	***Max electric power output***	$P_{el_\mathrm{A}} > P_{el_\mathrm{UD}}$	$\dot{Q}_{CHP_\mathrm{A}} > \dot{Q}_{CHP_\mathrm{UD}}$
	Export electric power to the grid		
	Bypass		
B	***Thermal load-following***	$P_{el_\mathrm{B}} > P_{el_\mathrm{UD}}$	$\dot{Q}_{CHP_\mathrm{B}} = \dot{Q}_{CHP_\mathrm{UD}}$
	Export electric power to the grid		
C	***Electric load-following***	$P_{el_\mathrm{C}} = P_{el_\mathrm{UD}}$	$\dot{Q}_{CHP_\mathrm{C}} < \dot{Q}_{CHP_\mathrm{UD}}$
	Supplemental firing		
D	***Min electric power output***	$P_{el_\mathrm{D}} < P_{el_\mathrm{UD}}$	$\dot{Q}_{CHP_\mathrm{D}} < \dot{Q}_{CHP_\mathrm{UD}}$
	Import electric power from the grid		
	Supplemental firing		



The choice of the best power plant operating point depends on energy as well as economic aspects.

Gas-turbine CHP systems

Gas-turbine CHP plants are capable of serving a wide range of heat and power needs. Conventional CHP plants based on gas turbines are available in a wide range of sizes, from just few kilowatts (microturbines) up to 500 MW.

The largest plants operate as electric power generators while providing either process heat for industrial heat users or for district heating. These plants usually operate with high efficiency, often up to 85% in CHP mode.

Smaller CHP plants based on small industrial or aero-derivative gas turbines are commonly used by industries that have a need for both heat and power. These plants usually have a limited electric power capability, with output sufficient only for the industry they serve, and frequently use supplementary firing to provide extra steam or heat output.

Large microturbines (up to 400 kW) might also be used in an industrial setting but most of these units are designed to provide power, heating and hot water. Typical applications include hospitals, retail centers, office blocks and leisure and recreation centers.

Small microturbines, in the 1 to 10 kW range, are aimed at the domestic and small commercial market. This is a relatively new area for CHP units of any type and there are many competing technologies.

Electrical efficiency of these small machines is relatively low with a 30 kW machine typically capable of around 23% efficiency. CHP efficiency is much higher and a 30 kW microturbine might achieve 67% CHP efficiency.

Integrated Gasification Combined Cycle Technologies

Irrespective of new discoveries of natural gas reserves and new techniques being developed to increase cheaper natural gas production, coal is still one the most abundant and cheaper fossil fuel.

Therefore, it may be convenient to keep using this energy source to produce electricity in the world, either for economic reasons or as a strategy to safeguard national energy security and independence.

However, the conventional way of burning coal is environmentally unfriendly: therefore, it is essential to develop and adopt cleaner methods of utilizing coal.

IGCC is an acronym for **Integrated Gasification Combined Cycle**.

The major purpose of IGCC is to use hydrocarbon fuels in solid or liquid phases to produce electrical power in a cleaner and more efficient way via gasification, compared to directly combusting the fuels.

The hydrocarbon fuels typically include coal, biomass, refinery bottom residues (such as petroleum coke, asphalt, etc.), and municipal wastes.

Although the gasification process can be applied to various carbon fuels, the major developments and applications involves coal.

The approach to achieve a “cleaner” production of power is to convert solid/liquid fuels to gas first, so that they can be cleaned before they are burned by removing mainly particulates, sulfur, mercury, and other trace elements.

The cleaned gas, called *synthetic* or *synthesis gas* (**syngas**), which primarily consists of **carbon monoxide (CO) and hydrogen (H2)**, can then be sent to a conventional combined cycle to produce electricity.

Integrated Gasification Combined Cycle Technologies

https://www.youtube.com/watch?v=V3jfECTjMS8

Integrated Gasification Combined Cycle Technologies

A typical IGCC process diagram comprises three major *islands*:

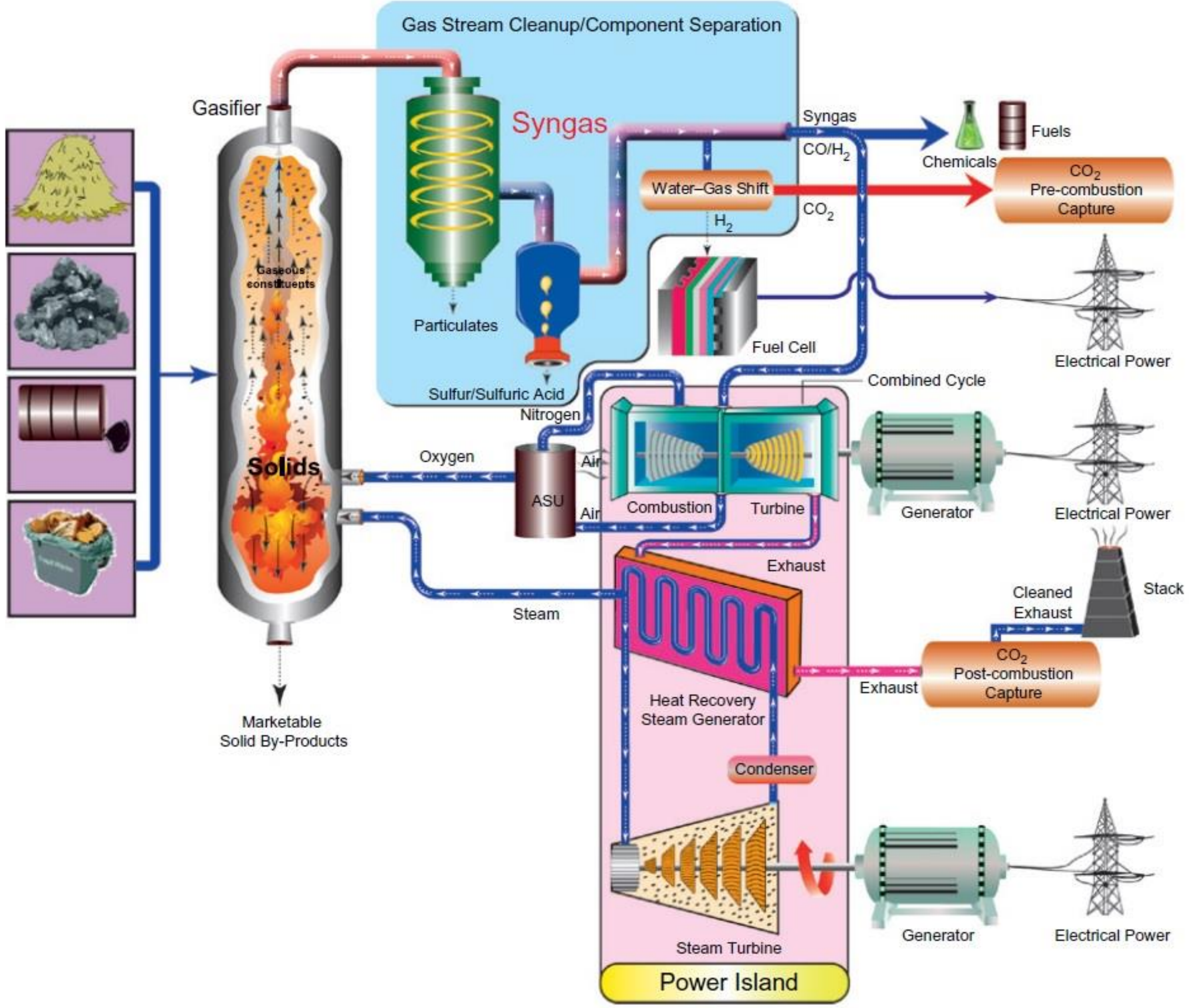
- gasification,
- gas cleanup,
- power.

The ultimate goal for IGCC is to achieve a lower cost of electricity than natural gas-fired combined-cycle systems with comparable emissions.

While **clean power generation** is the primary driving motivation for entering the business of IGCC, **increasing plant efficiency** is the second driving motivation.

To achieve higher efficiency, **integration** between sub-systems becomes necessary.

Integration consists of all aspects of the operation, including mechanical, thermal, and dynamic process control.



Integrated Gasification Combined Cycle Technologies

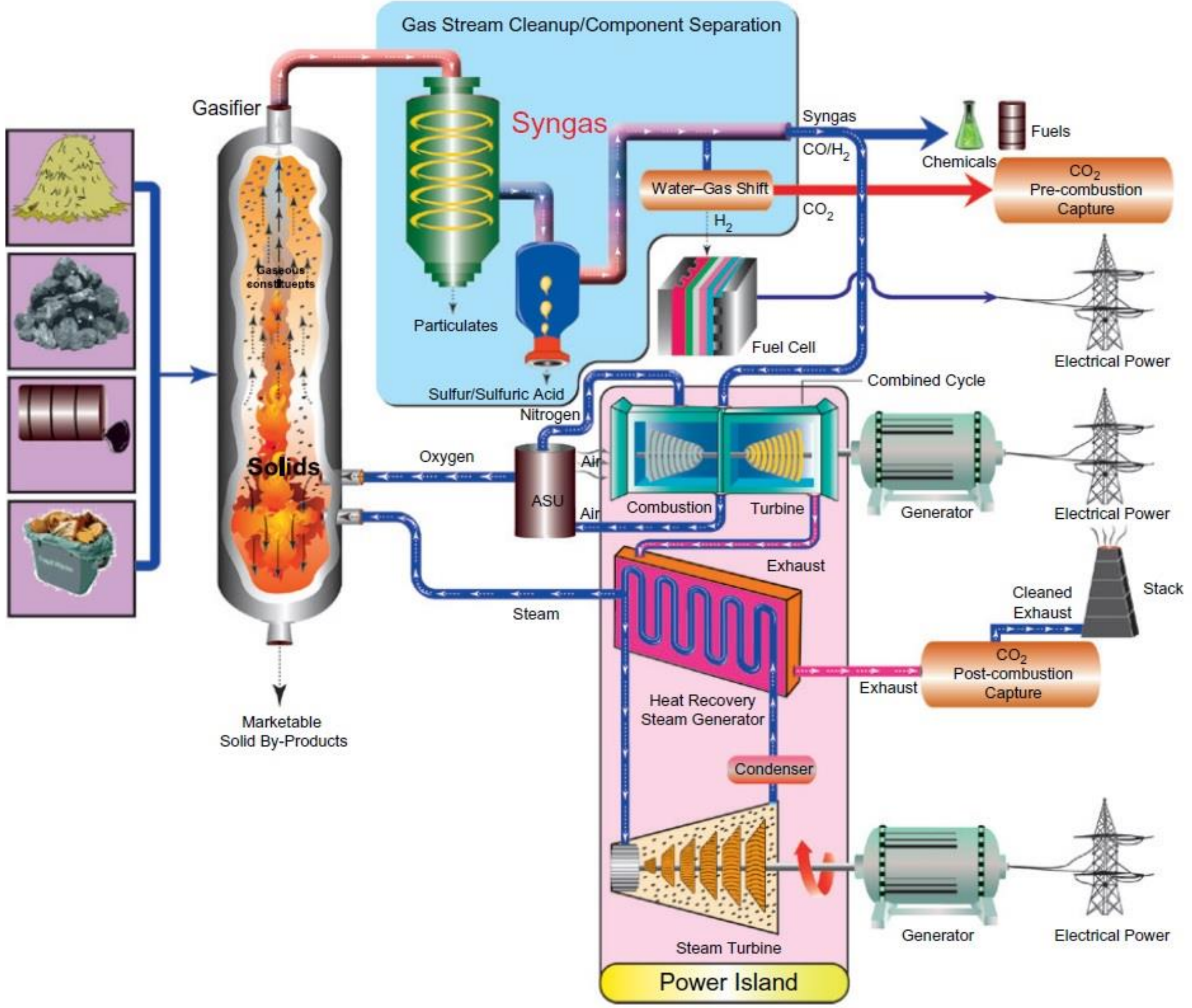
A typical IGCC process diagram comprises three major *islands*:

- gasification,
- gas cleanup,
- power.

For example, **mechanical integration** can be achieved between the compressor of the gas turbine and the Air Separation Unit (ASU), aiming to save some compression power.

To reduce the large energy consumption of compressors used in the ASU, one approach is to take advantage of the gas-turbine compressor power by extracting part of the compressed air at the exit of the compressor and sending it to the inlet of the ASU.

Full air integration does enhance the overall plant efficiency positively by about three to four percentage points (but it also increases the complexity of construction, operation, and maintenance).



Integrated Gasification Combined Cycle Technologies

A typical IGCC process diagram comprises three major *islands*:

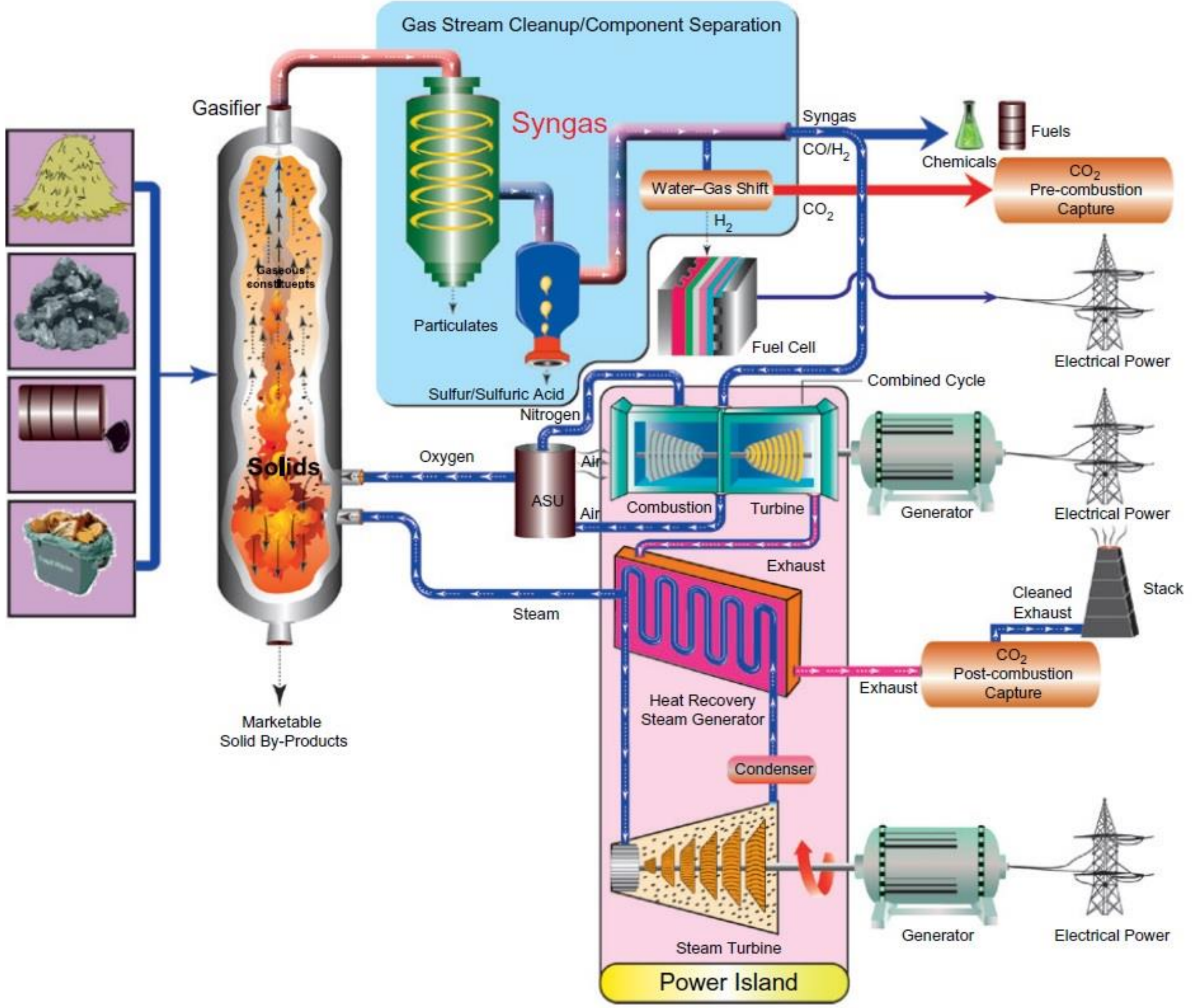
- gasification,
- gas cleanup,
- power.

Thermal integration can be implemented by strategically interconnecting the various grades of steam generated during the syngas cooling, gas cleanup, and/or water-gas shift processes with the Heat Recovery Steam Generator and the steam turbine system.

For example:

The syngas cooling process immediately downstream of the gasifier generates high-pressure steam for the HRSG.

The high-pressure steam is needed to drive the water-gas shift process, and, in return, the exothermic process heat from the WGS reaction is used to heat steam.



Integrated Gasification Combined Cycle Technologies

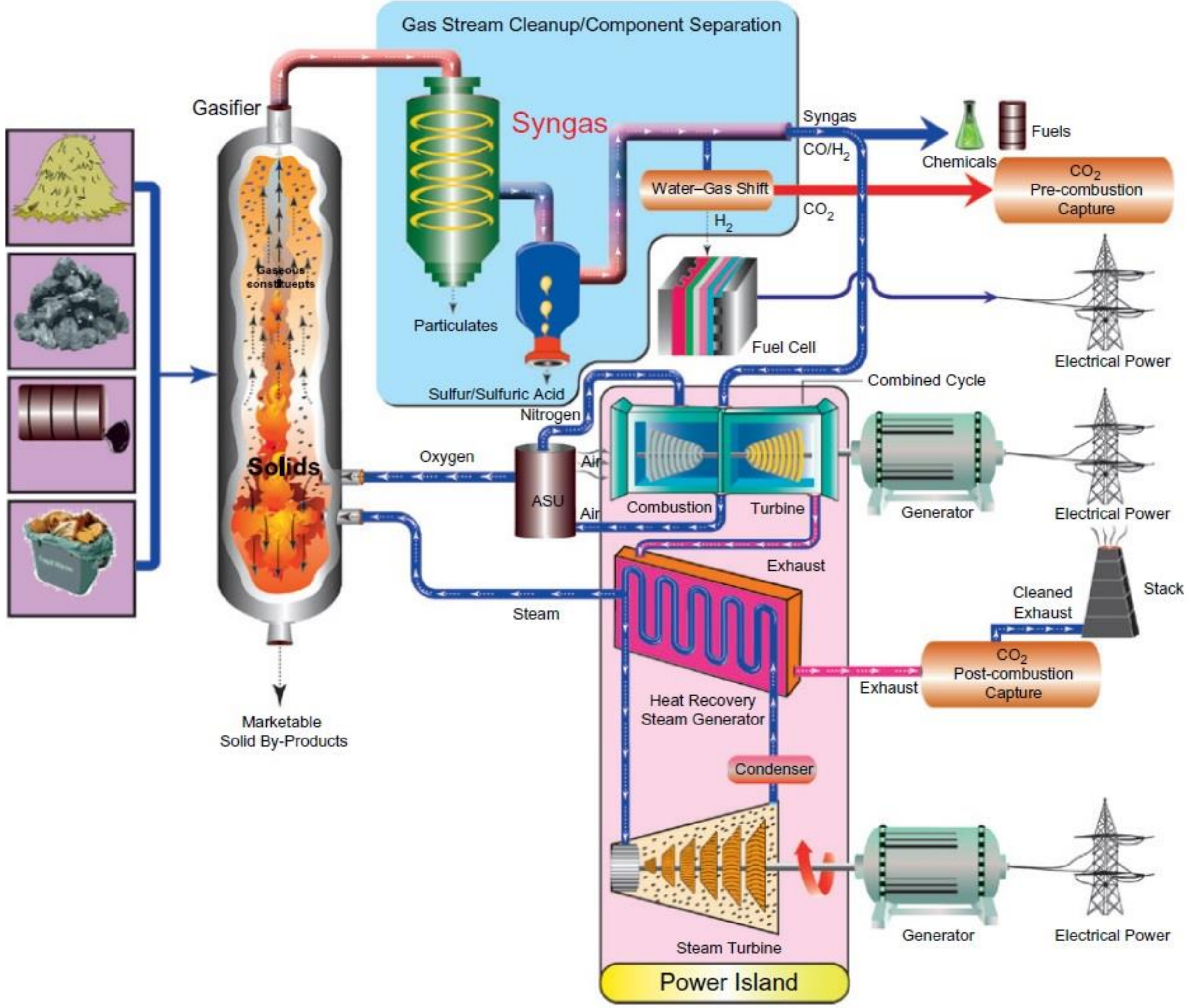
Usually, there are three ways to reduce CO_2 emissions:

- increasing the overall system efficiency,
- capturing a portion of the CO_2 and sequestering it, called **Carbon Capture and Sequestration** (CCS),
- utilizing the captured CO_2 multiple times.

The syngas generated via the gasification process can be more readily separated into highly concentrated H_2 and CO_2 through the **water-gas shift** (WGS) process before the combustion stage (i.e., pre-combustion capture).

It is significantly cheaper to perform pre-combustion carbon capture than post-combustion carbon capture due to the nature of the processes involved and the reduced size of equipment.

CCS imposes a severe penalty on power output, plant efficiency, and costs.



Gasification process

Gasification converts any carbon-containing material into **synthesis gas (syngas)**, composed primarily of carbon monoxide and hydrogen.

In general, syngas can be used:

- as a fuel to generate electricity or steam,
- as a basic chemical building block for a large number of uses in the petrochemical and refining industries,
- for the production of hydrogen.

Gasification is different from combustion: the purpose of combustion is to produce heat, whereas *the purpose of gasification is to produce fuels or chemicals*.

Therefore, during a combustion process, the stoichiometric amount of oxidant is used/needed to completely oxidize the feedstock and obtain the maximum thermal energy output.

Whereas, during a gasification process, as little thermal energy as possible is intended to be used (and, thus, limited oxidant is needed) to convert the feedstock to useful fuels, preserving as much of the original fuel's chemical energy (heating value) as desired.

Typically, a stoichiometric ratio of 0.25-0.35 (i.e., 25-35% of the oxygen theoretically needed for complete combustion) is implemented in a gasification process.

Since only limited oxidant is needed, the gasification process has been commonly introduced as an incomplete combustion or partial combustion process. Although it is not wrong to say so, it could be misleading because the purpose of incomplete or partial oxidation is to produce heat, which is only the first step.

The actual reactions involved with gasification are extremely complicated and vary with the properties of the feedstock.

Gasification process

For the convenience of explaining the gasification process, a set of simplified, major global reactions involved in a gasification process are summarized as follows:

$C + {}^1\!/_2\, O_2 \rightarrow CO + \Delta H_R$	$\Delta H_R = +110.6$ MJ/kmol	⇒	PARTIAL OXIDATION
$C + O_2 \rightarrow CO_2 + \Delta H_R$	$\Delta H_R = +393.7$ MJ/kmol	⇒	COMPLETE OXIDATION
$C + H_2O \rightarrow CO + H_2 + \Delta H_R$	$\Delta H_R = -131.4$ MJ/kmol	⇒	STEAM-CHAR GASIFICATION
$CO + H_2O \rightarrow CO_2 + H_2 + \Delta H_R$	$\Delta H_R = +\ 41.2$ MJ/kmol	⇒	WATER-GAS SHIFT
$CO + 3H_2 \rightarrow CH_4 + H_2O + \Delta H_R$	$\Delta H_R = +206.4$ MJ/kmol	⇒	METHANATION

where:

- all the reaction heats (ΔH_R) are based on 298 K and 1 atm;
- sign “–” indicates *endothermic* (absorbing heat) reaction, sign “+” indicates *exothermic* (releasing heat) reaction;
- partial oxidation, complete oxidation and gasification are *heterogeneous* reactions, that are, reactions between different phases (coal solid particles reacting with various gases);
- water-gas shift and methanation are *homogeneous* reactions, that are, reactions occurring entirely within the gas phase.

Water-gas shift (WGS) process inside gasifiers

The water-gas shift reaction is an equilibrium process:

$$CO + H_2O \rightarrow CO_2 + H_2 + \Delta H_R \qquad \Delta H_R = +\ 41.2\ \text{MJ/kmol}$$

The forward reaction is exothermic, converting carbon monoxide and steam to hydrogen and carbon dioxide.

The forward reaction is active at temperatures lower than 700°C.

At higher temperatures, near 1000°C, the net reaction is slow and negligible.

Beyond 1200°C, the backward reaction becomes dominant.

The reaction rate of the WGS is typically slow without using catalysts; however, in the gasifier, the reaction rate is usually enhanced by the catalytic effect of metal components in the coal.

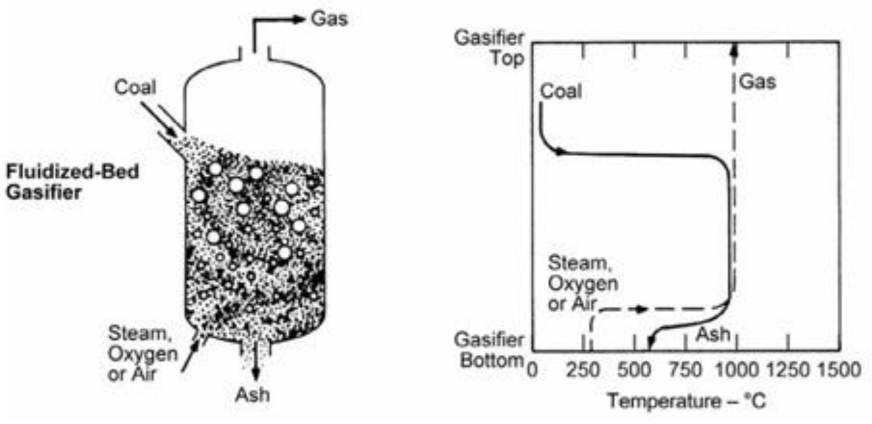
Since the forward reaction occurs at relatively low temperatures, the WGS typically occurs in the region in the gasifier where the temperature is reduced due to the endothermic steam-char gasification process.

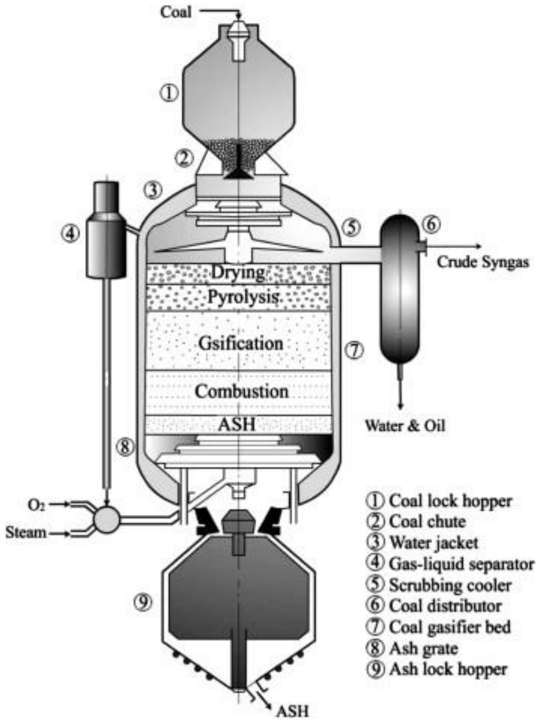
The WGS is an important process which dictates the final composition of the raw syngas, that is, the CO/H2 ratio.

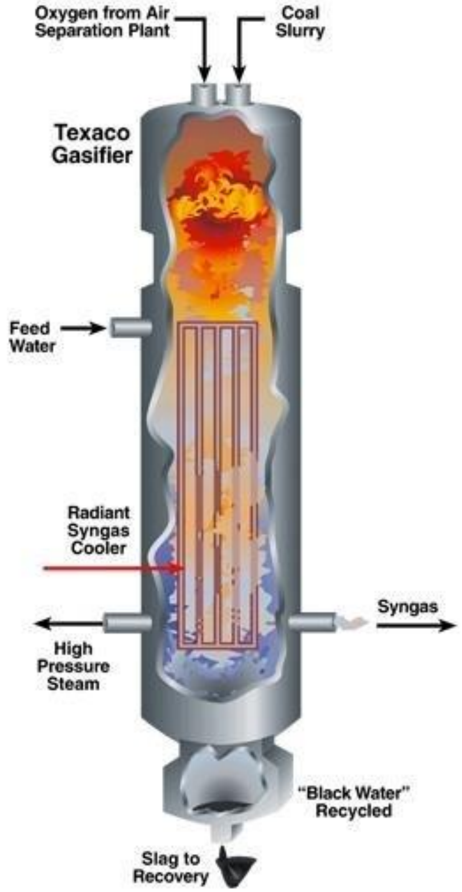
Gasifiers technologies

Many different gasifiers have been designed to best achieve certain target syngas compositions with the goals of minimizing the gasifier's size (thus reducing cost), maximizing output yield, enhancing gasification efficiency, lowering maintenance frequency, and increasing reliability and availability.

- **Fixed bed gasifiers**: low-temperature, need less oxygen, long coal residence time, require large amounts of steam, low carbon conversion efficiency.
- **Fluidized bed gasifiers**: moderate temperature, medium residence time, suitable for coals with high ash fusion temperatures, medium to high carbon conversion efficiency.
- **Entrained flow gasifiers**: high-temperature (>1220°C), produce molten slag, demand higher oxygen to coal ratio, require low amounts of steam, very short residence times - few seconds, high carbon conversion.







Indexes of performance

The performance of a gasifier can be evaluated by three indices:

1. Carbon Conversion Ratio (CCR) or Carbon Conversion Efficiency (CCE)
2. Cold Gasification Efficiency (CGE) or Hot Gasification Efficiency (HGE)
3. Resulting syngas Lower or Higher Heating Values (HHV or LHV).

Carbon Conversion Ratio (**CCR**) or Carbon Conversion Efficiency (**CCE**), representing the mass percentage of total carbon in the gasifier feedstock (i.e., coal or biomass) converted to syngas, is defined as:

$$\mathrm{CCR} = \frac{\text{mass of carbon in the syngas}}{\text{mass of carbon in the feedstock}}$$

Although CCR provides information on how much carbon has been converted, it can’t really assess the value of the syngas.

Indexes of performance

The performance of a gasifier can be evaluated by three indices:

1. Carbon Conversion Ratio (CCR) or Carbon Conversion Efficiency (CCE)
2. Cold Gasification Efficiency (CGE) or Hot Gasification Efficiency (HGE)
3. Resulting syngas Lower or Higher Heating Values (HHV or LHV).

For IGCC systems, the only purpose of producing syngas is to have it burned to generate electricity. Under this stipulation, the performance of a gasifier can be evaluated by either the Cold Gasification Efficiency (**CGE**) or the Hot Gasification Efficiency (**HGE**) as follows:

$$\mathrm{CGE} = \frac{\dot{m}_{\mathrm{syngas}}\mathrm{LHV}_{\mathrm{syngas}}}{\dot{m}_{\mathrm{feedstock}}\mathrm{LHV}_{\mathrm{feedstock}}} \quad ; \quad \mathrm{HGE} = \frac{\dot{m}_{\mathrm{syngas}}\mathrm{HHV}_{\mathrm{syngas}}}{\dot{m}_{\mathrm{feedstock}}\mathrm{HHV}_{\mathrm{feedstock}}}$$

The CGE is defined based on the principle that the syngas needs to be cooled to near the ambient temperature in order to go through the gas cleanup process. Thus, the value of the syngas is only meaningful when it is evaluated at the (cold) ambient temperature.

In contrast, the HGE gives credit to the sensible heat. This is based on the principle that most of the sensible heat (about 80%) could be recovered one way or another, so it is arguably unfair to discount, totally, its contribution to the cycle efficiency.

Syngas cooling

The raw syngas exiting the gasifier is at a high-temperature (around 1500°C).

At this high-temperature, if this raw syngas could be burned directly in the gas-turbine, all of the heat generated in the gasifier that wasn't consumed by the endothermic gasification reactions would have been saved and effectively used by the gas-turbine to produce power.

In reality, unfortunately, this ideal situation doesn't happen because the raw syngas is dirty and needs to be cleaned up.

Two of the conventional cleanup processes must be performed at low temperatures, namely:

- mercury removal at ambient temperature around 30-38°C
- carbonyl sulphide (COS) hydrolysis at 177-204°C.

Hence, the raw syngas must be cooled all the way down to the ambient temperature through the syngas cooling system.

The most practical approach is to integrate the syngas cooling system thermally with the HRSG to transfer the raw syngas's thermal energy to producing high and/or medium pressure steam, which can be used to drive the steam turbines to produce power.

Syngas and hydrogen-rich fuel combustion

The primary fuel components in syngas are CO and H2. For partial CO2 capture systems, the H2 content increases, resulting in hydrogen-rich fuels.

The energy content (heating value) of syngas is lower than that of natural gas, ranging from about 35% of the natural gas's heating value for oxygen-blown systems to about 10% for air-blown systems.

Since the syngas heating value varies from about 35% (oxygen-blown systems) to 10% (air-blown systems) of NG's heating value, three to eight times more fuel is needed to drive the gas-turbine in order to obtain the same rated output power as that of a natural gas power system.

Also, carbon monoxide and hydrogen in the syngas both have higher flame speeds than the natural gas does.

Hence, the combustors, originally designed for burning natural gas, must be modified, in terms of: fuel injector's design, size, control algorithm for the flow speed at the nozzle of the turbine, approaches for combustion stability.

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Thank you for your attention.