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GHGT-11

## Addressing technology uncertainties in power plants with post-combustion capture

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### Abstract

Risks associated with technology, market and regulatory uncertainties for First-Of-A-Kind fossil power generation with CCS can be mitigated through innovative engineering approaches that will allow solvent developments occurring during the early stage of the deployment of post-combustion CO<sub>2</sub> capture to be subsequently incorporated into the next generation of CCS plants. Power plants capable of improving their economic performance will benefit financially from being able to upgrade their solvent technology. One of the most important requirements for upgradeability is for the base power plant to be able to operate with any level of steam extraction and also with any level of electricity output up to the maximum rating without capture. This requirement will also confer operational flexibility and so is likely to be implemented in practice on new plants or on any integrated CCS retrofit project.

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Post-combustion capture, upgradeability, solvent upgrade, future-proofing

### 1. Introduction

Several investment cycles are expected to be required to demonstrate and rollout Carbon Capture and Storage (CCS) at scale. Commercial-scale application of CCS will likely start with an initial tranche of First Of A Kind (FOAK) projects demonstrating the full chain of capture, transport and storage followed by a second tranche of plants implementing lessons learned from this first tranche. This model suggests that CCS technologies could be rolled out globally with a larger third tranches of plants in the 2020s, but also implies that several learning cycles are likely to occur over, at least, the next decade through consecutive tranches of projects. Particularly for early demonstration projects, and for plants already

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permitted as Carbon Capture-Ready (CCR), a period with fast learning-curves lies ahead for equipment manufacturers, utilities, policymakers and regulators. Technology, market and regulatory uncertainties lead to a set of challenging risks for electricity utilities considering investing as ‘first movers’ in fossil power generation with CCS. FOAK/CCR ‘technology lock-in’ risks can be mitigated through innovative engineering approaches that will allow technology developments occurring during the early stage of CCS deployment subsequently to be incorporated into the next generation of CCS plants. This would avoid locking these plants into a specific version of capture technology, and by extension into higher than necessary electricity generation costs and/or reduced performance (e.g. lower capture levels) throughout the life of the plant. In this context, future-proofing CCS units by enabling them to incorporate future improved technologies effectively acts as a hedge against a wide range of risks including those associated with:

- technology obsolescence in competitive electricity markets;
- evolving regulatory frameworks on by-products of capture technologies; and
- future regulatory frameworks on CO<sub>2</sub> emissions imposing capture levels from CCS power plants beyond the current standards adopted by the industry.

Very little underpinning research has been undertaken to develop the approaches required to mitigate the technology lock-in risks that first-movers in demonstrating and deploying current state-of-the art CCS technologies will encounter. Most of the current research on CO<sub>2</sub> capture from power stations is instead typically focused on operation of the power cycle and the capture plant with the assumption of a fixed technology throughout the life of the plant.

## **2. Methodology: Assessing the implications of solvent upgrade**

It is important to recognise that it is not feasible accurately to predict with any meaningful accuracy details of future technical improvements, when they will occur, the nature of the plants which will want to be upgraded, the costs of implementing the upgrades or the benefits from doing so in future energy markets. Thus, cost-benefit analyses of the capital cost implications of designing selected pieces of equipment to be more upgradeable than they otherwise might have been vs future costs savings due to improved upgradeability are unlikely to provide, at this stage of technology development, any meaningful answers and have not been carried out.

The main purpose of this work is, instead, to examine, at a generic level, the scope for future-proofing CCS plants against technology developments so that they are able to incorporate technology improvements and to assess the performance lock-in that CCS power plants may encounter, when they have not been designed for upgradeability. Illustrative studies based on real option analysis method have been undertaken to illustrate the impact that future fuel prices, carbon prices, load factor and technology learning rates will have on the decision to incorporate future technology improvements in existing power plants with CCS. They are presented in a separate paper at this conference assessing the financial value of the option to upgrade a pulverised coal plant with post-combustion capture [1].

The scope of the analysis in this paper is principally limited to pulverised coal plants with post-combustion CO<sub>2</sub> capture using flue gas wet scrubbing with liquid solvents, since this technology is likely to be used on many of the first CCS plants and is inherently upgradeable through replacement of the solvent. The analysis assesses the associated technical implications for amine scrubbing plants integrated with a compression train and a thermal plant power cycle. A sensitivity analysis is performed, which

relates changes in key solvent properties to the thermal power of the amine process and to the electric power of the compression and ancillaries.

Four key solvent properties are varied independently to generate a series of hypothetical solvents.

- Mass transfer
- Solvent heat capacity,
- Enthalpy of absorption, and
- Thermal stability (and its associated consequences on the temperature of regeneration)

Although the approach of assuming these properties can vary independently is not thermodynamically consistent and the majority of the modelled ‘solvents’ cannot, therefore, exist, using this broad envelope of possibilities is a useful step to identify critical pieces of hardware that are likely to limit the performance of CCS power plant designed for e.g. 30%wt MEA, and then operated with improved solvents. The results are presented on the basis of the overall Electricity Output Penalty (EOP) of the plant, expressed in units of electrical energy lost per unit of CO<sub>2</sub> captured and compressed, e.g. kWh/tCO<sub>2</sub>. Unlike other metrics typically used to report performance, the Electricity Output Penalty is independent of fuel composition and the ratio of carbon content to heating value and allows comparisons of performance independent of site-specific fuel-related parameters. Careful consideration of the way the power plant is integrated with the carbon capture and compression equipment - and not just the amine CO<sub>2</sub> capture process in isolation - is needed to characterise the overall Electricity Output Penalty as solvents are replaced.

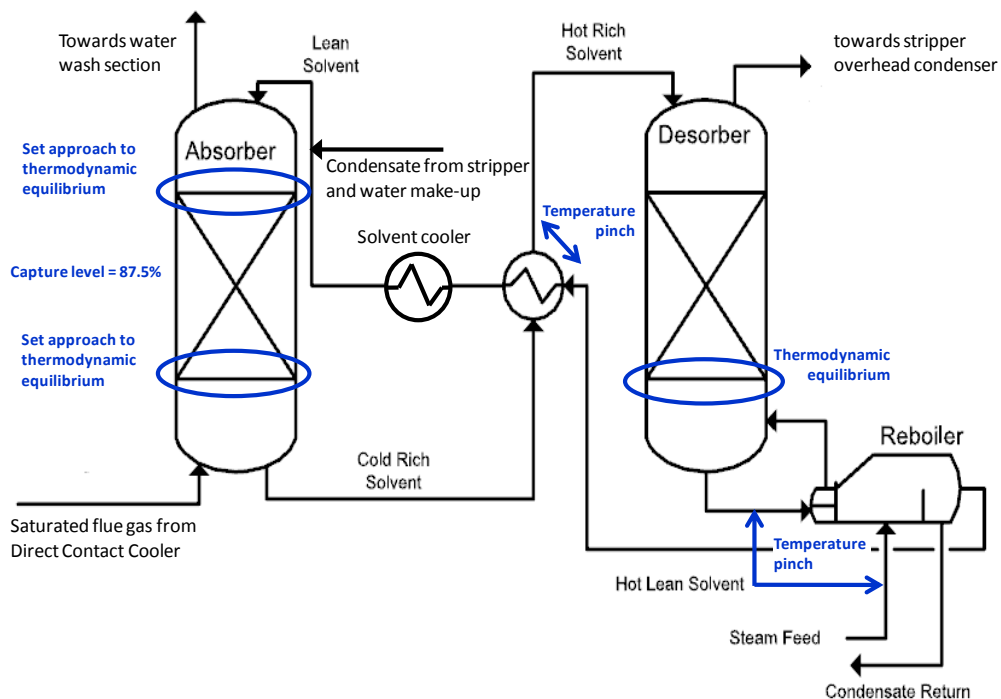


Figure 1: Amine capture process simplified flowsheet – Key assumptions are highlighted in blue

A model implemented in gPROMS [2] of a post-combustion capture unit, with 30%wt MEA as the initial solvent, integrated with a compression train and a pulverised coal plant power cycle is used to identify key pieces of equipment that may lock-in the EOP of a coal plant to a specific level when its solvent is upgraded and prevent full advantage being taken of the improved solvent properties. It is based on previous work evaluating the EOP of a coal plant for varying amine process parameters [3, 4] and a specific solvent/amine process model developed for this study. The “performance lock-in” associated with changing specific solvent property is defined as the additional EOP that may occur when the solvent inventory of the base case CCS power plant solvent, i.e. 30% wt MEA, is replaced to be upgraded with a new improved solvent, compared to the EOP of a new-build CCS power plant designed to operate with that improved solvent from the start. Performance lock-in may occur due to sizing of equipment or the operating conditions of the hardware of the capture unit, the compression unit or the power cycle. Its effect is to prevent full advantage being taken of improved solvents. If a solvent inventory is replaced with an improved solvent, the power plant and/or the capture unit may, in practice, not be capable of operating at the process conditions that are necessary to optimise the performance of that new solvent. Thus, although performance would improve to some degree with the solvent upgrade, the plant would not attain the maximum potential performance achievable for a comparable plant that has been designed from the outset to match the new solvent.

For a locked-in plant the solvent upgrade may reduce the EOP of the existing CCS power plant, but the EOP is, in most cases, still higher than that of a new-build unit designed to operate with the improved solvent, resulting in a performance lock-in. Design options and strategies for critical pieces of hardware are then identified to allow incorporating solvent improvements with minimal performance lock-in. The options presented follow the principles of low additional initial capital cost, minimal upfront performance penalty and good performance with improved solvents.

### 3. Performance lock-in of CCS power plants with solvent upgrades

Performance lock-in of CCS power plants with solvent upgrade can be quite significant. To illustrate this, it can be expected that a nth of a kind CCS plant with current state-of-the-art solvent technology will have, as a baseline value, an electricity output penalty of the order of 250-300 kWh/tCO<sub>2</sub>.

#### 3.1. Sensitivity to mass transfer

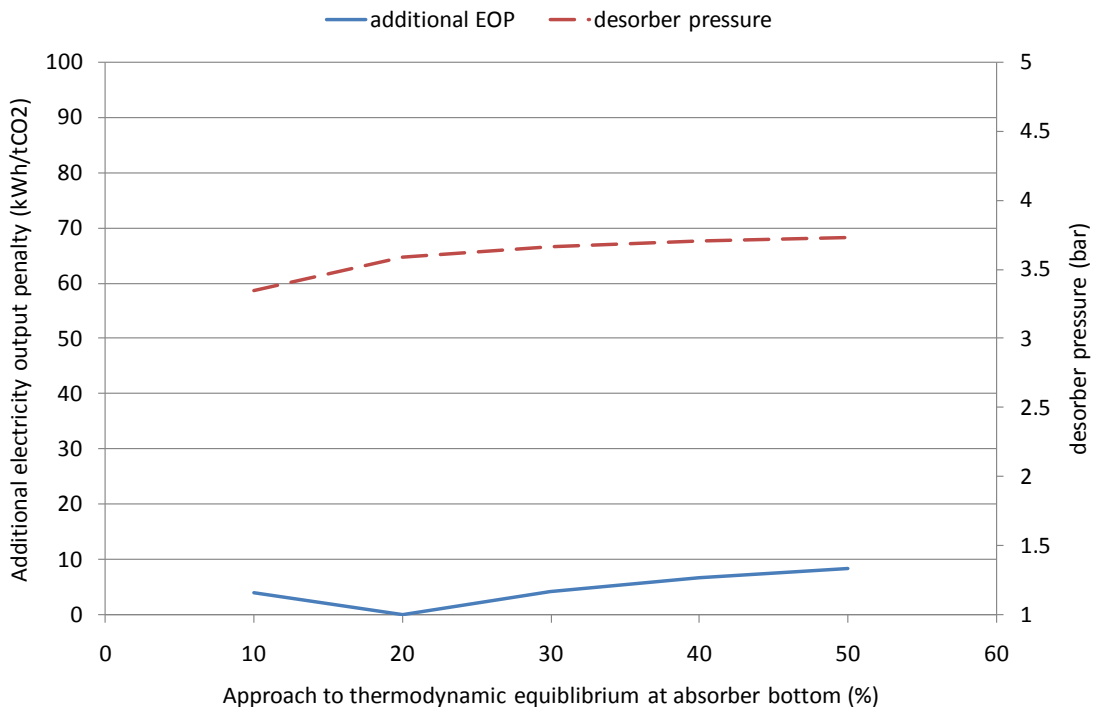
A schematic diagram of the amine process flowsheet is illustrated in Figure 1. Consideration of mass transfer is taken into account by controlling the approach to equilibrium at the bottom and at the top of the absorber so that mass transfer is controlled in the section of packing where CO<sub>2</sub> is absorbed. In an infinitely tall section of packing equilibrium would be reached in the absorber and the value of parameter  $\beta$  in Equation 1 would be equal to one.

Variations of mass transfer in the absorber may be affected by a range of solvent properties but also by process modifications, e.g. through the addition of intercooling in the absorber column. Obviously, in practice thermodynamic limits constrain the approach to equilibrium at the bottom of the absorber. Solvent upgrades, e.g. with the addition of additives to reduce solvent degradation or hardware corrosion, may reduce mass transfer, while promoters may be added to a specific solvent to increase mass transfer. These effects of changes of the approach to equilibrium at the bottom of the absorber, all other properties

being constant, are presented in Figure 2. The overall EOP is modified by changes of the sensible heat contribution of solvent energy of regeneration to the reboiler duty, as solvent capacity changes. The performance lock-in is found to be no greater than 10kWh/tCO<sub>2</sub> for the additional electricity output penalty over the range of inputs considered here.

### 3.2. Sensitivity to solvent specific heat capacity

Changes in solvent specific heat capacity modify the sensible heat contribution to solvent energy of regeneration. It results in changes in the amount of steam extracted from the turbines and, by extension, relates to the power plant's capacity to utilise additional steam available for power generation and export additional power if needed. The low pressure steam turbine (and alternator and electricity export capacity) and power cycle condenser capacity are the most critical limiting factor for changes in solvent heat capacity. A reduction in solvent heat capacity lowers the thermal energy of regeneration of the solvent and more steam is available for power generation. If the plant has not been designed to cope with a reduction of steam extraction level, the low pressure steam turbine is unable to benefit from the additional steam available (unless a capital intensive retrofit with a separate turbine feeding into a dedicated condenser is added to the power cycle). A performance lock-in then occurs, as shown in Figure 3.



**Figure 2: Additional electricity output penalty and desorber pressure for a range of approaches to equilibrium at absorber bottom for a constrained plant compared to the electricity output penalties of purposely built plants (and a fixed capture level) – Reference plant: approach to equilibrium: 20%**

For an increase in solvent heat capacity whole system performance is limited by the heat transfer surface area in the solvent reboiler and the cross-flow heat exchanger (between the absorber and the desorber) respectively. Two separate effects then limit performance when improved solvents with higher heat capacity are incorporated. First, a larger temperature pinch in the cross flow heat exchanger increases the sensible heat contribution to solvent energy of regeneration. Second, a larger approach temperature in the reboiler between condensing steam extracted from the power cycle and boiling solvent on the other side results in a lower temperature of regeneration with more water vaporisation per unit of CO<sub>2</sub> desorbed.

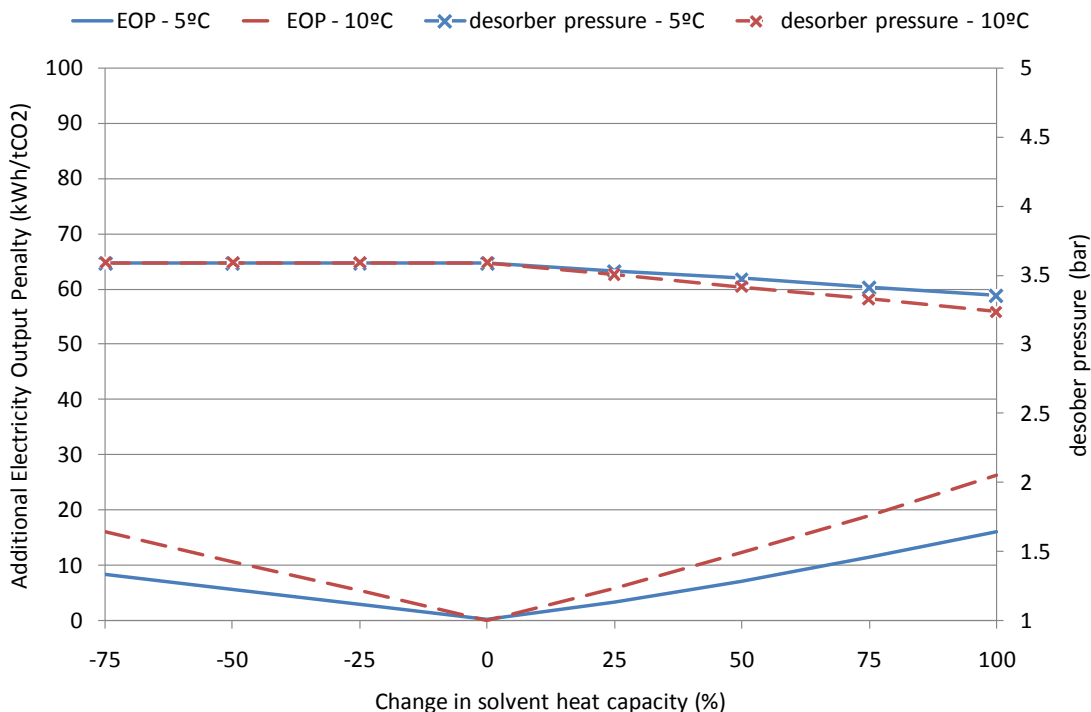


Figure 3: Additional electricity output penalty and desorber pressure for a range of solvent heat capacities compared to the electricity output penalties of plants purposely built for each solvent. Two cases of cross-flow heat exchanger temperature pinch are illustrated. Fixed capture level

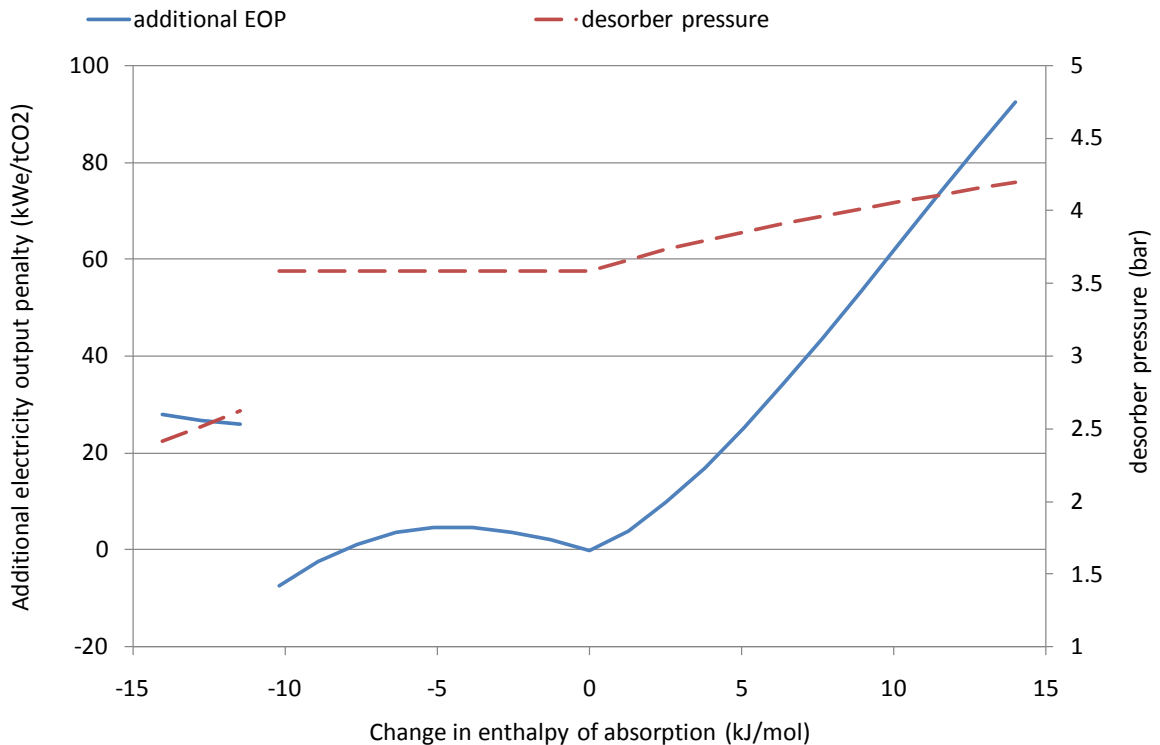
### 3.3. Sensitivity to solvent enthalpy of absorption

Changes to solvent enthalpy of absorption have wider effect on the overall capture process and constraints on the hardware of plants that have not been commissioned to handle solvent upgrades. Figure 4 notably shows the performance lock-in for a range of hypothetical solvents with their enthalpy of absorption varying from -15 to +15 kJ/mol compared to the enthalpy of absorption of the reference solvent (82kJ/mol). For higher enthalpies of absorption than the reference solvent, solvent energy of regeneration of the constrained reference plant is increased and this is not compensated by an increase in the compressor suction pressure that would otherwise be the likely offsetting factor [3]. An increase of 15kJ/mol in enthalpy of absorption results in a performance lock-in of the order of 90kWh/tCO<sub>2</sub>,

equivalent to 3.15% percentage point of plant efficiency with fuel specific emissions of 350gm of CO<sub>2</sub> per kWh.

For lower enthalpies of regeneration down to -10 kJ/mol compared to the reference solvent and hence lower solvent energy of regeneration, the constrained reference plant does not have capacity in the low pressure turbine to generate additional power from the excess steam available, and is unable to operate with this family of hypothetical improved solvents. The performance lock-in is, however, relatively small, or, in some instances, negative. The latter is here due to the fact that there is an optimum enthalpy of absorption around -5kJ/mol (equivalent to 77kJ/mol), as shown in Figure 5-7, different from the enthalpy of absorption of the reference solvent: 82kJ/mol. At enthalpies of absorption ranging from -10 to 0 kJ/mol example, solvent energy of regeneration is lower than that of the reference solvent. The constrained plant is unable to fit these solvents, whereas the electricity output penalty of purposely-built plants goes through a minimum and then increases when it is gradually reduces to -10kJ/mol.

At -11kJ/mol, corresponding to 71kJ/mol, solvent energy of regeneration is now higher than that of the reference solvent, due to increased vaporisation of water per unit of CO<sub>2</sub> desorbed. The constrained plant electricity is unable to fit this range of solvents resulting in a performance lock-in of 25-30 kWh/tCO<sub>2</sub>.



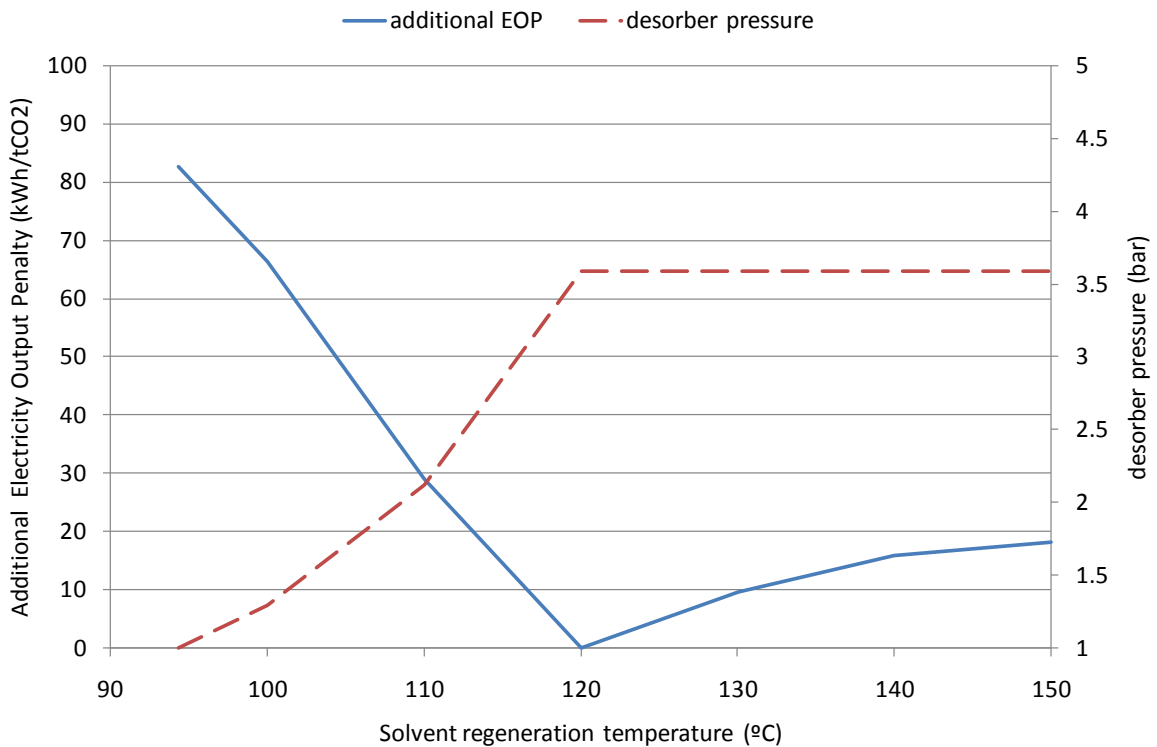
**Figure 4: Additional electricity output penalty and desorber pressure for a range of solvent enthalpy of absorption for a constrained plant compared to the electricity output penalties of purposely built plants. Constant cross heat exchanger temperature pinch: 5K – Fixed capture level.**



### 3.4. Sensitivity to solvent temperature of regeneration

The performance lock-in associated with solvent temperature of regeneration is directly related to the capacity of the power cycle to provide heating steam for the reboiler at the pressure required to minimise the overall electricity output penalty. Unlike solvent properties associated with a change of mass transfer, the additional electricity output penalty of plants with a power cycle unable to provide steam at the required pressure for improved solvents can be significant. This is illustrated in Figure 5 for solvent temperature of regeneration varying from 90°C to 150°C for a reference plant designed to supply heating steam at a pressure suitable for solvent regeneration at 120°C.

For temperatures of regeneration above 120°C, on the right hand side of the horizontal axis, a constrained plant is unable to supply steam at the required pressure, and the additional electricity output penalty is the difference between the electricity output penalty of a purposely-built plant for an elevated temperature of regeneration and the electricity output penalty of a constrained plant regenerating the reference solvent at 120°C.



**Figure 5: Additional electricity output penalty and desorber pressure for a range of solvent temperature of regeneration for a constrained plant compared to the electricity output penalties of purposely built plants - Constant cross heat exchanger temperature pinch: 5K – Fixed capture level.**

For temperature of regeneration lower than 120°C, the additional electricity output penalty results from throttling losses of a valve in the extraction line going to the reboiler, and from an increased compression duty associated with a lower desorber operating pressure, as indicated in Figure 5-7. In

practice, the throttling losses could be avoided by the addition in the steam extraction line of a back-pressure turbine capable of handling large flows and a relatively small pressure ratio. This option, however, requires modifications to the turbine hall foundation and to the power cycle, requiring design specific strategies at the time of the design of the plant. The performance lock-in is significant for low temperature solvents regenerated around 95°C, and is of the order of 80kWh/tCO<sub>2</sub>, equivalent to 2.8% percentage point for coals with fuel specific emissions around 350gm of CO<sub>2</sub> per kWh. It is also important to note that solvents regenerated at temperatures below 95°C will operate with a desorber pressure below atmospheric pressure and will therefore require a reinforcement of the mechanical structure of the desorber.

#### 4. Conclusions

The two critical components likely to generate significant additional electricity output penalties and result in major performance lock-in are:

- The steam turbines of the plant power cycle. This is directly related to the capacity of the power cycle to provide heating steam for the reboiler at the pressure required to minimise the overall electricity output penalty. The performance lock-in is significant for low temperature solvents regenerated around 95°C, and is of the order of 80kWh/tCO<sub>2</sub>, equivalent to 2.5-3% percentage point of efficiency for coal plants.
- The desorber and the compression train, with solvent enthalpy of absorption having a large effect on the overall capture process. Figure 4 shows the performance lock-in for a range of hypothetical solvents with an enthalpy of absorption varying from -15 to +15 kJ/mol compared to the enthalpy of absorption of the reference solvent.

Based on a direct analogy with capture readiness, where there are clear benefits to society of avoiding ‘carbon emissions lock-in’, upgradeability by future-proofing the design of CCS power plants for improved technology may also become a regulatory requirement for new capture plants. This may be implemented to ensure that the cost of electricity generation with CCS can be gradually reduced by incorporating learning from the first generation of CCS plants. In addition, upgradeability can avoid carbon emission lock-in by facilitating an increase of the capture levels of existing CCS plants. The alternative is, effectively, to build new CCS capacity to pursue higher capture levels >95% necessary to achieve climate change targets in the 2030s when the overall carbon intensity of electricity generation is expected to be lower than 50gCO<sub>2</sub>/kWh.

Power plants capable of improving their economic performance will benefit financially from being able to upgrade their technology. Technology options that allow developments that occur during the early stage of CCS deployment to be subsequently incorporated into new plants to lower the cost to society of CCS electricity generation may potentially be worth billions to the electricity consumers.

One of the most important requirements for upgradeability is for the base power plant to be able to operate with any level of steam extraction and also with any level of electricity output up to the maximum rating without capture. But this requirement will also confer operational flexibility and so is likely to be implemented in practice on new plants or on any integrated CCS retrofit project. Even if new pulverised coal post-combustion plants were to be built without the steam turbine capacity to handle the maximum possible steam flow it would still be possible to leave scope to add an additional LP cylinder (and

condenser), using a speed-synchronised clutch (e.g. a SSS model [5]) to the ‘free’ end of the alternator. The upgradeability requirements for a post-combustion capture pulverised coal power plant are:

- Ability to operate with any extraction steam flow and export the resulting net power output
- Scope to change the pressure at which extracted steam is used (typically through the installation of additional back-pressure turbine units)
- Space for additional electricity supplies for alternative capture system options (e.g. blowers for vapour compression, low-pressure compressor boosters for membranes, heat pumps or chillers etc.)

Upgradability options for CO<sub>2</sub> compression and transport systems might include:

- Strategies to compress and transport 95% or higher of the likely future CO<sub>2</sub> production from the plant (these will depend on the number and size of compressors fitted and the pipeline system downstream)
- Options to change the CO<sub>2</sub> compressor inlet pressure and first stage volumetric flow (due to changing water vapour/CO<sub>2</sub> ratios). This could include scope to add an additional blower first stage for reduced inlet pressures or to disconnect or bypass an existing first stage for higher inlet pressures.

Details of the novel technology post-combustion capture systems are less clear but, should their benefits prove sufficient to justify completely replacing an existing solvent-based system, their operation would also require varying amounts of electricity and steam, probably within envelopes that would also apply for a range of solvent systems and for plant operation without capture.

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