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COMMISSION ENERGY 2030
Classical electricity production
CO2 capture and storage

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1 INTRODUCTION

The main objectives of the present section is to provide up to date data about actual and future technologies dedicated to electricity centralized production on one hand, and for CO2 capture/storage on the other hand.

For classical power plants it is relatively easy to have consistent and validated data. But for future technologies, it is not so evident to make a clear difference between actual performances and targeted or expected values. Future performances are not only linked to technical questions but are also related to the economic environment and to others non-defined constraints (i.e.: future environmental standards…).

In the section devoted to classical electricity power plant systems, we did not consider nuclear power plants and we restricted our presentation to open cycle gas turbine and combined cycles based on gas turbine and steam turbine who are today the most popular systems burning natural gas.

Moreover we consider different solutions able to burn coal. Even coal is in bad position for CO2 emissions this solid fuel is abundant and widely available.

Main solution for using coal is presently classical sub-critical steam cycle. This cycle is now changing to supercritical steam cycle.

Other solutions are still under development since many years as Atmospheric Fluidised Bed (AFB) or Pressurised Fluidised Bed (PFB) combustion and Integrated Gas Coal Gasification plant IGCC. Some could be interesting in the future considering low grade fuels, more stringent environmental legislation and CO2 capture.

In correlation with the use of coal, we have to be very concerned, due to the high carbon content of the fuel, with CO2 capture and storage.

In the last section we will examine CO2 capture systems and storages systems.

2 CLASSICAL ELECTRICAL POWERPLANT

2.1 Mature technologies

We have at disposal different technologies already described in the AMPERE commission report.

We consider here as mature technologies only open cycle gas turbine, combined cycle gas turbine (GTCC) and coal sub-critical steam power plant.

2.1.1 Open cycle gas turbine

In the open cycle gas turbine, atmospheric air is compressed in a rotating compressor, and then is mixed with natural gas in a combustion chamber. The hot combustion gases are expanded in a turbine. Compressor and turbine are coupled on a single shaft with the alternator producing electricity.

Such equipments are installed in Belgium as peak units to face the peak of electricity demand. The main advantages are a fast response time, a low cost per kW installed and a modular installation.

Due to the use of aero-derivative gas turbine, instead of industrial gas turbine, the global efficiency, direct linked with the temperature at the inlet of turbine is now currently 39%.

Research is focused on the increase of this temperature from 1260 °C to 1430 °C. The global efficiency could then reach in 2030: 44%.

The development of gas turbine open cycle in a given geographic area is linked with the ability of other power plants to offer good performances at partial load and to be able to fulfil quickly the spot demand of electricity.

The gas turbine improvements will also benefit to combined cycles described in the following section.

2.1.2 Gas turbine combined cycle (GTCC)

Gas turbine combined cycle (GTCC power plant) combines two systems: an open gas turbine cycle and a closed steam turbine cycle.

The residual heat contained in the exhaust gases of the gas turbine is used as hot source in a boiler (HRSG) to produce steam. This steam is expanded in a steam turbine, then is condensed in a condenser and pumped to the boiler.
The electricity produced by each alternator coupled to the turbines is added so the total efficiency of the combined cycle is increased and can reach a value a bit less of 60%.
These installations are modular and can be rapidly erected.
Reasonable improvement of the cycle will allow reaching 65% global efficiency in 2020 (68% claimed). Efficiency is important not only from the economic point of view but also for CO_2 emissions. (Reduction expected to 350g CO_2/kWh).

Today the unique fuel burned in these cycles in Belgium is natural gas.

Works are under consideration for hydrogen use but actually with no guarantee from the turbine manufacturers. If using H_2, exhaust gases are CO_2 free but the problem is reported to the hydrogen production plant.

The power range of actual gas turbine combined cycles is around 300 MWe (2/3 produced by the gas turbine, 1/3 produced by the steam turbine).

Improvements are expected not only for efficiency (65%) but also for availability and reliability.

Combined cycle technology burning natural gas is popular and will continue to play an important role in Belgium until 2030 despite the fact that the price of the kWh depends strongly with the natural gas prize.

2.1.3 Coal fired classical steam power plant

Since many years steam power plant burning pulverised coal are used worldwide.

In these installations, water under pressure is heated and evaporated in a boiler burning coal. The steam produced is expanded in a steam turbine coupled to an alternator.
After expansion in the turbine, steam is condensed in a condenser cooled with cold water from river.

The temperature and the pressure at the inlet of the turbine are usually under the critical conditions for steam (221 bars, 375°C). With these conditions, global efficiency is limited to 45-47%. The efficiency is of course linked to the coal quality. In brown coal fired plants currently under construction in Germany, the efficiency is around 42%. In new bituminous coal fired units, efficiency is around 45%.
Pulverised coal boilers have been built to match steam turbines with electrical outputs between 50 and 1300MWe.
These installations are interesting because the load can be varied in a large domain without loosing too much efficiency.

Various measures can be used to increase the thermal efficiency in particular: reducing the excess air ratio in the boiler, reducing the stack gas exit temperature, increasing pressure and temperature at the inlet of the turbine, using a second reheat stage and decreasing the condenser pressure. 47% efficiency seems to be a practical limit for coal fired classical steam power plant.

On another hand, there are problems with SOx emissions (due to sulphur content of the coal) and NOx emissions (due to high temperature and low air excess in the burner). Flue gas cleaning is imperative to meet actual environmental standards. The after-treatments have a small effect on overall thermal efficiency but the capital cost of the measures can represent about one third of the cost of the unit.
The sub-critical steam cycle is now mature, there are thousands of units around the world and we can not expect new major improvements.

2.2 Advanced technologies

2.2.1 Coal fired super-critical power plant

When the temperature or the pressure of the steam at the inlet of the turbine is higher than critical values, the thermodynamic cycle is called super-critical.

Based on temperature and pressure values, the cycles are divided into three categories:

- SC super-critical (pressure up to 250 bars, temperature up to 565 °C)
- ASC advanced super-critical (pressure up to 300 bars, temperature up to 585°C)
- USC Ultra-super-critical (pressure above 300 bars, temperature above 585°C)

Increasing temperature and pressure is not easy and requires new high performance materials.

The maximum efficiency is expected for ultra super-critical cycle and is around 55%

An increasing of 1-2% of the efficiency is possible with a cycle using a double reheat of the steam. Such system is in service in a power plant in USA since 1960 and in Japan since 1990. The complexity of the cycle will limit the use of a double reheat.

SOx and NOx emissions are a problem for sub-critical cycles but also for super-critical cycles.
Solutions exist but are expensive. SOx are limited with dolomite injection in flue gases and NOx are limited with urea injection in flue gases. The chemical reactions can be improved with catalyst. These equipments are costly and reduce the global efficiency about 1-2 points.

Super-critical power plant will be an attractive solution to replace old sub-critical installation.

2.2.2 Integrated gas coal gasification plant

The IGCC power plant is a combined cycle burning in a conventional steam plant a synthesis gas (CO +H2) obtained by upstream coal gasification. The syngas is burned in a conventional gas turbine. A heat recovery system HRSG placed in the exhaust of the turbine produce steam for a classical steam cycle. The media used for gasification could be oxygen or air. Different type of gasifier has been developed using a fixed bed, a fluidised bed or an entrained flow.
The entrained flow oxygen gasifier seems to be the most promising technology. It is used at Buggenum power plant (253 MWe; efficiency 43%) since 10 years. The oxygen is produced in a distinct unit of air separation using a cryogenic process. The compressed air is extracted from the compressor of the gas turbine so we can speak about a completely integrated cycle.

The maximum efficiency forecasted in 2030 is around 55%. This technology presents a good potential for improvement and will be able to burn low grade fuels. We note that the part load efficiency is lower than the corresponding supercritical power plant.

A number of demonstration units, mainly around 250 MWe size are being operated in Europe and USA. The 253MWe unit at Buggenum started up in 1993 in the Netherlands, three plants is in the USA at Wabash River in Indiana, at Polk Power in Florida and Pinon Pine in Nevada. The largest unit is in Spain at Puertollano with a capacity of 330MWe.

All the current IGCC coal-fuelled demonstration plant are subsidised so it is not evident to estimate exact cost of kWh for future commercial installations.

IGCC may be able to achieve higher thermal efficiency than super-critical steam power plant and be able to match the environmental performances of gas-fired plants.

2.2.3 Coal fluidized bed technologies (AFBC, PFBC)

The combustion in fluidized bed is a technology where coal is burned in a bed composed mainly by inert solid maintained in suspension by air flow. A heat exchanger placed in the bed produce the steam.

The steam is expanded in a turbine linked to the alternator.

If the bed is at atmospheric pressure the system is named AFBC. The efficiency is relatively low: 38%.

If the bed is under pressure (10-15 bars), the system is named PFBC. In PFBC, combustion gases under pressure are expanded in a gas turbine. The power of the gas turbine and the steam turbine are added so the global efficiency could reach 49% (coupling with a super-critical steam cycle).

Filtration problems of combustion gases at the inlet of the gas turbine are not solved and new high resistance materials have to be developed for the heat exchanger and for the gas turbine.

Combustion takes place at temperatures around 800-900°C allowing a reduction in NOx formation compared with super-critical power plant. SOx emissions can be reduced by injection of sorbent (limestone or dolomite) in the bed and subsequent removal of ash.

The current PFBC demonstration units are all around 80 MWe capacity but two larger units have been started up in Japan at Karita (360 MWe) and Osaki (250 MWe).

There are several inherent problems with PFBC technology that have limited its application: durability problems in the gas turbine due to ash in the hot exhaust gas from the boiler, low temperature operation of the gas turbine which reduces the cycle efficiency, complexity of the configuration and difficult access to the boiler internals, high cost of electricity.

One of the main advantages of fluidized bed technologies consist in the capacity of burning a wide variety of fuel including low grade fuels.

3 FORECASTS

Considering the actual and the estimated performances of mature and advanced technologies for non-nuclear or non-renewable electricity production, we can forecast at the 2030 horizon:

- For burning natural gas, the installation of **combined cycle gas turbine** GTCC (High efficiency, low kWh cost, modular installations, rapid erection, CO2 emissions moderated)

- For burning coal, the installation of **advanced supercritical cycle** (high efficiency, good partial load performances, fuel availability at low price). **IGCC** with good improvement potential could be an interesting competitor in respect with environmental considerations, **PFBC** seems to be reserved to low grade fuels. In every case, due to high carbon content of coal, the question of CO2 emissions has to be addressed and solutions has to be found for storage.

4 CO2 Capture/Storage

4.1 Introduction

In the world, the contribution of electricity power plant to CO2 emissions is around 40 %.

The CO2 reduction could be done:
- by using a fuel with low Carbon/Hydrogen ratio (this is not in favour of coal)
- by capturing CO2 in the exhaust gases (post-treatment)
- by capturing carbon in the fuel before combustion (pre-treatment)
- by integrated solutions

Different technologies are studied. They are all costly end reduce the global efficiency of the power plant about 10 points of efficiency. They increase the kWhe cost of a factor 2 (less than 2 for IGCC power plant).

In any case, the question of what to do with CO2 after separation is open. Usually CO2 is compressed to reduce the volume and to permit transportation and eventual re-injection in the soil or saline aquifer.

4.2 Post-treatment

CO2 reduction out of flue gases as "post-treatment process" is possible for all power plants fuelled with natural gas or pulverised coal. Combustion is not really affected but high loss in global efficiency is observed (10 points for pulverised coal or GTCC, 8 points for IGCC including compression unit).

Since power plant flue gases are generally at atmospheric pressure, CO2 partial pressure is very low and the solvent must be properly chosen. 5 solvents are available commercially from the alkanolamine family.

The main technology is a scrubber feed with monoethanolamines. The installation is called "CO2 MEA scrubber".

This technology is mature but not popular because the costs are high.

Research is needed into post-combustion decarbonisation technologies, with special emphasis on new solvent technologies in integrated plants, development of novel chemical solvents. Examples of current developments are: dedicated amine mixtures, ammonia, aqueous potassium carbonate, non aqueous solvents amino-acid salt solutions, di-amines components, ionic liquids.

Other systems exist like selective diffusion of CO2 through membranes, cryogenic process based on condensation or solidification of CO2 at low temperature.

Membrane processes are used commercially for CO2 removal from natural gas at high pressure and high CO2 concentration. In an electrical power plant, the flue gas has to be compressed with the consequence that the removal of CO2 using commercially available polymeric gas separation membrane presents higher energy penalties compared to a standard chemical absorption process.

4.3 Pre-treatment

The pre-treatment is currently known as “pre-combustion decarbonisation process”.
The carbon is captured before burning the fuel.
The method has many parallels to the method of producing hydrogen, ammonia or syngas and could be considered as a mature technology.

The technology comprises three steps:
- reforming/conversion of fossil fuel to a mixture containing hydrogen,
- CO_2 and CO: shifting this mixture to a mixture with CO_2 and H_2
- Separation of CO_2 and hydrogen.

Extensive research is ongoing worldwide to reduce the costs of pre-treatment. New ideas are studied like integrated reforming combined cycle, new membranes, generation of H_2.
The tendency for pre-treatment is to move to integrated solutions more efficients.

4.4 Integrated solutions

This technology is not really a CO_2 capture system. The idea is to produce exhaust gases with 90% CO_2 after combustion with pure oxygen instead of air. Oxygen separation from air is obtained in a cryogenic installation but this is energy costly (around 15% of the total electricity produced by the power plant).

To avoid this cryogenic step, a new technology is studied: chemical looping combustion. In this technology, oxygen is transferred through a circulating metallic support.
The combustion air and the fuel are never mixed. The system is composed of two reactors, an air reactor and a fuel reactor. The flue gas at the outlet of the air reactor contains only oxygen and nitrogen, the flue gas at the outlet of the fuel reactor contains only CO_2 and water. The process uses technology very similar to circulating bed combustion.
A 50kW chemical-looping combustor has been recently designed at Korea Institute of energy research (2004).

In other ways, new processes are studied like:
- anti-sublimation : CO_2 is captured by-anti-sublimation on a low temperature surface at atmospheric temperature
- HyGenSys : production of Hydrogen and power with CO_2 capture at pre-combustion stage

4.5 Storage

The CO_2 extracted from the power plants has to be stored surely and for a long period of time. The storage is only possible in geological systems. Until now only pilot units are operated.

The geological CO_2 storage options are:
- Depleted oil and gas fields.
- Deep saline aquifers
- Deep unminable coal seams
- Caverns and mines

An important challenge is the estimation of the capacity of geological storage. 40Gt could be store in depleted oil and gas fields in Western Europe and 150 to 1500 Gt CO2 of theoretical potential for deep saline aquifer in Western Europe (IEA GHG 2005).

The first large-scale CO2 storage plants injects CO2 in an aquifer which is at a depth of 800 to 1000 m below the sea bottom near the Sleipner gas field in the Norvegian North Sea.

4.6 Perspectives

CO2 capture technologies constitute a critical component of zero emission power generation schemes.

Post-treatment with monoethanolamine solvent is a mature technology. It increases the kWh costs of a factor 2 and reduce global thermal efficiency around 10 points but this is acceptable. Research is needed into post-combustion decarbonisation technologies, with special emphasis on new solvent technologies in integrated plants, development of novel chemical solvents.

Post treatment with membranes is today too costly and need further improvements to be competitive.

Pre-treatment is a complex operation, different new routes are under investigations.

The integration of pre-treatment in an IGCC will be interesting. It is necessary to work on development and validation of new integrated processes providing near-complete CO2 capture.

In most of new CO2-free technologies, only small pilots are operated and the risk associated to the up-scaling is high. Real operating costs are difficult to estimate correctly at this stage.

In order to assess better the storage potential, especially in the case of deep aquifer, large R&D efforts are still needed for predicting the long term behaviour of the storage.

CO2 capture and storage will be a must to allow a return to coal use at large scale in our country.