Desalination and Water Treatment
www.deswater.com

7 (2009) 124–131

Integration of MED with captured CO_2 flue gas compression

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Received 30 September 2008; accepted in revised form 24 April 2009

ABSTRACT

The improvement of specific energy consumption and the reduction of steam temperature to drive the system are two of the main challenges to improve the performance of distillation processes in desalination plants, especially for multi-effect distillation technique. The low temperature requirement is a suitable characteristic to integrate multi-effect distillation units as bottom system. Obviously, one of the best options is to use low-grade heat from power plants or gas turbines as a cogeneration system. Mitigation of CO_2 emissions from power plants will be a priority for most of power companies in a near future, one of the most promising techniques is carbon capture and storage. Nevertheless, energy requirements and efficiency penalties in the overall system are some of their disadvantages. They are largely caused by CO_2 compression above both its critical temperature and pressure prior storage. There are a huge low-grade heat coming from condensing water in the CO_2 stream and from compressors intercooling that is suitable to reduce energy penalties in CO_2 capture process and to produce desalted water. With the aim of analyzing these combined systems (desalination unit, power plant and CO_2 capture), five different integration configurations have been proposed and simulated. Three aspects have been analyzed: the energy penalty in the steam cycle, the water costs associated to thermal energy and their environmental impact. Results show that although CO_2 capture systems reduce power generation and therefore increases its costs, available heat from those systems could produce distilled water at affordable costs.

Keywords: Multi-effect distillation; Residual heat; Energy integration; CO_2 capture

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1. Introduction

Combined power and water desalination plants have been widely studied in the literature during last years [1–18]. Seawater distillation with both MSF and MED is an energy-intensive process, and cogeneration is the most suitable technology to reduce this drawback. The most common system is to use steam turbines to desalt seawater in MSF with steam bleedings [1–6], although gas turbines (in open or combined cycle) with RO have been also proposed [1,7–10]. With the aim of increasing overall system efficiency and reducing distillation cost, several researchers have proposed the concept of polygeneration [11,12]. This system combines a power plant, in this case based on internal combustion engines to provide electricity, a desalination system (RO unit) to supply fresh water, an absorption chiller for cooling requirements, and other systems for hot sanitary water supply. The use of internal combustion engines for hybrid desalination plants have been extended coupled with MED and RO [13].

One common characteristic in combined power and desalination is the use of low grade heat or waste heat

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Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

from one top generation cycle. In particular, TVC and MED are the most efficient systems when low pressure and temperature steam does not directly comes from a boiler or a turbine extraction: MED has the ability of using this heat in the most efficient (water per heat used) thermal desalination process currently in use [13], reducing to a minimum the energy requirements of these installations. In this way, it could be competitive with respect to RO, in which integration with the top cycle is not feasible.

In a carbon constrained world, where the Kyoto agreements have been adopted by the majority of developed countries, is necessary to establish a new energetic strategy based on renewable energy sources, reduction of energy patterns and introduction of clean technologies for power generation. In the last point, the CO_2 capture and storage systems (CCS) are going to play an essential role in a near future [19–23]. CCS process includes the separation of CO_2 from flue gases (capture), its compression to supercritical stage and, finally, the injection and storage in a safe geological trap (Fig. 1). Three capture technologies are at present available in a pre-commercial stage for large combustion installations [20].

- In post-combustion capture technologies the gas treatment is once combustion has been carried out. The main technology in this stage is the chemical absorption with amine derived compounds
- Oxy-fuel combustion, in which combustion is carried out using oxygen instead of air, having a flue gas with CO_2 as main component and steam. Part of the produced CO_2 is recycled for a controlled combustion.
- Pre-combustion capture systems, requires great changes in the whole combustion process. A shift reaction takes place before combustion and so, CO_2 is separated before the combustion process itself.

The CO_2 compression and transport process is considered to be analogous to the process currently used for natural gas transport. Before entering into the compression train, CO_2 and water mixture produced in the postcombustion or oxyfuel capture processes needs to be cooled down to separate water from CO_2, avoiding ice and chlorates formation [21]. In the case of pipeline transportation, pressures as high as 100–140 bar would be required to achieve a supercritical fluid, increasing fluid density and making possible its injection and storage in a deep geological formation (800–1200 m depth). For reaching such pressure values several compression stages are needed, including intercoolers to reduce power needs [24].

Any CO_2 capture process has important energy requirements, and there are great energy penalties in the overall system, i.e. combustion process (power plant) with capture system. One of the capture technologies that has been used in other sectors and is near a commercial stage is the absorption process based on amines. It offers high CO_2 capture efficiency and a good selectivity at acceptable costs. Its main drawbacks are the need of flue gas pre-treatment and energy penalties [20]. Thermal energy requirements are solved with low pressure, low temperature steam bleeding from steam turbines, that regenerate the amine. Nevertheless, there is a waste heat from the condensate of this steam and from multi-stage compression intercooling, and although some works have analyzed the way of integrating this process in the plant itself [25–28] it is impossible to reuse this low temperature energy in the power generation cycle.

One of the challenges of both, future CO_2 capture systems and desalination plants are the economic cost reduction. The future combination of power generation with CO_2 capture (contributing to reduce global warming) and desalination could help to tackle this problem. The main objective of this paper is to present several schemes about the integration of MED in a power plant with CO_2 capture, modelling the system and evaluating the results in reduction of CO_2 specific emissions per produced water and electrical power and in water energy cost and highlighting the opportunities that the proposed system could have in a near future.

2. Power and water production including CCS

The multi-effect distillation is the oldest and the most efficient thermal desalination process for water production [3]. In spite of having less capacity per unit, compared with MSF process [14], the power consumption of a MED plant is significantly lower than that of an

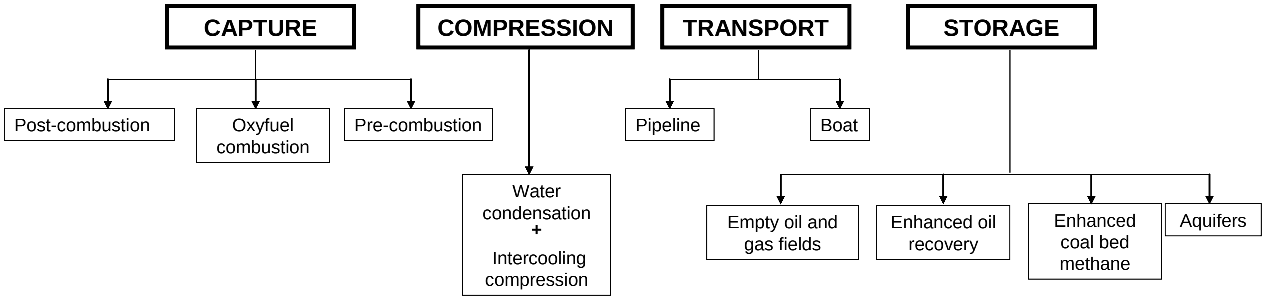


Fig. 1. Present CCS stages.

MSF plant (1.8 kWh/m^3 of distillate water, compared with 4 kWh/m^3 in MSF case). Furthermore, distillate production per steam consumed is also higher, as GOR values confirm [18]. On the other side, although thermal distillation processes as MSF or MED consume a larger amount of primary energy than RO process, thermal distillation systems have shown a great reliability [3]. This makes that the unit product cost of the distillate systems is close to the RO one, around \$0.7/m^3.

Besides technical advantages explained above, the main feature of MED process is that it operates at a quite low TBT between 60–70°C, consuming a low-pressure vapour (or even hot water) at around 70°C. This makes this technology highly suitable for thermal integration with residual heat available at the industrial or tertiary sector. New technologies to reduce CO_2 emissions are one of the providers of those residual heats, which could be freely taken to produce desalted water by means of a MED unit.

The case study includes an originally 350 MW$_e$ net power output coal power plant (36.93% LHV) with CO_2 capture in a postcombustion scheme and a MED for water desalination (Fig. 2). Several integration schemes are proposed and the simulation results are analysed to select the proper layout of combined water and power production with CO_2 capture. Power plant steam cycle is composed of two high-pressure and three low-pressure feedwater heaters and a steam extraction to deaerator. Steam production is 342.3 kg/s of live steam (168 bar/540°C) with reheat (39 bar/540°C). Combustion flue gases are 472 kg/s with 12.7% v. CO_2 concentration.

Each absorption train could treat a maximum volume flow rate around 300,000 m^3/h. Thus, four amine absorption trains are needed to capture 65% of CO_2, what is required for fulfil CO_2 National Allocations Plan for this case. The main disadvantage of amine scrubbing is the energetic cost, so it is necessary to regenerate the sorbent in a closed cycle. Regeneration heat is required at around 130°C and it must be extracted from the medium-low pressure steam turbine, in order to minimize the global energy penalty. Thus, design capacity and efficiency of the original coal power plant is considerably reduced, as it is shown in Table 1 and Fig. 2.

The power demand to drive the CO_2 compressor is 25 MW$_e$ (around 8% of net power output), but the main energy requirement is 260 MW$_{th}$ for amine regeneration. Nevertheless, energy penalty could be reduced when the heat flows from CO_2 compression intercooling are integrated into the original steam cycle. Unfortunately the temperature level and the quantity of intercooling heat make impossible to use it completely. These heat flows could be used to desalt water and/or other low-grade heat purposes. Table 1 illustrates the available energy from intercooling compression with a temperature range of 40–170°C. That makes suitable steam generation required for the thermal distillation system and still it allows taking advantage of the remaining heat for the power plant low pressure train.

Fig. 3 shows a possible thermal scheme of CO_2 intercooling compression (excluding gas conditioning). Heat required for steam production to MED unit could be obtained: (i) from the flue gas water condenser before compression trains (Q_{cond}), where temperature of CO_2 stream leaving condenser is around 108°C and, (ii) from the intercoolers between compressors ($Q_{intercool,i}$), since

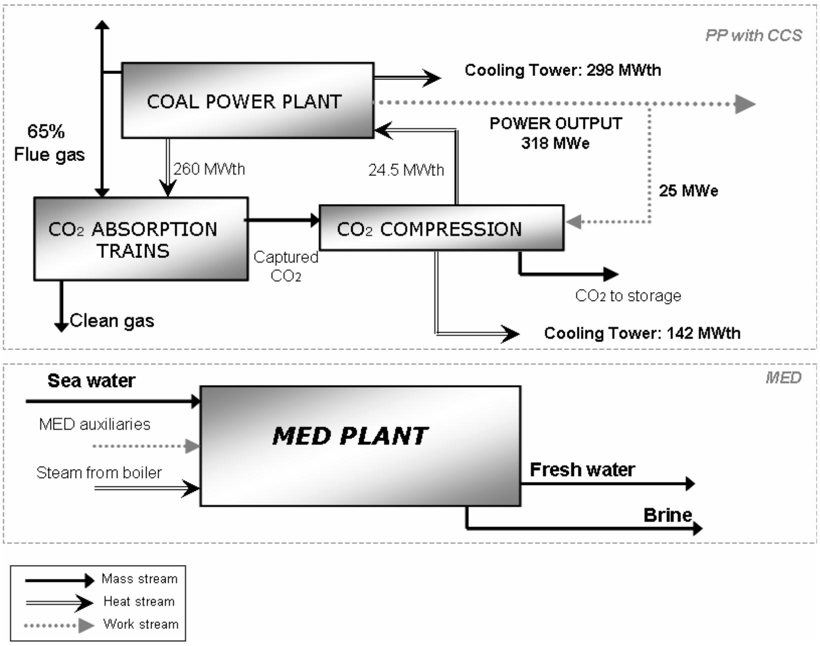
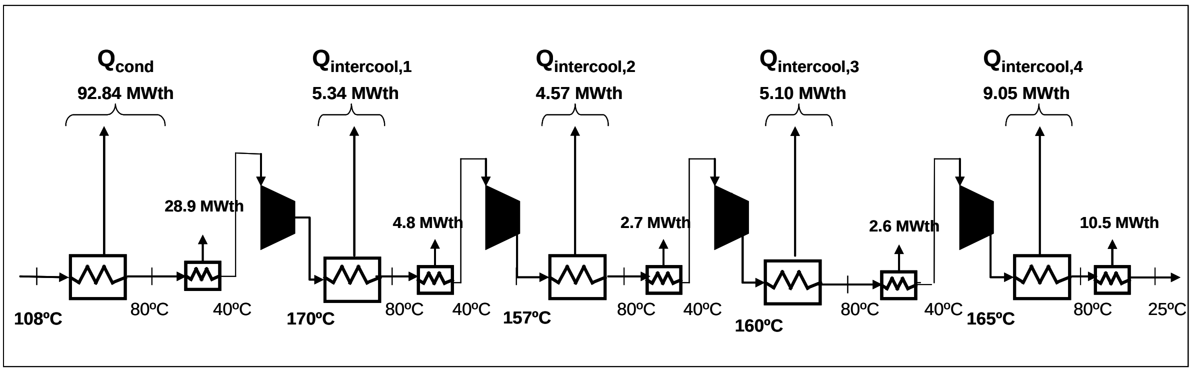


Fig. 2. Reference case, power plant with CCS and MED plant for water desalination.

Table 1
Reference case main data

Power plant with CO_2 amine capture system	Power plant net output, MW$_e$	318.0
	Power plant LHV efficiency, %	30.11[a]
	Amine regeneration energy requirement, MW$_{th}$	260.0
	CO_2 compression energy requirement, MW$_e$	25.0
	Energy to low pressure train, MW$_{th}$	24.5
	CO_2 captured, ton/h	214.0
Compression stage	Available energy from condenser, MW$_{th}$	124.0[b]
	Available energy from Intercooling, MW$_{th}$	38.3[c]

[a] Calculation of this efficiency includes electricity requirements of CO_2 compression
[b] Considering cooling down to 50°C for water condensation
[c] Considering cooling down to 50°C before each compressor



Fig, 3. Available heat from CO_2 compression stage.

temperature of each compressor outlet can be as high as 170°C.

Part of this residual heat is used as low pressure heaters in the power plant steam cycle avoiding or reducing the steam bleedings from low-pressure turbines and therefore producing additional power. Also, this temperature level makes it possible the steam production at 70°C, required for a MED plant. It should be also noticed that the lower intercooling temperature the lower compressor power consumption [27], for this reason a second cooling stage should be required to minimize these requirements [28]. These very-low quality heat is yet available for other purposes (here a total amount of 47 MW$_{th}$ could be used for tap water preheating, for instance).

3. Analysis and discussion of the proposed integration configurations

Proposed integration schemes have been simulated with Aspen Plus software [29] assuming a continuous operation of MED unit driven by steam at 70°C. Energy saving, CO_2 emissions and water production are compared with reference case. Energy consumptions associated to the MED unit were calculated by means of the Lost Kilowatt Method [30], that is, the ratio between the power penalty due to the vapour extraction to MED and the distillate production. Fuel cost of water is then calculated as that power penalty multiplied by the cost of electricity (COE) paid to the power plant owner. Cases analysed are illustrated in Fig. 4.

Case 1 (Fig. 4a) .Desalination with MED is driven with water-condensing flue gas thermal energy recovery heat exchanger before CO_2 conditioning and compression. Heat available makes it possible to produce up to 32,235 kg/s of steam at 70°C for MED plant.

Case 2 (Fig. 4b). For comparison purposes, a low-pressure steam bleeding is used for driving the MED unit. Flue gas is cooled down to condensate the water content before CO_2 conditioning.

Case 3 (Fig. 4c). Compressor power requirements are significantly reduced with intercooling stages. The cooling process is split in two levels of temperature and the heat required by MED could be produced in the high temperature heat exchangers. Additionally, part of water-condensing flue gas thermal energy is still available.

Case 4 (Fig. 4b). As in case 2, a low-pressure steam

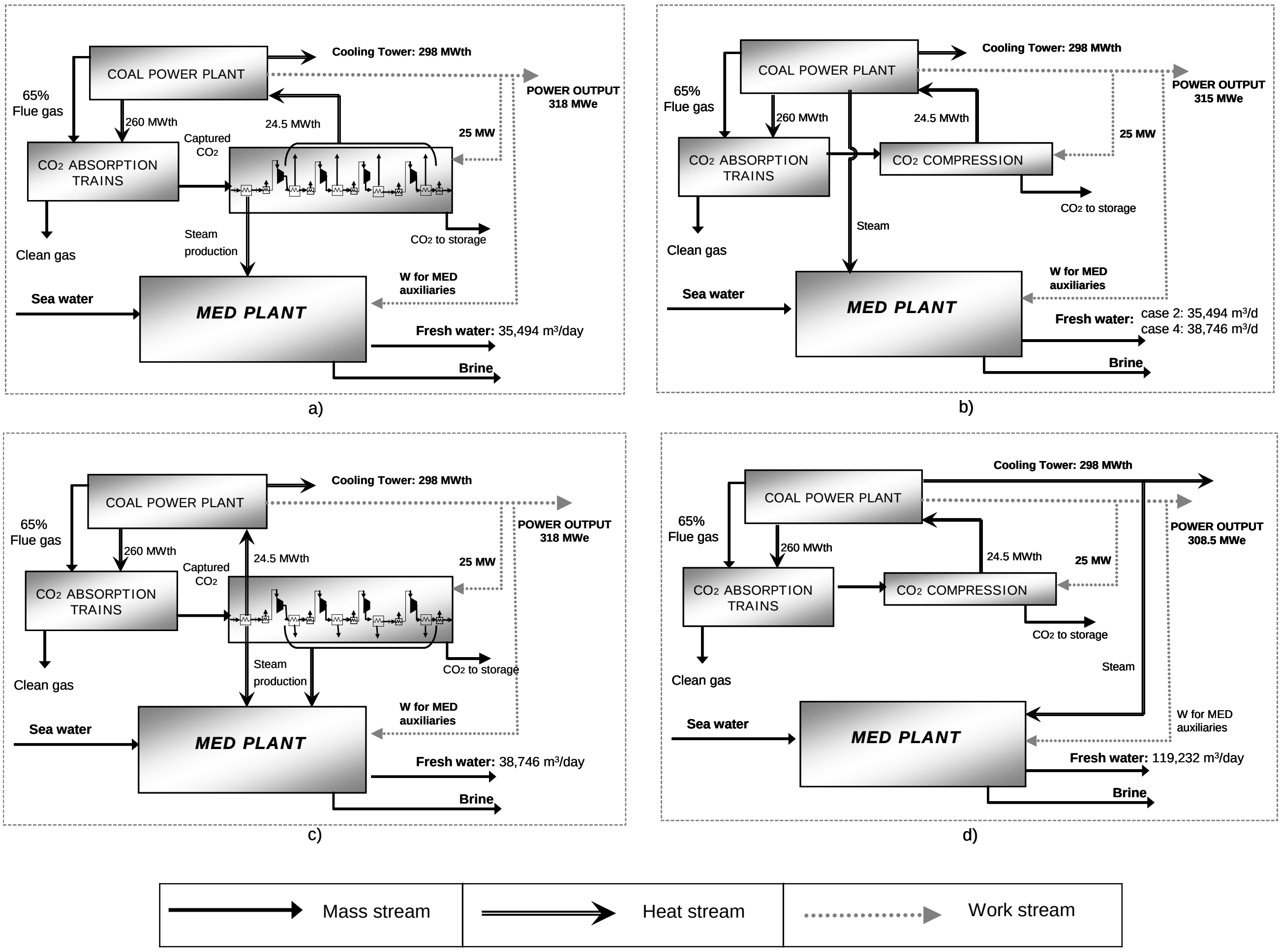


Fig. 4. Proposed integrated configurations. Cases a–e.

bleeding is used for driving the MED unit and flue gas is cooled down to condensate the water content before CO_2 conditioning.

Case 5 (Fig. 4d). Original low pressure part of the steam cycle is modified. Condensing steam turbine is replaced by back-pressure turbine at 3 bar. This pressure level is suitable for amine regeneration and MED water production plant operation.

Table 2 illustrates the advantage of obtaining distilled water when heat is delivered from the compression intercooling (cases 1 and 3), with respect to deliver the same thermal energy from a power plant steam extraction (cases 2 and 4). Comparison between cases 1 and 2 shows that there is a reduction of around 3 MWe when the low pressure steam bleeding is used to drive the MED. The heat stream available at flue gas condenser could produce 32.2 kg/s of steam and finally 35,494 m^3/d of desalted water. When the intercooling energy is used to increase the water production, an additional steam flow of 3.1 kg/s is produced. In case 4, the reduction in power plant production is similar to commented values in case 1 and 2. Case 5 should be carefully analyzed. Evidently, there is an important power production reduction of 10 MW$_e$ due to back-pressure steam turbine, nevertheless this heat is used for water desalination at MED and its production increases sharply from 38,746 to 119,232 m^3/d. Fig. 5 shows the enthalpy drops in each process and could help to understand the MED integration implications in the plant with included CCS. It can be seen that the great enthalpy drop caused by the condenser, in a conventional power plant can be compared with the necessary enthalpy drop for steam production in the MED plant, unlike the drop for the capture process.

It should be noticed that the power penalty caused by CO_2 capture and compression system (more than 10% of the same power plant without CCS) is similar to the effect of CO_2 capture due to the MEA (net power output from 350 to 318 MW$_e$). In any case, the reduction by MED integration and water production is between 3 and 10 MW$_e$.

The positive effects of producing water desalination with very low energy costs and emissions are illustrated in Table 2. Water energy consumption and water energy

Table 2
Simulation results of a MED plant integrated with the CO_2 compression heat train

Case	Net power output (MWe)	Power to compression (MWe)	MED auxiliaries (MWe)	Heat from compression to MED plant (MWth)	Specific emissions (t CO_2/MWh)	Steam to water production (kg/s)	MED production (m^3/d)	Water energy consumption (kWh/m^3)	Water energy cost (€/m^3)*
Ref	318.03	25.00	—	—	0.361	—	-—	—	—
1	318.03	25.00	2.22	92.84	0.361	34.24	35,494.8	1.28	0.08
2	315.23	25.00	2.22	—	0.367	34.24	35,494.8	2.89	0.17
3	318.03	25.00	2.42	101.34	0.361	37.37	38,746.2	1.28	0.08
4	314.97	25.00	2.42	—	0.368	37.37	38,746.2	2.89	0.17
5	308.58	25.00	7.45	295.24	0.383	115.00	119,232.0	2.89	0.17

*Considering COE: 60€/MWh

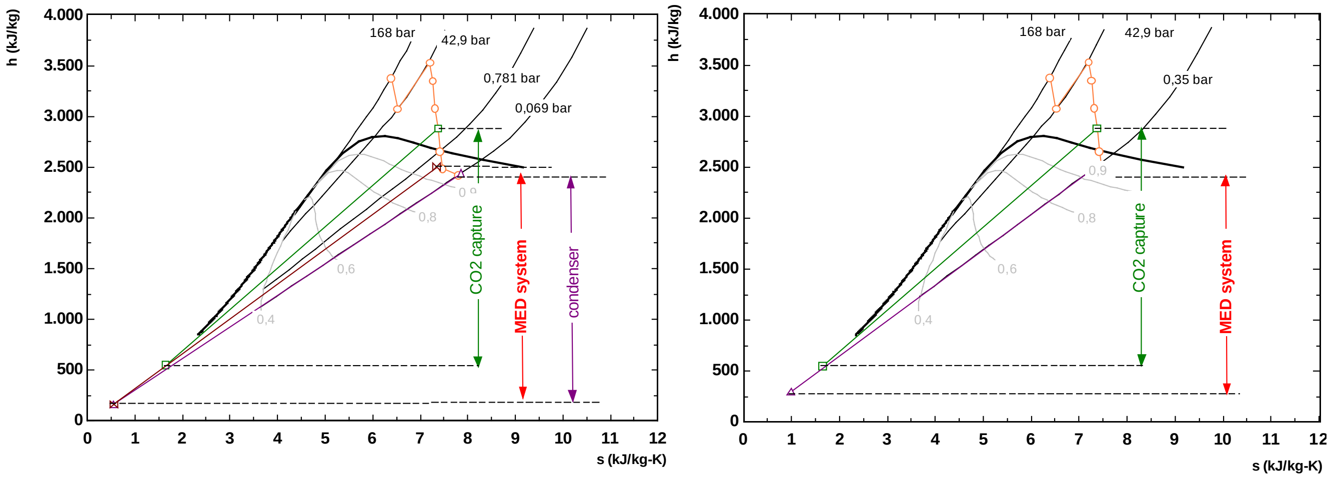


Fig. 5. Enthalpy drop comparison for case 2 (or 4) and case 5.

cost are low in cases 1 and 3 due to thermal integration. This causes a low specific CO_2 emissions related to the MWh produced.

In Table 3 it can be observed how CO_2 emissions associated to MED unit are reduced when steam is obtained by the CCS (case 1 and 3), when they are compared with steam extracted directly from the steam boiler (case 6), or from the LP turbine (case 2 and 4). Calculations about water production emissions were made similarly as energy and economic analysis, charging the emissions according to the power that is not produced when the MED unit is integrated into the CCS. Specific emissions calculation results are around 0.6 kg CO_2 per m^3 of fresh water produced, when steam for MED is produced from CCS waste heat. When the same steam is extracted from the turbines, specific emissions doubled the original values due to the reduction in power output. For comparing these results, a sixth case has been simulated, when considering an independent boiler for the steam production. Obviously emissions are larger in this case even when CO_2 capture is considered for this process as well, up to 8.5 kg/m^3 of fresh water. Associated emissions to generated water could be 45 times higher without any integrated MED without a CCS in the power plant (case 6).

In order to have a global perspective of the opportunities that the proposed integration could suppose, calculations for existing littoral coal power plants in Spain and Italy have been made. Considering a capture ratio of 65% and post-combustion technology for CO_2 capture, as explained above, Table 4 shows the feasible distilled water production that could be produced if the best case explained above, case 3, and if new hypothetical MED units were linked to those plants in case of installing CCS.

5. Conclusions

Along this paper it has been highlighted the necessity of taking into account the opportunities offered by the introduction of CO_2 capture and compression systems in terms of water production when integrated in coastal

Table 3
Specific emissions for m^3 of produced fresh water for different steam sources

	Power plant with capture			Power plant without capture	
	Steam from CO_2 compression (kgCO_2/m^3 fresh water)	Steam from the boiler (kgCO_2/m^3 fresh water)	Steam from the turbines (kgCO_2/m^3 fresh water)	Steam from the boiler (kgCO_2/m^3 fresh water)	Steam from the turbines (kgCO_2/m^3 fresh water)
Case 1	0.587	—	—	—	—
Case 2	—	—	1.330	—	3.352
Case 3	0.587	—	—	—	—
Case 4	—	—	1.329	—	3.352
Case 5	—	—	0.744	—	1.877
Case 6	—	8.478	—	25.537	—

Table 4
Distilled water potential in littoral Mediterranean coal power plants from CO_2 compression integration

	Litoral coal power plants	Capacity (Mwe)	Produced water (m^3/d)
Italy*	Fumesanto	640	70,850
	Sulcis	240	26,569
	Brinidisi Nord	640	70,850
	Brindisi Sud	1320	146,129
Spain**	Litoral Almeria	1160	128,416
	Los Barrios	570	63,101
	Alcudia II	510	56,459
Total		5,080	562,374

* Source: Asso Carboni [31]
* *Source: Red Eléctrica Española [32]

power plants. Thus, this type of integration could be a sustainable solution for those areas, since water would not be extracted from overexploited aquifers or scarce surface waters.

Taking advantage of heat from the CO_2 compression stage, water distillation by MED system could be implemented with very low energy costs. As an example of integration, a subcritical power plant producing originally 350 MW$_e$ with an integrating a CO_2 post-combustion capture system with steam de-rating has been simulated. With low-grade steam produced from intercooling and CO_2-water stream condenser, it can be produced about 38700 m^3 of fresh water per day without any substantial modification in the power plant.

CO_2 capture systems suppose good opportunities to produce additional desalted water derived from removing pollution associated to present fossil-fuel power plants. This means that the integration of desalination and power plant with CCS are a promising combination to overcome the energetic and economic penalties associated to zero emissions energy generation.

Acknowledgements

The authors are grateful for the financial support from the Spanish Government, without which, this work could not have been undertaken. The work described in this paper was supported by the R+D Spanish National Program from the Spanish Ministry of Science and Education under project ENE2004-06053 (Cuasi-zero CO_2 emissions power plant technologies research. The Spanish case).

Symbols and abbreviations

CCS — Carbon capture and storage
COE — Cost of electricity
GOR — Gained output ratio
LHV — Low heating value
MED — Multi-effect distillation
MSF — Multi-stage flash
RO — Reverse osmosis
TBT — Top brine temperature
TVC — Thermo-vapour compression
Q — Heat (MWth)

Subscripts

cond — Condensation
intercool$_i$ — ith intercooler

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