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On the flexibility of coal-fired power plants with integrated Ca-looping CO_2 capture process.

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Abstract

The share of renewable energy production is growing quickly. The output and variability of renewable power will force to fossil fuel power plants to adapt its electricity production to variable demand. In a future scenario, with CO_2 capture systems installed in power plants, the variable performance will affect not only to fossil fuel power plant but also to the CO_2 capture behavior. The knowledge of part load performance of fossil fuel power plants with CO_2 capture systems will be essential in a near future.
This paper analyzes the integration between Ca-looping cycles and power plants to foresee the requirements derived from a flexible operation. With this goal, the performance of the integrated system under different load scenarios is studied. An integration scheme designed for nominal load is proposed under different load scenarios at steady state, to study their performance. Then, for each load scenario, the optimum integration is designed, to quantify the minimum energy penalty of each specific load level. Finally, a comparative analysis of the general integration against the optimum one for each scenario is performed.

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Keywords: Ca-looping; CO2 capture; energy integration; flexibility; load-following

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1. Introduction

While in 2004 an 8.3% of the energy in Europe came from renewable sources, in 2013 this amount nearly doubled up to a 15%. Both, the development of wind and solar technologies has been the responsible of this change. Renewable electricity generation also depends on factors such time of the day and meteorology. As a result, the remaining generation sources are affected and require the baseload plants to be available during peak periods and to compensate power fluctuations. Also, with increasing amounts of renewable energy penetration rates, the load-following scenario is going to be the standard for baseload plants. The increase of renewable rates demands these sources a more flexible operation, both to cover the demand and to assure the grid stability.

Coal power plants may play this role to balance the renewable sources adopting a narrow load-following strategy. This may lead to maximum load demands several times in the same day, to operate under the plant technical minimum or even require to shut down and to start up on a daily basis. Although the vast majority of conventional coal plants can operate dynamically, these new requirements may present problems of costs and maintenance and the plants need to be adapted to them.

At the same time, these power plants must reduce their emissions according to more restrictive regulations to accomplish the emissions reduction levels. To achieve these reductions in the medium term, one of the feasible options is the use of CO_2 capture systems. Post-combustion CO_2 capture systems are well suited for high stationary emissions, but have been typically designed for steady state and specific capture levels, so their performance against load-following operation is a main issue to address.

CO_2 capture systems impose an energy penalty to the power plants, and a certain amount of integration is required to reduce these percentages as much as possible but, depending on the technology and configuration of the capture unit, different limitations when flexibility is considered may appear.

In amine scrubbing for example, a high amount of energy for solvent regeneration is required typically from steam bleeds themselves. Chalmers and Gibbins [1] analyzed this cycle, including different operation options, such as venting, CO_2 storage or extra solvent regeneration.

High temperature Ca-looping cycles present high integration capabilities that may diminish the capture energy penalty by using the waste heat to run a bottoming power plant. However, when the main power plant is load following, the amount of CO_2 captured and the amount of recovered energy change, which may affect the second plant efficiency and the performance of the whole system. Those highly integrated schemes may be in conflict with part-load operation, or with prolonged flexibility periods, so their behavior under these conditions must be analyzed. Only Hanak et al. [2] and Cormos et al. [3] analyzed the performance of this type of system under variable loads. More research is needed in order to choose the optimum design depending on the future performance conditions of the installation.

This study focuses on the intersection of two important work areas of power plants: on one hand the load following requirements in the new energy context; on the other hand, the requirements of CO_2 capture systems to reduce emissions. Due to the importance the waste energy recovery presents in Ca-looping systems, it is essential their capability to react to load changes. While the systems efficiency may increase when integrating high-energy amounts, a highly integrated system may compromise flexibility.

The main objective is to characterize the integration between Ca-looping cycles and power plants to foresee the requirements derived from a flexible operation. With this goal, the performance of the integrated system under different load scenarios will be studied. First, an integration scheme designed for nominal load will be analyzed under different load scenarios at steady state, to study their performance. After that, for each load scenario, the optimum integration will be designed, to quantify the minimum energy penalty of each specific load level. Finally, a comparative analysis of the general integration against the optimum one for each scenario will be performed.

The objective of the present work is to assess if the general integration is a feasible option in different scenarios and to which extent. Also, to study the feasibility of in situ modifying the general integration to adapt their performance as much as possible to the optimum one in the corresponding scenario. This will allow to assess the efficiency penalty of the installation under different conditions and to assess which integration configurations are more adequate for each scenario and how to implement them.

Nomenclature

ASU	Air Separation Unit
HEN	Heat Exchanger Network
HRSG	Heat Recovery Steam Generator
RR	Regeneration Reactor
SR	Sorption Reactor

2. Base case definition and analysis

The initial system is formed by the following differentiated parts: A reference power plant, the capture cycle, the compression train and the newly-designed supercritical power plant.

Being a post combustion capture process, Ca-looping needs to be associated with an emissions source. The reference power plant is a 500MW$_e$ gross and releases 551 kg/s of flue gas, which enters the capture cycle.

This flue gas enters the carbonator at 180 ºC. The carbonator has been designed based on the model provided by Alonso et al. [4] and Charitos et al. [5]. Capture efficiency (93%) depends on parameters as sorbent capture capacity, CaO/CO_2 ratio, solids inventory in the reactor, temperature and CO_2 partial pressure. As the capture reaction is exothermal, there is an excess of energy in the reactor that must be evacuated (Table 1, Stream 1)

Table 1. Base case energy streams

		Stream	Tin[°C]	Tfin[°C]	Q [MW$_{th}$]	Type
Capture cycle	1	Surplus heat carbonator	650.00	650.00	157.10	HOT
	2	Gas flow leaving carbonator	650.00	190.00	230.60	HOT
	3	Purge flow	950.00	200.00	26.40	HOT
	4	Solids from RR to SR	950.00	650.00	365.00	HOT
	5	Captured CO_2 to compression	950.00	329.70	307.80	HOT
	6	CO_2+O_2 to calciner	180.00	296.40	26.40	COLD
	7	CO_2 to compression (2nd step)	329.70	190.00	44.30	HOT
	11	CO_2 to compression (3rd step)	190.00	55.22	37.38	HOT
Compression train	12	1st intercooler	171.50	50.00	30.02	HOT
	13	2nd intercooler	163.20	50.00	27.86	HOT
	14	3rd intercooler	164.60	50.00	28.22	HOT
	15	4th intercooler	173.60	80.00	23.48	HOT
Supercritical steam cycle	20	HRSG	402.40	618.50	400.80	COLD
	21	Reheating steam	328.10	620.00	224.41	COLD
	22	Preheating steam	168.80	402.40	464.42	COLD
	23	Condensate	30.00	153.20	161.90	COLD

Clean gas leave the carbonator to the stack, while the solids flow to the calciner for sorbent regeneration. The calciner model used is the developed by Martínez et al [6]. To maintain sorbent activity the continuous introduction of a make-up of fresh sorbent is required, as well as to purge the deactivated sorbent. The concentrated CO_2 stream is directed to the compression train and the regenerated sorbent goes back to carbonator to continue with capture process. Part of the CO_2 is circulated back to the calciner to maintain an adequate O_2 ratio. Before entering the compression train, the temperature of the CO_2 stream is reduced to condensing the water present in the gas.

As the CO_2 transport has to take place at high pressures, a compression train is required for condition the gas, which leaves the plant at atmospheric pressure. The compression train consists of four compressors with a 3.3 pressure ratio and five intercoolers, which allow to decrease the CO_2 temperature, thus reducing the train power requirements. CO_2 leaves the compression train at 80ºC and 120 bar.

The supercritical steam cycle is characterized by the energy requirements of four main streams; the heat recovery steam generator, the reheating steam, the water leaving the condenser and the steam preheating prior to the HRSG.

To perform the energy integration, a process based on pinch analysis has been used. Pinch methodology looks for internally use the available energy to reduce additional energy requirements, maintaining a minimum temperature difference between the inlets and outlets of the heat exchangers. The energy streams of the cycle have been characterized (Table 1). The streams have been classified as hot (if they need to evacuate energy to reach their objective temperature) or cold ones (if they need to absorb energy to reach their objective temperature); and the heat exchanger network has been designed according to this energy streams distribution, with a ΔT_{pinch}=20 ºC.

The algorithm shown in [7] applied for the HEN design, is based on pinch analysis, and consists of increase the cold streams temperature by exchanging heat with the hot ones, according to a set of rules which define the best match in each situation.

The obtained HEN consists of 15 heat exchangers, as shown in Figure 1. The heat exchangers defining the system (characterized by inlet and outlet temperature differences, amount of exchanged heat and UA coefficient) are shown in Table 2.

Table 2. Base case heat exchangers

HE	ΔT inlet [°C]	ΔQ [MW]	ΔT outlet [°C]	UA [W/K]
1	330.0	205.11	429.4	586.5
2	166.0	159.93	169.0	913.5
3	469.0	260.19	32.4	1640.0
4	248.9	157.08	287.3	591.9
5	287.3	191.72	20.0	1912.0
6	653.6	26.37	20.0	145.1
7	182.8	47.60	112.3	337.0
8	53.3	38.91	21.1	1164.0
9	112.3	27.87	74.3	329.9
10	91.3	16.48	50.2	233.3
11	50.2	37.39	25.2	1054.0
12	33.8	23.48	50.0	584.0
13	31.7	30.02	20.0	1224.0
14	24.8	28.22	20.0	1322.0
15	23.4	27.57	21.3	1293.0

The next step is to implement the HEN design to obtain the power produced in the bottoming steam cycle. When implementing the system and, due to the load following requirements, the steam turbines of the supercritical steam cycle were defined with an isentropic efficiency depending on the load, as proposed by Sun and Smith [8].

For nominal load, isentropic efficiency is defined according to equation (1), where a and b are coefficients that depends of the turbine type and inlet and outlet pressures of the system.

$$\eta_{iso,max} = \frac{1}{a}\left(1 - \frac{b}{\Delta H_{is} \cdot m_{max}}\right) \qquad (1)$$

The use of the capture cycle waste energy is able to provide energy to a supercritical steam cycle producing 407.3 MW_e, with 32.5% efficiency, including the power required by the compression train. The work explained below has been based on this reference case.

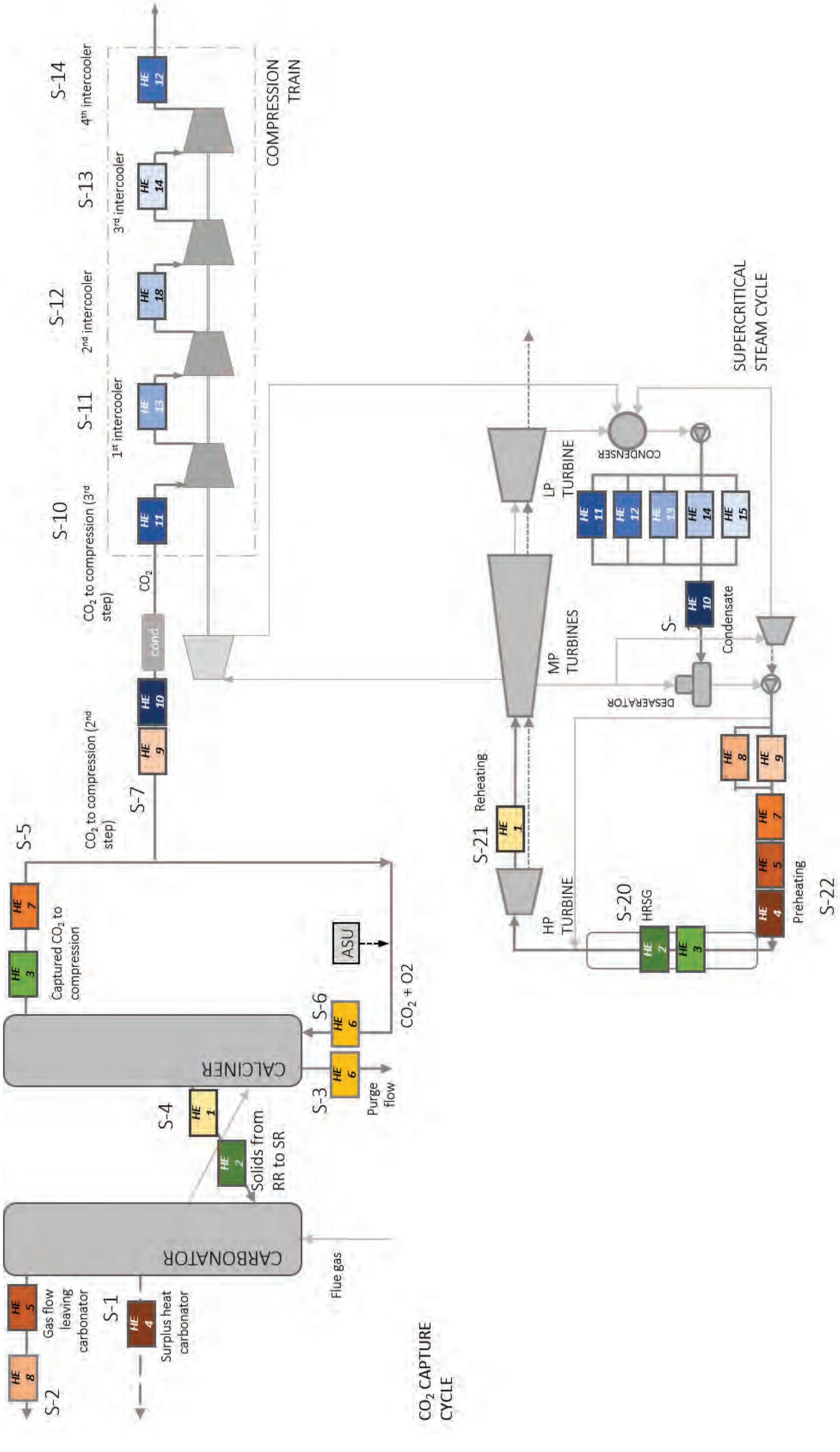


Figure 1. Heat exchanger network. Base case

3. Load scenarios in the initial integration

In the initial integration analysis, the HEN design is maintained the same than the base case. Two modifications have been introduced in the system, regarding steam turbines and heat transfer coefficients (UA) of the heat exchangers, to take into account the load changes. Temperature variation in each heat exchanger is considered an output variable needed for comparison and analysis of the design feasibility.

Equation (1), which models the steam turbines in the base case, and defines their work at nominal load, has been substituted by equation (2), in which the load variation penalty is included, according to Sun and Smith [8]. Parameters a, b and c are calculated by equations shown in (3), depending on some coefficients associated with turbine type [8].

$$\eta_{iso} = \frac{(1+c)}{a}\left(1 - \frac{b}{\Delta H_{is} \cdot m_{max}}\right) - \frac{c}{a}\left(\frac{m_{max}}{m} - \frac{b}{\Delta H_{is} \cdot m}\right) \qquad (2)$$

$$\begin{aligned} a &= a_1 + a_2 P_{in} + a_3 P_{out} \\ b &= b_1 + b_2 P_{in} + b_3 P_{out} \\ c &= c_1 + c_2 P_{in} + c_3 P_{out} \end{aligned} \qquad (3)$$

The second modification included in the system is related to the heat transfer coefficients (UA, W/K). When modifying the load scenarios, the heat exchangers will work out of their design point. To take into account this variation, a reduction of the heat transfer coefficient has been included in calculations, equation (4). The mass flow is related to the stream that influence the most in the heat transfer for each equipment.

$$UA = UA_{design}\left(\frac{m}{m_{design}}\right)^{0,8} \qquad (4)$$

Eight different load scenarios have been proposed by modifying the amount of the gas entering the capture plant - which directly depends on the reference plant load- in 10% intervals, from nominal load to 30% load. For each proposed scenario, the heat exchangers have been calculated and their inlet and outlet temperature differences have been analyzed.

The HEN design based on pinch method relays on maintain a minimum temperature difference between the inlet and outlet of each heat exchanger. Nevertheless, in the new scenarios analyzed, as the HEN distribution is constant, the heat exchangers are going to work outside of their design point. For this reason, temperature differences lower than ΔT_{pinch} have been accepted. This is precisely what the analysis is looking for: how the behavior of the network varies under different situations.

One of the most affected heat exchangers is HE15. This is the one that closes the network and also the one suffering the highest temperature constraints, which has been observed along the whole analysis. In the load scenarios among 90-60%, the inlet temperature difference has been progressively diminished, up to 3 ºC. From this load level on, the inlet temperature difference approaches asymptotically to 0 ºC. The relative importance of HE15 is very low as it is one of the smallest heat exchangers (27.6 MW) representing a 2% of the overall energy streams.

When the load goes under 60%, negative temperature difference values appear, which means that the heat transfer would change their direction. HE2 is affected by this problem from loads lower than 52%. So, in these load scenarios, HE2 and HE15 must be bypassed; which changes the whole system operation for load levels between 50 and 30%. HE2 is a relevant heat exchanger as it works as evaporator so a detailed analysis of their design, out of the scope of this paper, is needed.

Figure 2 a) shows the evolution of power production of the analyzed case depending on the load level, as well as the available and the used heat at each studied scenario. The amount of available heat in the system is proportional to the load, due to no penalties depending on the load percentage have been considered in the capture system (that is, the capture system always adapts to the flue gas entering the carbonator). When analyzing the heat used in the heat exchangers, it can be seen that it is not proportional to the load. Also, a drop between 60 and 50% load levels can be seen, derived from the fact that HE2 and HE15 have to be avoided, which causes a diminution of the used heat in the system, as well as a decrease in the produced power.

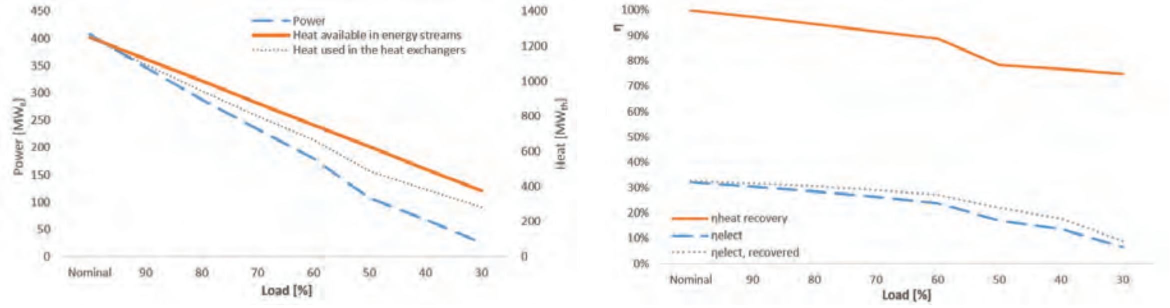
Three values have been used to analyze the system efficiency. The heat recovery efficiency (equation (5)), which compares the available heat in the energy streams with the amount of heat effectively used in the system; the electric efficiency of the recovered heat, equation (6), and a typical electric efficiency (equation (7)), comparing power production with the amount of coal introduced to the calciner. The electric efficiency of the supercritical power plant, in nominal case, sums up to 32.5%, and decreases with the load level of the reference power plant.

$$\eta_{heat\ recovery} = \frac{H_{used}}{H_{available}} \tag{5}$$

$$\eta_{elec,recovered} = \frac{W_{elect}}{H_{used}} \tag{6}$$

$$\eta_{elec} = \frac{W_{elect}}{H_{coal}} \tag{7}$$

An important drop can be seen when moving from 60 to 50% load, related with the decrease of the amount of heat used in the system, Figure 2 b).



a) Produced power and heat used

b) Efficiency

Figure 2. General integration at different load scenarios

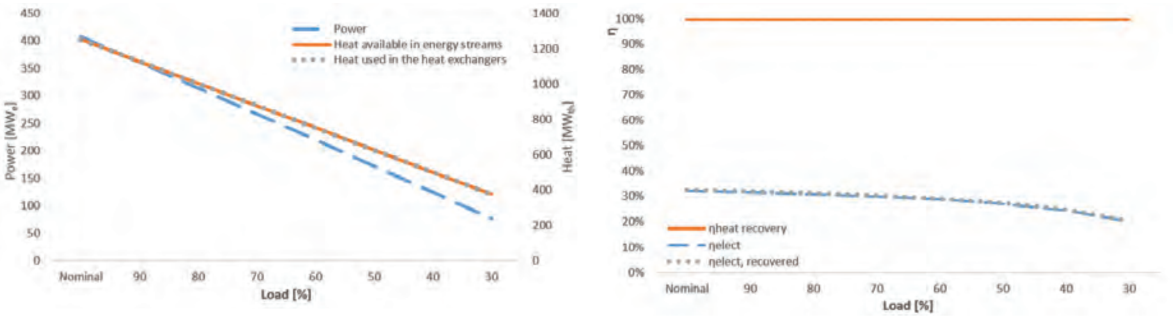
4. Specific integrations for each load scenario

After the initial analysis, a specific integration for each load scenario, based on the corresponding energy streams, was calculated. For each load level defined in section 3, the HEN that makes use of the most of the energy available in each scenario was calculated. As the capture cycle reacts based on the flue gas entering the system, the energy streams for each load level are directly proportional to the corresponding level.

When implementing the algorithm, the HEN remains the same for the whole set of scenarios. Although the available energy in each stream varies, maintaining a proportional distribution in each scenario, the supply and objective temperatures of the energy streams are kept constant in all cases. Due to this fact, when implementing the algorithm, which is closely related with the streams temperatures, the HEN that leads to the highest energy use is constant; although the amount of energy exchanged between devices changes.

In this step, when implementing the network to calculate the supercritical steam cycle, it has been considered that the steam turbines are affected by the load levels, applying equation (2) to obtain their isentropic efficiency. Nevertheless, as the objective is to find the optimum integration for each level, it has been assumed that the heat exchangers are designed for each load level, and the UA has been calculated for each device, not varied depending on a nominal case.

Figure 3 a) shows the power production, available heat and used heat for each scenario. As the network has been designed to take advantage of the most of the available energy, can be seen that the available heat in the energy streams is the same than the recovered heat in each scenario. This can be also seen in Figure 3 b), where it can be observed that the heat recovery efficiency is the 100% for all scenarios, and that the electric efficiency is the same that the electric efficiency of the recovered heat for all scenarios.



a) Produced power and heat used

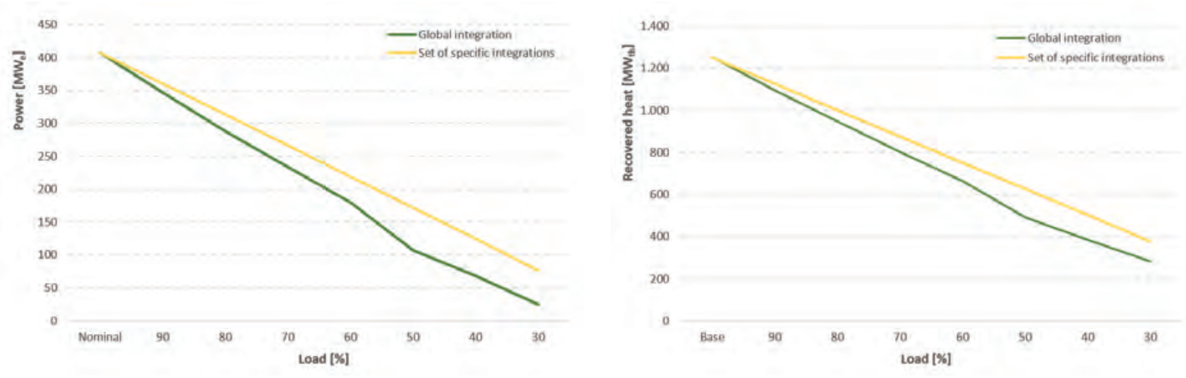
b) Efficiency

Figure 3. Specific integrations for each load scenario

5. Comparative analysis of the proposed integrations

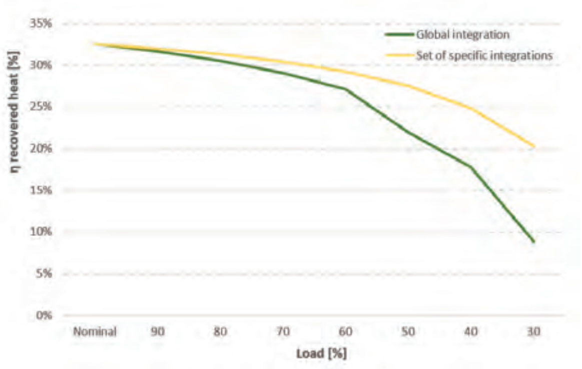
The behavior of the general integration against the specific integration developed to each load scenario based on the parameters listed above has been studied. The objective of the comparison was to analyze the efficiency penalty experienced by each integration and to define the best operational characteristics for each scenario.

By comparing the evolution of power production of both cases in the whole set of scenarios, Figure 4 a), it can be seen that there is a deviation between the global and the specific integration for each load scenario, deviation that suddenly increases between 60 and 50% load, due to the requirement of bypassing HE2 and HE15, whose consequence is that not all the available heat can be recovered. This fact can also be seen in Figure 4 b), which shows the heat recovered in each case in the different scenarios. The available heat is the same in both cases; nevertheless, while in the set of specific integrations, recovered heat and available heat coincide; in the global integration, the system is not able to recover all the available heat.



a) Power produced

b)Heat recovered



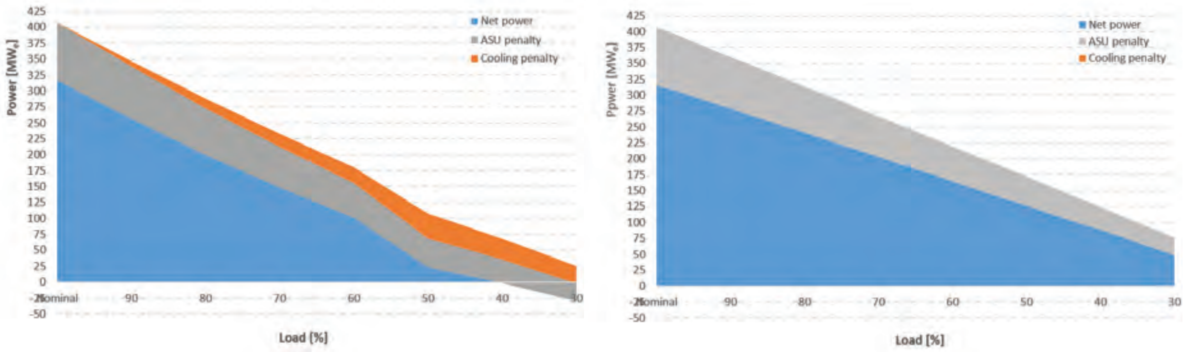
c) Efficiency of the recovered heat

Figure 4. Comparative analysis between cases

The comparison between the efficiency of the recovered heat in each scenario is shown in Figure 4 c), where the drop between 60 and 50% load levels can be easily located; not only for the general integration but also for the set of specific integrations. In the case of general integration this is due to the heat exchangers bypass; while in the set of specific integrations, the efficiency reduction is directly linked with the power production reduction due to the isentropic efficiency of the turbines is lower at low loads.

To finish the analysis, the effect of cooling requirements in power production was added to the comparison. While in the set of specific integrations the cooling requirements are close to zero, in the global integration these requirements increase with decreasing loads, because the energy streams are not totally used and have to reach their corresponding objective temperatures.

When including this penalty in the analysis, the power produced by the system changes. In addition to this penalty, the power requirements of the air separation unit (ASU) has been included in the system. It has been assumed that this unit produces only the O_2 required by the capture cycle at each defined scenario.



a) Global integration

b) Set of specific integrations

Figure 5. Power production including penalties

When taking into account these penalties, the power obtained in the global integration varies as shown in Figure 5 a). It can be seen that the ASU penalty is an important one, requiring an amount of power proportional to the load in each scenario. The cooling penalty increases along the load level decreases, due to the lower use of the heat. When including these penalties it can be seen that the global integration will require additional energy from load levels below

40%, which makes the operation at this loads unfeasible. In the scenario of 50% load, the net power production of the supercritical steam cycle sums up 23 MW_e, which implies a 51% reduction with respect to the net power obtained in the 60% load level.

When taking into account the penalties in the set of specific integrations, Figure 5 b), as the HEN is designed according to each load level, there are minimal penalties associated with cooling requirements. The ASU penalty remains proportional to the load level.

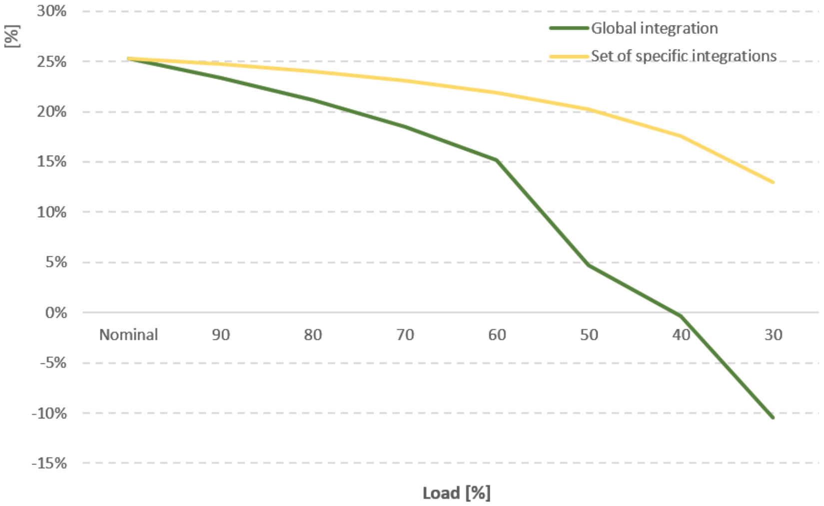


Figure 6. Efficiency of recovered heat including penalties

Regarding the efficiency of the recovered heat, the addition of these penalties to the system markedly influences it, as shown in Figure 6. It can be seen that the efficiency drop in the general integration case is not admissible for load levels below 60%. The drop between 60 and 50% load levels amounts 15 percentage points. Due to this, a minimum level of load for the capture and integration system can be defined. This lower limit will be the one that covers the energy requirements of the system. In order for the capture cycle to operate, the load level must be enough as the heat recovery configuration -the integration defining the supercritical steam cycle- provides, at least, the energy required by the system without additional energy requirements. Also, the production of additional energy is required to minimize the penalty of the capture system.

6. Conclusions

In a future scenario with high share and variable renewable energy production, fossil fuel power plants will be forced to adapt its production to variable and rapid demand. If CO_2 capture systems are installed in these power plants, its performance will have to adapt also to load changes. It is essential not only to design the base load integration between power plant and CO_2 capture system, but to analyze in detail the performance of this integration at partial load, which has been the objective of this work. A minimum load level for the integrated scheme can be defined. If the capture system has to work at partial load, the integration defined for nominal load may be oversized. To overcome this problem, the design of the bottoming steam cycle may be downsized to allow operation at lower loads.

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