EUROPEAN
COMMISSION

Brussels, 9.1.2023
SWD(2023) 1 final

PART 1/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

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

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

{COM(2023) 1 final}

EN EN

Assessment of the potential for energy efficiency in electricity generation, transmission and storage.

Berizzi, A.
Benato, R.
Bosisio, A.
Petrelli, M.
Vicario, A.
Serrenho, T.
Bertoldi, P.

2021

EU Science Hub
https://ec.europa.eu/jrc

JRC125030

Luxembourg: Publications Office of the European Union, 2021

How to cite this report: Berizzi, A., Benato, R., Bosisio, A., Petrelli, M., Vicario, A., Serrenho, T., Bertoldi, P., *Assessment of the potential for energy efficiency in electricity generation, transmission and storage*, Publications Office of the European Union, Luxembourg, 2021, JRC125030.

Contents

Abstract

The revised Energy Efficiency Directive (2018/2002) in Article 23 15 (b) 13 states that "the Commission shall carry out an assessment of the potential for energy efficiency in conversion, transformation, transmission, transportation and storage of energy, and shall submit a report to the European Parliament and to the Council." This Report presents the results of the assessment of the potential for energy efficiency in conversion, transformation, transmission and storage of electric energy. The report is focused on three main pillars of possible energy efficiency imporvements, namely conventional fuels power generation, energy storage and High Voltage Direct Current (HVDC) transmission. In this report, those three main technological solutions have been taken into account in the light of the energy efficiency, to identify possible energy savings potential. For each topic considered, a review of current efficiency levels has been carried out, margins for improvements have been identified, and simple quantitative assessments have been made in order to estimate possible primary energy savings at European level. The document is organized as follows: first the single technological solutions have been investigated separately; then, conclusions and ranking are presented in the last Chapter.

1 Introduction

In this Report, the results of an assessment carried out to perform research for the identification and preparation of a study evaluating the potential for energy efficiency in conversion, transformation, transmission and storage of electric energy is presented.

The guideline is outlined in Article 23 (b) 13. of the revised Energy Efficiency Directive; the report is focused on three main pillars of possible energy efficiency development, namely conventional fuels, storage and High Voltage Direct Current (HVDC) transmission. Therefore, in this document, those three main technological solutions have been taken into account in the light of the energy efficiency, to identify possible savings potentially obtainable. For each topic considered, a review of current efficiency levels has been carried out, margins for improvements have been identified, and rough quantitative assessments have been made in order to estimate possible primary energy savings at European level. The document is organized as follows: first the single technological solutions have been investigated separately; then, conclusions and ranking are presented in the last Chapter.

Chapter 2 presents the results on the technology adopted and efficiency assessment in thermal power plants, with particular reference to conventional fossil fuels (coal, gas, oil) power stations. Some statistical data about efficiencies, consumptions, capacities, etc. are also shown. Current and perspective efficiency levels are described and estimates of potential primary energy savings have been determined under some assumptions related to the decarbonisation policy currently adopted.

Regarding storage, in Chapter 3, different types of storage useful for electric systems are considered and described with reference to the maturity of technology. Details are provided for those technologies that show current and future better perspectives (hydro pumped power stations, batteries, compressed air, flywheel). It is worth noticing that it is difficult to compare directly, in terms of efficiency, storage alternatives that might be addressed to the solution of very different technical issues (in other words, one cannot use supercapacitors to deal with large amount of energy issues): each technical problem should be addressed by the proper class of storage systems; within that class, of course, the most efficient technology should be adopted. In general, storage technologies are interesting not because they allow a direct saving of primary energy, but because they make it possible to integrate energy coming from Renewable Energy Sources (RES) into power systems, thus saving primary energy indirectly.

The same concept is true also for HVDC systems, dealt with in Chapter 4. HVDC transmission is not suitable to improve the efficiency of transmission systems, which is already very high (about 98%) and could be hardly increased. HVDC transmission is interesting because it makes it possible to transfer energy in conditions where HVAC systems would neither be technically nor economically affordable, and this is true in particular for subsea cables that allow the integration of wind power from large off-shore wind farms, thus resulting in an indirect saving of primary energy. In Chapter 4, the main characteristics of HVDC systems are hence described; for such systems, the operating conditions leading to best efficiency are derived and present and possible future uses in the European context are highlighted.

Chapter 5 reports the conclusions of the assessment carried out on the potentials of each technology for what the energy efficiency is concerned. Wherever possible, a quantification of realistic saving has been performed, under simplifying assumption, showing the potential for improvements in terms of primary energy saving.

2 Fossil fuels power plants

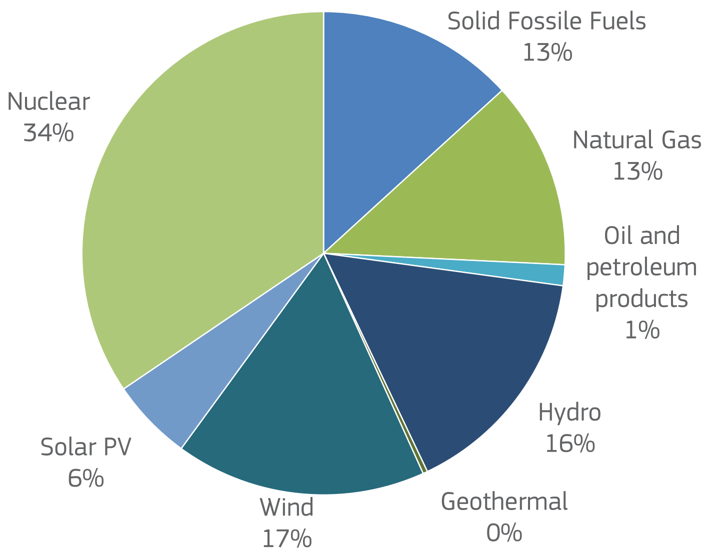
2.1.1 Introduction

In this chapter, the main characteristics of European thermal power stations fed by fossil fuel are described and their actual efficiency levels are analysed based on public data available from the Eurostat database [1] and by the most recent analysis reported in [2], with particular reference to coal, oil and gas thermal plants only.

A wider review of European energy sector is presented in the annual statistical book [3]. In [4], critical factors that influence the development of the fossil-fuel fired power generation are investigated; moreover, an updated analysis can be found in [5], where the results of a baseline scenario of the total European energy system up to 2050 are also shown. Finally, the perspective of the International Energy Agency is presented in the well-known 2020 World Energy Outlook [6].

According to the Eurostat database, the European Union still highly relies on conventional thermal generation for the electricity production. As shown in the following chart1 (Figure 1), in 2019 about 61 % of the electricity production has been generated by conventional thermal and nuclear power plants; hence, renewables were responsible for the 39 % of the total generation. As a comparison, in 2010, the renewable share was around 25 %, mainly hydropower [1].

Figure 1. Gross electricity production in 2019 in percentage. Elaboration of data from [1].



The chart[2] in Figure 2 shows the installed capacity in Europe in 2019. Out of a total capacity of 868,7 GW, conventional fossil fuels plants represent 40 %.

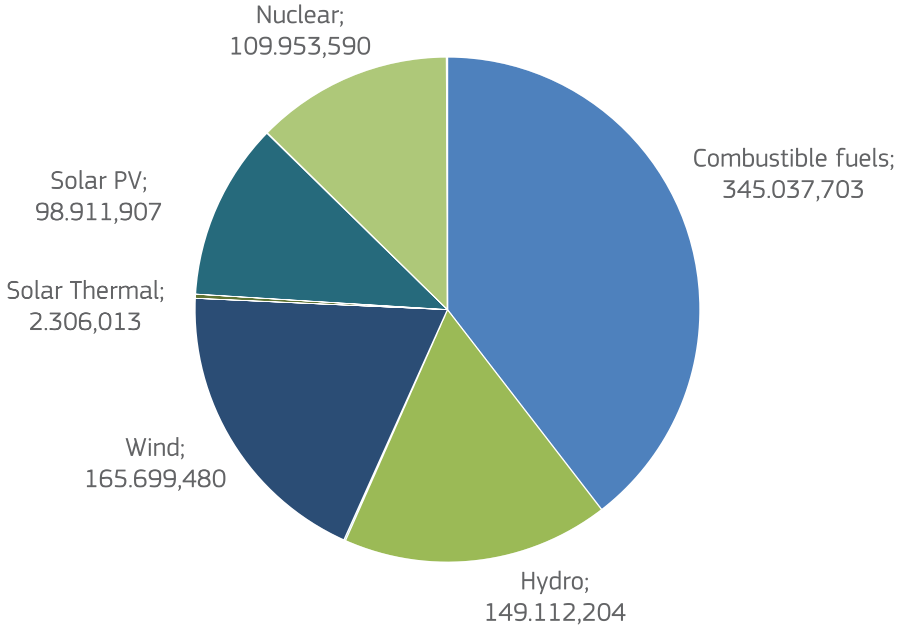
Focusing on the 27 European countries in EU27, their thermal power plants can be categorized according to the type of fuel and technology. Considering fuel, the main categories identified are [4]:

- Coal plants: including plants that use hard coal, lignite or peat;
- Oil plants: plants fed by petroleum-derived fuel;
- Gas plants: including natural gas and derived gas.

1 Production of electricity and derived heat by type of fuel [nrg_bal_peh]:
Gross electricity production - main activity producer and autoproducer - electricity only
Solid fossil fuels, Oil and petroleum products, Natural gas, Nuclear, Renewables and biofuels, Non-Renewable – waste.

2 Electricity production capacities by main fuel groups and operator [nrg_inf_epc]: Combustible fuels, Hydro, Wind, Solar PV, Nuclear.

Figure 2. Installed capacity in 2019 in Megawatt. Elaboration of data from [1].



For what technology is concerned, there are:

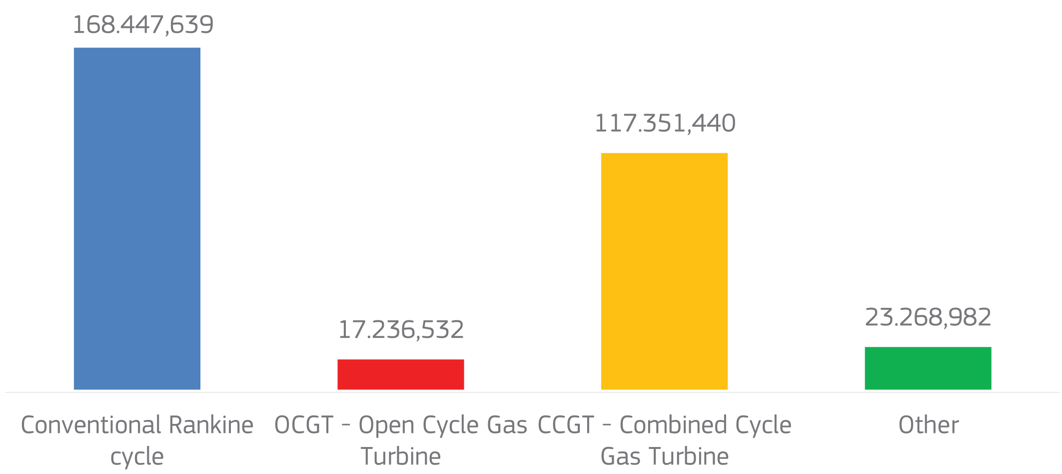
— Steam plants (based on Rankine cycle), including the vast majority of coal and oil-fired plants, although few gas-fired boilers are still in operation;

— Open Cycle Gas Turbine (OCGT, Brayton cycle);

— Combined Cycle plants (CCGT), typically made by gas turbines, fired by natural gas, combined with downstream steam turbines, i.e., a combination of Brayton and Rankine cycles.

The chart[3] in Figure 3 shows the overall installed capacity in Europe in 2019 for each aforementioned technology [1]: traditional steam plants and combined cycles are widely spread in the European Union.

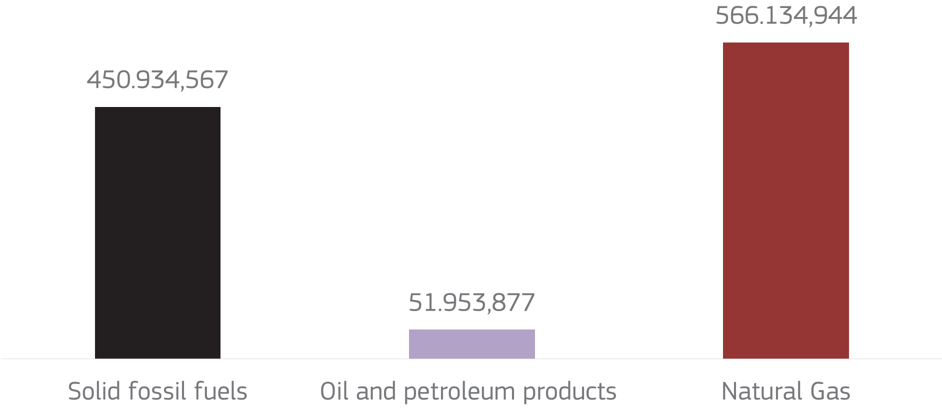
Figure 3. Classification of the installed thermal capacity [MW]. Elaboration of data from [1].



3 Electricity production capacities for combustible fuels by technology and operator [nrg_inf_epct]: Steam, Gas turbine, Combined cycle, Other. Auto-producers not included.

Coming to fuels, solid fuels, i.e., coal, are the main source of electricity production generated by thermal plants[4] (Figure 4) in 2019 [1]:

Figure 4. Gross electricity production of the thermal plants in Europe by type of fuel [GWh]. Elaboration of data from [1].



4 Production of electricity and derived heat by type of fuel [nrg_bal_peh]: Solid fossil fuels, Oil and petroleum products, Natural Gas, main activity producer and autoproducer - electricity only.

EUROPEAN
COMMISSION

Brussels, 9.1.2023
SWD(2023) 1 final

PART 2/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

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

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

{COM(2023) 1 final}

Contents

2.2 Thermodynamics and thermal generation

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

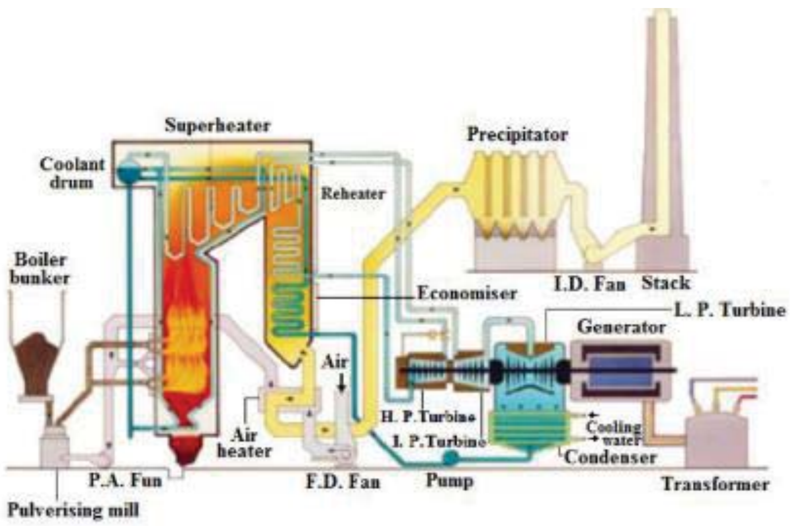
- Rankine cycle, used in conventional thermal plant (fuelled by coal, oil, gas or other fuels) as well as in nuclear power stations;
- Brayton cycle, used in Gas Turbines (GT).

2.2.1 The Rankine cycle

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

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

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



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

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

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

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

- The cooling system: after the steam is discharged by the LP steam turbine, it has to be converted back to water by cooling. When cooling water is available (sea or river water), condensers are typically used, as they are more efficient; however, when cooling water is not available (because the power station is far from any sea or river) or its use is subject to restrictions or it is too expensive, cooling towers or air-cooled condensers are used.

  - Condenser: the condenser is installed at the outlet of the steam turbine. The cooling water, flowing through the pipes, condensates the steam, that enters from the shell side and drops down into the hotwell. The cooling water is usually provided by either large rivers or the sea: that water is hence pumped into the condenser. The condenser, along with the drums and the deaerator, is also important from the operational point of view, because it is a reserve of condensate to compensate load variations and transients.

  - In cooling towers, the heat is ejected into the atmosphere by the partial evaporation of the water into a tower. Cooling towers are less efficient than condensers, but more efficient than air cooled condensers.

  - Air cooled condensers are made up of modules are arranged in parallel rows. Each module contains a number of fin tube bundles. An axial flow forces the cooling air across the heat exchange area of the fin tubes.

- Feedwater pumps: needed to increase the pressure of the feedwater and to pump it into the boiled and the turbines.

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

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

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

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

2.2.1.1 *Coal power plants*

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

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

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

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

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

Table 1. Boiler types and main features

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

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

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

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

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

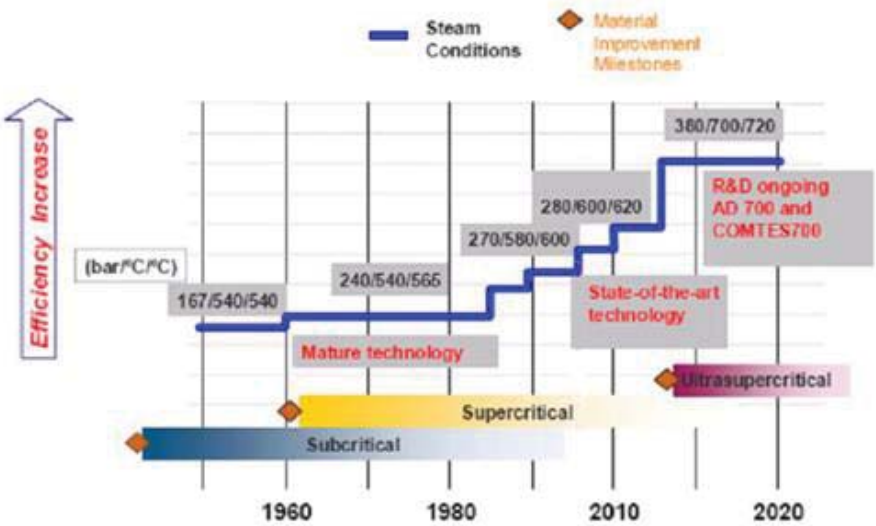
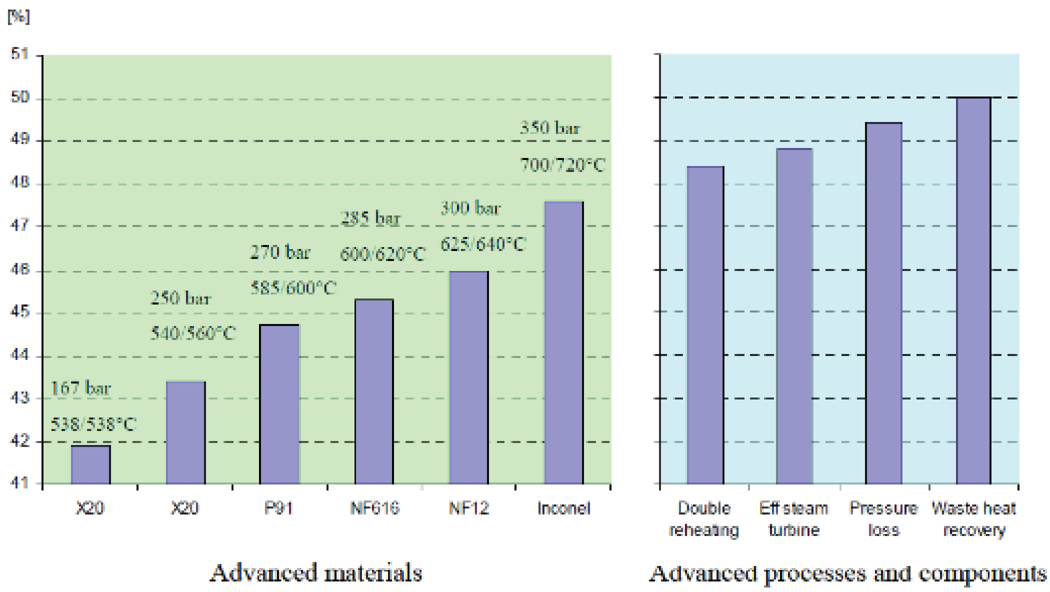


Figure 7. Efficiency improvements of pulverised coal power plants [14].



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

2.2.1.2 Oil power plants

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

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

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

2.2.1.3 Gas power plants

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

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

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

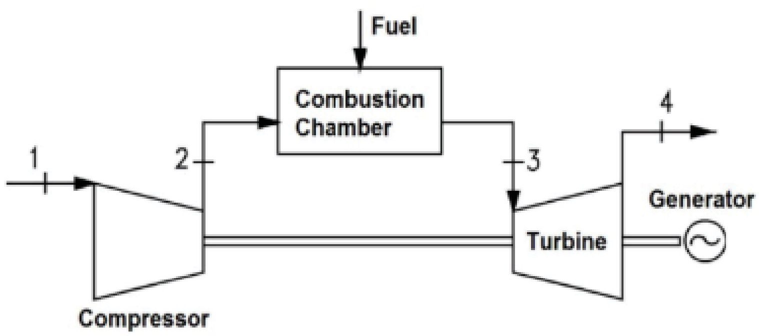
Like oil power stations, also gas-based Rankine cycles are currently out of the market, as generation costs are even higher than oil-based generation. Few power stations of this type are still in operation, but they are typically used as reserve.

2.2.1.4 The Brayton cycle

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

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

Figure 8. Gas turbine [15].



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

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

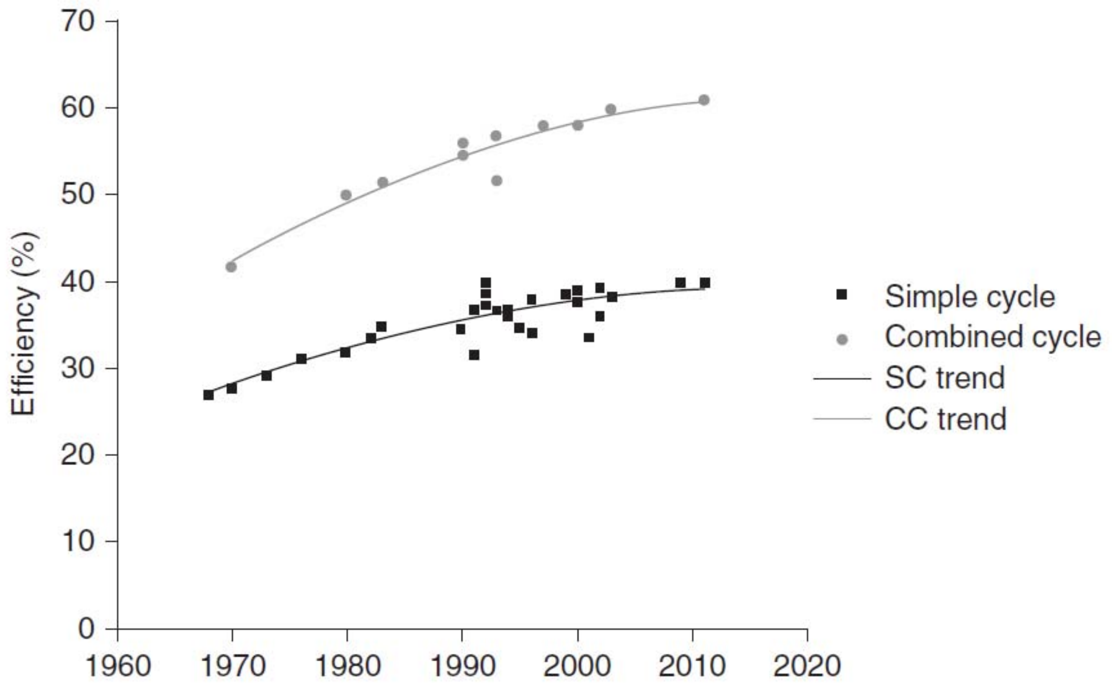
- Compressor: a multi-stage axial compressor that compresses the ambient air. An efficient multistage filter is always installed before the compressor, to avoid the turbine damage and deterioration. The compression ratio can vary between 16:1 and 30:1, depending on turbine requirements. Instabilities,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

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

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

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

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



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

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

2.2.2 The Combined cycle

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

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

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

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

Figure 10. Combined power plant [17].

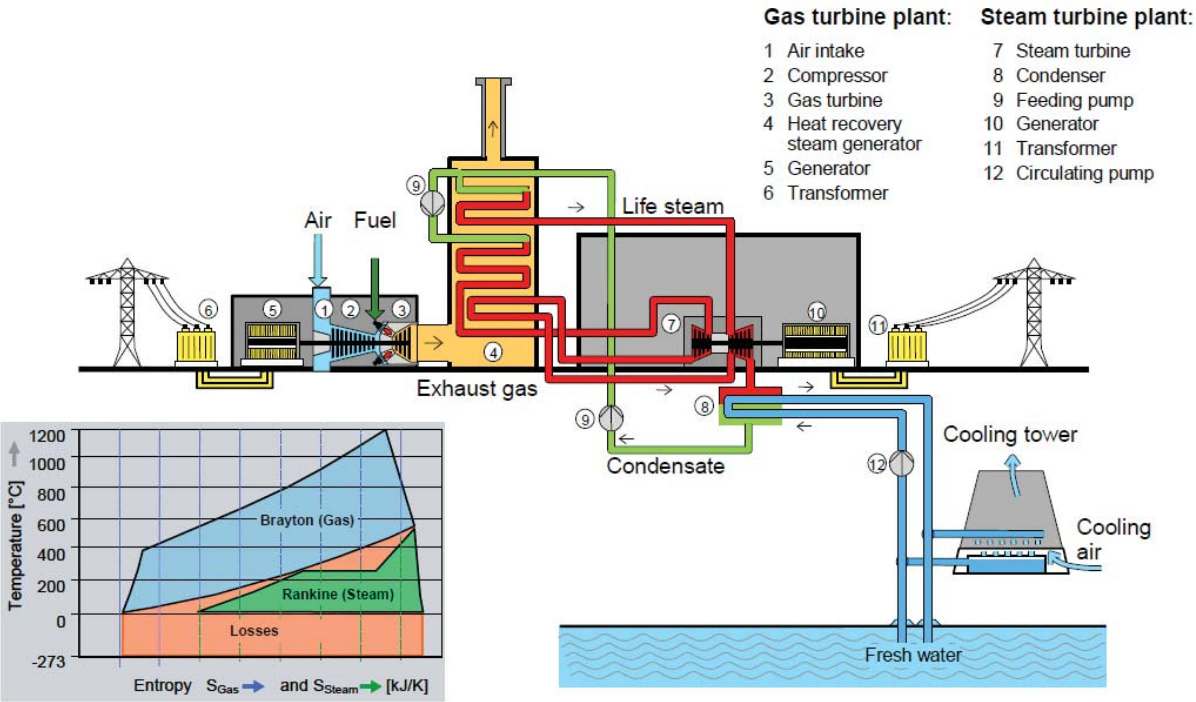
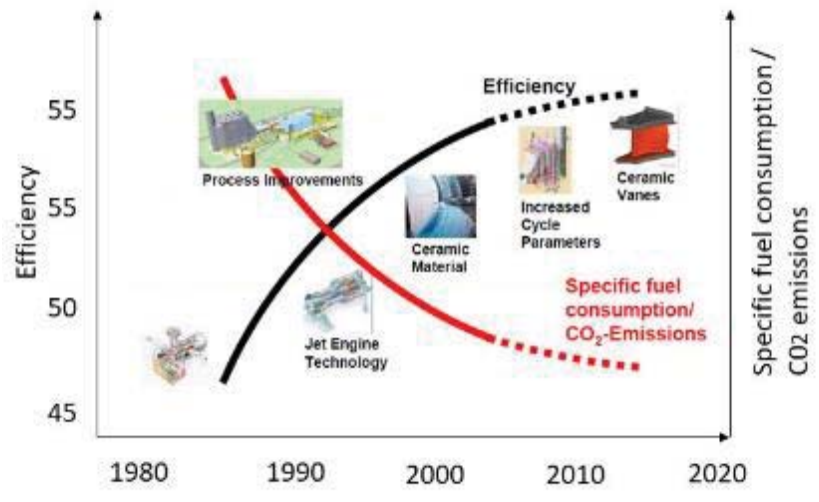


Figure 11 shows the evolution of the combined cycle efficiency over the years: the efficiency has been constantly increased thanks to the new technologies, especially in GT technology and the specific fuel consumption and CO_2 emissions have significantly decreased, making this type of plants very efficient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

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



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

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

EUROPEAN
COMMISSION

Brussels, 9.1.2023
SWD(2023) 1 final

PART 3/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

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

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

{COM(2023) 1 final}

Contents

2.3 Current efficiency of the European thermal power plants

Using the data available in the Eurostat database [1], the yearly average efficiency and production of the European thermal plants can be calculated, computing the ratio (using suitable units):

$$Efficiency = \frac{Gross\ electricity\ production}{Energy\ content\ of\ the\ primary\ source}$$

Regarding the EU27 thermal plants, the following graphs show the gross production of electricity in thermal power stations and the gross efficiency of coal and gas plants till 2019[1] (Figure 12 and Figure 13): lignite and other bituminous coal still represent the main source of electricity.

It is worth noticing that efficiencies are average values and include any loading level of generators as well as starting (when different fuels – e.g., diesel – can be used and in general the efficiency is very low). Moreover, there is no difference made between OCGT and CCGT, so that it is difficult to make conclusions about the distinct efficiency resulting from the two gas technologies.

Figure 12. Gross electricity production [GWh]. Elaboration of data from [1].

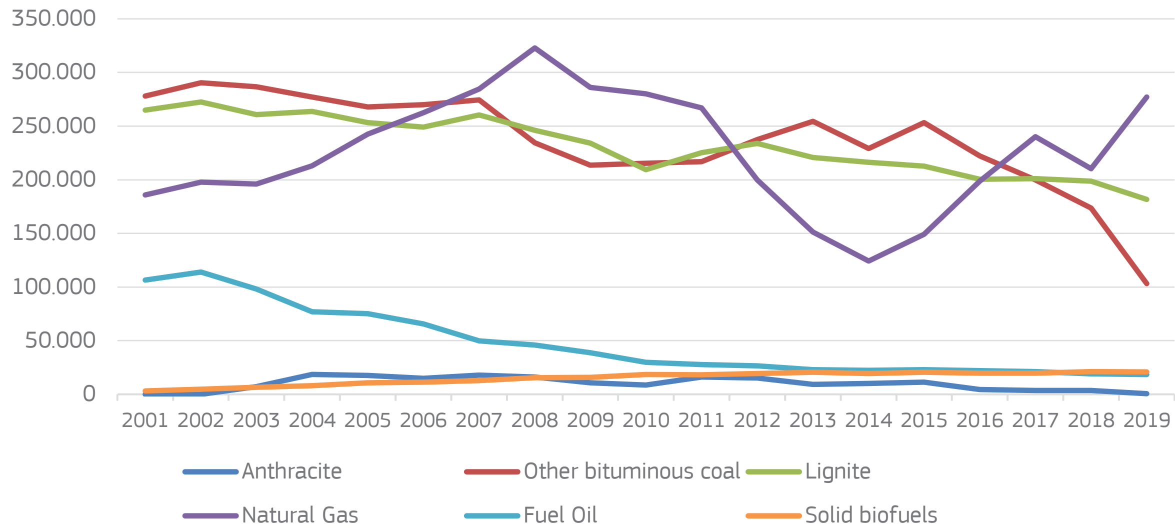
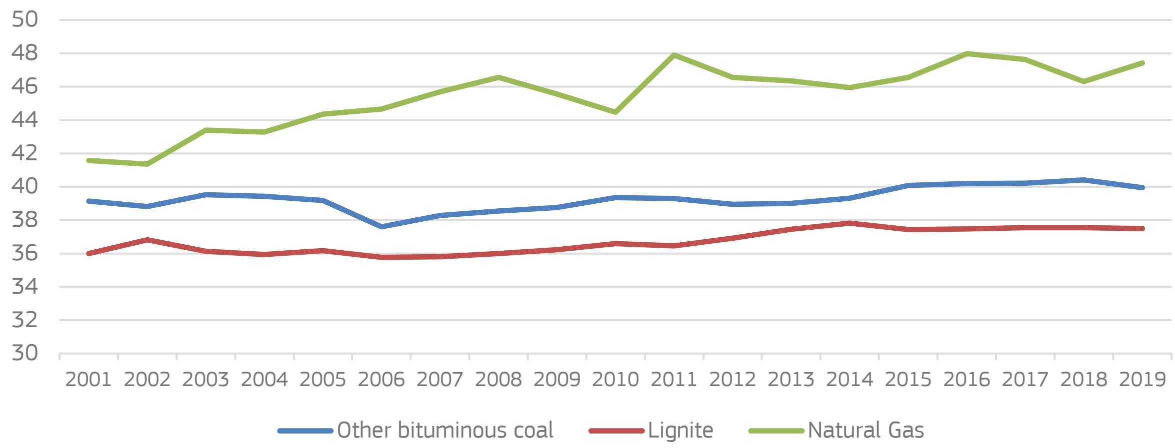


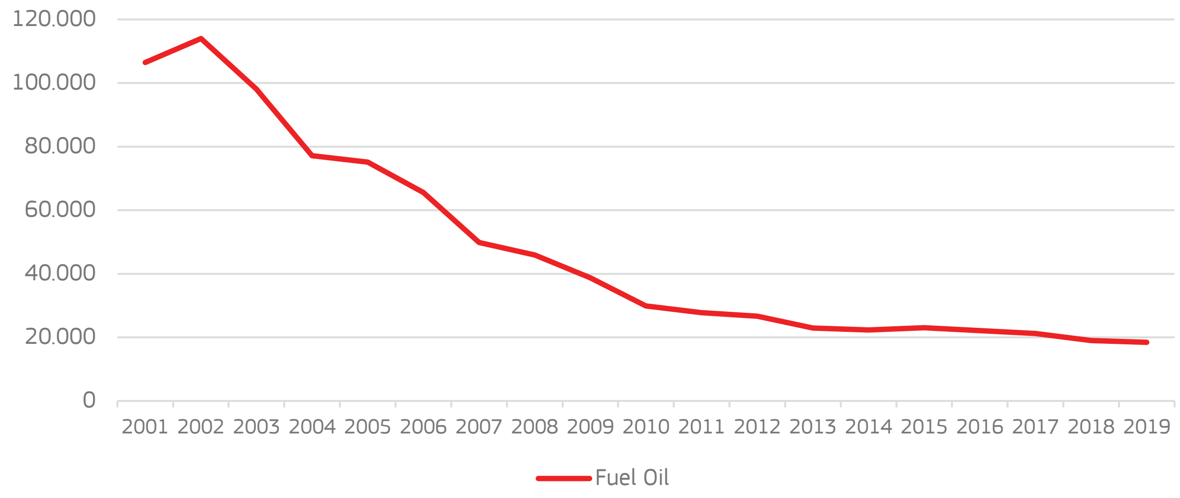
Figure 13. Gross Efficiency of the Thermal plants. Elaboration of data from [1].



1 Gross production of electricity and derived heat from combustible fuels by type of plant and operator [nrg_ind_pehcf]

Concerning oil power stations, the high cost of the fuel combined to low efficiencies and environmental issues led the operators to dismantle, decommission or reconvert them into the more efficient combined cycle plants as already underlined in 2004 by [19] and in [20]. The electricity produced[2] by these plants (Figure 14) faced a huge decline in the last 20 years [1], confirming this change.

Figure 14. Electricity production of the European oil thermal plants [GWh]. Elaboration of data from [1].



2.4 Summary of the thermal plant efficiencies

Table 2 reports a summary of the efficiencies of the described thermal plants:

Table 2. Efficiencies of thermal plants.

Fuel	Coal			Oil	Gas		
Type	**Subcritical**	**Supercritical**	**Ultra-supercritical**	**Rankine**	**Rankine**	**OCGT**	**CCGT**
Efficiency	36 %	40-42 %	47 %	38-40 %	38-40 %	38-40 %	56-64 %

In order to evaluate a reasonable simple scenario, based on the decision of complete European coal phase out by 2030 [21], we estimated the saving of primary energy assuming that the amount of energy produced in 2019 (which is the latest year with available consolidated data) by coal power stations, is substituted by the most efficient CCGT thermal power stations. That scenario is on one side realistic enough, as the de-carbonisation has been already decided in Europe and can be considered a matter of fact, and on the other side it is also conservative, as that energy might be substituted also by RES generation, thus resulting in further primary energy savings.

Considering 2019 (EU27), the electrical energy produced by coal plants (other bituminous coal and lignite) has been equal to 284.92 TWh, corresponding to 743.20 TWh of combustible fuel [1]. Hence, the average efficiency has been 38.3 %. The same amount of electricity could be produced by last generation CCGTs with the best efficiency of 64 %: in that case, the required primary energy would be 284.92/0.64=445.19 TWh, thus saving 743.20-445.19=298.01 TWh of primary energy per year, corresponding to 25.62 Mtoe. It is worth noticing that this value is on the safe side, given that auxiliary services of coal power stations are much more requiring than auxiliary services of CCGT power stations, thus resulting in further primary energy saving. That substitution would also imply as further advantage from the environmental point of view a significant amount of CO_2 savings, as the primary fossil fuel would be gas instead of coal.

2 Gross production of electricity and derived heat from combustible fuels by type of plant and operator [nrg_ind_pehcf]: Fuel Oil

EUROPEAN
COMMISSION

Brussels, 9.1.2023
SWD(2023) 1 final

PART 4/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

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

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

{COM(2023) 1 final}

EN EN

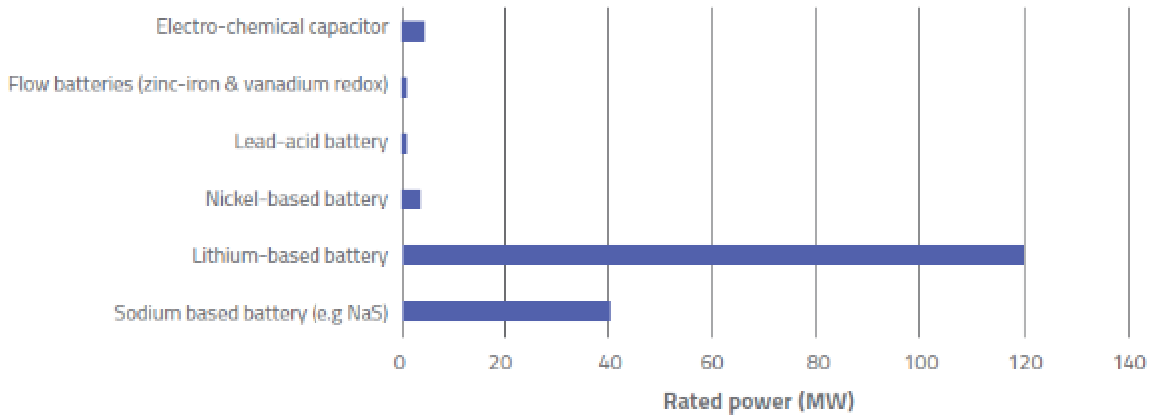
Contents

3 Storage technologies

3.1 Introduction

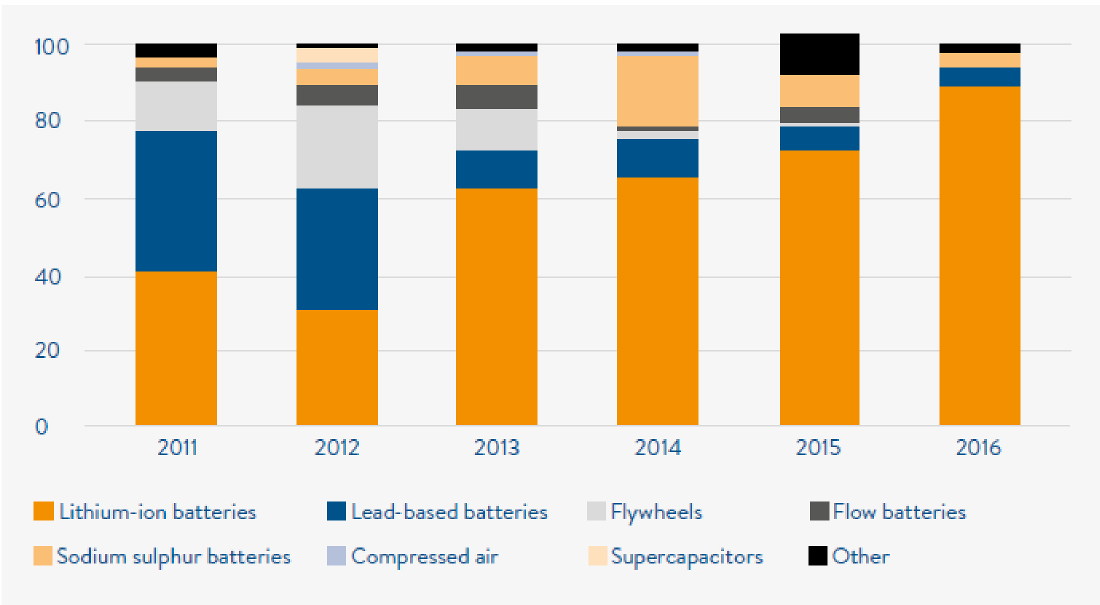
In a power network increasingly penetrated by renewable energy production, characterized by large variability, storage plays a pivotal role in improving the efficiency of the system while pursuing the objective of a transition towards a carbon-neutral power system. To date, pumped hydro is by far the most widespread type of storage, accounting for more than 90 % of the total capacity installed worldwide [22]. In the European Union, more than 45 GW of pumped hydro are installed [23], while less than 200 MW of electro-chemical storage are available (Figure 15).

Figure 15: Electro-chemical storage deployment in Europe [24]



Given the strict relation of pumped hydro with the availability of suitable geographical locations, largely already in use, the other storage opportunities are increasingly gaining attention. In particular, lithium-ion batteries are earning a prominent role in the storage market, as shown in Figure 16.

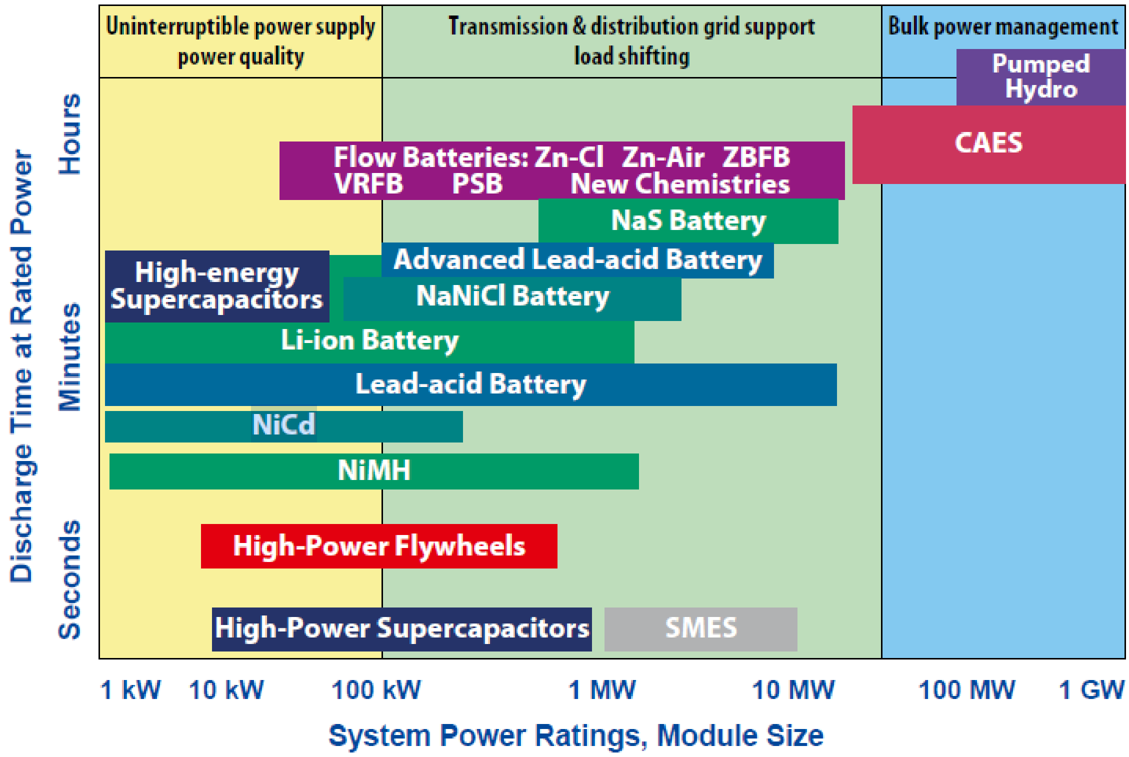
Figure 16: Technology mix in storage installations excluding pumped hydro [25]



In the scope of the "Clean planet for all" EU strategy, total storage installed for stationary applications in the European power system is expected to reach between 250 TWh and 450 TWh by 2050 [26].

There is a wide variety of available technologies, each characterized by its response time, efficiency, cycle lifetime, power and energy features, etc. According to these features and to the typical power ratings, a classification of possible services to be provided to the power network is shown in Figure 17.

Figure 17: System services that storage technologies can provide depending on the service timescale and typical power ratings [27]



The technologies analysed in this report can be divided into the following categories:

— Mechanical energy storage: pumped hydro storage, Compressed Air Energy Storage (CAES), Liquid Air Energy Storage (LAES), flywheels;

— Electrochemical energy storage: lead-acid batteries, lithium-ion batteries, flow batteries, high-temperature batteries;

— Electrical energy storage: supercapacitors, superconducting magnetic energy storage (SMES);

— Chemical energy storage: power-to-hydrogen.

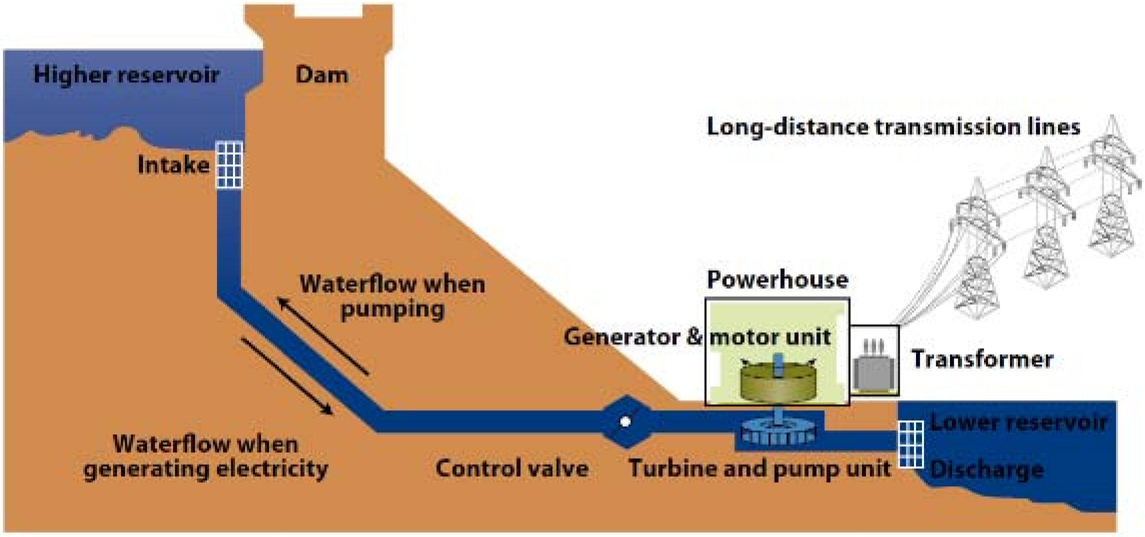
An efficiency overview of the electric energy storage systems is presented in Appendix III.

3.2 Mechanical energy storage

3.2.1 Pumped hydro storage

Pumped hydro storage (PHS) constitutes more than 90 % of the total storage capacity installed worldwide [22]. It is a very mature and flexible technology, whose most common sizes currently range from few MW up to thousands of MW. A 3600 MW PHS project is currently under construction in China and will become the largest of the world [28]. PHS allows to store electric energy in the form of gravitational potential energy: water is pumped from a lower to an upper reservoir during off-peak hours or in case of excess of energy; water is then sent to the turbine during peak hours or in case of supply of system service to the network. The layout of a typical PHS plant is shown in Figure 18.

Figure 18: PHS plant layout [29].



Three configurations are possible [30]:

- Quaternary set: this was the first configuration been adopted, in which the pump is driven by a motor and the turbine powers a generator. Hence, the two groups are completely decoupled and individually optimized. This is the most expensive option, which also allows the best overall efficiency, because each functionality is optimized;
- Ternary set: pump and turbine on a single shaft, together with the electrical machine. The latter works as either motor or generator, depending on the operating mode of the plant. Also in this case, pump and turbine can be designed individually and high efficiencies are reached.
- Binary set: a reversible hydraulic machine is used both in pumping and generation mode (depending on the rotation of the shaft) and it is coupled with an electrical machine working either as generator or as a motor. To date, this is the most widespread configuration due to its reduced cost, but this comes at the expense of efficiency, as the hydraulic machine is designed as a compromise of its double use.

The basic layout of a pumped-storage hydropower plant involves two reservoirs, one above the other, and a turbine/pumping hall capable of both generating power from the stored water in the upper reservoir and pumping water from the lower reservoir back to the upper. For hydropower plants in general, the energy available from a given volume of water is greater, the greater the head of water. In the case of the pumped-storage plant, this head is the vertical distance between the upper reservoir and the turbines.

Roundtrip efficiencies (RTE) range from 70 to 84 %, where the highest values are achieved thanks to the development of variable speed PHS [27], [31]. The per-unit cost of the energy produced may vary approximately in the range from 5 up to 100 €/kWh [32], [33].

PHS can provide large-scale storage and a plant can last many decades; on the other side, suitable geographical sites need to be found and the environmental impacts to be carefully considered: indeed, the expansion of this technology in Europe is held back by environmental restrictions and by the fact that most suitable sites have already been exploited [27]. For this reason, some new approaches are under consideration, in particular the use of the sea/ocean or underground caverns as lower reservoirs [34].

Moreover, small scale plants are today considered to store renewable energy produced locally, but their economic sustainability is questionable today, in comparison to other types of storage. For such smaller plants, efficiencies are lower and may fall below 50 %, as machines are not singularly designed and optimized, like in the case of larger power stations.

Given the high maturity of the technology, no significant improvements in terms of technical and cost performance are expected in the coming years.

3.2.2 Compressed Air Energy Storage (CAES)

In Compressed Air Energy Storage (CAES), energy is stored in the form of pressurized air, in a cavern in case of large size plants: electric energy is used to drive compressors to store air in a reservoir. The cavern can be either a former salt or gas reserve or a purpose-built cavern. This last option is rarely adopted, as it leads to a dramatic cost increase. This kind of storage is able to provide very large amount of power (above 100 MW); hence, it results in an interesting option for network operators.

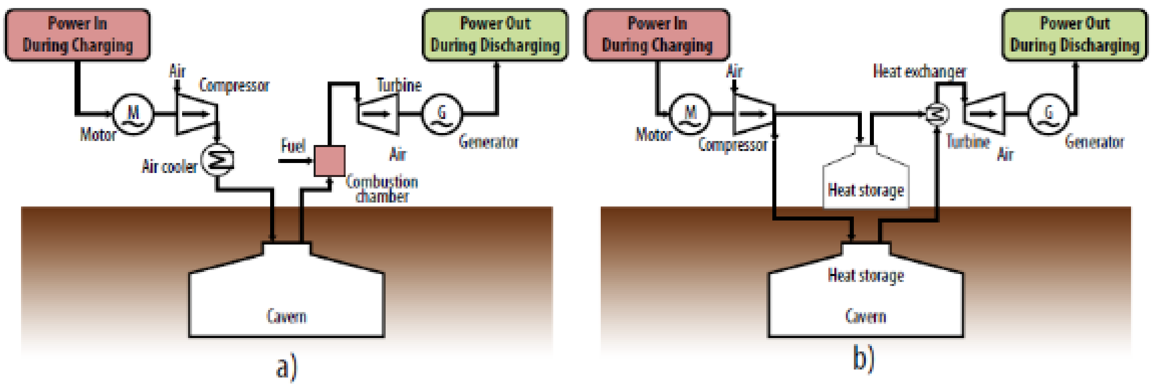
CAES stores the energy by compressing air as an elastic potential energy. It has separate compression and expansion processes. During low demand, the extra electrical energy is stored in the form of compressed air in air storage vessels. When the demand is high, the compressed air is converted to electrical energy through an energy conversion process using a high-pressure turbine where the compressed air is mixed with the gas.

Two main CAES technologies are available [25], [27], [35], as discussed below and shown in Figure 19:

— Diabatic CAES: the compressed air, which needs to be heated when exiting the reservoir, is mixed with natural gas in a combustion chamber and expanded in a gas turbine. This is the only commercially available option, which comes with a cost of about 50 €/kWh and RTE of 55 %. The low efficiency is one of the main drawbacks, together with emissions related to the combustion process.

— Adiabatic CAES: the technology stores the heat generated during the compression cycle and uses it to heat the air up before expansion. This removes the need of a combustion and efficiency can reach 70 %. Adiabatic CAES has been under study for years and is now close to reach commercialization phase.

Figure 19: Diabatic (a) and adiabatic (b) CAES layout [27]



Furthermore, isothermal CAES is currently under development: nearly isothermal compression and expansion would improve the efficiency up to 80 %. No combustion is needed [33].

Several projects have been commissioned in Europe for the years 2020-2024 [25]; this is expected to push towards a cost reduction and an improved efficiency.

Some innovative projects have been proposed. In Germany, the world's first large-scale AA-CAES project—ADELE—with 70% cycle efficiency has been designed by RWE Power, General Electric and other partners [36] [37]. The aim of this project is to optimize the co-existence and smooth interaction of the individual energy sources, especially for wind power. It is planned to have 1 GWh storage capacity and be capable of generating up to 200 MW, said the RWE power. The ADELE project could provide backup capacity within a very short time and replace forty state-of-the -art wind turbines for a period of 5 h. The project is currently in its final phase of development.

In the Netherlands, the CAES Zuidwending project, scheduled for commissioning in 2024-25, will have a generation capacity of approximately 300 MW and a daily storage/delivery capacity of approximately 3-4 GWh (gigawatt-hours).

In UK, the Gaelectric Energy Storage Ltd promoted the Cheshire CAES project, with a maximum active power of 268 MW and a storage capacity of 1,6 GWh.

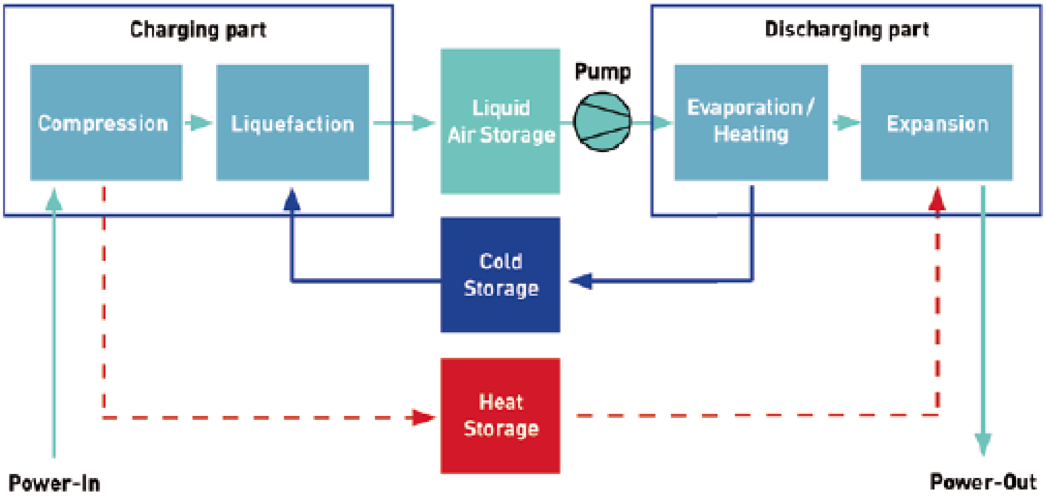
In China, on July 16, 2020, the Chinese Academy of Sciences Institute of Engineering Thermophysics achieved a new breakthrough successfully performed the integration test of the world's first 100 MW CAES expander.

There is another 50 MW AA-CAES project underway in Jiangsu, China, in 2017, which is certified by the consulting panel. In this 50 MW AA-CAES system, underground salt caverns are adopted as the air reservoirs. The final objective is to build 100 MW AA-CAES informed by the learnings from the 50 MW system. In 2015, Hydrostor has started a pilot project for the World's First Offshore Compressed-Air Energy Storage Project in Toronto (Canada). It was the first test of an underwater compressed-air energy storage system. The project used drilling techniques that reduces the demand for boats and cranes at the surface to deploy the pipes and storage balloons.

3.2.3 Liquid air energy storage

Liquid air energy storage (LAES) is based on cryogenic energy conversion: electric energy is used to remove heat from ambient air taken from the environment to produce liquid air. The fluid is then stored in an insulated tank at low pressure. When electricity is needed, the liquid air is pumped to high pressure, heated and expanded in a turbine [38], [39]. LAES layout is shown in Figure 20.

Figure 20: LAES mode of operation [40]



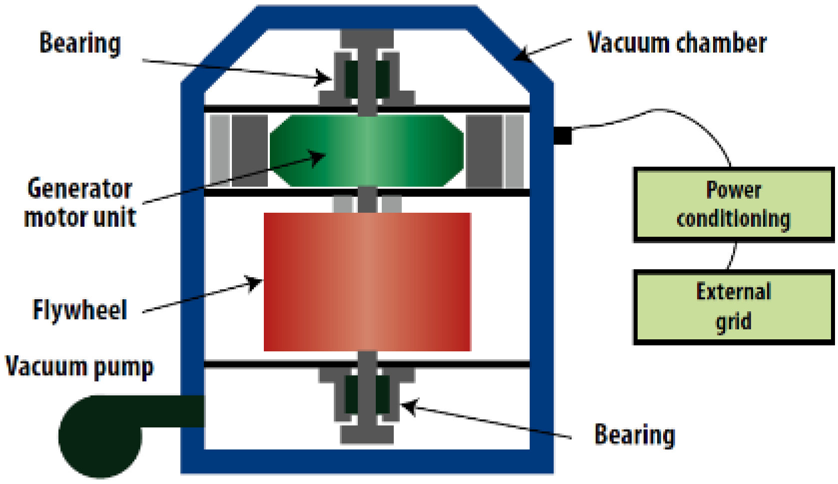
The advantage of LAES over CAES is that it does not come with any geographical restriction, as the high energy density allows the use of tanks to store the liquified air [39]. The cost of the technology is 250÷600 €/kWh and is expected to decrease to 150÷400 €/kWh by 2030 [40].

This storage option takes advantage of the use of mature supply chains and components, but it is currently at demonstration phase. Few small-scale pilots have been fully built and have shown a roundtrip efficiency below 20 % [38], [40]. Researchers claim this result is strictly related to the size of the system, and efficiencies of around 50% could be reached for wider scales. An important boost in the efficiency could be obtained by coupling LAES with industrial processes providing waste heat to be used upon expansion. This option could lead to an efficiency >65 % [40].

3.2.4 Flywheels

Flywheels store energy in the form of kinetic energy. A rotating mass is connected to a reversible electrical machine which acts as a motor in charging phase, increasing the speed of the rotating mass and the relative stored energy, and as a generator in discharging phase, extracting energy and decreasing the speed of the rotating mass [41]. The system is enclosed in a vacuum chamber to reduce aerodynamic drag and rotation is smoothed by magnetic bearings. These elements allow flywheels to keep their maximum speed for days by only being provided the energy to compensate idle losses [25], [40]. The state of charge is easily determinable from the rotational speed [27].

Figure 21: Flywheels layout [29]



There are two types of flywheel: low-speed (<10000 rpm) and high-speed (up to 100000 rpm). The former is made of metallic materials, is easier to build and is characterized by higher weights; hence, it is more suitable for stationary applications. The latter is made of composite materials, such as carbon fibres, which provide better performances at higher costs; this option is adopted for low-energy applications [25], [40].

This system is mainly applied to the high power/short duration EES applications (e.g., 100 kW/10 s), which provide support power during interruptions, for short time periods or when shifting from one power source to another.

Flywheels can usually respond extremely quickly. In grid backup systems[42][43] they should be capable of reaching full power within half a cycle (25 ms at 50 Hz), and some are quoted with response times of 5 ms. Such units will probably be able to supply their full output for between 5 and 15 seconds. Commercial flywheels are available with power ratings of between 2 kW and 2 MW and with storage capacities of between 1 and 100 kWh.

One of the largest commercial systems is a unit with ten 100 kW flywheels used by the New York Transit System to support its electric traction power network. This system can supply 1 MW of power for 6 seconds. However, the largest flywheel is the one used in Japan for nuclear fusion research. This system can supply 340 MW for 30 seconds.

In North Western Australia, a flywheel system has been integrated into a town's power supply to support the increased power demand during the tourist season [43]. Coral Bay, a wind energy operated power station, consisted of seven 320 kW low-load diesel generators with three 200 kW wind turbines. In 2007, the integration of a 500 kW flywheel virtual generator into the system allowed the wind turbines to provide up to 95% of Coral Bay's supply at peak times. The reported data shows that for nearly 900 h per year, 90% of the power station's total supply comes from wind generation. In addition, while maintaining the grid standards and improving the power quality, 80% of this total power is wind-generated for one-third of the year [43]. Another flywheel-based stabilisation system has been planned for the Marsabit wind farm, a remote community served by an isolated microgrid in northern Kenya. A 500 kW flywheel-based system will be integrated into the existing two 275 kW wind turbines and diesel generators. The PowerStore flywheel to be installed by ABB will stabilise the grid connection to maximise renewable energy penetration [43]. Power Store is a flywheel-based stabilising generator which is mainly used for improving the power quality. It enables the integration and control of renewable wind and solar energy in the electrical grid. Acting like a static synchronous compensator (STATCOM), it combines an 18 MWs (Megawatt second) low-speed flywheel with solid state converters that absorb or inject full energy in 1 millisecond. The range of models from 500 kW to 1,5 MW allows the configuration of either a grid support mode for MW scale grids, or as a virtual generator for use in smaller isolated grids.

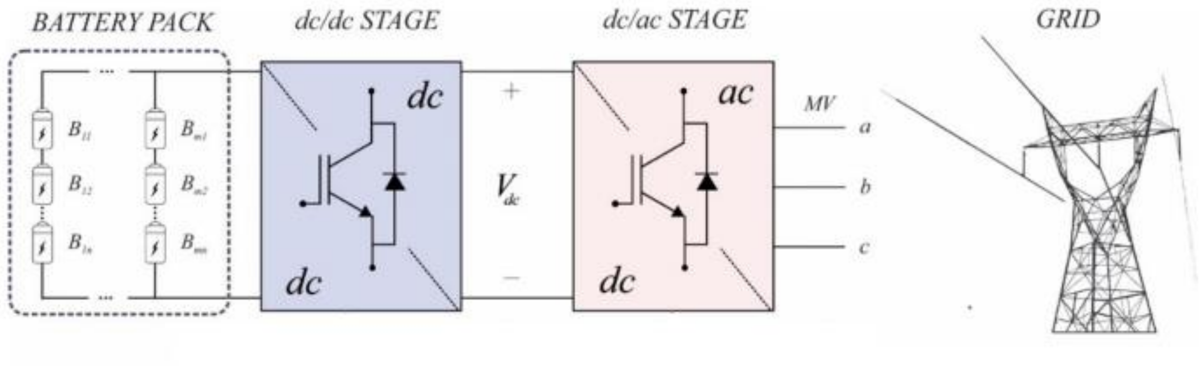
In general, flywheels provide fast-response services thanks to their high power density, their rapidity of charging/discharging and to minimize the impact of idle losses. They are characterized by a long cycle-life and ask for limited maintenance. RTE can reach 90 % in optimal operating conditions [44] and is not expected to go through a significant improvement in the future, while research on material will most likely enable a relevant reduction of costs, currently in the range 500÷3000 €/kWh [40].

3.3 Electrochemical energy storage

All the technologies belonging to this category can be identifies as Battery Energy Storage Systems (BESS). The basic concept behind BESS is that both electrical and chemical energy use electrons as carriers. This makes the storage particularly efficient, because it avoids losses due to conversion to any other type of energy. A cell of an electrochemical storage is basically composed by the following components: two electrodes, an electrolyte, a separator to avoid contact of the electrodes and a container. Reversible oxidation and reduction reactions cause the flow of electrons which allow to withdraw or inject energy in the system [25], [40].

Figure 22 shows the connection of BESS to the AC grid: an electronic converter is needed to get AC current and this affects the roundtrip efficiency. In case of connection to a DC bus, the DC/AC stage is not present. Efficiencies in the following subsections will refer to DC/DC RTE. The AC/AC RTE can be obtained by multiplying the DC/DC RTE by the roundtrip efficiency of the DC/AC converter (94÷95 %) [45].

Figure 22: BESS connection to AC grid [46]



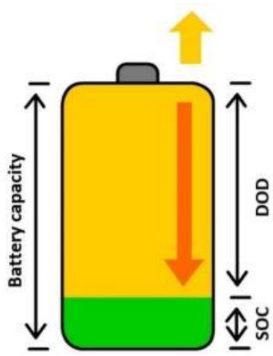
This kind of storage has the advantage of being highly modular, cells can be connected in different configurations in order to reach the desired voltage, energy capacity and power, but care must be taken to prevent non-optimal usage from rapidly reducing battery life or even damaging it. The technology is currently increasing its market penetration, exploiting the significant progress made in terms of cost and lifecycle.

3.3.1 Lead-acid batteries

Lead-acid batteries have been the first to reach technological maturity and are currently the most widespread battery type. There are two types of lead-acid batteries: vented lead-acid (VLA), in which oxygen and hydrogen are dispersed into the environment, and valve-regulated lead-acid (VRLA), in which oxygen and hydrogen are recombined to form water. VLA batteries have lower cost and longer lifetime, but requires more maintenance than VRLA batteries [27], [32].

Lead-acid batteries are normally subject to a 2-3 % monthly self-discharge and do not respond well to deep discharging: the maximum Depth of Discharge (DOD), i.e., the complement of the State of Charge (SOC) (see Figure 23), should be at most 50 %. The maximum number of full charge/discharge cycles can reach 2500 if operated in optimal conditions [32]. Lead toxicity may be an issue for some applications; on the other hand, materials are highly recyclable [27].

Figure 23: Depth of Discharge and State of Charge of BESS



Their roundtrip efficiency is in the range 70÷90 % and their cost is around 120÷200€/kWh. These two characteristics make lead-acid batteries one of the most convenient batteries in terms of performance/cost trade-off. Limited improvements in the manufacturing process are expected, which may lead to reduce the cost below 100€/kWh while maintaining similar RTE [27], [40].

Several very large-energy storage facilities based on lead-acid batteries have been built. These include an 8,5 MW unit constructed in West Berlin in 1986, while the city was still divided into East and West and a 20 MW unit built in Puerto Rico in 1994. Although the former operated successfully for several years, cell degradation led to the latter closing after only 5 years. Lead-acid cells have been very popular for renewable applications such as small wind or solar installations where they are used to store intermittently generated power to make it continuously available [47]. Duke Energy added 36 MW of lead-acid battery storage to its Notrees wind power facility in West Texas. When the lead-acid batteries were first installed, the battery system participated in the region's frequency regulation market, which required rapid charging and discharging that significantly degraded the batteries. In 2016, Duke Energy replaced the original lead-acid batteries with better performing lithium-ion batteries [48].

3.3.2 Lithium-ion batteries

These batteries base their electrochemistry on the flow of lithium ions between the electrodes. The peculiarity of lithium ions stands in their very limited size, which allows this technology to have very high power and energy density [25].

Lithium batteries have very high DOD, up to 100 %, very limited self-discharge, impressive efficiencies in the range 92÷96 % and lifetime of 4000÷5000 cycles. The main disadvantage is the need of a battery management system, to improve safety and performance characteristics: in case of overheating, the battery degrades rapidly and gas leaks may even cause fires. Moreover, a robust metallic case is needed [27], [32]. These features lead to a high specific cost of around 250 €/kWh [40].

Besides the massive use of lithium batteries for electronic devices, medium and large size batteries are claiming attention for network services. Many efforts are currently put into improving the performances of such storage technology. By 2030, efficiencies are expected to reach 94÷98 % while costs are expected to decrease to less than 100 €/kWh [27], [40].

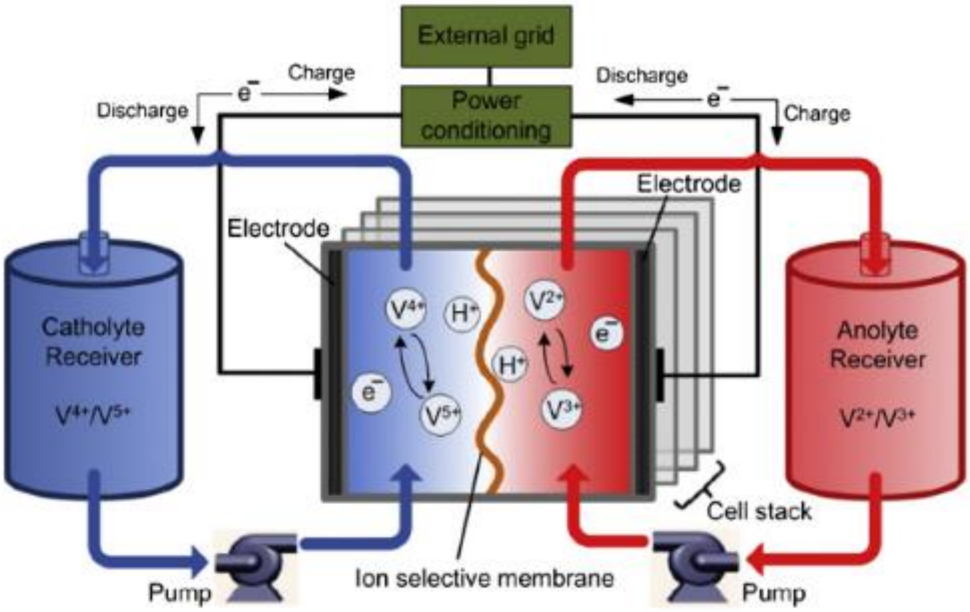
The very rapid growth in the use of this technology has brought to pay attention to problems on the supply of raw materials and on the recycling of degraded batteries, on which options are being developed but which at the moment are not yet widely applied given the scarce economic convenience [27].

An early large pilot battery storage installation rated at 2 MW was commissioned on the Orkney Islands, which are located off the coast of north-western Scotland, in 2013. This was topped in 2017 when the US utility San Diego Gas and Electric opened a 30 MW battery storage facility based on lithium-ion batteries with 120 MWh of storage capacity. A 20 MW facility is also being planned by the utility Southern California Edison. The world's largest lithium-ion power reserve (100 MW/129 MWh storage capacity, now expanded to 150 MW) is the Hornsdale battery energy storage system, in Australia. The future development of lithium batteries may benefit from interest by automotive manufacturers in their use in hybrid and electric vehicles [47].

3.3.3 Flow batteries

The electric energy circulates through flow batteries thanks to the presence of two electrolyte materials pumped into two separate loops. The movement of ions to the electrodes is enabled by a membrane putting in contact the two fluids [25]. The most common technologies are vanadium and zinc bromine flow batteries, but to date only the former has been widely employed around the world [27].

Figure 24: Schematic of vanadium redox flow battery [29]



This configuration requires the presence of pumps and sensors to regulate the flow (see Figure 24); moreover, the risk of leaking of acid fluids needs to be taken into account. Hence, the system is more complex compared to other types of batteries and it calls for more demanding maintenance. On the other hand, flow batteries respond well to deep discharges and their cycle lifetime can exceed 10000 [27]. A very important characteristic of flow batteries is that power and capacity are completely decoupled: the former depends on the pumps and on the membrane surface; the latter depends on the size of the tanks containing the electrolyte materials [25], [32]. The RTE of the battery is strictly related to the pumps and can vary in the range 60÷85 %; however, by 2030 efficiency is expected to reach and exceed 90 % in the best configuration [27], [33].

Given these interesting characteristics, many researchers have investigated possible advancements in the performances of flow batteries and new options in terms of fluids and materials are currently under study. The cost of this technology is around 400 €/kWh, but given the great research efforts, it is expected to fall below 100 €/kWh before 2050 [35].

3.3.4 High temperature batteries

The peculiarity of this kind of batteries is that the electrodes are separated by a solid ceramic electrolyte. They operate at 250÷350 °C in order to keep the electrodes in liquid state and to improve the conductivity of the electrolyte.

The two most common technologies are sodium sulphur (NaS) and sodium nickel chloride ($NaNiCl_2$) batteries: the former is characterized very high recyclability, safety issues related to the production of a corrosive compound and idle losses of around 3 % of the rated power to maintain the needed temperature; the latter has usually a shorter cycle life but requires lower operating temperatures and is made of less corrosive materials [27].

High temperature batteries are characterized by low self-discharge rates and their DOD can reach 100 %. Roundtrip efficiency is around 85 % and the number of cycles ranges from 1000 to 10000 [27], [33].

Current research is focusing on decreasing the working temperature, to operate in an all-solid state. The cost of the technology is in the range 250÷700 €/kWh, with the potential of decreasing by 75 % if progress is made in terms of operating temperatures. However, the presence of a very limited number of technology providers may slow down these developments [27], [40].

$NaNiCl_2$ batteries have been successfully installed in the Duke Energy Rankin Substation (North Carolina) with the purpose of PV power smoothing in combination with a 1 MWp PV plant. This installation won the 2013 "Grid Integration of Renewable Project of the year award". Another meaningful installation is the "Toucan Project", in French Guiana, where 2 MW of Sodium-Nickel batteries have been connected to the photovoltaic panels in the plant prepared in the area near to Montsinéry near a MV substation, in the back land of the French Guiana, whose energy will be stored by them during the day for releasing it during the night hours. Also, the Italian Transmission System Operator, Terna, is testing the Sodium-Nickel batteries with the installation of 3,4 MW in the high voltage network with the aim of providing grid services, above all the grid frequency regulation [[49][50][51][52].

The overall installed NaS power in the world is 365 MW. These batteries have been installed for both stationary applications and for power supply (UPS): they have found great applications for peak shaving with a twenty-year experience. The biggest installation in the world is at Rokkasho (Japan) with 34 MW rated power. The system is linked with a 51 MW wind farm [53]. In Italy, three NaS battery installations are in South Italy and have a total power of 34,8 MW. Their function in the grid is charging and discharging in long intervals in order to avoid congestions on the power transmission lines due to the great amount of renewable energy fed into the grid[53]. Other meaningful stationary applications are the 9,6 MW installation in the Hitachi car industry and the 6 MW/48 MWh installation in the Ohito substation owned by TEPCO[53].

3.4 Electrical energy storage

3.4.1 Supercapacitors

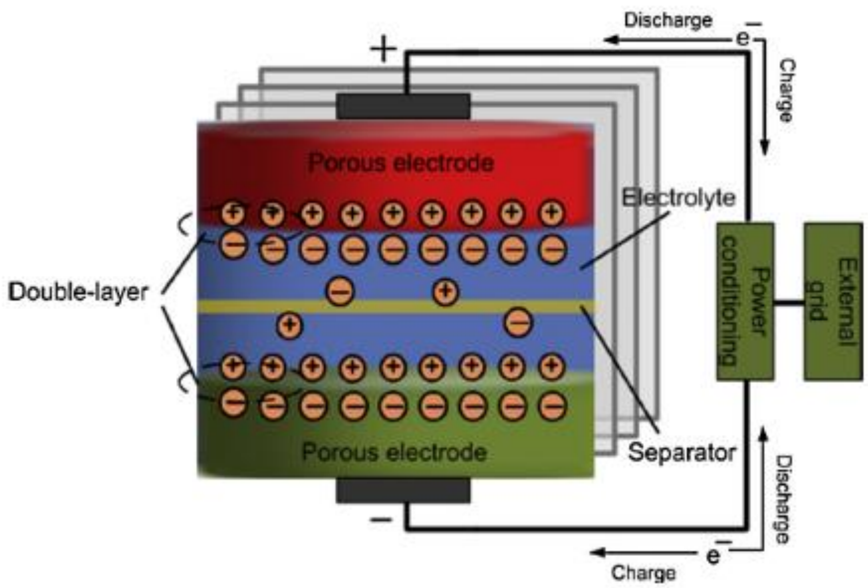
Supercapacitors are characterized by the presence of two electrodes immersed in an electrolytic solution and separated by a permeable membrane. Energy is stored in the form of static charge on the surfaces of the electrodes [25]. The most widespread configuration has carbon-based electrodes and organic electrolytic solution (Figure 25).

A simple electrostatic capacitor comprises two plates with a dielectric material between them. When a voltage is applied to the plates, charge builds up on them to neutralise the voltage by creating an equal and opposite static charge voltage across the plates. An electrochemical capacitor is similar to this in that it has a dielectric material between the capacitor plates but in this case the dielectric is a liquid electrolyte such as sulphuric acid or potassium hydroxide which can support a much higher build-up of charge. The capacitor plates themselves are inert materials which will not react with these reagents.

Electrochemical capacitors can be cycled for tens of thousands of times without degradation, provided the voltage across them is kept below the maximum so that no internal reaction takes place. However, once they are charged, they do lose charge slowly through leakage in the same way as a battery. The leakage levels in water-based electrochemical cells are similar to that of a lead-acid battery. Leakage levels are lower with organic-based electrolytes. Leakage will reduce long-term storage.

This technology is characterized by high power density (2000÷5000 W/kg) and low energy density (3÷5 Wh/kg), with a discharge time that spans from few seconds to one minute. The installation cost is in the range 250÷2000 €/kWh and the DC/DC RTE is above 95 % [31], [32].

Figure 25: Supercapacitor layout [29]

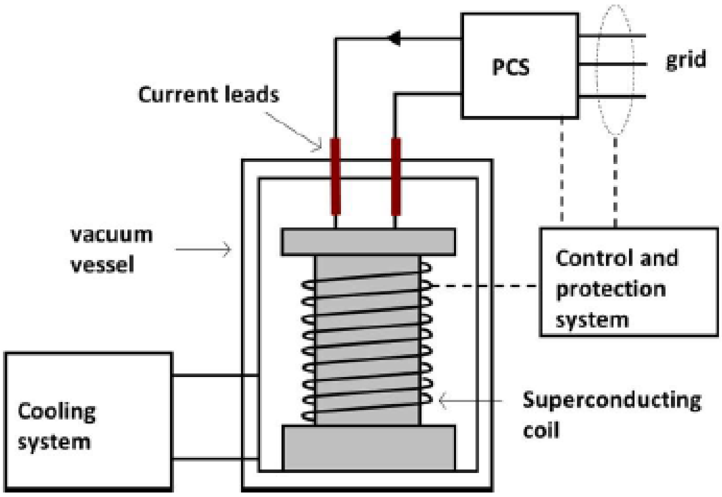


Despite the very high efficiency, this storage option is not considered for energy services in power systems, while it is already widely used for mitigation of power quality issues (short interruptions and high-power applications). Many aspects are still under development; in particular, much research is ongoing on materials. The high cost and the low energy density do not allow at the moment a wide employment of the technology for grid energy storage, which is mostly limited to pilot projects [32], [40]. Efforts in research are expected to produce a significant cost reduction in the coming years.

3.4.2 Superconducting Magnetic Energy Storage

In Superconducting Magnetic Energy Storage (SMES), electric energy is stored by making a current flow through a coil made of superconducting material, generating a magnetic field. A schematic representation of SMES is shown in Figure 26. A refrigeration system is needed to allow superconductivity; despite this, DC/DC RTE is extremely high (>95 %) as the resistance of the superconductor is practically null [25], [54].

Figure 26: SMES layout [54]



This technology is characterized by high power density. Hence, it would be prone to provide power systems with fast services. SMES are considered to be still under development; many researchers are investigating the potential of this kind of storage. Costs are currently high and extremely volatile, ranging from 300 to 2000 €/kWh [54], but are expected to fall to around 200 €/kWh by 2050 [40].

3.5 Chemical energy storage

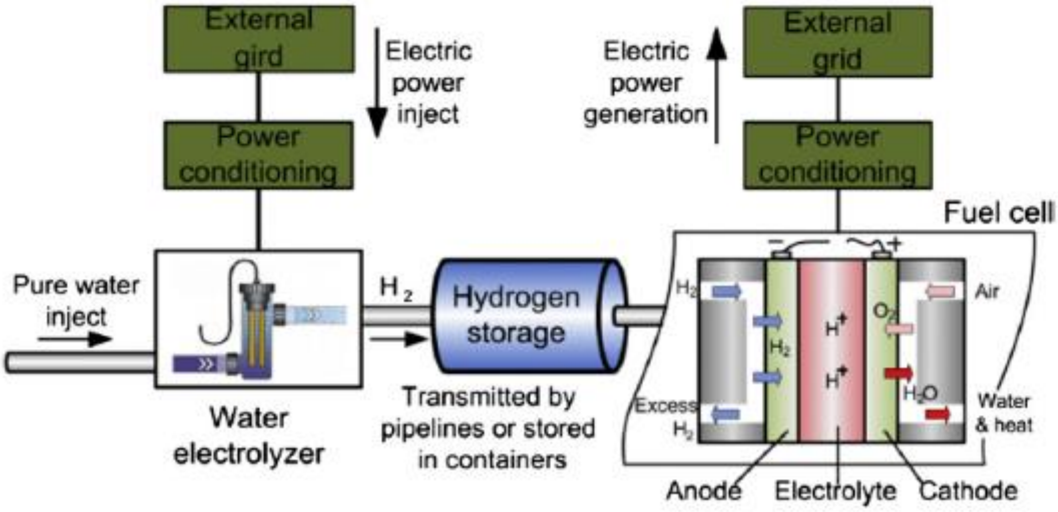
3.5.1 Power-to-hydrogen

In power-to-hydrogen (P2H) storage, electrolysers use electricity to split water into oxygen and hydrogen; the former is released, while the latter is stored. This can be done in various forms: at low pressure in caverns, at high pressure in tanks, as a liquid in cryogenic tanks (temperature below -253 °C), as a solid or liquid hydride (e.g., ammonia) [25], [35].

The most common electrolysers are ALKaline (ALK) and Proton Exchange Membrane (PEM) electrolysers. ALK are widely commercialized and cost around 750 €/kW; while PEM are still under demonstration phase, especially for large-size storage, and they provide higher efficiency and faster response at a cost of around 1200 €/kW. The technology of solid oxide electrolyser is currently under development; it provides the advantage of limited need of rare materials, but it is still quite expensive and requires to be close to a high-temperature heat source [55].

When the stored energy is needed, the electrolysis process may be reversed in a fuel cell to recombine oxygen and hydrogen to produce electricity and water (as shown in Figure 27), or the gas can be expanded in a gas turbine [25].

Figure 27: Hydrogen storage and electricity production with fuel cell [29]



Despite the low efficiency, which hardly exceeds 45 %, this technology has gained great attention because of the high density of energy, of the capacity to store for long periods and the suitability for large scale storage [32]; in a scenario of high penetration of renewables, P2H is expected to have a prominent role providing a cost-effective storage solution [56].. Costs are likely to decrease by more than 30 % by 2025 [55].

3.6 Summary of storage efficiencies

A summary of the efficiencies and costs of each technology described in this report is presented in Table 3.

Table 3: Efficiency and cost of each storage technology

	Mechanical				Electrochemical				Electrical		Chemical
	PHS	**CAES**	**LAES**	**Flywheels**	**Lead-acid**	**Li-ion**	**Flow**	**High-temperature**	**Super-capacitors**	**SMES**	**P2H**
RTE	70÷84 %	>55 %	<50 %	<90 %	70÷90 %	92÷96 %	60÷85 %	85 %	>95 %	>95 %	<45 %
Cost	5÷100 €/kWh	>50 €/kWh	250÷600 €/kWh	500÷3000 €/kWh	120÷200 €/kWh	250 €/kWh	400 €/kWh	250÷700 €/kWh	250÷2000 €/kWh	300÷2000 €/kWh	750÷1200 €/kW

Given that each technology is suited for a specific range of system services, the hybridization of the network in terms of storage technologies is considered beneficial. Still, support schemes are needed in order to make extensive storage employment profitable [33].

The European target of 32 % renewable generation at 2030 [57] must be enabled by actions in several areas of intervention, namely increased interconnections, demand flexibility and storage. In order to meet this target, ENTSO-E has recently released the Ten-Year Network Development Plan (TYNDP) 2020, which includes 23 storage projects for EU27: 2 BESS projects, 1 P2H project, 3 CAES projects, 17 PHS projects. This expansion of the storage availability is supposed to decrease the annual RES curtailment in 2030 by 10.6 TWh [59]. Moreover, storage may be used to flatten the generation curve of thermal plants, allowing a more efficient operation of these technologies.

EUROPEAN
COMMISSION

Brussels, 9.1.2023
SWD(2023) 1 final

PART 5/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

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

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

{COM(2023) 1 final}

Contents

4 Transmission High Voltage Direct Current systems

4.1 Introduction

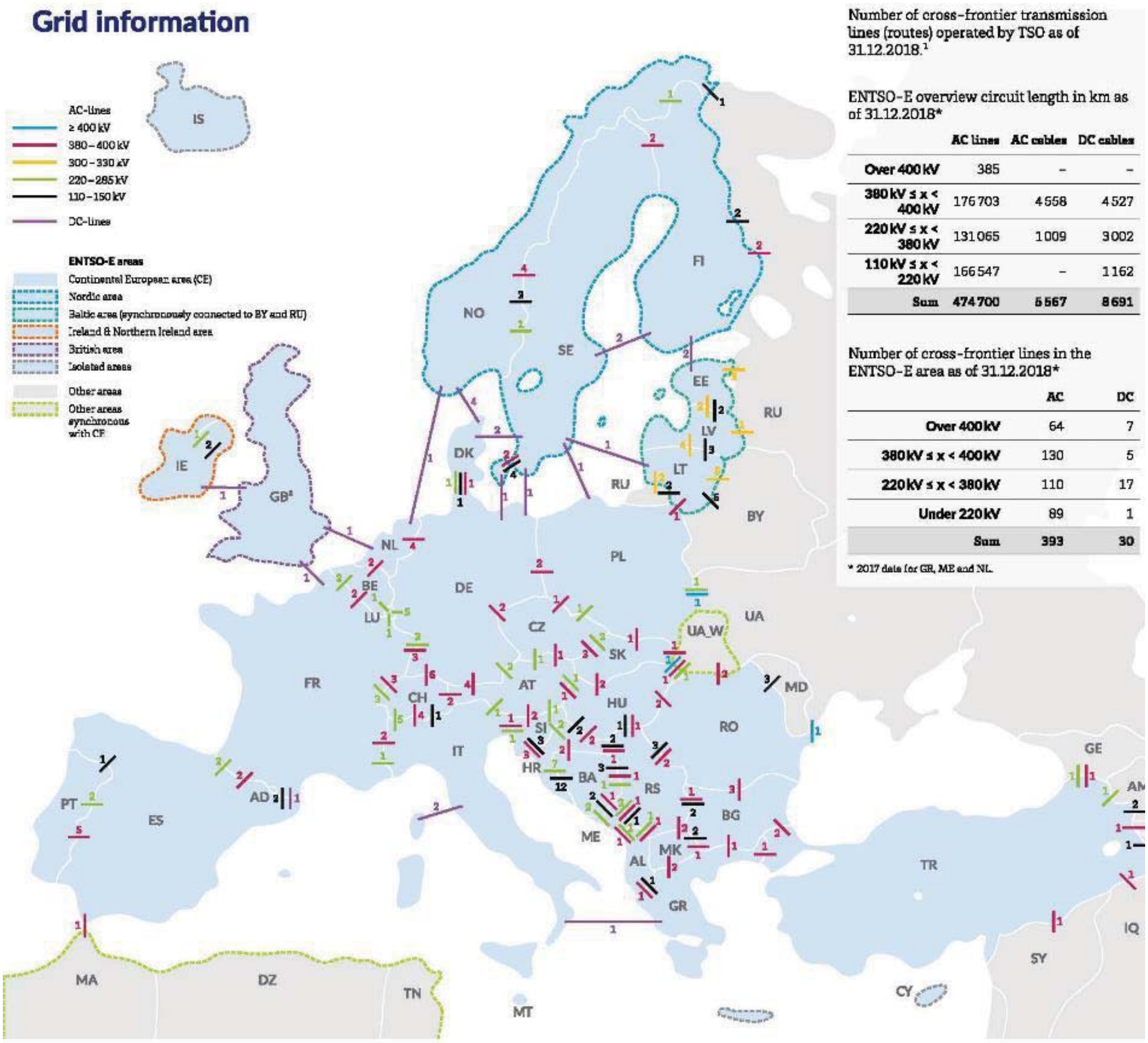
It has been widely documented in the history of the electricity industry that the first commercial electricity generated (by Thomas Alva Edison) was Direct Current (DC) electrical power. The first electricity transmission systems were also in DC. However, DC power at low voltage could not be transmitted over long distances, and that gave rise to high voltage Alternating Current (AC) electrical systems [60], leaving DC applications to very small-scale and particular cases. Nevertheless, with the development of high voltage power electronics, it was possible to transfer DC power once again at high voltages and over long distances for the DC interconnection of power systems, exploiting favourable efficiency of DC transmission. Since the first commercial installation in 1954, several HVDC transmission systems have been installed around the world.

High-voltage direct current (HVDC) is an increasingly important technology for transferring electrical power common also in the European transmission grid [61]. Figure 28 shows the cross-frontier transmission lines operated by European TSOs [62]. HVDC systems are used either for submarine interconnection or for cross-border interconnections, mostly cables. Several further projects are currently under construction. Among those, the second HVDC module (600 MW) of the Italy-Montenegro interconnection project is strictly correlated with the Transbalkan and the Mid Continental East corridors, and therefore will contribute significantly to enable the usage of an increased transmission capacity between Italy and South-East European Countries, especially Romania and Bulgaria. Another one, called ALEGrO, realizes the first interconnection between Belgium (Lixhe) and Germany (Oberzier) as a 100 km HVDC link with a bidirectional rated power of 1.000 MW capacity. ElecLink is, instead, a new FR – UK interconnection cable with 1000 MW capacity through the Channel Tunnel between Sellindge (UK) and Mandarins (FR). Converter stations will be located on Eurotunnel concession at Folkestone and Coquelles. Lastly, the interconnection of Crete to the Mainland System of Greece is already under construction. Crete is the largest electrically non-interconnected island system in Greece, representing a particular case, due to large size, rapid growth, remote location and large RES potential. The project aims at increasing security of supply and improve stability issues of the island. It is expected to contribute to the reduction of the operation of oil-fired units that currently supply the island and in the long run to allow their progressive decommissioning, thus contributing to the reduction of production variable costs and greenhouse gas emissions. This interconnection will be implemented in two phases. In Phase I Crete will be connected to Peloponnese with a 150 kV AC double circuit submarine cable interconnector of 2x200 MVA nominal transfer capacity. In Phase, II Crete will be connected to Attica with a bipolar submarine HVDC-VSC link of 2x500 MW capacity transfer.

There are further projects ongoing on offshore DC transmission connections. Most of the projects are either in North or Baltic sea. On the one hand, the NordLink is a new HVDC connection between Southern Norway and Northern Germany and consists in a 514 km subsea cable with a capacity of 1400 MW. On the other hand, North Sea Link is a 720 km long subsea interconnector between Norway and Great Britain which is planned to be commissioned in 2021. When realised, it will be the world longest subsea Interconnector. The main driver for the project is to integrate the hydro-based Norwegian system with the thermal, nuclear and wind-based British system. The interconnector will improve security of supply both in Norway in dry years and in Great Britain in periods with negative power balance (low wind, high demand etc.). In addition, the interconnector will be favourable for the European market integration, whilst also facilitating renewable energy in preparation for a power system with lower CO_2-emissions. The so-called Viking DKW-GB is, instead, a 2x700 MW HVDC subsea link across the North Seas which relies on new substations on both sides, Bicker Fen (GB) and Revsing (DK). The last project is related to the Baltic states synchronization with continental Europe. The project covers a lot of new investments for internal grid reinforcements - new 330 kV and 400 kV AC lines, voltage stabiliser units, synchronous compensators, upgrades of PSS in power stations, internal 110 kV network reinforcement required for synchronization and separation of 110 kV Baltic grid from IPS/UPS system. As part of the project, after the synchronization, a new HVDC connection will be established between LT-PL allowing for a commercial exchange of the Baltic States with Continental Europe in the amount of 700 MW.

Many other projects are still in the earliest or very early stages of implementation: 10 projects are in the authorization phase, 2 are planned but not yet authorized and 18 are being studied.

Figure 28: Cross-frontier transmission lines operated by European TSOs [62].



ENTSO-E overview circuit length in km as of 31.12.2018*

	AC lines	AC cables	DC cables
Over 400 kV	385	–	–
380 kV ≤ x < 400 kV	176 703	4 558	4 527
220 kV ≤ x < 380 kV	131 065	1 009	3 002
110 kV ≤ x < 220 kV	166 547	–	1 162
Sum	474 700	5 567	8 691

Number of cross-frontier lines in the ENTSO-E area as of 31.12.2018*

	AC	DC
Over 400 kV	64	7
380 kV ≤ x < 400 kV	130	5
220 kV ≤ x < 380 kV	110	17
Under 220 kV	89	1
Sum	393	30

* 2017 data for GR, ME and NL.

¹ Non geographic location of lines.

² All data with the country code GB represents data as sum of England, Northern Ireland, Scotland and Wales.

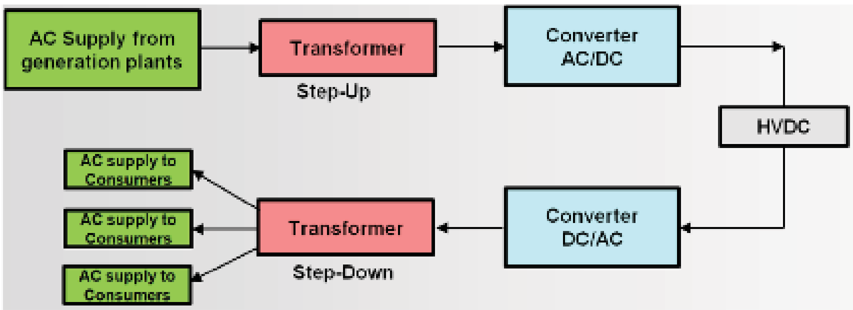
New HVDC links play a key role in future development plans for the European transmission grid and internal market. The use of the advanced functionalities of these HVDC links in system operations is essential for the secure and efficient operation of the grid. ENTSO-E, the European Network of Transmission System Operators which represents 43 electricity transmission system operators (TSOs) from 36 countries across Europe, recognizes the importance of the functionalities and ancillary services that can be provided by HVDC links. Moreover, the HVDC technology makes it possible to benefit from the efficiency that DC transmission can readily provide. The use of the functionalities of the HVDC links in system operations contributes to meeting current and future challenges, such as decarbonisation and large-scale integration of Renewable Energy Sources (RES) which are largely connected via Power Electronics (PE). Such technologies result in the decommissioning of classic rotating power plants and the disappearance of the physical characteristics the power system was built on. In addition, the HVDC technology may support the realisation of an integrated European energy market and the sharing of ancillary services between countries and synchronous areas. Today, HVDC links are typically used for long-distance bulk power interconnections, using both overhead lines and submarine cables, in some cases for connecting two asynchronous, non-embedded AC systems, and for the subsea interconnection of large offshore wind farms. They can also be designed to provide ancillary services to AC systems, such as frequency control, emergency controls, fast power reversal, etc.

The main advantages of DC over AC are the elimination of the reactive power requirement, lower operational losses in the DC link and the possibility to easily control real power flows in a meshed AC system. There are also disadvantages for HVDC systems: for voltage transformation, transformers cannot be used; circuit breakers and protections are still problematic, especially in case of meshed DC systems; the most important drawback is the high costs that, independent of the distance of transmission, are needed to provide AC/DC conversion at both ends of the DC link.

4.2 HVDC system structure

A generic HVDC system structure overview is reported in Figure 29. In the first HVDC station, the converter transformer changes the AC voltages to the required level. The converter station takes the electric power from the three-phase AC network and rectifies it into DC; the power is then transmitted through overhead lines or cables. At the receiving end of the DC line, an inverter converts the DC voltage back to AC, and a transformer connects the link to the local power system. This technology is suitable for transmitting power in the range 100 MW -10 GW.

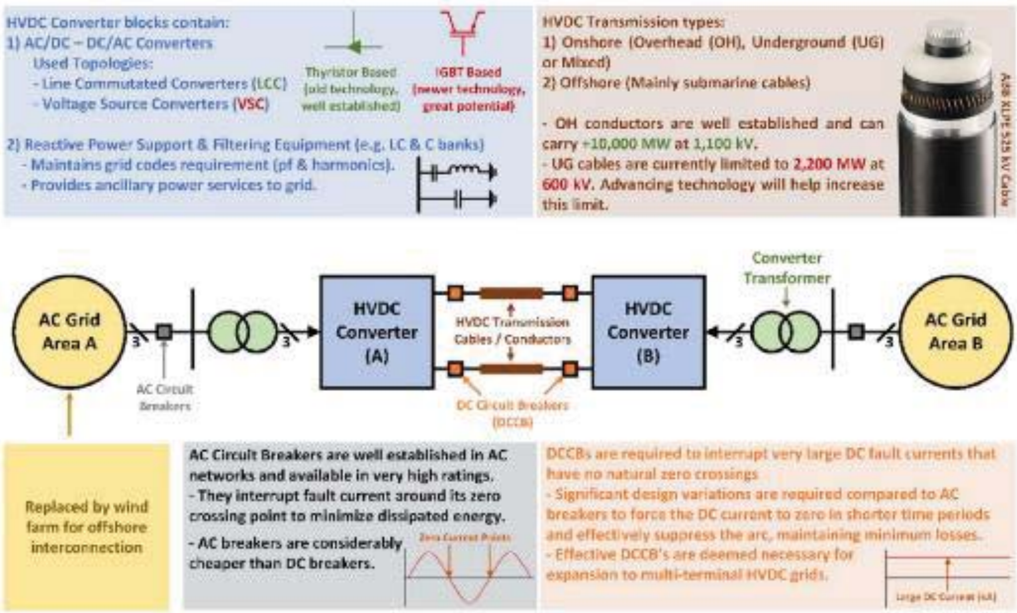
Figure 29: HVDC system structure [63].



As shown in Figure 30 the backbone of any HVDC system is the converter station which converts AC voltage to adequate DC transmission voltage level (AC/DC converter) at one end, and converts the DC voltage back to adequate AC grid interfacing voltage level (DC/ AC converter) at the other end. The notions of sending and receiving end are often used interchangeably depending on the power flow direction. The converters are protected by AC circuit breakers while the voltage is adjusted to the required level by means of transformers [64].

Short-circuit protection of HVDC transmission conductors requires DC circuit breakers (DCCB). Interrupting a DC current represents one of the principal technical challenge as, in contrast to AC, there is no natural zero crossing which provides an opportunity for current flow to be broken.

Figure 30: Generic HVDC transmission system layout with component-based description. DCCBs are not typically implemented in point-to-point links and are displayed to illustrate their principal of operation [65].



Two main converter types are being used in HVDC links:

- Line Commutated Converters (LCCs), which employ line-commutated thyristor valves;
- Voltage Source Converters (VSCs) which rely on Insulated Gate Bipolar Transistors (IGBTs).

Additionally, reactive power banks and filtering equipment have to be installed to maintain grid codes requirement in terms of power factor and harmonics as well as to provide ancillary services to the AC grids.

Both LCC and VSC links can be connected using different network configurations. The DC network topology or configuration selection is mainly influenced by the required level of reliability, rating, cost-effectiveness and compliance with policies and regulations [66]. Commonly used topologies of HVDC transmission systems are DC monopoles and bipolar system, while DC tripolar system are rarely implemented and mostly based on design variations of the other common configurations [67]. Appendix IV gives out an overview of the comparison between the two different HVDC technologies in terms of power transmission .

A particular case is Back-to-Back connections, primarily used to link unsynchronized neighbouring AC networks. With a back-to-back HVDC link, two independent neighbouring transmission systems with incompatible electrical frequencies, with exceeding short-circuit power levels or with different operating philosophies are connected, putting converters in the same converter station.

Figure 31 reports the common HVDC transmission configurations. In the monopolar configuration, the power transfer between the two converter stations makes use of a single DC pole rated for full high-voltage DC capacity. The return circuit can be a low voltage return path (asymmetrical monopole), which may be realized using an earth electrode at each station, or a low-voltage metallic return link [68]. Earth electrodes require special design considerations to accommodate the fully rated DC current and are typically placed away from the converter stations and connected using electrode lines [69][70]. This option is cost effective and avoids the use of return cable/conductor extending over the whole link distance. Yet, several existing regulations/policies restrict the use of earth electrodes in many HVDC projects due to their negative environmental impact, especially in case of underground or subsea cables, potentially causing corrosion to nearby pipes and affecting sea creatures in the latter case [70]. When used, the metallic return link is rated for full current, but with low voltage insulation requirements.

Figure 31 (a) illustrates both conventional HVDC monopole connection options, which are applicable to both LCC and VSC configurations, but more commonly used with LCC. Another monopole configuration that equally shares the full rated HV between two positive and negative links connecting both stations is known as symmetrical monopole (e.g., 320 kV lines rather than single 640kV line to ground) [68]. The direct advantage in symmetrical monopole systems is the decreasing of the voltage rating of the links, which is especially important in underground/subsea cable transmission. Figure 31 (b) illustrates the symmetrical monopole configuration, where midpoint grounds are defined at both converter stations. This configuration is common for offshore VSC applications. On the other hand, it is rarely implemented in case of LCC [71]. The main disadvantage of the discussed monopole configurations remains in that there is no inherent redundancy in the design, meaning that when there is a fault in one of the lines or converters, then the full transmission capacity is lost [72]. To overcome this issue, the bipolar configuration can be adopted as it provides increased reliability.

Figure 31: Common HVDC transmission configurations: (a) Monopole with both metallic and earth electrode return options. (b) Symmetrical monopole. (c) Bipolar system with both return options.
Two return options are presented in (a) and (c) for illustration, real implementations use only one [65].

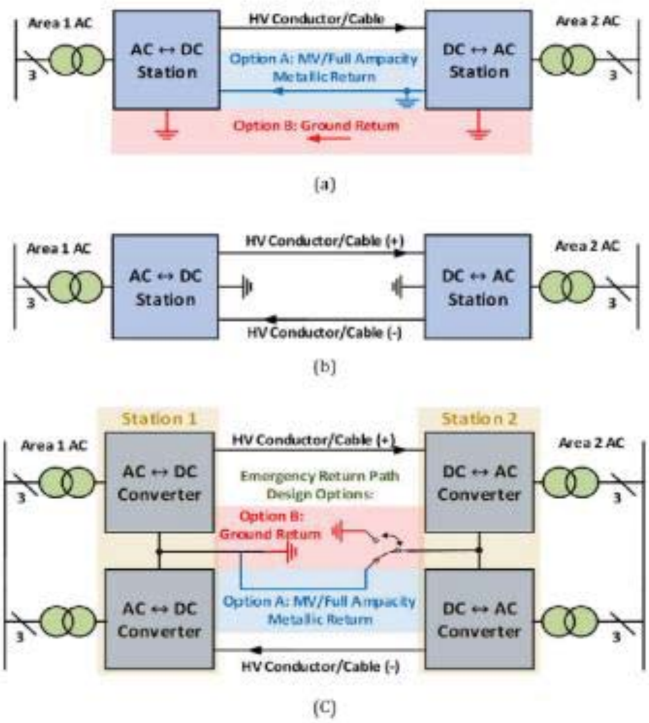
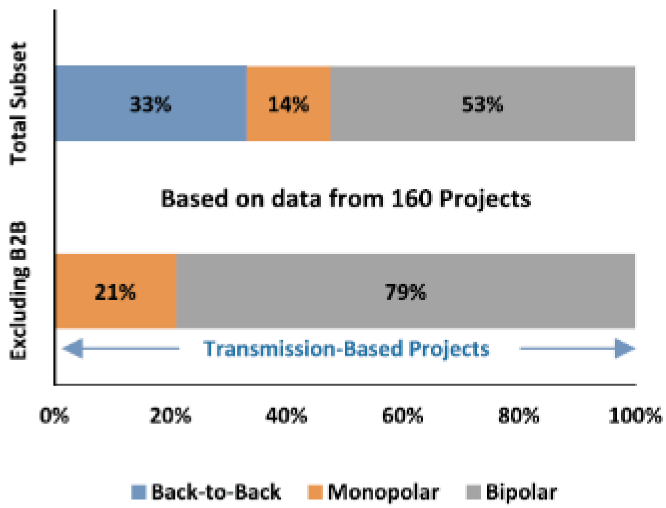


Figure 31 (c) illustrates a high-level block diagram of bipolar configuration alternatives, where in each station two converters grounded at midpoint are installed. These converters produce equal and opposite HV DC outputs, creating a normal energy flow path in the outer loop with negligible flow in the neutral/earth connection. The mid-point emergency return path can be designed using either earth electrodes or metallic return link, similarly to the monopole case. The main advantage of common bipolar configurations is the increased reliability, which is similar to that of a double-circuit AC transmission line. That is, a fault on any single transmission line/cable or converter pole results only in that link to independently shut down. In this scenario, provided that the fault does not affect other pole assets, the neutral link can be used as a low voltage return path, allowing for continued operation up to 50 % of the total HVDC power capacity [73][74][75]. As reported in Figure 32, 53 % out of 160 projects analysed by the Bloomberg New Energy Finance utilize bipolar links, 79 % not considering Back-to-Back projects [76].

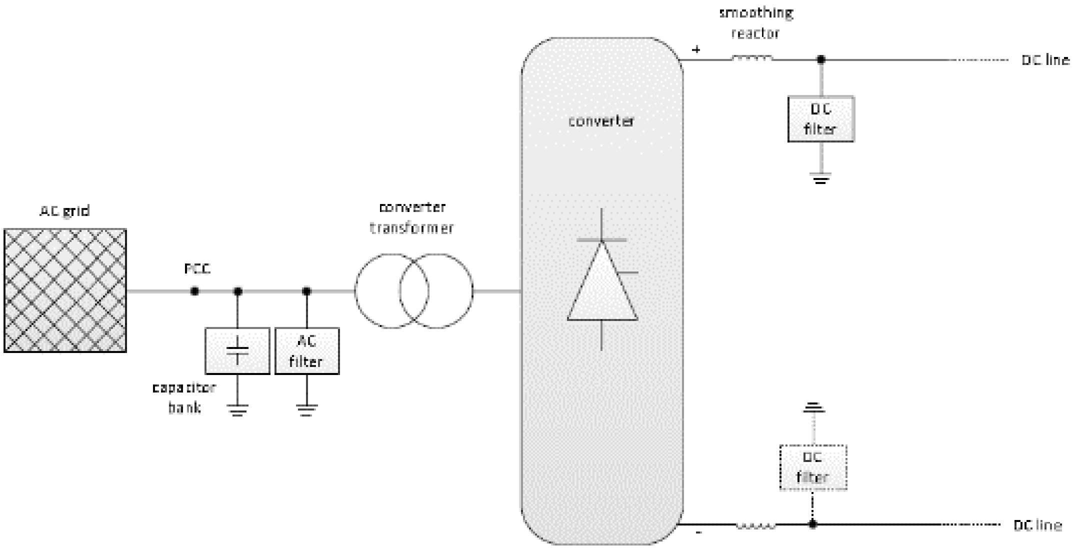
Figure 32: Market share of the main HVDC configurations, including and excluding Back-to-Back links, based on data from 160 projects [76].



4.3 Line Commutated Converters (LCC)

Line-Commutated Converter (LCC) HVDC is a mature technology with the highest power and efficiency rating used for more than 50 years for bulk power transfer. LCC-HVDC technical capabilities, combined with its economic advantages and low operating losses, make it a widely used solution for empowering or enhancing power system interconnections [77][78]. LCC-HVDC technology employs line-commutated thyristor valve converters. Early LCC systems employed mercury-arc valves, however many adaptations were necessary to make them suitable for HVDC. Nowadays mercury-arc valves have been replaced by thyristors. A thyristor is a controllable semiconductor able to carry very high currents (4000 A) and to block very high voltages (up to 10 kV). Many thyristors connected in series build a thyristor valve, suitable to operate at hundreds of kV at the network frequency (50 Hz in Europe). A LCC requires a stable AC system voltage (high short-circuit power) for a reliable commutation so that the difference in reactive power must be kept within defined values to maintain the AC voltage in the desired tolerance [79]; in some cases, synchronous capacitors and flywheels are used to fulfil this requirement. This limitation is overcome in VSC stations. Figure 33 shows the configuration of a LCC-HVDC system.

Figure 33: LCC-HVDC converter station [61]



The function of LCC-HVDC components are as follows:

- *Converters:* DC/AC and AC/DC conversion is performed in the rectifier and inverter units. Each unit typically has a 12-pulse arrangement consisting of two 6-pulse thyristor bridges connected in series on the DC side.
- *Converter transformers:* Transformers, with tap changers to adjust the supplied AC voltage to the valve bridges, ensure optimisation of HVDC operation and are designed to work with high harmonic currents and to withstand AC/DC voltage stresses. The transformer for a 12-pulse bridge has a star-star-delta three-winding configuration and typically has a leakage reactance to limit the current during a short-circuit fault of the bridge arm.
- *AC and DC side filters:* Converter operation generates harmonic currents and voltages on the AC and DC sides, respectively. Common issues with high harmonics include machine heating, insulation stress, overloading of capacitor banks and interference with communication equipment. Some HVDC designs with overhead lines also implement a DC filter. DC filters are not required in cable transmission or back-to-back schemes.
- *Reactive power compensation:* A LCC-HVDC link has a high reactive power demand that varies with its loading. Typically, a large percentage of reactive power compensation is required, up to 60 % of the DC power rating, and is provided by filter banks and switchable capacitor banks or FACTS-based devices such as a STATCOM or SVC. If the converter unit is in a weak AC grid, it may be necessary to install synchronous condensers to increase the short-circuit level and improve the voltage control.
- *Control system:* The rectifier and inverter include various hierarchical control systems.

- *Smoothing reactors:* The DC side of the converter consists of smoothing reactors, which are primarily required to reduce harmonics on the DC side, prevent commutation failures and protect valves after DC faults [78].
- *DC connections:* Cables or overhead lines are always present on the pole connections, except in back-to-back systems. DC faults can be managed with LCC-HVDC technologies by controlling the short-circuit current, whereas in VSC-HVDC systems DC short-circuits could be more critical.

Losses in a single converter station can be assumed, for LCC technology, about 0.7 % of the power through the station. Of course, Joule losses on DC conductors should be added.

4.4 Voltage Source Converters (VSC)

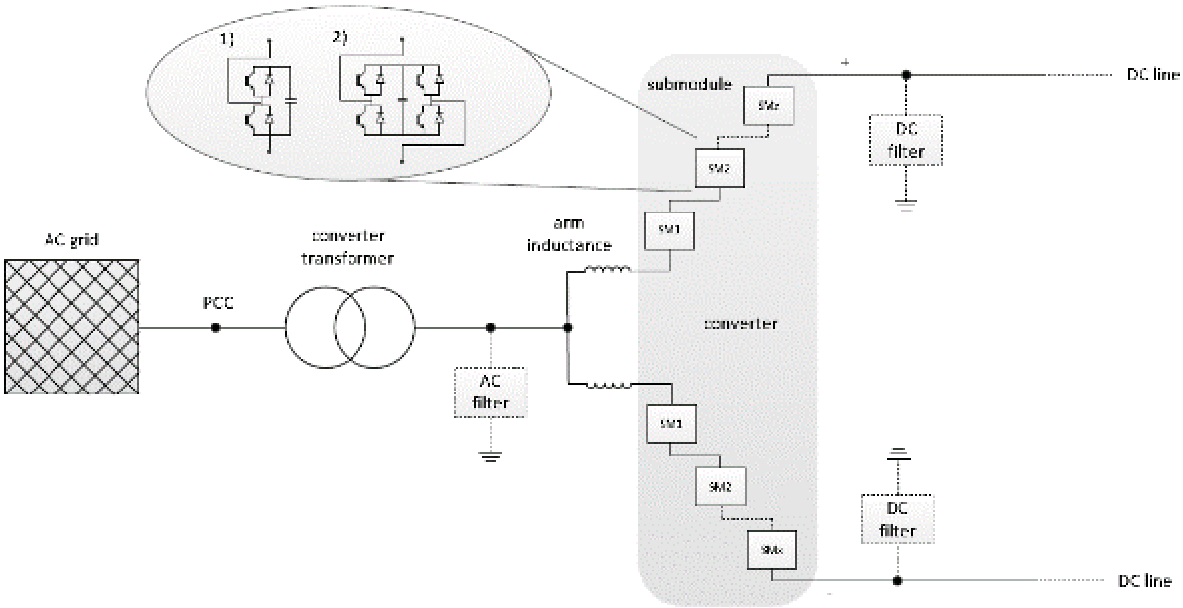
Voltage Source Converter (VSC) technology was employed for the first time in 1997 in the Hellsjön project in Sweden [80]. Since then, a considerable development of this technology has been achieved: the first VSC-HVDC system was commissioned with a voltage of ±10 kV and a transmission capacity of 3 MW; today VSC-HVDC systems with voltages above ±500 kV and 2 GW are feasible. The INELFE VSC-HVDC system between France and Spain with a voltage of ±320 kV and a DC power of 2x1 GW is at present the VSC system with the highest transmission capability [81]. The newest generation applies a modular concept (Modular Multilevel Converter, MMC) with an arbitrary number of voltage levels (dependent on the manufacturer), which leads to reduced losses and improved harmonic behaviour.

VSC uses Insulated Gate Bipolar Transistors (IGBTs) which can be both turned on and off. The turn-on and -off capabilities of IGBTs enable voltage generation on the AC side with a specific amplitude and phase angle. On the other side, as mentioned, thyristors can only be turned on, and this is why synchronous machines must be available in the AC system to which the LCC-HVDC is connected, in order to provide the commutating voltage. This makes VSC more flexible than LCC, as the VSC valves are independent on the operation of the AC grid. Hence, a VSC-HVDC system can be operated in weaker, and even in passive, AC systems (providing, e.g., black start capability). Furthermore, VSC can control the power flow and provide dynamic voltage regulation to the AC system [79][82][83]. Additionally, no reactive power compensation and less harmonic filtering are needed which results in more compact converter stations, making the use of VSC-HVDC advantageous for instance on offshore platforms, where space saving is an important issue. Lastly, in LCC stations the direction of power flow can be changed only by reversing the polarity of DC voltage at both stations. In VSC it can be achieved by reversing the current direction, keeping the polarity of DC voltage constant. By this means, VSC can be easily connected to Multi-terminal HVDC systems [84].

Figure 34 shows the configuration of a VSC-HVDC system. The function of VSC-HVDC components are as follows:

- *Converter:* A VSC-HVDC system (point-to-point connection) consists of two converters (rectifier and inverter) at both ends in monopolar or bipolar configuration. The modular concept – with many series of connected submodules (half-bridge or full-bridge modules) in each arm – enables generation of an almost perfect sinusoidal voltage on the AC side of the converter.
- *Converter transformer:* Conventional two- or three-winding transformers are applied in VSC-HVDC systems to adapt the AC system voltage to an appropriate level for the operation of the converter. Tap-changers could be used in addition to the reactive power control of the converter to support voltage control.
- *Arm inductance:* The arm inductance determines the active and reactive power exchange between the AC system and the converter. Additionally, the inductances keep the loop currents between the parallel converter legs to a low level.
- *AC and DC side filters:* Generally, AC and DC filters can be omitted, as the voltage of the converter is almost perfectly sinusoidal and therefore the harmonic content is very low. In special cases, such as the application to overhead lines, DC filters are installed if required.
- *Control system:* The active and reactive power exchange is controlled by an outer and inner control loop. The outer loop calculates the reference values for the inner loop, which determines subsequently the firing pulses for the IGBTs.
- *DC capacitors:* The large DC capacitors of two- or three-level converters are – in cases of modular multilevel converters – distributed in the submodules along the converter arms.

Figure 34: VSC-HVDC converter station with modular multilevel converter:
1) half-bridge submodule, 2) full-bridge submodule [61]



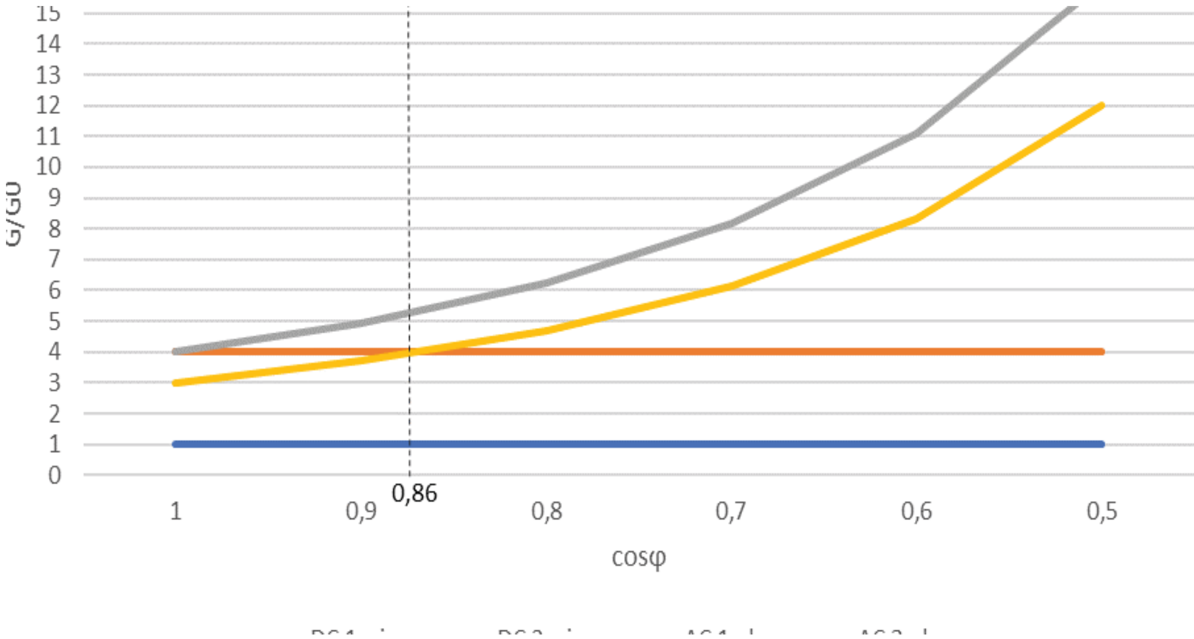
In the first VSC applications, losses in a single converter station were equal to 3 %. Afterwards, improvements accomplished have reduced losses up to 1.7 %. In the last years, a percentage of 1 % has been achieved [85]. Of course, Joule losses on conductors should be added. Despite the fact of being an emerging technology, VSC is facing a fast development. It is thus expected to become equivalent to LCC in terms of power capabilities and voltage levels. It is hence clear that VSC-HVDC represents a promising technology for the development of future HVDC grids.

4.5 Technical-economic HVAC vs. HVDC comparison

As already mentioned, the use of HVDC transmission over long distances provides several technical advantages when compared to HVAC [65]. In 2018 the maximum implemented distance for HVDC was the Changji-Guquan link in China which exceeds 3000 km [85]. In China was also the longest HVAC, the 1049 km Yuheng-Weifang link [87][88]. All overhead HVDC systems are characterized by very long length, and this can be explained as follows.

Considering the economic efficiency of the transmission lines alone (i.e., not including converter stations), DC transmission costs are significantly lower than AC three-phase transmission on equal power transferred. This statement is however limited to DC transmission losses and neglects the need for expensive AC line-reactive compensators [89]. HVDC also requires fewer cables/conductors and utilizes the full transmission capacity up to their thermal limits. This reduces the required cross-section for DC conductors and consequently the transmission cost [90]. As shown in Figure 35, a rough technical economic comparison shows that, neglecting costs and losses associated to the conversion, 1-wire DC transmission is always more economically efficient than 3-phase AC transmission (although it is not used due to reliability concerns), and that 2-wire DC transmission is more efficient than 3-phase AC transmission for AC power factors lower than 0.86 (in transmission systems, however, TSOs try to operate links at power factors higher than 0.86).

Figure 35. HVAC Vs HVDC line costs.



Right-of-Way (ROW) space (i.e., the required horizontal ground clearance distance) for DC transmission is also considerably lower compared to the AC equivalent, for both overhead and underground bulk power transmission options [91]. On the other hand, the expensive rectifier and inverter stations for AC/DC and DC/AC conversion, which are not required in HVAC case, significantly increase the overall HVDC transmission cost, thus offsetting efficiency benefits, depending on the distance.

Therefore, there is a HVDC breakeven distance, above which DC transmission becomes economically preferable than AC transmission: typical range is between ~300 km and ~800 km for overhead lines and ~50 km to ~100 km for offshore/underground cable links [89][90][73][92]. This variability is related to individual project conditions (e.g., MW/kV rating, transmission terrain and local policies). Figure 36 qualitatively summarizes the cost evolution of HVAC vs. HVDC with distance, indicating breakeven points, where it is also worth noticing that conversion losses at DC substations are not negligible for the overall transmission efficiency (notice that rated voltages are different, and so figures are not directly comparable). Figure 37 provides a comparison of the costs of different transmission alternatives for a 6000 MW/2000 km link [90].

Figure 36: qualitative breakeven distance assessment [91].

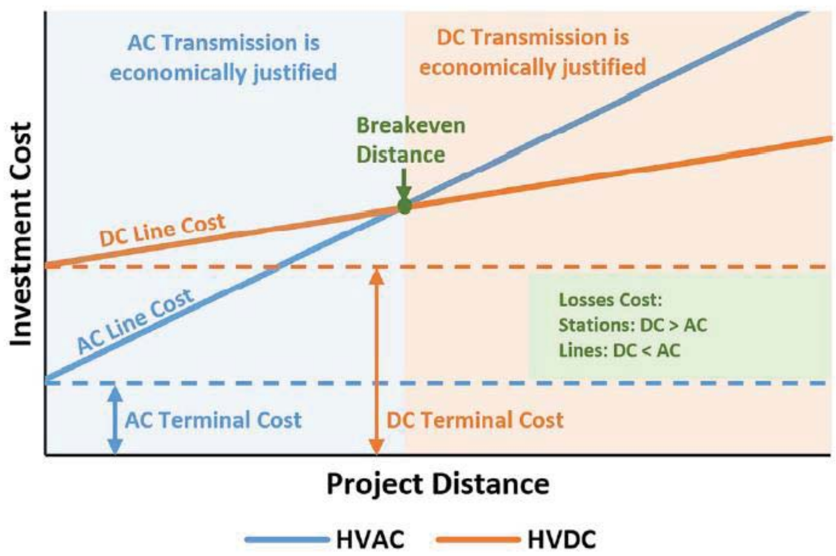
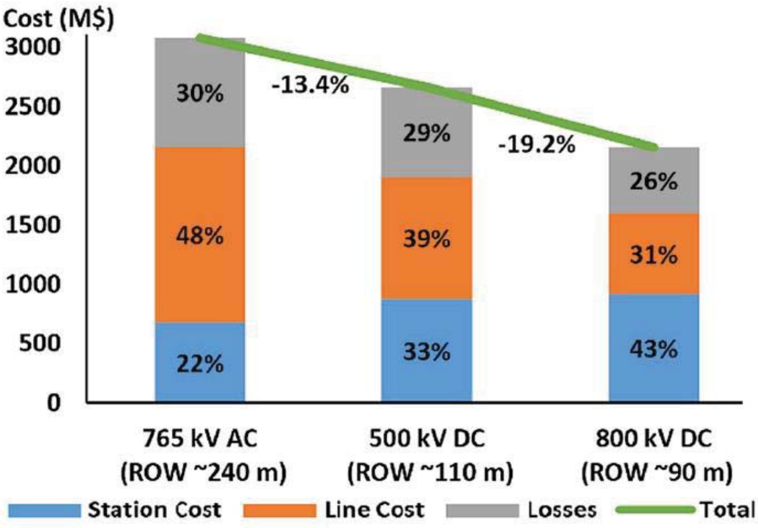


Figure 37: Cost and ROW estimation for a generic 6000 MW, 2000 km overhead transmission [91].



From a purely technical point of view instead, the primary advantages of HVDC links over HVAC links are [73][93]:

- The elimination of reactive power for power transmission purposes. Power can be transferred over long distances with constant voltage at the receiving end and therefore can enable full utilisation of the conductors for real power transmission. AC reactive compensation becomes intractable in case of long AC cables, due to the reactive power produced by the cable, that makes it necessary to compensate that power in intermediate points of the line (and that is almost impossible in case of subsea transmission).
- Higher power transfer with the same size and insulation level of DC lines compared to AC lines. The effective voltage can be higher, and the wire cross-section can be larger (it is limited for AC lines due to the skin effect whereas a DC line can, in principle, accommodate any cross section). This also allows some savings in terms of ROW and towers.
- Lower losses on DC lines; however, for total loss calculation, HVDC converter stations should be added.
- HVDC links allow the connection of substations of asynchronous AC grids; they then can be used for market purposes as well as for system support by means of ancillary services.
- System operators can control the power flow in HVDC and this makes it possible also to control power flow in the AC transmission system as well. This may be challenging from an operational point of view; however, an adequate complementary control system can be used along with the HVDC lines in a coordinated manner to support system operation, for example, by reducing the number of required remedial actions for assuring system security as well as by improving transient stability and damping oscillations in the power system. This in turn will allow the system operator to utilize the existing AC network more efficiently. In other words, HVDC would increase significantly the flexibility of the whole power system, making it possible to accommodate larger amounts of renewable non dispatchable generation.

On the other hand, the primary disadvantages of HVDC links over HVAC links are:

- Voltage transformation (through power electronics) and DC circuit breakers are two weak points, from both the technical and the economic point of view, and still need improvements.
- The need for AC/DC and DC/AC conversion at the terminals of the DC transmission line offsets the advantages of DC links, independent of the transmission distance.

4.6 Conclusions on power losses in HVAC and HVDC Transmission Systems

In power systems, a substantial amount of power is lost on transmission and distribution, especially when the power is delivered over long distance [94] or at low voltages.

The phenomenon of Joule losses on conductors depends on the voltage: increasing voltage, at equal power transferred, current decrease linearly and losses, that depend on the squared current, decrease quadratically with voltage. This means that doubling transmission voltage allows reducing losses to ¼. This is true for both AC and DC, and this is why long-distance transmission is always carried out at high voltage, both in AC and DC.

Voltages, however, cannot be increased boundlessly: increasing voltages results in increased clearances, cost of towers, cost of insulation and related devices, etc. This is why rated voltages of electrical lines are actually proportional to distances: for low distances it is not worth adopting high voltages, while for long distances, High Voltages (HV) or Extremely High Voltages (EHV) are used. In Europe, the transmission system is rated 400 kV, and there are a few lines with rated voltage higher (a couple of 750 kV lines, 4-500 km long, connecting the former Soviet Union system (CIS), in particular Ukraine, to Poland, Hungary and Romania systems). Actually, distances in the European grid do not justify the cost for higher rated voltages, while they are adopted in some cases when distances are longer, in Countries like Canada, USA, Russia, China (usually, max 800 kV).

Specifically, for losses in conductors, a comparison can be carried out between AC and DC transmission, under the following assumptions: the two systems will have the same requirements for voltage insulation to the ground, the conductors will have the same current density, the real power transferred is the same. Under such assumptions, losses on the DC system are 40 % -70 % of losses on the AC system, depending on the power factor on the AC system (in the following, let us assume 50 % for the sake of simplicity). However, it is necessary to sum, for HVDC, losses on converter stations that range from 1.4 % to 2 % of the transferred power.

As reported in [95] ENTOSE-E estimates that the AC EHV and HV transmission network losses in 2018 were 1.77 % of total consumption (on 400 kV grids); the International Electrotechnical Commission estimates about 2.5 % of energy lost in transmission systems [96]. Let us assume for the sake of simplicity a value of 2 %, the comparison is shown in **Table 4Table** . Similar conclusions are derived in [97][98][99]. Appendix IV gives out further information on converter station power losses.

Table 4 Sample of loss comparison for HVAC and HVDC Transmission systems.

Technology	Losses on conductors	Losses on Converter stations	Total losses
HVAC	2%	---	2%
HVDC-LCC	1%	1.4%	2.4%
HVDC-VSC	1%	2.0%	3%

It is worth noticing that HVDC systems are adopted in practice and are more economically efficient than HVAC systems in the following conditions:

- transmission over about 800 km for overhead lines (in such cases, AC transmission would be either impossible or very expensive for technical reasons);
- transmission over about 100 km for cables, especially undersea cables, for example to connect offshore wind farms (in such cases, AC transmission would be either impossible or very expensive for technical reasons);
- connection of two electric systems with different frequency;
- connection of a weak power systems to a very strong power system;
- need to accurately control real power flows between either two power system areas or two or more corridors;
- Frequency control reserve;
- Electricity market issues;
- Management of emergency conditions.

EUROPEAN
COMMISSION

Brussels, 9.1.2023
SWD(2023) 1 final

PART 6/6

COMMISSION STAFF WORKING DOCUMENT

Accompanying the document

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

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

{COM(2023) 1 final}

EN EN

Contents

5 Conclusions

The present document discusses some technologies in the field of power generation, management and transmission of electrical energy in terms of efficiency, and identifies among them the most promising sectors for energy saving at the EU level.

Electricity generation looks like the sector where efficiency improvement can result in a significant saving of primary energy. This is due to the fact that efficiency in traditional thermal generation has values in the range 35-64 %, which is very low compared to efficiency in HV transmission (about 98 %) and storage (from 50 to 95 %).

Therefore, **thermal generation presents the highest saving margins** compared to HVDC and storage. Among different technologies, and considering the decarbonisation policies, the substitution of older and less efficient technologies (efficiency of 40 % or so) with CCGT would result in a significantly lower consumption of primary energy, as latest CCGT are claimed to reach an efficiency of 64 %. For example, a simplified analysis carried out for an ideal case of complete substitution of coal electricity generation by CCGT (considering data of 2018) shows that it would make it possible to save about 378 TWh/year. Of course, other considerations should be done in order to guarantee all necessary flexibility options to make it possible to run the power system in security conditions.

As for **storage** options, many technologies are available, with completely different features and uses. Therefore, their efficiencies cannot be simply compared, as fields of applications of various technologies are different. Some storage systems are more oriented to energy applications, some to power applications; some can store large amount of energy, some can provide small amount of energy but in very short time. Hence, for example, one cannot decide to substitute a PHS with a Supercapacitor in order to increase the overall efficiency.

However, this is not an issue, as it should be kept in mind that the goal of storage is not to save primary energy *directly*, but to make it possible the best integration of RES, thus substituting electricity from fossil fuels with RES based electricity, improving at the same time efficiency of residual thermal plants by flattening their load diagram, obtaining a significant *indirect* saving of primary. According to estimates by ENTSOE, the not curtailed RES energy could be reduced in 2030 by 10.6 TWh/year thanks to storage employment.

As for **HVDC transmission systems**, it is worth noticing that transmission efficiency of traditional HVAC systems is today about 98 %, thanks to the extremely high rated voltage of the European transmission system (400 kV). Therefore, there is not much room for further efficiency improvements, unless higher voltages are adopted, for both DC and AC solutions, that would be not justified economically, however. At equal voltage levels, HVDC systems are not an option to increase efficiency compared to HVAC transmission systems. They are a solution when the HVAC transmission is not viable, i.e., in case of very long transmission lines (overhead lines longer that about 800 km, cable lines longer than 100 km, interconnections of not synchronous areas, etc.). Moreover, they should be considered as a tool to make the transmission system more flexible, in order to – again – better integrate RES generation, thus saving *indirectly* primary energy. The typical example is the HVDC interconnection of large offshore wind farms, which is sometimes the only feasible option to make it possible their connection to the bulk power system.

References

[1] Eurostat database - https://ec.europa.eu/eurostat, accessed March 2021;

[2] C. Redl, F. Hein, M. Buck, P. Graichen, D. Jones, Agora Energiewende and Sandbag (2020): "*The European Power Sector in 2019: Up-to-Date Analysis of the Electricity Transition*", Agora Energiewende, March 2020;

[3] Eurostat, "*Energy, Transport and Environment Statistics, 2019 Edition*", Statistical Books 2019;

[4] E. Tzimas, A. Georgakaky, S. D. Peteves, "*Future Fossil Fuel Electricity Generation in Europe: Options and Consequences*", JRC Reference Reports, 2009;

[5] W. Nijs, P. R. Castellò, I. H. Gonzàlez, "*Baseline Scenario of the Total Energy System up to 2050*", Heat Roadmap Europe, A low-carbon heating and cooling strategy, 2017;

[6] IEA, "*World Energy Outlook 2020*", International Energy Agency;

[7] A. Kiss, "*Thermal Hydraulic Investigation of the Coolant Flow in Supercritical Water – Cooled Reactor Relevant Geometries*", PhD Dissertation, DOI: 10.13140/RG.2.2.17769.24163;

[8] M. Belaid, R. Falcon, P. Vainikka, "*Pulverized Coal Versus Circulating Fluidized-bed Boilers. Perspectives and Challenges for South Africa*", South African Institution of Chemical Engineers (SAIChE);

[9] Bright Hup Engineering, "*Comparison of Circulating Fluidized Bed Boiler and Pulverized Coal Boiler*", https://www.brighthubengineering.com;

[10] L. Leoncini, "European Union Energy Trends from 2020 to 2050", 2019;

[11] M. Child, C. Kemfert, D. Bogdanov, C. Breyer, "*Flexible Electricity Generation, Grid Exchange and Storage for the Transition to a 100 % Renewable Energy System in Europe*", Renewable Energy, Volume 139, August 2019, Pages 80-101;

[12] S. Budinis, S. Krevor, N. M. Dowell, N. Brandon, A. Hawkes, "*An Assessment of CCS Costs, Barriers and Potential*", Energy Strategy and Reviews 22, 2018, Pages 61-81;

[13] X. Xie, Y. Wu, C. Chi, M. Zhang, "*Superalloys for Advanced Ultra-Super-Critical Fossil Power Plant Application*", DOI: 10.5772/61139, November 2015;

[14] P. Lako, "*Coal-fired Power Technologies. Coal-fired Power Options on the Brink of Climate Policies*", ECN-C-04-076, October 2004;

[15] M. A. R. do Nascimento, L. O. Rodrigues, E. C. dos Santos, E. E. B. Gomes, F. L. G. Dias, E. I. G. Velàsques, R. A. M. Carrillo, "*Micro Gas turbine Engine: A Review*", DOI: 10.5772/54444;

[16] General Electric web site - https://www.ge.com/power/gas/gas-turbines, access November 2020;

[17] K. Willnow, "Energy Efficiency Technologies – Annex III, Technical report. Energy Efficient Solutions for Thermal Power Plants", World Energy Council, 2013;

[18] CTCN – Climate Technology Center & Network, "Integrated Gasification Combined-Cycle", https://www.ctc-n.org/technologies/integrated-gasification-combined-cycle;

[19] European Environment Agency, "*EN19 Efficiency of Conventional Thermal electricity Production*", 2006;

[20] Petroleum Economist, "*Coal and CCGT Help Support Steam Turbine Market*", https://www.petroleum-economist.com/articles;

[21] Kanellopoulos K., "*Scenario Analysis of Accelerated Coal Phase-out by 2030. A Study on the European Power System Based on the EUCO27 Scenario using the METIS Model*", JRC Technical Reports, 2018;

[22] IEA, "World Energy Outlook 2020," 2020.

[23] Eurostat, "Electricity production capacities by main fuel groups and operator." [Online]. Available: https://ec.europa.eu/eurostat/data/database .

[24] ENTSO-E, "POWERFACTS," 2019.

[25] World Energy Council, "Five Steps to Energy Storage. Innovation Insights Brief 2020," 2020.

[26] European Association for Storage of Energy, "Energy Storage for a Decarbonised Europe by 2050," 2019.

[27] IRENA, "Electricity storage and renewables: Costs and markets to 2030," 2017.

[28] International Hydropower Association, "The world's water battery: Pumped hydropower storage and the clean energy transition," IHA Working Paper, 2018.

[29] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," Applied Energy, vol. 137, pp. 511–536, 2015.

[30] J. I. Pérez-Díaz et al., “Technological Developments for Pumped-Hydro Energy Storage,” in Mechanical Storage Subprogramme, Joint Programme on Energy Storage, European Energy Research Alliance, 2014.
[31] K. Mongird et al., “Energy Storage Technology and Cost Characterization Report,” 2019.
[32] G. Rossi et al., “AR1.3 Classificazione dei sistemi di accumulo in base all’applicazione ed al contesto,” 2020.
[33] G. F. Frate, L. Ferrari, and U. Desideri, “Energy storage for grid-scale applications: Technology review and economic feasibility analysis,” Renewable Energy, vol. 163, pp. 1754–1772, 2021.
[34] T. M. Letcher, Storing Energy: With Special Reference to Renewable Energy Sources. 2016.
[35] REEEM, “Innovation Readiness Level Report - Energy Storage Technologies,” 2017.
[36]] J Wang, K. Lu, L. Ma, J Wang, M. Dooner, S.Miao, J. Li, D. Wang: “Overview of Compressed Air Energy Storage and Technology Development”, *Energies*, 10, 991, 2017
[37] J.Cho, S. Jeong , Y. Kim: “Commercial and research battery technologies for electrical energy storage applications”, *Progress in Energy and Combustion Science*, 48, 2015
[38] C. Damak, D. Leducq, H. M. Hoang, D. Negro, and A. Delahaye, “Liquid Air Energy Storage (LAES) as a large-scale storage technology for renewable energy integration – A review of investigation studies and near perspectives of LAES,” International Journal of Refrigeration, vol. 110, pp. 208–218, 2020.
[39] C. Montorfano, “Sizing of a stand alone Liquid Air Energy Storage (LAES),” 2019.
[40] Ease and Eera, “European Energy Storage Technology Development Roadmap,” 2017.
[41] Sandia National Laboratories, “Flywheels,” 2015.
[42] Bolund B, Bernhoff H, Leijon M.: "Flywheel energy and power storage systems", *Renewable and Sustainable Energy Reviews*, Vol. 11, Issue 2, 2007.
[43] Benato, R., Dambone Sessa, S., Bevilacqua, F., Palone, F.: “Measurement-based lithium-manganese oxide battery model”, 2017 AEIT International Annual Conference: Infrastructures for Energy and ICT: Opportunities for Fostering Innovation, AEIT 2017, 2017-January, pp. 1-6.
[44] K. R. Pullen, “The Status and Future of Flywheel Energy Storage,” Joule, vol. 3, no. 6, pp. 1394–1399, 2019.
[45] N. Müller, S. Kouro, P. Zanchetta, P. Wheeler, G. Bittner, and F. Girardi, “Energy storage sizing strategy for grid-tied PV plants under power clipping limitations,” *Energies*, vol. 12, no. 9, pp. 1–17, 2019.
[46] L. S. Xavier, W. C. S. Amorim, A. F. Cupertino, V. F. Mendes, W. C. Boaventura, and H. A. Pereira, “Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review,” BCM Energy, vol. 1, no. 5, 2019.
[47] P. Breeze: “*Power generation technologies*”, Newnes publications, 3rd edition, 2019
[48] Battery Storage in the United States: An Update on Market Trends, U.S. Department of Energy, Washington, DC 20585, 2020.
[49] R. Benato, N. Cosciani, G. Crugnola, S. Dambone Sessa, G. Lodi, C. Parmeggiani, M. Todeschini: “Sodium nickel chloride battery technology for large-scale stationary storage in the high voltage network” *Journal of Power Sources*, 293, art. no. 21197, pp. 127-136., 2015.
[50] S. Dambone Sessa, G. Crugnola, M. Todeschini, S.Zin, R. Benato: “Sodium nickel chloride battery steady-state regime model for stationary electrical energy storage”, *Journal of Energy Storage*, 6, pp. 105-115, 2016.
[51] S. Dambone Sessa, F. Palone, A. Necci, R. Benato: “Sodium-nickel chloride battery experimental transient modelling for energy stationary storage”, *Journal of Energy Storage*, 9, pp. 40-46, 2017
[52] R. Benato, G. Bruno, F. Palone, R. M. Polito, M. Rebolini: ”Large-Scale Electrochemical Energy Storage in High Voltage Grids: Overview of the Italian Experience”, *Energies*, 10(1), 108, 2017
[53] Andriollo, M., Benato, R., Dambone Sessa, S., Di Pietro, N., Hirai, N., Nakanishi, Y., Senatore, E.: “Energy intensive electrochemical storage in Italy: 34.8 MW sodium-sulphur secondary cells”, *Journal of Energy Storage*, 5, pp. 146-155., 2016.
[54] EERA, “Superconducting magnetic energy storage - Fact Sheet 01,” 2019.
[55] IRENA, “Hydrogen from Renewable Power: Technology outlook for the energy transition,” 2018.
[56] IRENA, “Hydrogen: A renewable energy perspective,” 2019.
[57] European Commission, “Renewable Energy Progress Report,” 2020.
[58] IRENA, “Renewable Energy Prospects for the European Union,” 2018.
[59] ENTSO-E, Storage projects sheets, https://tyndp2020-project-platform.azurewebsites.net/projectsheets/storage .

[60] R. Rudervall, J.P. Charpentier, R. Sharma, *"High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper"*, in Energy Week 2000, Washington, D.C, USA, March 7-8, 2000.
[61] ENTSO-E, *"HVDC Links in System Operations",* Technical paper, 2019.
[62] ENTSO-E, *"TYNDP 2020 Main Report November 2020 – Version for public consultation",* Technical paper, 2020.
[63] V. Gabor Csutar, S. Kallikuppa and L. Charles, *"Introduction to HVDC Architecture and Solutions for Control and Protection",* application report, 2020
[64] Arda-Garibaldi G, Cruz-Romero P, Gomez-Exposito A., *"Future power transmission: visions, technologies and challenges",* Renew Sustain Energy Rev, 2018,94:285-301.
[65] A. Alassi, S. Bañales, O. Ellabban, G. Adam, and C. MacIver, *"HVDC Transmission: Technology Review, Market Trends and Future Outlook,"* Renewable and Sustainable Energy Reviews, vol. 112. Elsevier Ltd, pp. 530–554, 01-Sep-2019.
[66] Van Hertem D, Delimar M., *"6 - High Voltage Direct Current (HVDC) electric power transmission systems",* in Melhem Z, editor. Electricity transmission, distribution and storage systems. Woodhead Publishing, 2013, p. 143-73.
[67] Barthold LO, *"Technical and economic aspects of tripole HVDC"* in 2006 international conference on power system technology, 2006.
[68] Sellick RL, Àkerberg M., *"Comparison of HVDC Light (VSC) and HVDC Classic (LCC) site aspects, for a 500 MW 400kV HVDC transmission scheme",* in 10th IET international conference on AC and DC power transmission (ACDC 2012), 2012.
[69] Pan Z, Wang X, Mei G, Liu Y, Yao W, Liu H, et al., *"A transformer neutral current balancing device to restrain half-cycle saturation induced by HVDC monopolar operations",* Electr Power Syst Res, 2016,132:104-14.
[70] Marzinotto M, Mazzanti G, Nervi M., "*Ground/sea return with electrode systems for HVDC transmission",* Int J Electr Power Energy Syst, 2018,100:222-30.
[71] Skog J-E, Koreman K, Pàajarvi B, Worzyk T, Andersrod T. The NorNed, *"HVDC cable link: a power transmission highway between Norway and The Netherlands",* ABB Online Library.
[72] Boeck SD, Tielens P, Leterme W, Hertem DV, *"Configurations and earthing of HVDC grids"* in 2013 IEEE power & energy society general meeting, 2013.
[73] Kalair A, Abas N, Khan N., *"Comparative study of HVAC and HVDC transmission systems",* Renew Sustain Energy Rev, 2016,59:1653-75
[74] Bahrman MP, Johnson BK, *"The ABCs of HVDC transmission technologies",* IEEE Power Energy Mag 2007,5:32-44.
[75] Kalair A, Abas N, Khan N., *"Comparative study of HVAC and HVDC transmission systems",* Renew Sustain Energy Rev, 2016,59:1653-75
[76] Aspinall N, *"Electric transmission: HVDC and interconnectors",* BNEF, 2016.
[77] D. Jovcic and K. Ahmed, *"High-Voltage Direct Current Transmission: Converters, Systems and DC Grids",* Wiley 2015, 201AD.
[78] J. Burr, S. Finney, C. Booth, *"Comparison of Different Technologies for Improving Commutation Failure Immunity Index for LCC HVDC in Weak AC Systems,"* 11th IET International Conference on AC and DC Power Transmission, 2015.
[79] Bahrman MP, Johansson JG, Nilsson BA*, "Voltage source converter transmission technologies - the right fit for the application",* Power Eng Soc Gen Meet, 2003,1-8.
[80] Asplund G, Eriksson K, Jiang H, Lindberg J, Pàlsson R, Svensson K, *"DC transmission based on voltage source converters",* in Proceedings CIGRE SC14 Colloq. South Africa 1997, 1997.
[81] Oluwafemi E. Oni, Innocent E. Davidso, Kamati N.I. Mbangula *"A Review of LCC-HVDC and VSC-HVDC Technologies and Applications",* 978-1-5090-2320-2016 IEEE
[82]] Latorre HF, Ghandhari M, "*Improvement of power system stability by using a VSC-HVDC*", Int J Electr Power Energy Syst, 2011,33(2):332-9.
[83] Beerten J, Cole S, Belmans R, *"Generalized steady-state VSC MTDC model for sequential AC/DC power flow algorithms"*, IEEE Trans Power Syst, Vol Appear 2012,2:1-9.
[84] Mukhedkar R, *"Introduction to HVDC LCC & VSC - comparison HVDC converter technology",* South Asia Reg Initiat Energy Integr, 2010:1-9.
[85] Barnes M, Beddard A, *"Voltage source converter HVDC links - the state of the art and issues going forward",* in Energy Procedia, 2012,24:108-22.

[86] Gu X, He S, Xu Y, Yan Y, Hou S, Fu M., *"Partial discharge detection on 320 kV VSC-HVDC XLPE cable with artificial defects under DC voltage",* IEEE Trans Dielectr Electr Insul, 2018,25:939-46.

[87] Yuheng-Weifang, "*1000kV UHV AC transmission and transformation project starts construction",* China: State Grid, 2015.

[88] Chen G, Zhou X, Chen R, *"Variable frequency transformers for large scale power systems interconnection: theory and applications",* Wiley, 2018.

[89] Pierri E, Binder O, Hemdan NGA, Kurrat M., *"Challenges and opportunities for a European HVDC grid",* Renew Sustain Energy Rev, 2017,70:427-56.

[90] Sood VK., *"31 - HVDC transmission",* In: Rashid MH, editor. Power electronics handbook third ed. Boston: Butterworth-Heinemann, 2011. p. 823-49.

[91] Dynamic reactive compensation - MV STATCOM ABB, 2008.

[92] Jung H, Biletskiy Y., *"Evaluation and comparison of economical efficiency of HVDC and AC transmission",* in 2009 Canadian conference on electrical and computer engineering, 2009.

[93] N. Flourentzou, V.G. Agelidis, and G.D. Demetriades, *"VSC-Based HVDC Power Transmission Systems: An Overview,"* IEEE Trans. Power Electron., vol. 24, no. 3, pp. 592–602, 2009.

[94] T. W. May, Y. M. Yeap and A. Ukil, *"Comparative evaluation of power loss in HVAC and HVDC transmission systems,"* 2016 IEEE Region 10 Conference (TENCON), Singapore, 2016, pp. 637-641, doi: 10.1109/TENCON.2016.7848080.

[95] ENTSO-E, *"Statistical factsheet 2018",* Technical report, 2019.

[96] IEC – Transmission and distribution. https://www.iec.ch/resource-centre/transmission-and-distribution-td. Access December 2020.

[97] N. B. Negra, J. Todorovic, and T. Ackerrnann, *"Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms,"* Electric Power Systems Research, vol. 76, no. 11, pp. 916-927, 2006.

[98] D. V. Hertern and M. Ghandhar, *"Multi-terminal VSC-HVDC for the European supergrid: Obstacles,"* Renewable and sustainable energy reviews, vol. 14, no. 9, pp. 3156-3163, 2010.

[99] H. Pang, G. Tang, and Z. He, "*Evaluation of losses in VSC-HVDC transmission system,"* in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, July 2008, pp. 1-6.

[100] P. Jansohn: Modern gas turbine systems: High efficiency, low emission, fuel flexible power generation, Woodhead Publishing, ISBN: 9781845697280, 2013.

[101] P. Breeze: Gas-Turbine Power Generation, Elsevier, ISBN 13: 9780128040058, 2016.

[102] A. Benabouda, Alfred Ruferb: "Gas Turbine: Optimization of Energy Production and High Efficiency by Using Power Electronics", Procedia Engineering 138, pp. 337 – 346, 2016.

[103] Cigré Technical Brochure 492: "Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies", ISBN: 978-2-85873-184-8, 2012.

[104] IEC 61803: Determination of Power Losses in High-Voltage Direct Current (HVDC) Converter Stations, 1999.

[105] P. L. Jones and C. C. Davidson, "Calculation of power losses for MMC-based VSC HVDC stations," *Proc. Of 15th Eur. Conf. Power Electron. Appl.*, Lille, Sep. 2013, pp. 1–10.

List of abbreviations and definitions

AC	Alternate Current
ALK	ALKaline electrolyser
BESS	Battery Energy Storage Systems
CAES	Compressed Air Energy Systems
CCGT	Combined Cycle Gas Turbine
DC	Direct Current
DCCB	Direct Current Circuit Breaker
DOD	Depth Of Discharge
EHV	Extremely High Voltages
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible AC Transmission Systems
GT	Gas Turbine
HP	High Pressure
HRSG	Heat Recovery Steam Generator
HV	High Voltage
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IGCC	Integrated Gasification Combined Cycle
LAES	Liquid Air Energy Systems
LCC	Line Commutated Converter
LP	Low Pressure
MMC	Modular Multilevel Converter
MP	Medium Pressure
OCGT	Open Cycle Gas Turbine
P2H	Power to Hydrogen
PEM	Proton Exchange Membrane
PHS	Pumped Hydro Storage
RES	Renewable Energy System
ROW	Right-Of-Way
RTE	Round Trip Efficiency
SMES	Super Magnetic Energy System
SOC	State of Charge
STATCOM	STATic synchronous COMpensator
SVC	Static Var Compensator
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VLA	Vented Lead-Acid

VRLA	Valve-Regulated Lead-Acid
VSC	Voltage Source Converter

List of figures

List of tables

APPENDIX I – Coal

Table A.1 EU Annual Production of Electricity from Coal [TWh] (Source Bp Stats review 2020)

Year	EU Annual Production of Electricity from Coal [TWh]	EU Total Annual Electricity Production [TWh]	Coal Production as a Proportion of Annual EU Electricity Generation [%]
1985	969,7	2321,0	41,8
1986	994,9	2377,1	41,9
1987	1010,0	2450,4	41,2
1988	998,7	2507,2	39,8
1989	1022,5	2564,0	39,9
1990	1040,2	2594,9	40,1
1991	1042,8	2640,8	39,5
1992	996,3	2624,6	38,0
1993	951,7	2627,2	36,2
1994	955,8	2665,8	35,9
1995	965,2	2747,0	35,1
1996	976,6	2842,4	34,4
1997	926,2	2858,3	32,4
1998	931,4	2925,1	31,8
1999	896,3	2955,4	30,3
2000	948,5	3037,7	31,2
2001	960,7	3119,7	30,8
2002	967,7	3142,9	30,8
2003	1025,5	3237,2	31,7
2004	1005,1	3305,6	30,4
2005	981,1	3327,3	29,5
2006	1003,8	3371,2	29,8
2007	1006,6	3384,3	29,7
2008	919,2	3388,7	27,1
2009	836,3	3224,4	25,9
2010	846,1	3364,7	25,1
2011	869,7	3299,2	26,4
2012	920,1	3295,4	27,9
2013	892,8	3269,6	27,3
2014	825,7	3188,4	25,9
2015	811,1	3236,6	25,1
2016	721,2	3259,4	22,1
2017	694,2	3290,0	21,1
2018	643,6	3270,1	19,7
2019	488,4	3215,3	15,2

Table A.2. Classification of pulverized coal combustion (PCC) power plants in terms of steam parameters i.e., steam temperature and pressure and materials necessary in high temperature components [1.3, 1.7]

Technology	**Superheater temperature and pressure**	**Material in high temperature components**	**η Efficiency LHV net Hard coal [%]**	**Coal Consumption [gCOAL/kWh]**
SUBCRITICAL **SB**	≤ 540°C < 22,1 MPa	Low alloy CMn and Mo ferritic steels	**<35**	≥380
SUPERCRITICAL **SC**	540°C÷580°C 22,1÷25 MPa	Low alloy CrMo steels and 9–12% Cr martensitic steel	**35÷40**	380÷340
ULTRASUPERCRITICAL **USC**	580°C÷620°C 22÷25 MPa	Improved 9–12% Cr martensitic steels and austenitic steels	**40÷45**	340÷320
ADVANCED ULTRASUPERCRITICAL **A-USC** **(ONLY UNDER STUDY)**	700°C÷720°C 25÷35 MPa	Advanced 10–12% Cr steels and nickel alloys	**45÷52**	320÷290

APPENDIX II – Gas

Table A.3. Natural gas production as a proportion of annual global electricity generation (Source: Bp Stats review 2020)

Year	Annual Production of Electricity from Natural Gas [TWh]	Total Global Annual Electricity Production [TWh]	Natural Gas Production as a Proportion of Annual Global Electricity Generation [%]
1973	740	6117	12,1
2004	3420	17 450	19,6
2005	3623	18 239	19,7
2006	3805	18 930	20,1
2007	4132	19 771	20,9
2008	4299	20 181	21,3
2009	4292	20 055	21,4
2010	4758	21 431	22,2
2011	4846	22 126	21,9
2012	5100	22 668	22,5
2013	5084	23 434	21,7
2014	5241	24 030	21,8
2015	5588	24 266	23,0
2016	5824	24 923	23,4
2017	5926	25 643	23,1
2018	6083	26 653	22,8
2019	6298	27 005	23,3

Table A.4. EU Annual Production of Electricity from Natural Gas [TWh] (Source Bp Stats review 2020)

Year	EU Annual Production of Electricity from Natural Gas [TWh]	EU Total Annual Electricity Production [TWh]	Natural Gas Production as a Proportion of Annual EU Electricity Generation [%]
1985	169,0	2321,0	7,28
1986	171,3	2377,1	7,21
1987	181,4	2450,4	7,40
1988	181,3	2507,2	7,23
1989	198,1	2564,0	7,73
1990	190,1	2594,9	7,33
1991	190,7	2640,8	7,22
1992	186,7	2624,6	7,11
1993	213,5	2627,2	8,13
1994	242,1	2665,8	9,08
1995	267,8	2747,0	9,75
1996	312,3	2842,4	10,99
1997	360,2	2858,3	12,60
1998	390,5	2925,1	13,35
1999	453,7	2955,4	15,35
2000	477,9	3037,7	15,73
2001	494,5	3119,7	15,85
2002	527,6	3142,9	16,79

Year	EU Annual Production of Electricity from Natural Gas [TWh]	EU Total Annual Electricity Production [TWh]	Natural Gas Production as a Proportion of Annual EU Electricity Generation [%]
2003	570,5	3237,2	17,62
2004	617,6	3305,6	18,68
2005	668,5	3327,3	20,09
2006	683,1	3371,2	20,26
2007	738,8	3384,3	21,83
2008	790,7	3388,7	23,33
2009	733,1	3224,4	22,74
2010	764,8	3364,7	22,73
2011	701,3	3299,2	21,26
2012	580,6	3295,4	17,62
2013	507,4	3269,6	15,52
2014	456,0	3188,4	14,30
2015	495,3	3236,6	15,30
2016	608,1	3259,4	18,66
2017	660,7	3290,0	20,08
2018	621,2	3270,1	19,00
2019	692,2	3215,3	21,53

Overview of GT manufacturers

1. General Electric (including former Alstom, acquired at the end of 2015);
2. Siemens (formerly Siemens–Westinghouse, formerly separate companies, i.e., Kraftwerk Union (KWU) Siemens Power Generation and Westinghouse Electric Corporation);
3. Mitsubishi Hitachi Power Systems (MHPS, formerly Mitsubishi Heavy Industries, MHI);
4. Ansaldo Energia.

Ratings and efficiencies of GTs are annually reported in two Journals i.e.:

- Gas Turbine World (GTW), http://www.gasturbineworld.com;
- Turbomachinery International (TMI), https://www.turbomachinerymag.com.

Table A.5 reports all the heavy-duty gas turbine up to 2020 with power ratings greater than 100 MW.

In order to understand the symbols in Table A.5, the following classification is used. In fact, heavy-duty industrial gas turbines are subdivided in accordance with their nominal **TIT** (as already explained, the hot gas temperature at the exit of the combustion section just before entry into the turbine). There are four major classes:

- E class with nominal TIT of 1 300°C;
- F class with nominal TIT of 1 400°C;
- H class with nominal TIT of 1 500°C;
- J class with nominal TIT of 1 600°C.

Table A.5 2018-2018 GT world simple cycle specifications [1.18]: power ratings > 100 MW

MODEL	YEAR OF INTRODUCTION	ISO BASE LOAD RATING [MW]	η **[%]**	NOTES
ANSALDO ENERGIA				
AE94.2	1981	185	**36,2**	
AE94.2K	1981	170	**36,5**	LOW LHV FUEL
AE 94.3A	1995	325	**40,1**	
GT26	2011	345	**41,0**	
GT36-S6	2016	340	**41,0**	
GT36-S5	2016	500	**41,5**	
GENERAL ELECTRIC				
9E.03	1992	132	**34,6**	
9E.04	2014	145	**37,0**	
9F.03	1996	265	**37,8**	
9F.04	2015	288	**38,7**	
9F.05	2003	314	**38,2**	
9HA.01	2011	446	**43,1**	
9HA.02	2014	557	**44,0**	Calculated TIT =1670 °C
MITSUBISHI HITACHI POWER SYSTEMS (50 Hz)				
H-100	2013	118,08	**38,3**	
M701DA	1981	144,09	**34,8**	
M701G	1997	334	**39,5**	
M701F	1992	385	**41,9**	
M701J	2014	478	**42,3**	
M701JAC	2015	493	**42,9**	
SIEMENS ENERGY (50 Hz)				
SGT5-2000E	1981	187	**36,2**	
SGT5-4000F	1995	329	**41,0**	

MODEL	YEAR OF INTRODUCTION	ISO BASE LOAD RATING [MW]	η [%]	NOTES
SGT5-8000H	2008	450	**41,0**	
SGT5-8000HL	2017	465	**42,0**	
SGT5-9000HL	2017	564	**42,5**	
PW POWER SYSTEMS (50 Hz)				
FT4000SWIFTPAC120	2012	140,376	**40,9**	
ETHOSENERGY				
TG50D5U	2007	144,5	**34,6**	
BHARAT HEAVY ELECTRICALS				
MS9001E(9E.03)	2012	130,4	**34,4**	
MS9001FB(9F.03)	1996	250,2	**37,5**	
MS9001FB (9E.05)	2004	297,0	**38,9**	

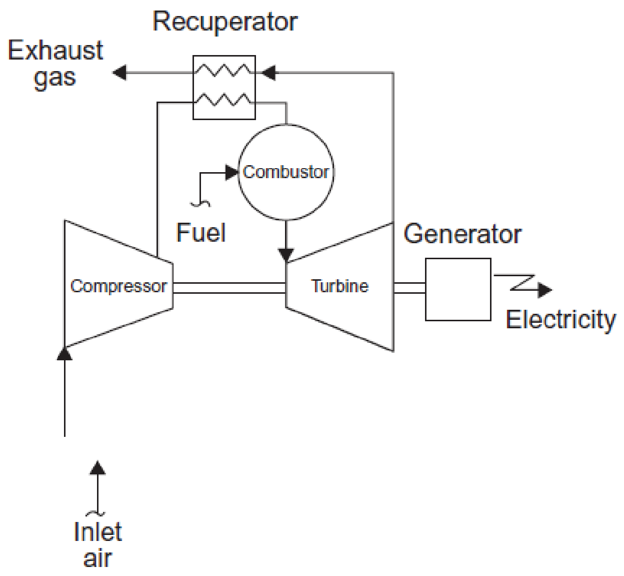
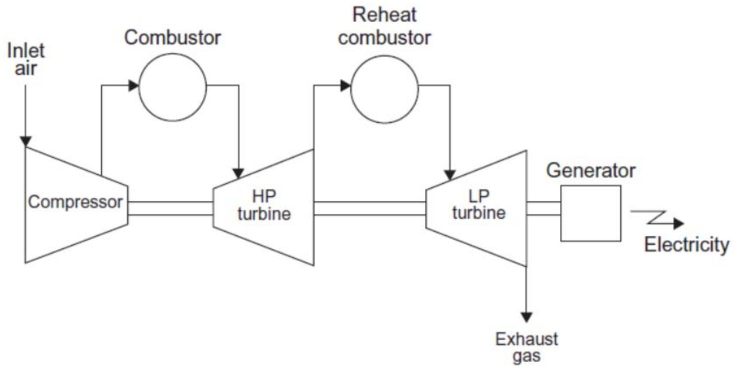
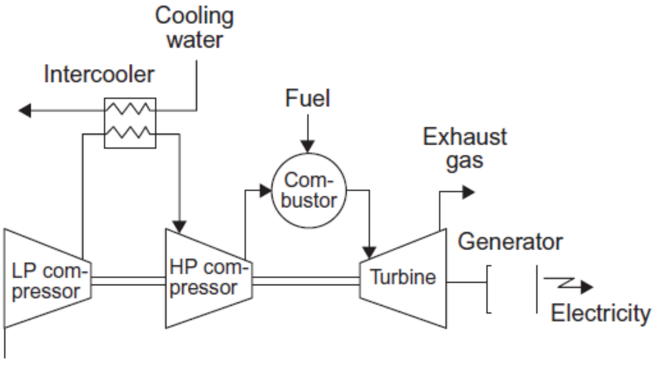
From Table A.5, state of the art in the largest and most efficient heavy-duty GTs can be summarized as follows:

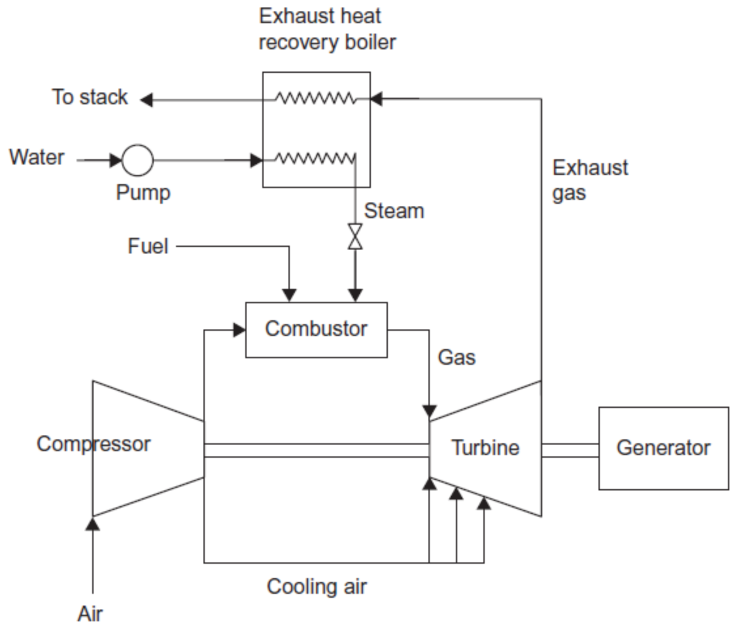
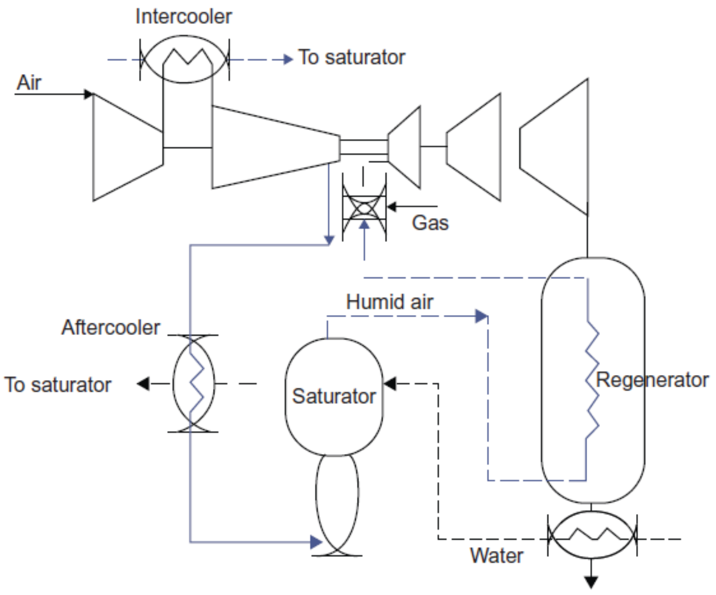
- Outputs of 500 MWe;
- TITs of 1700°C;
- Cycle pressure ratios above 20:1 and as high as 25:1;
- Maximum Efficiency of 44%.

Advanced gas turbine

Many modifications can be implemented to the simple cycle of a GT in order to improve its overall efficiency. Table A.6 sums up the different possibilities and the achievable efficiencies [101].

Table A.6 Modifications in GT cycle in order to increase efficiency

Typology of modification	Efficiency	Scheme
Recuperation	40,2	
Reheating	Alstom	
Intercooling	46 % GE LMS 100	

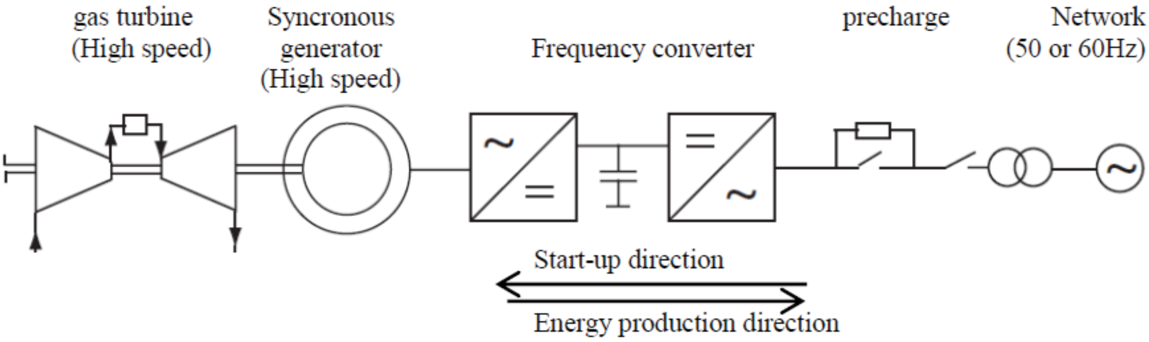
Typology of modification	Efficiency	Scheme
Mass Injection	The net result is an increase in efficiency compared to the same turbine without steam injection of 2% - 4%.	
Humid **A**ir **T**urbine (**HAT**) cycle	55 %	

Some authors propose to substitute the mechanical gearbox that links the turbine shaft with the synchronous generator: this gearbox reduces the rotational speed by maintaining the rpm necessary to the synchronous generator (depending on the polar couples). The gearbox could be substituted by a flexible electronic solution, which offers the ability to operate with very high power and increases turbine efficiency by using variable speed[102].

The paper does not give the overall efficiency gain, but it only specifies that the frequency converter efficiency is 99,5 % whereas the typical efficiency of a gearbox is 98,5 %.

Figure B1 offers a suggestion of the electrical power generation system by using frequency converter.

Figure B1. Scheme of the electrical power generation system using frequency converter



APPENDIX III – Storage

Table C.1 Overview of the life of electric energy storage systems

Technology	Average Life [years]	Discharge time
PHS	50	1 hour-more than 24 hours
CAES	20-40	1 hour-more than 24 hours
FES	15-20	seconds - 15 min
Pb-A	15-30	Typical rated discharge time: 5 h
Li-ion	5-16	Typical rated discharge time: 1 h
NiCd	10-15	10 minutes-5 hours
NaS	15-20	Typical rated discharge time: 8 h
$NaNiCl_2$	15	Typical rated discharge time: 3 h
ULTRACAP	10-15	milliseconds-hours

APPENDIX IV – HVDC Technologies

Table D.1. is adapted and updated from Cigré TB # 432 "Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies" [103] Moreover, table D.1 gives an immediate comparison between the two different HVDC technologies in terms of power transmission.

Table D.1 Bulk Power transmission by means of HVDC-LCC and HVDC-VSC (updated from [103])

Power Range	HVDC- LCC	HVDC- VSC
7500 MW-12000 MW	UHVDC Bulk (Bipole DC 1100 kV)	
5000 MW- 7500 MW	UHVDC Bulk (Bipole DC 800 kV)	-
2500 MW-5000 MW	UHVDC Bulk (Bipole DC 800 kV)	-
1800 MW-3500 MW	HVDC Classic (Bipole DC 500 kV)	Bulk power VSC HVDC (Overhead line)
700 MW-2000 MW	HVDC Classic (Bipole DC 400kV-500kV)	High power VSC HVDC
300 MW-800 MW	HVDC Classic (Monopole DC 300kV-500kV)	Medium power VSC HVDC
< 300 MW	HVDC Classic (Monopole DC< 300kV)	Low power VSC HVDC

The main characteristics of HVDC-LCC are summed up in Table D.2. The table is taken from [103] but it has been updated and adapted.

Table D.2 State of the art of HVDC – LCC (updated from [103])

Power Transmission	**Overhead lines**	**Insulated Cables**
Maximum voltage level	**1100 kV DC**	**500 kV DC (600 kV_{dc} with PPL MI)**
Maximum power rating	**<12000 MW**	
Maximum transmission distance	**Unlimited**	
Footprint	**200 x 120 x 20 m (600 MW)**	
Active power flow control	**Continuous, min. 10% load**	
Reactive power demand	**50%-60% of converter power rating** **Compensated by breaker switched ac harmonic filters and reactive power banks**	
AC Voltage control	**Slow, transformer tap change**	
Power Reversal	**DC voltage reversal**	
Necessary filter equipment	**High demand**	
Grid connection requirements	**SCR> 2 x power rating**	
Black start / island supply	**Not inherently available**	
Typical Power Loss in the two converter stations at full power	**1,4%**	

Table D.3 sums up the main characteristics of HVDC-VSC.

Table D.3 State of the art of HVDC – VSC (updated from [103])

Power Transmission	**Overhead lines**	**Insulated Cables**
Maximum voltage level	**≤ 640 kV**	**≤ 600 kV**
Maximum power rating	**< 1600 MW**	
Maximum transmission distance	**Theoretically unlimited (voltage drop over line)**	
Space requirements (examples)	**120 x 50 x 11 m (550 MW); 48 x 25 x 27 m (500 MW) [w x l x h]**	
Active power flow control	**Fast continuous**	
Reactive power demand	**Can provide or consume controlled reactive power as required**	
AC Voltage control	**Continuous, full response in < 100 ms**	
Power Reversal	**DC current reversal**	
Necessary filter equipment	**Low demand (PWM); Not necessary with other topologies**	
Grid connection requirements	**Can supply power to a passive network**	
Black start / island supply	**Black-start capability and island supply requires an aux. power system to initially energize the cooling system (e.g.,by means of a diesel generator)**	

HVDC-LCC converter station power losses

Table D.4 Converter station power losses due to each component in HVDC-LCC

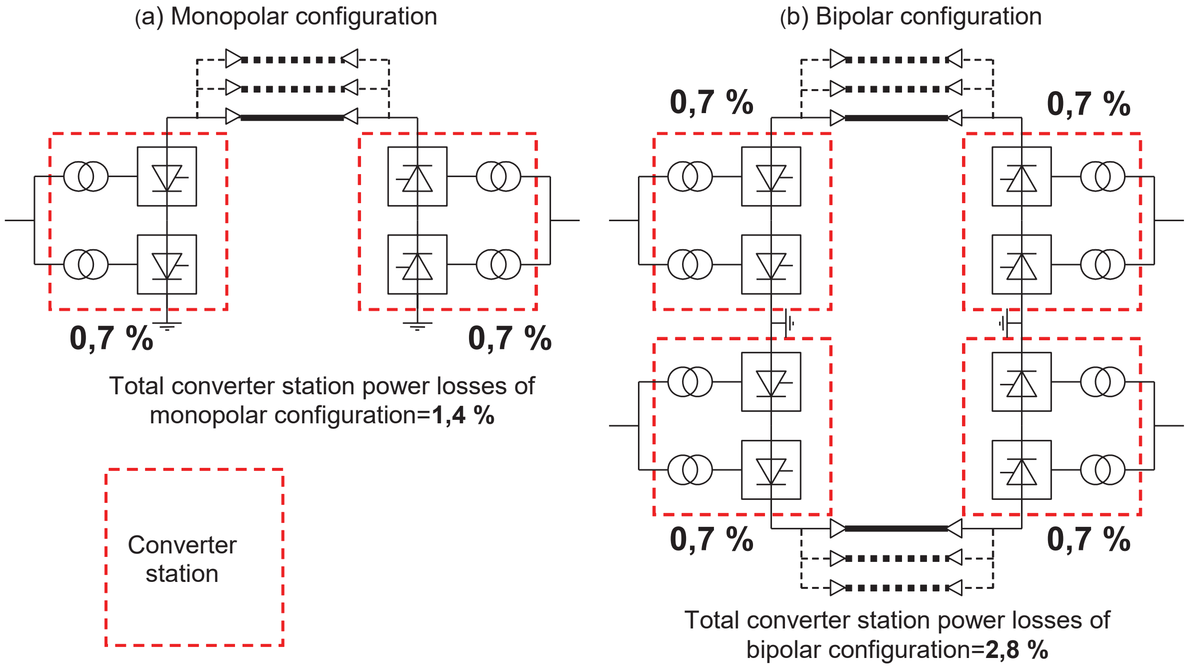
Components		**Operation**	
		Standby	**Rated power**
Filters	**AC**	4%	4%
	DC	0%	<0.1%
Converter transformers		53%	47%
Thyristor valves		10%	36%
Smoothing reactor		0%	4%
Auxiliary systems	**Valve cooling system**	4%	3%
	Transformer cooling system	4%	1%
	Cooling system	15%	4%
	Other systems	10%	1%
Total power losses @20 °C		100%	100%
Power loss Percentage (with reference to rated power)		***0,11%***	***0,70%***

Table D.5 Typical station losses due to each component in HVDC-LCC (after Annex B IEC 61803 [104])

Item	Typical losses at nominal operating conditions %
Thyristor valves	20-40*
Converter transformers	40-55
AC filters	4-10
Shunt capacitors (if used)	0,5-3
Shunt reactors (if used)	2-5
Smoothing reactor	4-13
DC filters	0,1-1
Auxiliaries	3-10
Total	100

* The total station no-load operation losses range from 10 % to 20 % of the total station operating losses at rated power under nominal operating conditions

Figure. D1 HVDC-LCC: power losses of each converter station as a percentage of rated power for monopolar and bipolar configurations



GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub

ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub