Techno-Economic Optimization of First Generation Oxy-Fired Pulverized-Coal Power Plant

Hayato HAGI [1,2], Maroun Nemer[2], Yann Le Moullec[1]*, Chakib Bouallou[2]

[1] *EDF R&D, Fluid Dynamics Power Generation and Environment Department, 6 quai Watier, F-78401 Chatou, France*
[2] *MINES ParisTech, PSL – Research University, CES – Centre for energy efficiency of systems, 60 Bd St Michel, F-75272 Paris Cedex 06, France*

Introduction

A significant reduction of anthropogenic emissions of greenhouse gases is necessary in order to limit the effects of global warming, and, in this context, CO_2 capture on coal-fired power plants is a particularly promising option. Today, oxy-combustion is the most credible alternative to the currently foreseen chemical absorption process. Despite having the advantage to allow the capture without resorting to products that could be harmful to the environment, the cost of CO_2 avoidance relative this capture route has to be drastically reduced in order to become competitive. Many studies in the literature suggest process modifications to reduce the energy penalty, such as advanced low energy consumption air separation units (ASU) [Chang et al., 2012; Davidian, 2012] and compression and purification units (CPU) [Ritter et al., 2009; Mirza et al., 2013], waste compression heat valorization [Fu et al., 2014] or flue gas recycle options [Hu et al., 2012]. However, those studies do not adopt a holistic approach and the economic aspect is often not considered. In this work, the techno-economic optimization of a first generation oxy-fired power plant, including the above mentioned process modifications, is carried out.

Methodology

To perform the techno-economic optimization, a two-step procedure is carried out. The first step, thoroughly described in Hagi et al. (2014), consists in the minimization of the energy penalty: exergy analysis is carried out on a base-case oxy-fired power plant, at unit operation level, to identify process modifications leading to increased energy performances of the whole system. Then, heat integration is performed using a systematic procedure, consisting in valorizing waste heat sources into the steam cycle feedwater preheating train, in order to compare the energetic performances of the different configurations, including the coupling of different structural process modifications. This energetic optimization is then followed by a second step, in which the process modifications that were previously identified as beneficial to the system performance are reevaluated taking into account the additional investment they induce. Indeed, the introduction of a process modification leads to a plant capital cost (CAPEX) modification, and consequently a techno-economic criterion is necessary in order to determine whether it is profitable or not.

The levelized cost of electricity (LCOE) is the most commonly used figure to characterize the economic performance of a power generation unit. The LCOE is defined as follows:

*corresponding author: yann.le-moullec@edf.fr

$$LCOE\ [€_{2011}/MWh] = \frac{CAPEX.f_a + OPEX}{P \times H}$$

with CAPEX the capital expenditure ($€_{2011}$), f_a the levelization factor (h^{-1}), OPEX the operating expenditure ($€_{2011}.h^{-1}$), P the net electric production (MW_e) and H the annual operation time (h).

The LCOE is an increasing function of CAPEX and decreasing function of the net electric production. Consequently, a process modification increasing the plant efficiency (and thus the net electric production) is justified only if the induced CAPEX increase leads to a LCOE reduction and, for a given plant layout, there is a breakeven cost (C_{BE}), expressed in $€_{2011}/MW_e$, representing the limit between profitability and unprofitability (see Figure 1).

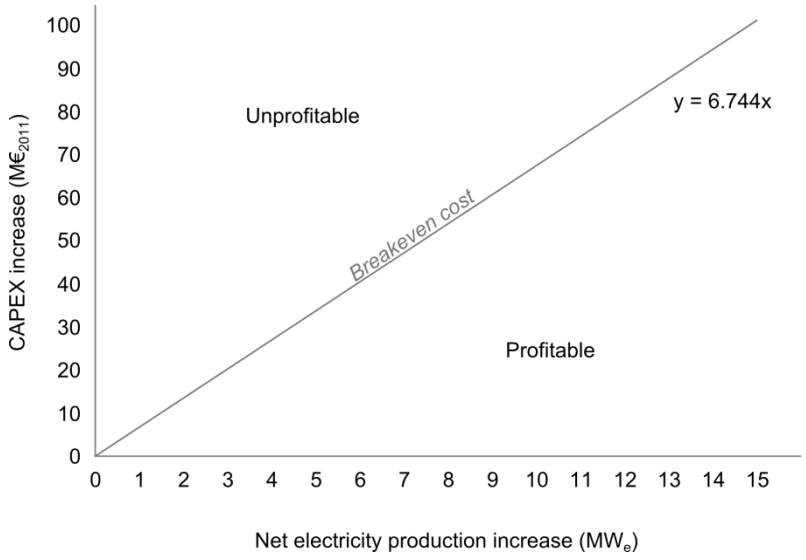

Figure 1 Breakeven cost of electricity for a given process configuration

Each process modification is then characterized by its marginal cost of electricity production, C_{marg} ($€_{2011}/MW_e$), which is defined as the ratio between the additional CAPEX it induces and the net electricity production increase it brings. These marginal costs of electricity production allow a ranking of the process modification on a techno-economic point of view. However, the breakeven cost of electricity shifting towards lower values after the introduction of a profitable process modification ($C_{BE,\ i} > C_{BE,\ i+1}$), a special attention has to be paid to the implementation order. When *n* process modifications are considered, the process modifications must be implemented with increasing C_{marg} and $C_{marg,i+1}$ is compared to $C_{BE,\ i}$ (and not the breakeven cost of the base-case plant). The optimal process layout is determined by repeating this procedure until $C_{marg,\ i+1} > C_{BE,\ i}$.

Concerning the cost estimations, the purpose being the comparison of different configurations rather than the accurate estimation of the absolute CAPEX figure, a factorial method has been used. Those methods, despite leading to uncertainties of around 30 to 40 % in absolute value, are the most suited for process conception studies since accurate relative costs can be obtained with a relatively limited input data requirement.

System description and energetic optimization

In this paragraph, the considered base-case plant as well as the investigated process modifications and the energetically optimal configuration are described. For more detailed information about the modeling approach and the hypotheses, see Hagi et al. (2014).

Description of the base-case oxy-fired power plant

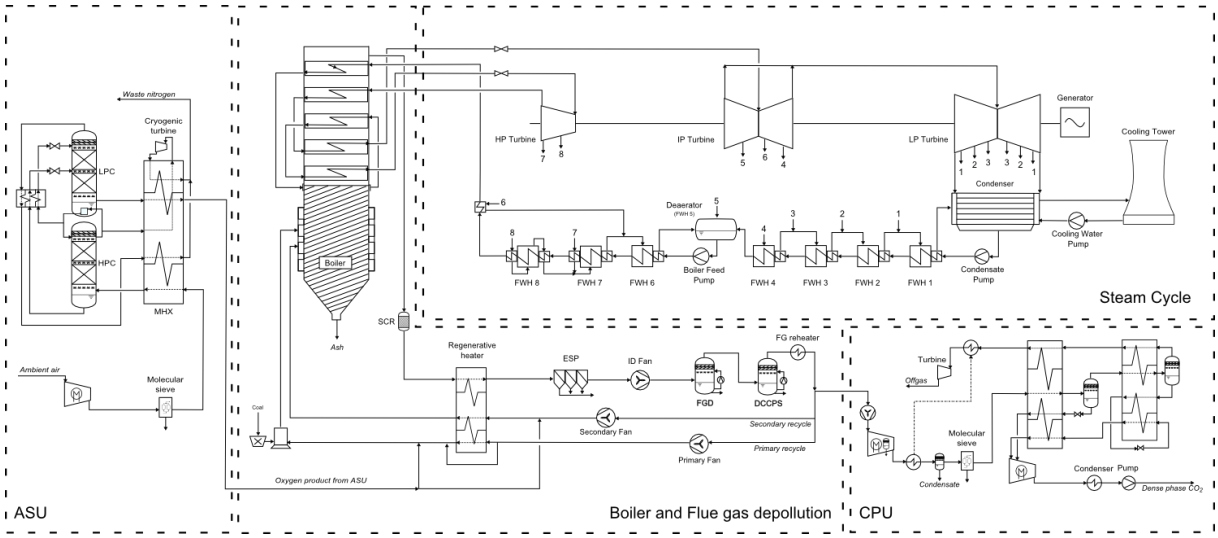

Figure 2 Simplified flowsheet of the base-case oxy-fired power plant

The base-case oxy-fired coal power plant (Figure 2) is a state-of-the-art ultra-supercritical single reheat Hirn cycle with steam conditions of 300 bars/600 °C/620 °C with a feedwater (FW) preheating temperature of 315 °C. Flue gas exiting the boiler, operating in slight vacuum, undergoes successively through a denitrification (SCR), particle removal (ESP), desulfurisation (wet FGD) and a direct contact cooler polishing scrubber (DCCPS). A regenerative heater is placed right after the SCR in order to preheat the recycle flue gas. The temperature of the primary recycle, heading the coal preparation section, is maintained at 110 °C for security issues. The most conservative flue gas recycle option, in which both primary and secondary recycle are realized after full depollution, is adopted. A conventional double-column cryogenic air separation unit (ASU) providing gaseous oxygen at 95 $\%_{mol}$ purity at 1.2 bars is considered and the compression and the purification of the flue gas is realized in a conventional cryogenic double-flash process. The compression and purification unit (CPU) provides CO_2 at 96 $\%_{mol}$ purity at 110 bars with a recovery rate of 90 %. Staged compression with intermediate cooling is adopted for both the ASU and the CPU in order to minimize their standalone energy consumption. The specific consumptions for the ASU and the CPU are respectively 202 kWh/t_{O2} and 113 kWh/t_{CO2}. The net plant efficiency (NPE) of the base-case power plant is 36.4 $\%_{LHV}$, which corresponds to an energy penalty of 9.7 %-pts.

Description of the process modifications

The investigated process modifications can be sorted into two distinct categories: heat integration at fixed process architecture and structural modification of the process. Again, the heat integration methodology, based on the systematic resort on the feedwater by the means of parallel heat exchangers, as well as the detailed information concerning the structural process modifications are described in Hagi et al. (2014).

- Heat integration at fixed process architecture

Table 1 Heat sources and heat sinks identified by exergy analysis on the base-case plant

Heat sources		Heat sinks	
ASU main air compressor intercooler	Q_{comp_ASU}	Flue gas reheater	Q_{FG_reheat}
CPU Flue gas compressor intercooler	Q_{comp_FGC}	Primary oxygen preheater	Q_{PO}
CPU CO_2 compressor intercooler	Q_{comp_CO2C}	Secondary oxygen preheater	Q_{SO}
Flue gas heat after the regenerative	Q_{FG_cooler}	CPU offgas reheater	Q_{offgas}
Flue gas heat before the wet FGD	Q_{FGD}	FW preheaters parallel exchangers	Q_{HI-i}
Flue gas heat before the DCCPS	Q_{DCCPS}		

- Structural modification of the process

- Substitution of the conventional double column ASU by an advanced low energy consumption ASU. Two low operating pressure triple-column multi-reboiler ASU schemes, are considered: an *Air Liquide* design [Davidian, 2012] and an *Air Product* design [Dillon et al., 2005].

- Deviation of a portion of the flue gas prior the regenerative heater. This allows an increase of the temperature level at which the flue gas heat can be integrated into the steam cycle.

- Several secondary flue gas recycle location have been investigated : prior the regenerative heater (Case A), prior the FGD (Case B) and after the FGD (Case C).

- Substitution of the intercooled compressions by single step compressions (adiabatic compressions)

Energetic optimization

The optimal process layout with regard to an energetic criteria is displayed in Figure 3.

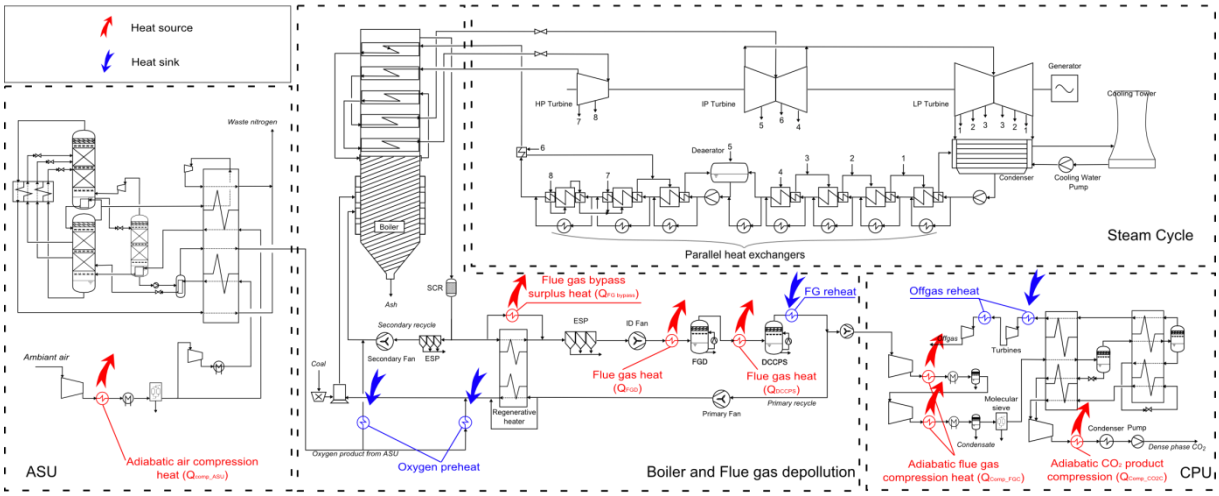

Figure 3 Process layout leading to the best energy performances

The optimized process exhibit an net plant efficiency of 10.1 $\%_{LHV}$, which corresponds to an energy penalty of 6.0 %-pts. The main features of this configuration is a hot secondary recycle scheme, a flue gas bypass at the regenerative heater, integration of the flue gas heat before and after the FGD, integration of the adiabatic compression heats and an advanced ASU instead of a dual-column ASU.

Techno-economic optimization

Breakeven cost of electricity production

First, the CAPEX of the base-case plant is evaluated in order to evaluate the breakeven cost of electricity production (Figure 4). An environmental factor of 2.36, typical for an power production process, is used to estimate the CAPEX from the bare erected cost of the process.

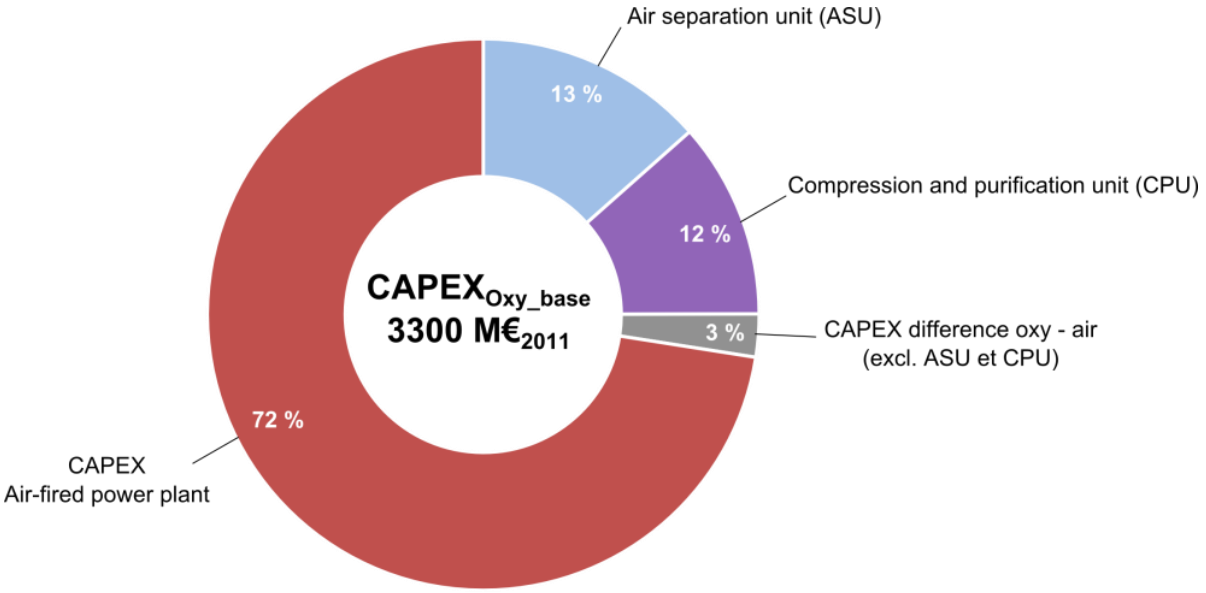

Figure 4 CAPEX of the base-case oxy-fired power plant

The LCOE associated to the base-case plant, calculated considering a levelization factor of 0.0776 yr^{-1} (40 years lifetime and 8 % escalation rate) and a annual plant operating time of 7560 h/yr, is 85.8 $€_{2011}$/MWh (without transportation and storage). Compared to the reference air-fired power plant, the LCOE increase of about 55 %, which leads to a cost of avoided CO_2 of 46.5 $€_{2011}/t_{CO2}$. Using the previous information, the breakeven cost of electricity production of the base-case plant, $C_{BE, base}$, has been evaluated to 6744 $€_{2011}$/kW.

Estimation of the marginal cost of electricity production

The process modifications considered during the energetic optimization induce various CAPEX modifications. Considering heat integration in the feedwater preheater parallel heat exchangers in baseline operation, the expanded steam flowrates, especially for the low pressure turbine, are increased. Thus, the steam turbine have to be modified accordingly. Naturally, the additional investments relative to the parallel heat exchangers, the flue gas heat valorization heat exchangers ($Q_{FG\ bypass}$, Q_{FGD}, Q_{DCCPS}) as well as the oxygen preheaters are also taken into account. In addition to those, the modification of the flue gas recycle scheme leads to a reduction of the flue gas flow downstream the recycle, leading a size reduction, and thus the cost, of the depollution equipments. Finally, substitution of the staged compression by adiabatic compression leads to an increased investment.

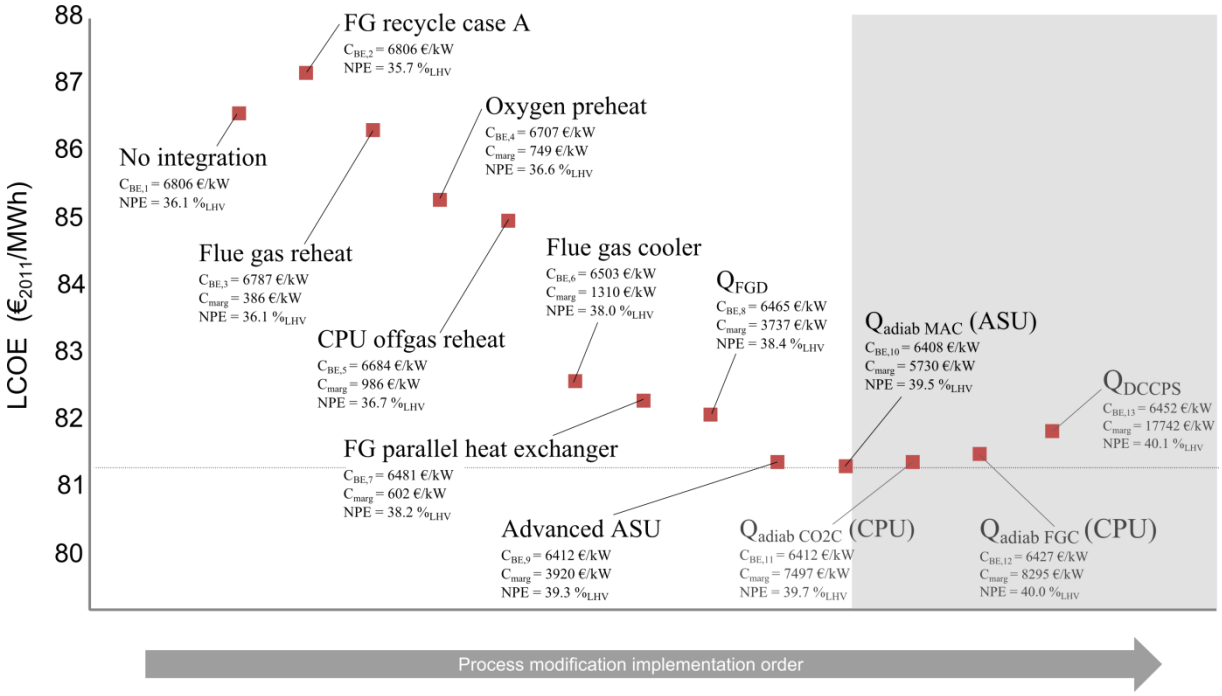

Figure 5 Illustration of the techno-economic optimization procedure

The induced LCOE increase is due to the fact that switching from a cold recycle scheme to a hot recycle scheme, without considering further heat integration benefits, leads to a NPE decrease. In order to fully assess the potential of the hot flue gas recycle scheme, the investigation of the other process modification and associated heat integration is needed. Process modifications are implemented with increasing marginal cost (C_{marg}), unless one modification needs another one to be realized. This can be witnessed for the "FG parallel heat exchanger" which can be implemented only after the consideration of the valorization of the flue gas heat ("flue gas cooler"). The techno-economic optimization shows that despite a significant energetic gains, the marginal cost associated to the advanced ASU is relatively high because of the important CAPEX increase. This figure also highlights that the CPU compressors adiabatic compressions are not profitable despite the energetic gains those modification provide. This can be explained by the fact that adiabatic compression leads to an increased compressor size, which in turn increases their costs, especially when considering stainless steel compressors to fight against corrosion problems. The valorization of the flue gas heat after the wet FGD (Q_{DCCPS}) is also not profitable because of the low quality of the heat, inducing a large surface area for a relatively modest plant performance increase.

In the same way, the procedure has been applied to all the configurations considered during energy optimization (see Figure 6). Flue gas recycle after the FGD (case C) has been discarded due to lower energy performance and higher investment costs. Compared to the base-case oxy-fired power plant, heat integration at fixed process architecture allows a 4 % LCOE reduction. The best configuration is a hot secondary flue gas recycle scheme (case A) with an *Air Product* ASU design with oxygen preheating, valorization of the flue gas heat in a parallel heat exchanger and prior the FGD. The marginal costs associated to the integration of the adiabatic compression heat of the Air Product ASU main air compressor, CPU's flue gas compressor and CO_2 compressors being respectively of 7700 €$_{2011}$/kW, 9300 €$_{2011}$/kW and 7500 €$_{2011}$/kW, those modifications are not economically viable. This configuration leads to a LCOE of 80.6 €$_{2011}$/MWh which corresponds to a 7 % improvement compared to the base-case.

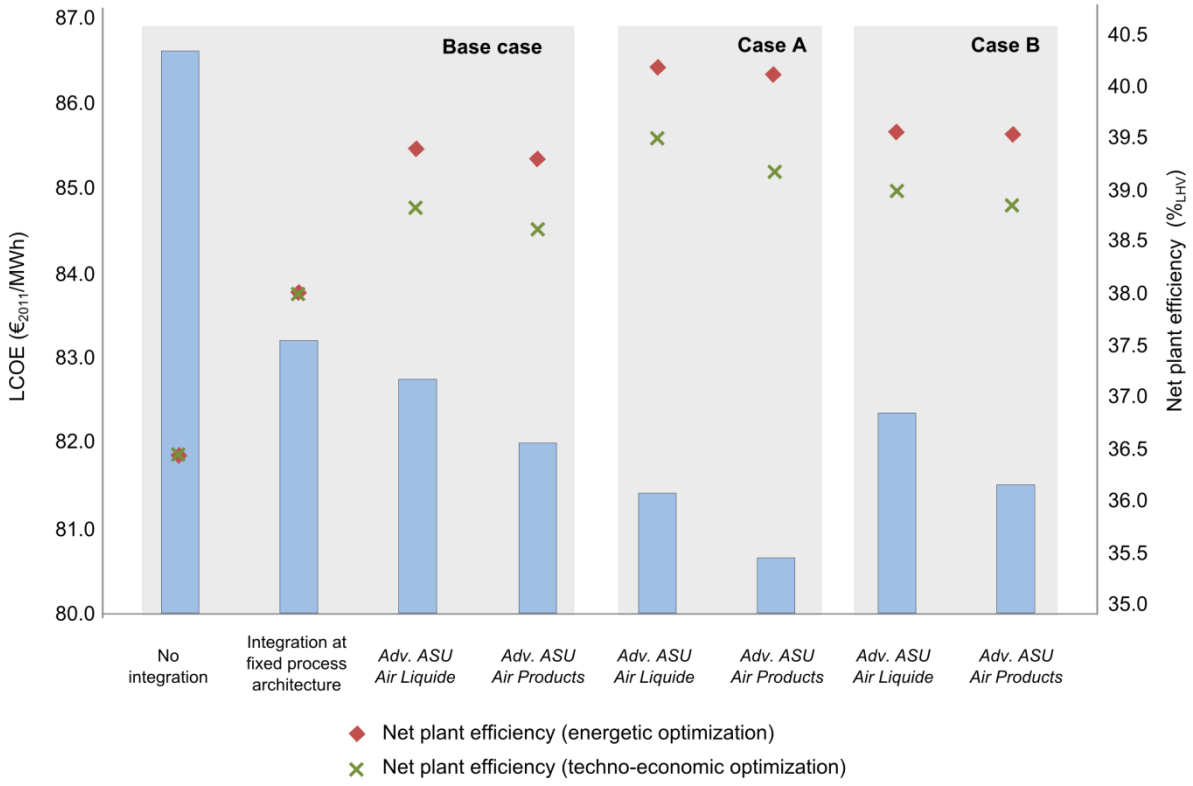

Figure 6 Results of the techno-economic optimization

The net plant efficiency difference between the energetically optimum solution and the techno-economic optimum solution highlights the fact that, for all the configurations where structural modification of the process have been considered, some modifications increasing the NPE is not profitable in terms of the plant economics. For example, the previously described configuration leading to the minimal LCOE has an associated NPE of 39.2 $\%_{LHV}$, which is 0.6 %-pts lower than the energetic optimum.

Conclusion

In this study, a two step optimization procedure allowing the determination of an optimal process layout regarding an economic criteria, the LCOE, has been presented. This procedure has been applied to a first generation system, featuring mature technologies, in order to assess the short term potential of oxy-combustion. This study has shown that some process modifications allowing a net plant efficiency increase are not economically viable, despite the high breakeven cost of electricity production associated to a pulverized coal power plant with carbon capture. It is important to stress that, because of the adopted cost estimation method, the estimated LCOE are subject to an uncertainty of about 10 % in absolute value. However, the comparison between the different process layouts, which is carried out in this study, is reliable. Using a structured methodology, different process modifications and heat integration layouts have been compared in terms of both energetic and economic criteria, leading to a realistic estimation of the potential of carbon capture by oxy-combustion on state-of-the-art pulverized-coal power plants.

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