Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia
Energy Procedia 37 (2013) 2727 – 2737

GHGT-11

Operating Flexibility of Power Plants with Carbon Capture and Storage (CCS)

Rosa Domenichini[a], Luca Mancuso[a]*, Noemi Ferrari[a], John Davison[b]
[a]Foster Wheeler, Via Caboto 1, 20094 Corsico, Italy
[b]IEA Greenhouse Gas R&D Programme, The Orchard Business Centre, Stoke Orchard, Cheltenham, Gloucestershire, GL52 7RZ, UK

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

Most assessments available in the literature have assumed that power plants with carbon capture and storage (CCS) will operate at base load. It is now becoming clear that in many cases CCS plants will need to be able to operate flexibly because of the variability of electricity demand, increased use of variable renewable energy sources and poor flexibility of other technologies such as nuclear. This paper summarizes the results of a study carried out by Foster Wheeler for the IEA Greenhouse Gas R&D Programme with the purpose of evaluating and proposing strategies for improving the operating flexibility of power plants with CCS.

"Keywords: CCS; Flexibility; CO2; power plant; NGCC; USC-PC, IGCC, Oxy-combustion"

1. Background

Power plants built in the 1990s and early years of the new millennium have been typically designed for base load operation, favouring higher efficiency and lower capital costs, with the main objective of minimizing the cost of electricity production. Nowadays, existing and new power plants must face the challenges of the liberalized electricity market, predictability issues regarding renewable sources and the requirement to cover intermediate and peak load constraints, to be able to respond to the variation of the electricity demand. Therefore, not only must conventional natural gas combined-cycle plants be designed for flexible operation, but also coal-fired power plants are now generally required to operate in the mid-merit market.

With this premise, IEA Greenhouse Gas R&D Programme (IEA GHG) commissioned Foster Wheeler to perform a study that assesses the potential flexibility of power plants with CCS [1]. The following coal- and natural-gas-fired power plants with the leading CO_2 capture technologies were considered:

* Corresponding author. Tel.: +39-02-4486-2670; fax: +39-02-4486-3045. *E-mail address*: luca_mancuso@fwceu.com

doi:10.1016/j.egypro.2013.06.157

- ✓ Natural gas combined cycle (NGCC) with post-combustion capture;
- ✓ Coal integrated gasification combined-cycle (IGCC) plant with pre-combustion capture;
- ✓ Ultra-super-critical pulverised coal (USC-PC) power plant with post-combustion capture;
- ✓ Oxy-combustion USC-PC power plant with cryogenic carbon dioxide (CO_2) capture.

Nomenclature

NGCC	Natural Gas Combined Cycle
IGCC	Integrated Gasification Combined Cycle
USCPC	Ultra-Super-Critical Pulverised Coal
CCS	Carbon Capture and Storage
CC	Combined Cycle
NPO	Net Power Output
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
ASU	Air Separation Unit
VFD	Variable Frequency Drives
AGRU	Acid Gas Removal Unit
LOX	Liquid Oxygen

2. Operating flexibility features of power plants with and without CCS

Table 1 summarizes the key flexibility features of the power plants with and without CCS, so to point out the impact of adding the carbon capture to the power plant.

For power plants without CCS, most of the information currently available in the public domain refers to combined cycles, especially in relation to the improvements made in the recent years to respond to customers' requirements for greater flexibility. Much less information is available on operational flexibility of USC-PC boiler plants, as well as IGCCs. This is because USC-PC boilers and IGCC plants have generally been designed to operate at base load, due to the lower weighting of the variable costs (i.e. fuel) on the overall cost of electricity.

Table 1 shows that "conventional" (i.e. without CCS) NGCC and USC-PC power plants have, respectively, high and medium operating flexibility, generally allowing cycling operation, rapid load changes and start-ups, as well as good efficiency at partial load and low minimum operating load. In contrast, "conventional" IGCC shows lower dispatch flexibility, due to the inertia of the process units, mainly the gasification and the ASU, to generate and prepare the fuel at the conditions required by the gas turbine.

For power plants with CCS, one of the general additional constraints is the part load operation of CO_2 compressors, which would typically be limited to around 70% turndown. Higher turndown could be achieved by recycling compressed CO_2, but this would impose a significant energy penalty, as the compressor would still be operating at 70% load even when the power plant was turned down further. It would therefore be advantageous to have either capital intensive variable frequency drives (VFDs) or multiple CO_2 compressors, which may be required anyway due to size limitations, particularly in multiple-train power plants.

Table 1. Flexibility features of power plants with and without CCS

	Turndown	Cycling capability Start-up to full load	Ramp rates	Part load efficiency
NGCC	Low load operation: 15-25% CC load (10-20% GT load) Min. environmental Load: 40-50% CC NPO (30-40% GT load)	Hot start-up: 45-55 min Warm start-up: 120 min Cold start-up: 180 min	35 - 50 MW/minute max Hot start-up load change rate: - 0-40% GT load: 3-5%/min - HRSG press.: 1-2%/min - 40-85% GT load: 4-6%/min - 85-100% GT load: 2-3%/min	Approx. constant efficiency down to 85% GT load 2-3 percentage points less @ 60% CC load
with CCS	Post-combustion unit min. load: 30% CO_2 compressor min. efficient load: 70%	Regenerator preheating: - hot start-up: 1-2 h - warm start-up: 3-4 h	Same as plant w/o CCS	Same as plant w/o CCS
IGCC	Min. env. GT Load: 60% PO. Process unit /air separation unit (ASU) cold box min. load: 50% ASU compr. min. load: 70%	Cold start-up: 80-90 h Gasification hot start-up: 6-8 h ASU hot start-up: 6 h	Gasification ramp rate: 3-5%/min ASU ramp rate: 3%/min	Gross electrical efficiency: 2 percentage points less @ 70% CC load
with CCS	CO_2 compressor min. efficient load: 70%	Same as plant w/o CCS	Same as plant w/o CCS	Same as plant w/o CCS
USC PC	Min. boiler load: 25-30%	Very hot start-up: < 1h Hot start-up: 1.5-2.5 h Warm start-up: 3-5 h Cold start-up: 6-7 h	30-50% load: 2-3%/min 50-90% load: 4-8%/min 90-100% load: 3-5%/min	Subcritical boiler: -4 perc. point @ 75% load Supercritical boiler:- 2 perc. point @ 75% load
with CCS	Post-combustion unit min. load: 30% CO_2 compressor min. efficient load: 70%	Regenerator preheating: - hot start-up: 1-2 h - warm start-up: 3-4 h	Same as plant w/o CCS	Same as plant w/o CCS
Oxy fuel				
Air-firing mode	Min. boiler load: 25-30%	Very hot start-up: < 1h Hot start-up: 1.5-2.5 h Warm start-up: 3-5 h Cold start-up: 6-7 h	30-50% load: 2-3%/min 50-90% load: 4-8%/min 90-100% load: 3-5%/min	Subcritical boiler: -4 perc. point @ 75% load Supercritical boiler: -2 perc. point @ 75% load
Oxy-firing mode	Cold box min. load: 40-50%. ASU compressor min. efficient load: 70% CO_2 compressor min. efficient load: 70%	Start-up in air-firing mode, ASU start-up completed in approx. 36 h	ASU ramp rate: 3%/min	Same as plant in air-firing mode

For NGCC and USC-PC with post-combustion capture, Table 1 shows that the introduction of the capture unit may impose additional constraints on the turndown, start-up and fast load changing of the plant. For oxy-combustion plants, the main constraint on flexibility is the ASU, which has a minimum operating load of the cold box of around 50% and a maximum ramp rate of 3% per minute (a boiler can typically ramp at 4-5%).

3. Strategies for improving the operating flexibility of power plants with CCS

The need to improve the operating flexibility of the power plants with CCS is based on the assumption that these plants will be requested to follow a variable electricity market demand trend, generally characterized by low and high electricity demand periods. Two possible electricity demand curves were assumed as an example (Fig.1):

- ✓ ***Scenario 1 (Weekly scenario)***: high electricity demand for 16 hours during weekday daytimes and low (USC-PC) or zero (NGCC) electricity demand during 8 hours of night-time and all weekend;
- ✓ ***Scenario 2 (Daily scenario)***: peak electricity demand for two hours during the weekday day-time, medium demand for the remaining 14 hours of the day-time and low (USC-PC) or zero (NGCC) demand for 8 hours of night-time and all weekend.

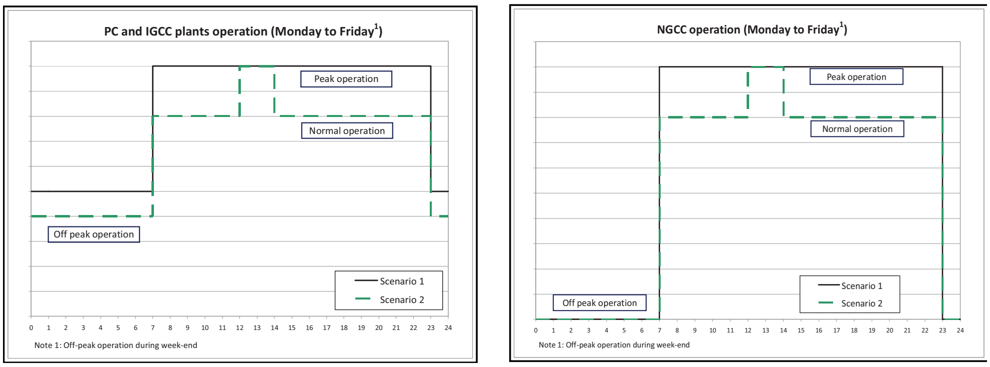

Fig 1. Power plant operating load following electricity demand trends

However, it is recognized that the characteristics of electricity systems may vary significantly in the future and that power plant flexible operation depends also on the needs of the operators, the costs and other external factors which may change during the operating life of the plant, like the increased use of variable renewable energy sources.

The evaluation of the various strategies made use of baseline plant performance and cost data from earlier IEAGHG studies [3-6], taking into account cost inflation that has occurred since those studies were undertaken. The assessment refers to power plants based on one or two power generation trains. For the combined-cycle alternatives, the design capacity of the plant is fixed to match the thermal requirement of two F-class gas turbines. For the boiler-based alternatives, the reference case design capacity is selected by referring to one boiler size that could be currently engineered and built, corresponding to approximately 750-1,000 MWe gross power production.

For each power plant type, Table 2 summarises the techniques that were assessed for improving flexibility and increasing peak power output, as described in the rest of the paper.

Table 2. Techniques for improving flexibility of power plants with CCS

Strategies for improving flexibility \ Power Plant type	NGCC	IGCC	USC PC	Oxy-combustion
Storage of CO_2 capture solvent	✓	-	✓	-
Storage of liquid oxygen	-	✓	-	✓
Co-production and storage of hydrogen	-	✓	-	-
Turning off CO_2 capture	✓	✓	✓	-
Buffer storage of CO_2 (constant flow to final storage)	✓	✓	✓	✓

3.1. Solvent storage in NGCC and USC-PC power plants

Solvent storage in post-combustion capture (NGCC and USC-PC) has the potential for improving the flexibility and the overall economics of power plants, as the electricity production can be increased when the market requires a higher electricity generation by operating the solvent regeneration at part load, while continuously capturing the CO_2 from the flue gases in the absorber [7]. In fact, the temporary storing of CO_2-rich solvent in dedicated storage tanks allows the energy penalty of the amine capture process to be reduced, as it is possible to save both the steam extracted from the steam cycle and the CO_2 compressor power demand. Then, regeneration of stored solvent and CO_2 compression is made during the low electricity demand periods.

When solvent storage is applied in post-combustion capture, the operating mode of the plant determines the required capacities of the solvent storage tanks and the solvent regeneration and CO_2 compression equipment. For example, if the plant is required to operate only at base load, then the solvent regenerator and CO_2 compressor would need to be oversized to cope with regeneration of the solvent stored during high electricity demand hours. On the other hand, if the plant is expected to operate for some of the time at reduced load, the stored solvent could be regenerated during these times and the regenerator and compressor would not need to be oversized. If a plant is expected to operate regularly at substantially reduced load at night and at weekends, the solvent regenerator and CO_2 compressor could be undersized, i.e. they could be made smaller than in a normal base-load power plant, thereby reducing capital costs. However, such a plant would not have the ability to operate at base load for long periods of time and this may not be attractive to the plant owner.

Solvent storage in IGCC was not considered because other strategies assessed in this study (described in the following sections) were deemed more economically attractive.

Table 3 summarizes the main performance and cost data for NGCC and USC-PC plants with Monoethanolamine (MEA) solvent storage, following the two operating modes described in Figure 1 and compared with the baseline plant performance and cost data from earlier IEAGHG studies.

Table 3. Post-combustion CO_2 capture solvent storage alternatives

Power Plant type	NGCC	NGCC	USC PC	USC PC
Electricity demand trend	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Hours per week of peak output	80	10	80	10
Off-peak hours plant load	Min. plant load	Plant shutdown	50% NPO	50% NPO
Regeneration load during peak hours	50%	No regeneration	75%	No regeneration
Increase of power output at peak time	+ 6%	+12%	+5%	+22%
Thermal efficiency				
Reference plant (base load)	50.6%	50.6%	34.8%	34.8%
Storage plant (peak-hours efficiency)	53.7%	56.7%	36.4%	42.5%
Reference plant (weekly average efficiency)	50.6%	50.6%	33.6%	33.6%
Storage plant (weekly average efficiency)	45.6%	50.5%	33.6%	33.6%
Increase of capital cost	+ 20%	+ 9%	+ 6%	+ 6%

In Scenario 1 (weekly scenario), the 'peak' hours are almost half of the total hours. To maximize power production, solvent regeneration could be switched off during peak times. However, the main factor limiting this operating mode is the very large volume and the area required for the storage tanks, as the plant is required to operate at peak load for a significant period of time. In addition, the regenerator would be substantially larger than that in the reference plant or it may even be difficult to provide sufficient steam for the regenerators during off-peak period, in particular for NGCC that is called to operate at its minimum environmental load. Therefore, different regeneration loads during peak times have been investigated in order to evaluate the most convenient operating conditions.

For the USC-PC plant, the solvent regeneration was reduced by 25% at peak times. As the regeneration is performed during off-peak times, when the plant is operating at 50% part load, the regeneration section could be operated at a load lower than base capacity to regenerate all the solvent stored during peak time. However, the most attractive solution from both flexibility and economical point of view is keeping a 100% sized regenerator, which would enable to operate the plant for long periods at 100% load, if required; in addition, to minimize the capacity of the storage tanks the regenerator can be operated at full capacity during the weekday night-times, and lower throughput during the weekends.

In the NGCC weekly scenario, the solvent is regenerated at off-peak time by operating the power plant at the minimum environmental load of the gas turbine. Only the amount of CO_2 corresponding to one gas turbine in operation at minimum load is generated during off-peak times, so it is possible to store 50% of the solvent during peak times without having to oversize the regenerator. Analogously to the USC-PC plant, the lowest cost and most flexible option is to keep a 100%-sized regenerator.

In Scenario 2 (daily scenario), solvent regeneration can be shut down completely during the two hours of peak operation, storing all of the CO_2–rich solvent produced during this time. In the USC-PC plants the stored solvent is regenerated during the night-time when the plant is operating at 50% load, with a 100% sized regenerator. In the NGCC plants the stored solvent is regenerated during the remaining 14 hours of daytime operation, as NGCCs are fully shut down during off-peak hours, which requires the regenerator to be over-sized by about 14% compared with a capture plant without solvent storage.

Solvent storage has very little effect on the thermal efficiency except in case the NGCC weekly scenario, in which the plant has to be operated at low load at low efficiencies at off-peak times to regenerate solvent. The solvent storage tanks are conventional-sized tanks as used at oil refineries but they are nevertheless substantial, particularly in Scenario 1. As an example, in the NGCC daily scenario four tanks each having a volume of 7,500 m^3 are required.

Licensors of the well referenced solvent washing technologies (Aker Clean Carbon, Alstom and Mitsubishi Heavy Industries) have all confirmed the technical feasibility of solvent storage, either lean or laden, provided the temperature of the rich solvent is maintained at, or slightly below, absorber bottom outlet temperature condition, to avoid degassing and potential tank over-pressurization. Furthermore, high rates of solvent degradation in the rich storage tank are not expected; degradation would be mainly due to the reaction with oxygen, therefore nitrogen or CO_2 blanketing should be considered. In addition, no safety issue is expected as solvent solution is not flammable at the concentration used in the capture plant and cannot be auto-ignited in the different operating modes.

Storage of CO_2-rich solvent can also be considered in NGCC and USC-PC plants to decouple the absorption section, which follows the gas turbine or the boiler load during their start-up, from the regeneration section. This allows the same thermal cycling capability to be maintained as for conventional plants without capture, with a marginal investment cost increase, equal to about 8% and 2% respectively for the NGCC and the USC-PC, with respect to the base-load plant.

3.2. Hydrogen co-production and storage in IGCC power plants

The operating flexibility and economics of IGCCs can be improved if the plant is designed for the co-production of electricity and hydrogen or if buffer storage of hydrogen-rich gas is introduced in the plant [6, 8]. In both cases, during low electricity demand periods, part of the hydrogen-rich gas from the CO_2 removal unit is fed to storage, to be used during electricity peak demand. This enables the process units to continue to operate at full load, while the hydrogen-fired power plant follows the requirements of the flexible market. With this strategy, the main constraints to power production flexibility are related to the gas turbine itself, while the process units can be under-sized with respect to the requirement of the power train at base load.

Table 4 summarizes the main performance and cost data for IGCC plants with hydrogen storage compared with the baseline plant designed at base load, for the two scenarios analyzed in the study. For the two alternatives without H_2 production, both following Scenario 1 but characterized by different off-peak loads, the increase in peak power output per unit of gas turbine capacity is relatively small but the increase per unit of gasification plant capacity is significant as the process units are undersized with respect to the gas turbine thermal input. The capital cost is also lower, but the plant would be unable to operate continuously at full load. As an alternative, if there is a market for hydrogen outside the power plant battery limits, part of the hydrogen rich gas can be fed to a pressure-swing adsorption (PSA) section, generating around 75,000 Nm^3/h of high purity hydrogen, which is the typical amount required by a large refinery, with a capital cost increase of about 3% with respect to the reference plant. The process unit will operate at 100% capacity, which would enable the power plant to operate for long periods at 100% load, if required.

The leading option for hydrogen storage would be underground salt caverns, which are a proven and relatively low-cost solution for large-scale hydrogen storage. As this study focused on short-term (up to a week) variability in electricity demand, the resulting hydrogen storage volumes are relatively small compared to a typical modern salt cavern; for example about 5% of the capacity of a storage cavern recently built in Texas by Praxair. The relatively low cost of underground hydrogen storage means that this technique could also be cost-effective for smoothing out longer-term seasonal variability in electricity demand.

Table 4. Hydrogen-rich gas storage alternatives

Power Plant type	IGCC	IGCC	IGCC +H_2 prod.
Electricity demand trend	Scenario 1	Scenario 1	Scenario 1
Off-peak hours plant load	50%	Island mode	50%
Process unit capacity, % reference case	82%	65%	100%
Hydrogen production	-	-	75,000 Nm^3/h
Increase of power output at peak time			
Referred to gas turbine capacity	+3%	+3%	+3%
Referred to process unit capacity	+26%	+63%	+3%
Changes of capital cost (w/o storage)	-6%	-12%	+3%
Hydrogen storage			
Working volumes @ reservoir operating pressure	100,000 m^3	200,000 m^3	100,000 m^3
Cost increase (depending on the storage techniques)	0.5-3%	1-6%	0.5-3%

3.3. Oxygen storage in IGGC and oxy-USCPC power plants

The ASU significantly impacts the overall net electricity production of the plant, mainly due to its high power demand. Storage of liquid oxygen (LOX) in oxy-combustion USC-PC and IGCC plants allows the energy requirement of this unit to be reduced during peak demand hours, increasing the overall net power export during remunerative hours and improving the economics of the plant. In fact, by supplying part of the oxygen required by the plant running at full load from the LOX storage, the ASU can be operated at partial load during peak hours, reducing the auxiliary consumption and increasing the overall net electricity production. Then, LOX storage can be re-filled during low electricity demand periods when the plant is required to operate at part load. Alternatively, the ASU can be designed for a reduced capacity and operated at constant load. This option would reduce the capital cost and oxygen storage requirement, but the plant would not have the flexibility to operate at full load for long periods of time, similar to the post-combustion cases with a reduced-size solvent regenerator, as mentioned earlier.

Table 5 summarizes the main performance and cost data for the IGCC and the oxy-combustion USC-PC power plants with oxygen storage, compared with the baseline plants, following the weekly (Scenario 1) and daily (Scenario 2) electricity demand scenarios shown Figure 1.

Operating the ASU at the minimum efficient turndown of the air compressor, i.e. 70%, would give only a marginal increase in net peak power output. Therefore, for operating the ASU at the minimum turndown of the cold box, i.e. around 50%, two smaller air compressors are considered, one of which is turned off during the time of peak demand. Having multiple compressors increases the capital cost but provides greater opportunity for high peak generation.

In IGCC plants, part of the compressed air for the ASU is provided by extraction from the gas turbine, which earlier studies and practical experience has shown results in relatively high efficiency, good operability and low costs. When the power plant is operating at partial load, less air is available from the gas turbine compressor. Therefore, the ASU operation at full load requires the installation of an additional compressor. In the IGCC plant liquid nitrogen also has to be stored, as nitrogen is required for the gas turbine. Nitrogen accounts for more than half of the total storage volume.

Table 5. LOX storage alternatives

Power Plant type	IGCC	IGCC	Oxy-USC PC	Oxy-USC PC
Electricity demand trend	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Hours per week of peak output	80	10	80	10
Off-peak hours plant load	50% NPO	50% NPO	50% NPO	50% NPO
ASU load during peak hours	67%	50%	57%	50%
Increase of power output at peak time	+8%	+10%	+5%	+6%
Thermal efficiency				
Reference plant (base load)	31.4%	31.4%	35.5%	35.5%
Storage plant (peak-hours efficiency)	33.9%	34.7%	37.3%	37.5%
Reference plant (weekly average efficiency)	31.0%	31.0%	34.0%	34.0%
Storage plant (weekly average efficiency)	30.0%	28.9%	34.8%	34.5%
Increase of capital cost	3%	1.5%	2%	1%

The volumes of storage are much smaller than in the solvent storage cases but vessels and tanks have to operate at cryogenic temperatures. No additional power generation equipment has to be installed, as the increased peak power is achieved by reducing the plant's ancillary power consumption, leading to a lower additional cost with respect to the solvent storage alternatives. Therefore, from this preliminary analysis, oxygen storage should be an attractive option for providing additional peak generation. Furthermore, the LOX storage provides higher flexibility to oxy-combustion power plants as it is possible to increase the typical ramp rate of the ASU (3% per minute) up to the typical rate of the boiler (4-5% per minute).

3.4. Turn off CO_2 capture in pre and post combustion power plants

Provided that design is adequate, power plants with pre- or post-combustion CO_2 capture can also be maintained in continuous operation without capturing the CO_2, if allowed by regulators. When CO_2 emission allowance costs are low, as in the present market situation, this operating flexibility may improve the economics of the plants [9]. In addition, the ability of a plant with capture to ramp up power output could actually be better than that of a plant without capture if the load of the capture unit is reduced at the same time as the load of the power generation unit is increased.

Flexible CO_2 capture operation is particularly suited for post-combustion CO_2 capture systems, as it is possible to by-pass totally the CO_2 capture unit, directly releasing to atmosphere the flue gases from the boiler/gas turbine, similarly to conventional power plants without capture. In this operating mode, the energy penalties related to the CO_2 capture and compression units, as well as the steam requirement for solvent regeneration, are avoided, leading to an overall higher plant net power production. This implies that the steam cycle has to be designed to accept all the steam from the steam generation, when the capture plant is turned off, increasing the plant capital cost and lowering the efficiency of the steam turbine low-pressure section, when operating at non-optimum conditions during normal operation with CO_2 capture.

In plants that have been retrofitted with capture this extra steam turbine capacity would already be available and even in new power plants with capture, extra turbine capacity may have been included to enable the plant to operate efficiently during outages of the CO_2 capture, transport and storage equipment. To avoid the efficiency reduction a separate steam turbine could be installed to use the low-pressure steam that is available when capture is turned off.

For IGCC plants with pre-combustion CO_2 capture processes, the acid gas removal unit (AGRU) cannot be shut down because it is necessary to remove at least the H_2S from the syngas to meet the design environmental emission limits. In addition, fuel composition to the gas turbine cannot be changed dramatically (e.g. CO shift unit cannot be by-passed, or tuning solvent circulation to capture only H_2S and not the CO_2) because it is necessary to respect the maximum range variation of fuel properties (e.g. LHV, Wobbe Index etc.) as tolerated by the machine. In the plant configuration assessed in the study, it has been considered that the AGRU continues capturing CO_2 from the syngas: part of it is used as diluent in the gas turbine for NOx reduction, while the remainder is released to atmosphere, saving the CO_2 compressor power demand. A proper AGRU design or dedicated purification system should be considered to reduce the toxic components content in the vented stream, in particular H_2S and CO, to the low limits.

3.5. Constant flow of CO_2 to transport and storage

For each power plant type, the cycling operation corresponds to a variation of the throughput of CO_2 to the transport and storage site. Little information is available on the capability of pipeline and storage wells to accept variable CO_2 flow. So, two techniques were assessed in the study for providing a constant flow of CO_2: buffer storage of CO_2 or buffer storage of CO_2 rich solvent combined with a reduced solvent regenerator capacity. The first technique does not affect the overall performance, while the plant additional investment cost (without pipeline) ranges from 2% to 3% of the baseline plant. With the latter technique for post-combustion power plants, the electricity production increases by 3% to 5% during peak hours but the investment cost increase is higher than the CO_2 buffer storage alternative. In both cases, the additional cost could, in principle, be offset by a reduction of pipeline size, but in this case it would not be possible to maintain the plant at high load factors, if required.

4. Conclusions

Nowadays, greater flexibility is required in operating power plants to cope with the challenge of the liberalized electricity market and the increasing generation from renewable sources. The flexibility of NGCC plants has already improved substantially over recent years to respond to this requirement. Modern NGCCs are typically capable of fast start-up, shut–down and load-cycling. USC-PC plants are also characterized by low minimum operating loads, good cycling capabilities and start-up times. In contrast, IGCC plants have relatively low cycling capabilities, high minimum load and long start-up times, due to the inertia of the process units.

CCS may impose additional constraints on the flexible operation of power plants but, depending on the specific characteristics of the power plants, there are ways of overcoming these limitations:

✓ Storing CO_2–rich solvent and regenerating it at a later time could be attractive as a way of increasing power plant ramp rates and for increasing the net power output during short-term peaks in power demand. However, the large quantity of solvent that would have to be stored would mean that operating at peak output for longer periods of time would not be attractive. Plants could be built with a wide range of storage volumes, solvent regenerator sizes and peak power generation capacities. Selecting the optimum would be a challenging commercial decision.

- ✓ Storing the hydrogen-rich gas produced in IGCC plants with pre-combustion capture in underground salt caverns would enable the gasification and CCS equipment to operate at continuous full load while providing a variable power output from the combined-cycle unit, and it would provide faster ramp rates and lower capital costs for non-base-load power plants. The stored hydrogen could be used to generate electricity at peak times or it could be supplied to a high-purity hydrogen generation unit. Underground hydrogen storage is a commercially proven technique with a relatively low specific cost, suitable for long-term as well as short-term storage.

- ✓ Liquid oxygen could be stored in oxy-combustion and IGCC plants to improve flexibility and peak generation capacity. From an economic perspective this is expected to be an option of primary importance, in particular for short-term peak of electricity demand.

- ✓ Flexibility of power plants with CO_2 pre- or post-combustion capture can be improved by operating the plant without capturing the CO_2, during the peak of electricity demand. Depending on possible low CO_2 emission allowance costs, this operating flexibility may improve the economics of the plants because of the resulting higher power production. Some plant units, particularly the steam turbine for the plant with post-combustion capture and the AGRU for the IGCC, would have to be designed for operation without CCS, which would increase the capital cost.

- ✓ If deemed necessary, constant flow of CO_2 to the transport and storage equipment can be ensured by buffer storage of either compressed CO_2 or CO_2-rich solvent.

In broader and more general terms, it can be concluded that performance of flexible CCS plants during peak hours is often better than those of base-load plants and, in most cases, the investment cost increase is not excessive. Therefore, flexible plants with leading CCS technologies have the potential for opening new business opportunities and improving the overall plant economics.

5. References

[1] IEA Greenhouse Gas R&D Programme (IEAGHG). Operating flexibility of power plants with CCS, report 2012/6, June 2012.
[2] Henkel E, Schmid E, Gobrecht E. Operational flexibility enhancements of combined cycle power plants, Power-Gen Asia 2008.
[3] IEA Greenhouse Gas R&D Programme (IEA GHG). Improvement in power generation with post combustion capture of carbon dioxide, report PH4/33, November 2004.
[4] IEA Greenhouse Gas R&D Programme (IEA GHG). Oxy combustion processes for CO_2 capture from power plant, report 2005/9, July 2005.
[5] IEA Greenhouse Gas R&D Programme (IEA GHG). Gasification power generation study, report PH4-19, May 2003.
[6] IEA Greenhouse Gas R&D Programme (IEA GHG). Co-production of electricity and hydrogen by coal gasification with CO_2 capture, report 2007-13, September 2007.
[7] Chalmers H, Leach M, Lucquiaud M, Gibbins J. Valuing flexible operation of power plants with CO_2 capture, Energy Procedia **1**:4289-4296, Elsevier 2009.
[8] Davison J, (IEA-GHG), Flexible CCS plants – A key to near-zero emission electricity systems, Energy Procedia **4**:2548-2555, Elsevier 2011.
[9] Wilson T. (Electric Power Research Institute), Value of flexible operation of advanced coal plants with CCS, IEAGHG workshop on operating flexibility of power plants with CCS, November 2009.